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RESEARCH MEMORANDUM

INVESTIGATION OF TURBINES FOR DRIVING SUPERSONIC COMPRESSORS

III - FIRST CONFIGURATION WITH FOUR NOZZLE SETTINGS AND ONE NOZZLE MODIFICATION

By Warner L. Stewart, Warren J. Whitney
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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

A turbine designed to power a supersonic compressor was investigated with four nozzle settings and one nozzle modification to determine the effect on turbine performance. The turbine configuration investigated utilized a convex insweep of the inner wall of the rotor and a high degree of blade taper in both blade thickness and blade chord. The analysis of the performance results of this turbine is used herein to illustrate the inherent aerodynamic problems associated with this turbine configuration and the effect of these problems on the applicability of the turbine.

For four nozzle settings the turbine performance indicated a considerable variation in efficiency at design specific work. With the correct ratio of nozzle throat area to rotor effective throat area, the design specific work was obtained near the peak efficiency. The performance of the turbine with the nozzle modification indicated about the same efficiency at design specific work output as was obtained for the turbine with the nozzle setting that effected greatest reduction in nozzle throat area. However, the specific work output at limiting loading was increased because of an increased specific work output at the tip before the tip reached limiting loading. It was also found that over the range of nozzle settings investigated the value of peak efficiency remained practically unchanged except for position on the performance map.

The investigation of this turbine configuration indicated that it has two inherent disadvantages in comparison with a turbine configuration with an axial inner wall at the rotor outlet and little chordwise taper: (1) The combination of the characteristics of a convex inswept hub contour and a high degree of taper in both blade thickness and blade chord, which causes most of the rotor throat area to lie within the rotor, reduces the weight flow from that which could be passed if the throat were at the rotor exit. (2) The rotor choking orthogonal, which lies

at the rotor exit at the tip, causes the tip to reach limiting loading considerably before the turbine limiting loading point. For a highly loaded turbine, this factor is undesirable with respect to efficiency, because the tip would probably be past limiting loading at the design point.

The turbine configuration having an axial inner wall at the rotor outlet and little external taper has aerodynamic advantages and can be used for this application if some form of internal taper is incorporated into the design to reduce the rotor centrifugal stresses.

INTRODUCTION

Considerable research and development of supersonic compressors has taken place in the past few years. The applicability of this type compressor in the aircraft power plant field is, of course, dependent on the attainment of suitable turbines designed to drive the compressor. Therefore, a research program has been in progress at the NACA Lewis laboratory to investigate the problems associated with turbines designed to drive these high-speed, high-specific-weight-flow compressors. The initial phase of the program consisted of the determination of the turbine design requirements from the operating characteristics of a typical supersonic compressor in an engine operating at supersonic flight velocities. The turbine design requirements and the design and performance of a first turbine configuration are presented in reference 1. The high-speed, high-specific-weight-flow characteristics of the compressor caused an extreme stress problem at the turbine rotor-blade hub. In an effort to reduce the stress to a practical value, the rotor blade was highly tapered in both thickness and blade chord and the rotor inner wall was contoured with a convex insweep to join the inlet and outlet inner walls. Although this turbine configuration was not necessarily optimum with respect to aerodynamics, it was necessary to diverge from conventional practice to reduce the rotor stress.

An analysis of the flow through the turbine rotor (ref. 2) indicated that with design nozzle-exit tangential velocities, the rotor throat area was insufficient to pass design weight flow. The experimental results (ref. 1) which were obtained on a 14-inch cold-air model of this turbine design confirmed the results of the analysis and showed that, because the rotor choked at less than design weight flow, the design nozzle-exit tangential velocities could not be obtained. At design speed the turbine limiting loading point was reached at a specific work output slightly less than design. Turbine limiting loading is defined as that point at which increases in total-pressure ratio result in no increase in work (ref. 3). The performance of this turbine with a 2.2-percent reduction in nozzle throat area (ref. 4) indicated that design work was obtained with an efficiency of 0.80, which represented a considerable improvement over that of the original nozzle setting. Because small changes in the ratio of nozzle throat area to rotor throat area were found to alter considerably the turbine efficiency near design work output, it was considered desirable to investigate the effect further by testing the turbine with two additional nozzle settings effecting nozzle throat area reductions of 4.7 and 6.8 percent from the original setting. In addition, because it was indicated that the rotor-blade tip section reached limiting loading before the other parts of the blade (see ref. 4), the turbine was investigated with the nozzles so modified that the blade was twisted to reduce the flow area at the tip section and increase the flow area at the hub, with the resulting average flow area reduced 6.2 percent from that of the original setting.

The purpose of this report is to investigate the effect of the ratio of nozzle throat area to rotor throat area on the turbine performance for four nozzle settings. The performance of the turbine with the nozzle modification will be presented to show the effect of twisting the nozzle blades on tip limiting loading. The experimental results of the investigation of this turbine with the four nozzle settings and the modification will then be used to discuss the aerodynamic problems associated with this turbine configuration and their effect on the applicability of the turbine to drive the high-speed, high-specific-weight-flow compressor.

SYMBOLS

The following symbols are used in this report:

Δh	specific enthalpy drop, Btu/lb
N	rotational speed, rpm
p	absolute pressure, lb/sq ft
r	radius, ft
T	absolute temperature, $^{\circ}R$
$\Delta T'$	total-temperature drop, $^{\circ}R$
U	blade velocity, ft/sec
w	weight-flow rate, lb/sec
$\Delta\alpha$	change in nozzle-exit blade angle
γ	ratio of specific heats

δ ratio of inlet-air pressure to NACA standard sea-level pressure, p_1'/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 adiabatic efficiency defined as ratio of turbine work based on temperature measurements to ideal turbine work based on inlet total temperature, and inlet and outlet total pressure, both defined as consisting of static pressure plus pressure corresponding to axial component of velocity

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:

des design

t rotor tip or outer radius

1 measuring station upstream of nozzles

2 measuring station at nozzle outlet, rotor inlet

3 measuring station downstream of rotor

4 measuring station in outlet pipe

Superscripts:

* NACA standard sea-level conditions

' total state

THEORETICAL CONSIDERATIONS

Reference 1 indicates that the subject turbine with the first nozzle setting reached limiting loading at a specific work output just below that of design as a result of rotor choking before the design nozzle-exit tangential velocities were obtained. For a given turbine configuration, the maximum nozzle-exit tangential velocity at a given speed is governed by the maximum total-to-static pressure ratio across the nozzle, which in turn is dependent upon the total-to-static pressure ratio across the turbine at which the rotor chokes. As the total-to-static pressure ratio across the turbine at which the rotor chokes is increased, there is a corresponding increase in the total-to-static pressure ratio across the nozzles. Since the rotor area remained the same, the three additional nozzle settings, which represent a reduction in the ratio of nozzle throat area to rotor effective throat area, caused the rotor to choke at a higher turbine total-to-static pressure ratio, with resulting increased nozzle-exit tangential velocities. Although the rotor-exit tangential velocity at limiting loading is reduced because of decreased total relative conditions, the reduction is small compared with the accompanying increase in the nozzle-exit tangential velocities. Thus, the specific work output at the turbine limiting loading point should be increased and for the second nozzle setting (ref. 4) was increased so that design specific work output was obtained at an efficiency of 0.80. Since the peak efficiency of 0.85 occurred below design specific work output but shifted nearer the design point from that of the initial setting (ref. 1), it would be expected that an increase in efficiency at design specific work output would be obtained as the nozzles are closed down further.

The aforementioned theory can be applied to a radial blade element as well as to the entire blade span. The results of reference 4 indicate that the rotor tip reached limiting loading at a specific work output below design and considerably below that corresponding to the turbine limiting loading point. Hence, if the throat area at the tip is reduced, it would be expected that the specific work output at the tip would be increased so that at design specific work output the tip would operate more efficiently. The modified turbine investigated in this report utilizes a twisted nozzle blade so that the tip throat area is reduced to determine whether an improvement in efficiency would be obtained.

TURBINE NOZZLE SETTINGS AND MODIFICATION

The turbine was investigated with four nozzle settings and one nozzle modification. The four turbine nozzle settings will herein be designated 1A (ref. 1), 1B (ref. 4), 1C, and 1D; and the turbine nozzle modification will be designated 1E. In table I are presented the average throat areas as compared with the original nozzle setting 1A and the change in nozzle-exit angle from that of 1A, $\Delta\alpha$. As indicated by the table, the nozzle blading for 1E was twisted and oriented so that the average area was approximately that of 1D.

APPARATUS, INSTRUMENTATION, AND METHODS

The apparatus, instrumentation, and methods of calculating the performance parameters used in this investigation were the same as those described in references 1 and 4, with the exception of the aforementioned nozzle changes and the addition of six static-pressure taps located on the turbine casing in an axial plane over the rotor. One pressure tap was located directly over the rotor-blade-tip trailing edge. Additional pressure taps were installed 1/4 and 1/2 inch upstream of the trailing edge and 1/4, 3/4, and $1\frac{1}{4}$ inches downstream of the trailing edge of the rotor blade. A photograph of the turbine setup is shown in figure 1, and a diagrammatic sketch of the turbine setup and its various components is shown in figure 2.

The turbine performance runs for 1C, 1D, and 1E were made in the same manner as those of reference 1. The turbine-inlet temperature and pressure were maintained constant at nominal values of 135° F and 32 inches of mercury absolute, respectively. The speed was varied from 60 to 130 percent of design speed in even increments of 10 percent. At each speed, the total-pressure ratio across the turbine was varied from the maximum possible (as dictated by the laboratory exhaust facilities) to approximately 1.40. Turbine adiabatic efficiency was based on the ratio of inlet total pressure to outlet total pressure (both defined as the sum of the static pressure and the pressure of the axial component of velocity; see ref. 1).

The absolute accuracy of the measured and calculated parameters is estimated to be within the following limits:

Temperature, $^{\circ}$F	±0.5
Pressure, in. Hg	±0.05
Weight flow, percent	±1.0
Turbine speed, rpm	±20
Efficiency, percent	±2.0

The reproducibility of the adiabatic efficiency at or near design operations was calculated to be within ±0.6 point.

RESULTS AND DISCUSSION

Effect of Change in Ratio of Nozzle Throat Area to Rotor Throat Area on Turbine Performance

Over-all performance. - The experimental performance of the four turbine nozzle-setting configurations 1A, 1B, 1C, and 1D can be compared to show the effect of the ratio of nozzle throat area to rotor effective throat area on the performance. The performance of 1D and 1E can be compared to show the effect on tip limiting loading, since the average throat areas were approximately the same. Table I summarizes the area variation and nozzle settings as well as the pertinent over-all performance results, and figure 3 presents the over-all performance maps. The equivalent specific work $\Delta h'/\theta_{cr}$ as calculated from the temperature measurements is shown as a function of the weight-flow parameter $\varepsilon w N/\delta$ (product of equivalent weight flow and turbine speed) with percent of design speed and total-pressure ratio as parameters. The efficiency contours are also included. Point A represents design specific work and design speed. It can be seen from figures 3(a) to 3(d) that, in general, the peak efficiency remained at about the same value (0.85) but shifted to a region of higher total-pressure ratio as the nozzle area was decreased. The specific work output at limiting loading would also increase as the nozzle area was decreased. Thus, a comparison of the design points A (design specific work and design speed) for the four performance maps shows a considerable improvement in the turbine efficiency as the nozzle area was reduced. Figure 3(a) shows that the turbine limiting loading point was reached before design specific work could be extracted (ref. 1), whereas for nozzle settings 1B, 1C, and 1D the adiabatic efficiency at the design point was 0.80, 0.82, and 0.84, respectively. The effect of twisting the nozzle blades can be seen by comparing figures 3(d) and 3(e). The region of highest efficiency for the nozzle modification 1E shifted nearer to the design point. However, the value of the maximum efficiency dropped slightly so that the efficiency at the design point for 1D and 1E was about the same, 0.84.

A comparison of the abscissas of points A shows that the equivalent weight flow decreased as the average nozzle area was decreased. A comparison of the equivalent weight flow is also made in table I. A drop in equivalent weight flow of 5 percent between 1A and 1D (from 14.5 lb/sec to 13.8 lb/sec) was obtained and can be attributed to the decreased total conditions relative to the rotor due to the increased nozzle-exit tangential velocities, since at design specific work output the rotor rather than the nozzles limited the weight flow.

A better comparison of the turbine performance at design speed can be made by use of figure 4, in which the equivalent specific work is shown as a function of the total-pressure ratio for the four nozzle settings and the modification. In the region of low specific work output the performance for 1A, 1B, 1C, 1D, and 1E is about the same. However, as the specific work is increased and approaches that corresponding to the turbine limiting loading point, the performance deviates considerably, in that the specific work output at the turbine limiting loading point is increased as the nozzle throat is decreased. This increase resulted in obtaining design work output at a lower total-pressure ratio and an increase in efficiency as shown in figure 5. The shift in peak efficiency to a region of higher total-pressure ratio may also be noted.

Nozzle-exit conditions. - As indicated in the THEORETICAL CONSIDERATIONS section, the improvement in turbine performance can be attributed to increased nozzle-exit tangential velocities resulting from an increased total-to-static pressure ratio across the nozzles before the rotor choked. Figure 6 presents the total-to-static pressure ratio across the nozzle hub and tip as a function of total-pressure ratio across the turbine. As the nozzles are closed down the total-to-static pressure ratio across the nozzles increases with an accompanying increase in the nozzle-exit velocity. Because the small changes in the nozzle angles were toward the tangential direction, the increase in nozzle-exit velocity results in an increase in the nozzle-exit tangential velocities. The point where the curves in figure 6 level off represents the total-pressure ratio at which the rotor chokes.

The effect of twisting the nozzle blades (1E) on the total-to-static pressure ratio across the nozzle can be seen in figure 6 by comparison with the curves for 1D. The total-to-static pressure ratio across the tip is seen to increase considerably. Therefore, at the tip the nozzle-exit tangential velocity has been increased over that of nozzle setting 1D.

Tip Limiting Loading

Total-temperature-drop surveys across the rotor from the inner wall to the outer wall were taken for nozzle settings 1C and 1D and the modification 1E. These surveys, taken at various total-pressure ratios and at design speed, are presented in figure 7. It can be seen that for 1C and 1D, as the total-pressure ratio across the turbine is increased, the specific work output at both the hub and tip is increased until the tip reaches its limiting loading point at a total-pressure ratio of about 2.0. At total-pressure ratios beyond this point, the work output increases near the hub section but remains constant near the tip section. As pressure ratio is further increased, the temperature-drop curves for the higher pressure ratios become coincident over a greater portion of the blade span and this coincidence progresses radially inward. At pressure ratios of about 2.4 and above, practically the entire blade span has reached limiting loading. At these high pressure ratios, losses resulting from limiting loading (ref. 3) would occur along most of the blade span, being more severe near the tip section. This phenomenon can also be illustrated by figure 8, which shows the variation for setting 1C of the outer-shroud static pressure with axial position for several turbine total-pressure ratios at design speed. For total-pressure ratios of 2.0 or greater, the static pressure at the blade outlet at the tip section is unaffected by increases in the total-pressure ratio across the turbine. This trend would indicate that an increase in the total-pressure ratio beyond this point is not accompanied by an increased expansion of the gas at the blade outlet, and thus the blade-outlet velocity and the work at this section remain constant.

The tip reaches limiting loading at a pressure ratio considerably below that corresponding to design work output. Hence, at design specific work output there is considerable drop in efficiency because of additional total-pressure losses near the tip section. Since the peak efficiency obtained with this rotor blade appeared to be relatively insensitive to small changes in nozzle angle setting, and since limiting loading losses were shown to be quite severe, nozzle modification 1E was investigated. The nozzle blade was twisted (table I) so as to increase the nozzle-exit tangential velocity at the tip section and thereby increase the specific work output of this section at limiting loading and at the same time maintain the same nozzle throat area as that of nozzle setting 1D. A comparison of the total-temperature-drop surveys for 1D and 1E (fig. 7) indicates that the tip reaches limiting loading before the other blade sections in both cases. However, the specific work output at the tip section at limiting loading was higher for 1E than for 1D.

Discussion of Aerodynamic Problems Associated With This Turbine Configuration

The experimental performance results presented in references 1 and 4 can be combined with the design problems discussed in reference 1 and the analytical investigation of reference 2 to indicate some of the characteristic problems associated with the turbine configuration being investigated.

The following rotor characteristics define this turbine configuration: (1) convex insweep of inner wall of rotor and (2) high degree of blade external taper in both blade thickness and blade chord.

Mass-flow problem. - The criticalness of certain problems in a particular turbine is, of course, dependent on the application of the turbine. For this application, a high weight flow per unit frontal area and high rotational speed were specified. The high rotational speed and large flow area required to pass the weight flow caused a severe stress problem at the rotor hub, which was minimized by this turbine configuration in which both the nozzle and the rotor operated close to choking at design conditions. The results of the analysis of reference 2 and the performance of the turbine show that this configuration has the inherent characteristic of a minimum effective area within the rotor that occurs at the trailing edge at the tip and inside the rotor at the hub. It is this area that limits the weight flow. The performance investigation verified these results and indicated that the maximum efficiency at design specific work output and design speed occurred for the setting corresponding to about 91-percent design weight flow. From the design considerations, the turbine-exit-annulus area is sufficient to pass design weight flow. Therefore, the drop in weight flow from design can be attributed to the choking condition within the rotor (ref. 2) inherent in this turbine configuration. Decreasing the hub-tip radius ratio downstream of this choking position only increases the blade stress unnecessarily, since the additional flow area provided is not needed (fig. 9(a)). The inner wall contour could simply be straightened out at this point, and the resulting blade (fig. 9(b)) would probably pass the same weight flow with a lower blade stress. A blade design for this application which would probably be a considerable improvement with respect to passing required weight flow is shown in figure 9(c). This configuration has an inner wall contour that sweeps inward in the nozzles and straightens out to an axial direction in the rotor blade. This contour in combination with stacking arrangement of the blade sections would cause the choking orthogonal, or effective throat, to lie at a position of minimum hub-tip radius ratio.

Tip limiting loading problem. - The experimental performance investigations of the turbine have indicated that the rotor tip reached limiting loading at a total-pressure ratio below that corresponding to design specific work output and considerably below that corresponding to the turbine limiting loading point. The fact that the tip reaches limiting loading considerably before other sections can be attributed to the position of the choking orthogonal and the effect of the pressure gradients. Figure 4 of reference 2, the analytical investigation of the flow through the turbine rotor, indicates that the choking orthogonal is at the trailing edge at the tip and well within the rotor at the hub. Therefore, further expansion from the choking point at the tip must be unguided and accomplished by the mechanism described in reference 3. However, at the hub considerable guided expansion can occur before limiting loading is approached.

The effect of this characteristic on the turbine performance is detrimental, especially for a turbine in which the design point is close to the turbine limiting loading point. At the design point, the turbine total-pressure ratio would be considerably greater than that corresponding to the tip limiting loading point. The design point will therefore be in an efficiency region removed from the peak efficiency region, where small increases in specific work output are accompanied by large losses in efficiency.

Adopting a blade configuration similar to that shown in figure 9(c) would also alleviate this situation. Because of the blade geometry, the choking orthogonal for this blade would occur nearer the trailing edge, and all the radial elements along the blade span would tend to reach limiting loading at about the same pressure ratio.

Comparison of the two blading designs. - It has been mentioned that a blading design such as shown in figure 9(c) would probably be superior to the subject turbine-blade design with respect to passing design weight flow and to limiting loading at the blade tip. The original turbine-blade design was based on free-stream conditions ahead of and downstream of the rotor blade at two radial sections, and it was desired to have a smooth convergent channel in the blade passage. It would be expected that a configuration such as 9(c) would produce a velocity diagram more nearly approximating that of design, since the flow passage of the subject turbine operated effectively as a convergent-divergent channel because of the position of the choking orthogonal. A blading configuration such as figure 9(c) would then be better generally with respect to aerodynamics. This blade would admittedly be more highly stressed, however, since the blade shape has very little external taper and has a somewhat greater average blade span than that of the subject turbine. Since stress is of critical importance, some form of internal taper would have to be employed to make this design usable.

SUMMARY OF RESULTS

The results of the investigation of a turbine designed to power a supersonic compressor can be summarized as follows:

1. The turbine performance for four nozzle settings indicated a considerable variation in the efficiency at design specific work. With the correct ratio of nozzle throat area to rotor effective throat area, the design specific work was obtained near the peak efficiency. The weight flow for this nozzle setting was 91 percent of design value and represented a decrease of 5 percent from that of the original nozzle setting.

2. For the four nozzle settings and one modification, the value of the peak efficiency remained practically unchanged, while the location on the performance maps did change.

3. The performance of the turbine with the twisted nozzle blade indicated about the same efficiency at design specific work output as the nozzle setting with the least area; however, the specific work output at limiting loading was increased because of the increased work output at the tip before this section reached limiting loading.

CONCLUSIONS

The investigation of the turbine configuration having the characteristics of convex insweep of the inner wall of the rotor and high degree of blade external taper in both blade thickness and blade chord has indicated that with respect to aerodynamics the configuration has two inherent disadvantages in comparison with a turbine configuration with an axial inner wall at the rotor outlet and little axial taper: (1) The combination of these two characteristics, which causes most of the rotor choking orthogonal to lie within the rotor, reduces the weight flow from that which could be passed if the throat were at the rotor exit. (2) The rotor choking orthogonal which lies at the rotor exit at the tip, causes the tip to reach limiting loading considerably before the turbine limiting loading point. For a highly loaded turbine this factor is undesirable with respect to efficiency, because the tip would probably be past limiting loading at the design point.

The turbine configuration having an axial inner wall at the rotor outlet and little external taper has aerodynamic advantages and can be used for this application if some form of internal taper is incorporated into the design to reduce the rotor centrifugal stresses.

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1. Stewart, Warner L., Schum, Harold J., and Whitney, Warren J.: Investigation of Turbines for Driving Supersonic Compressors. I - Design and Performance of First Configuration. NACA RM E52C25, 1952.

2. Stewart, Warner L.: Analytical Investigation of Flow Through High-Speed Mixed-Flow Turbine. NACA RM E51H06, 1951.

3. Hauser, Cavour H., and Plohr, Henry W.: Two-Dimensional Cascade Investigation of the Maximum Exit Tangential Velocity Component and Other Flow Conditions at the Exit of Several Turbine-Blade Designs at Supercritical Pressure Ratios. NACA RM E51F12, 1951.

4. Stewart, Warner L., Schum, Harold J., and Wong, Robert Y.: Investigation of Turbines for Driving Supersonic Compressors. II - Performance of First Configuration with 2.2-Percent Reduction in Nozzle Flow Area. NACA RM E52E26, 1952.

TABLE I. - DESIGN REQUIREMENTS AND EXPERIMENTAL RESULTS FOR TURBINE FOR DRIVING SUPERSONIC COMPRESSORS

	Design requirements	Turbine configuration				
		1A	1B	1C	1D	1E
Average area, percent of 1A	----	100	97.8	95.3	93.2	93.8
Reduction in nozzle angle, $\Delta\alpha$, deg	----	----	-1	-2	-3	---[a]
Equivalent weight flow, $\epsilon w \sqrt{\theta_{cr}}/\delta$, lb/sec	15.2	14.5	14.3	14.0	13.8	13.8
Weight flow, percent design	----	95.4	93.8	91.8	90.8	90.8
Equivalent tip speed, $U_t/\sqrt{\theta_{cr}}$, ft/sec	752	752	752	752	752	752
Equivalent specific work, $\Delta h'/\theta_{cr}$, Btu/lb	20.0	---[b]	20.0	20.0	20.0	20.0
Total-pressure ratio, p_1'/p_3'	2.19	---[b]	2.19	2.15	2.11	2.10
Adiabatic efficiency, η	0.80	----	0.80	0.82	0.84	0.84

[a]Hub, -2°; tip, -4°.

[b]Limiting loading of turbine reached before design work was obtained.

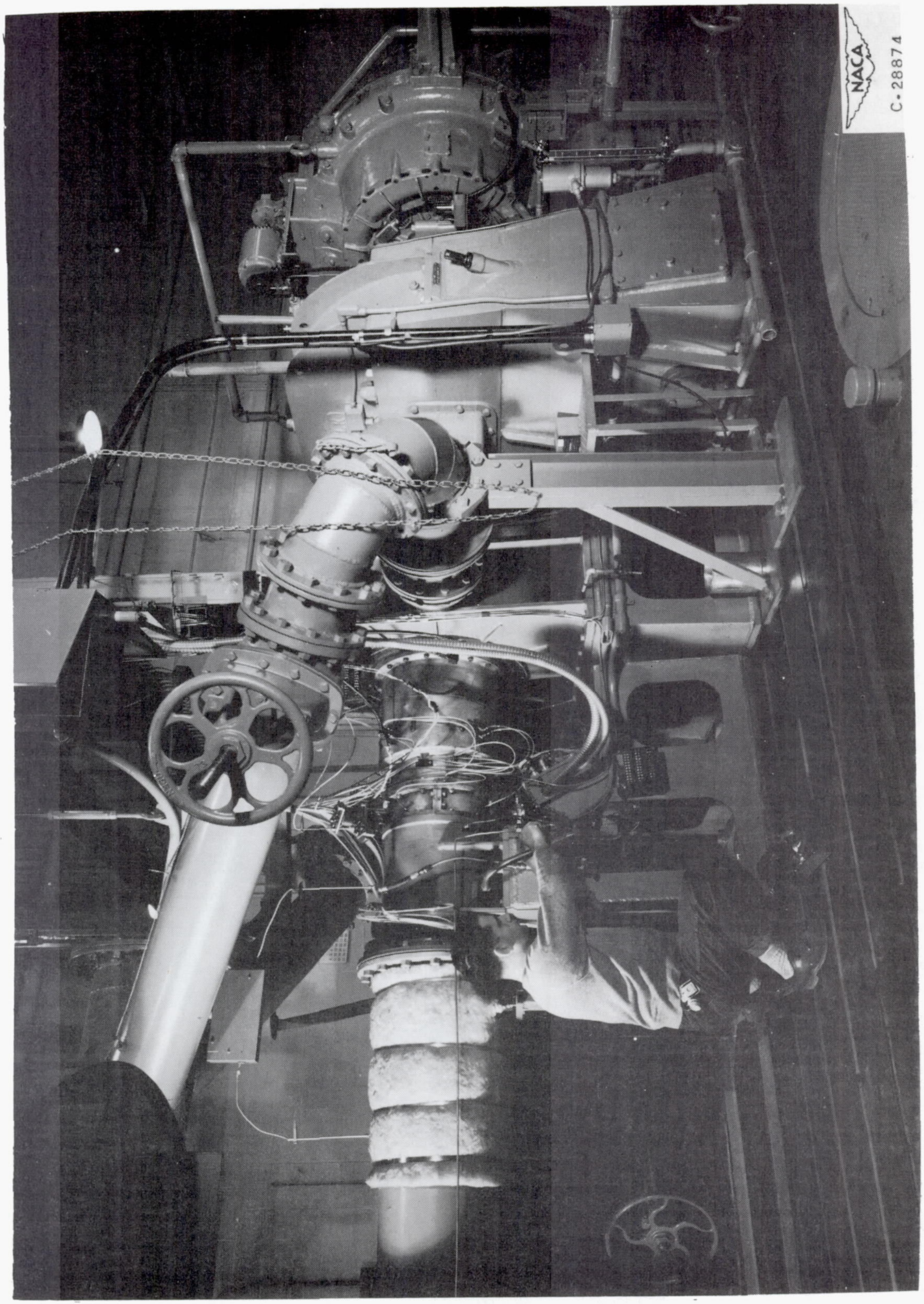


Figure 1. - Photograph of turbine setup.

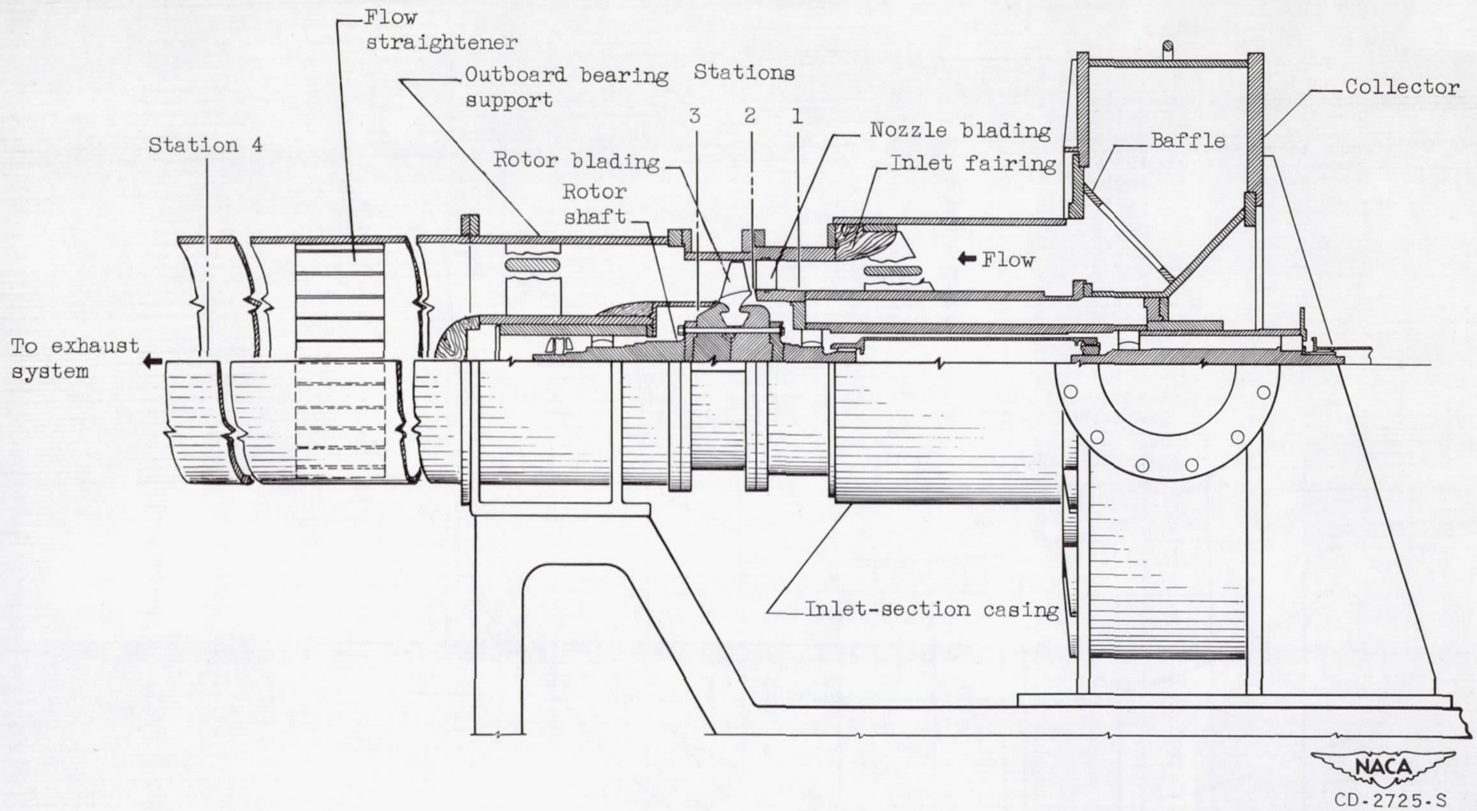
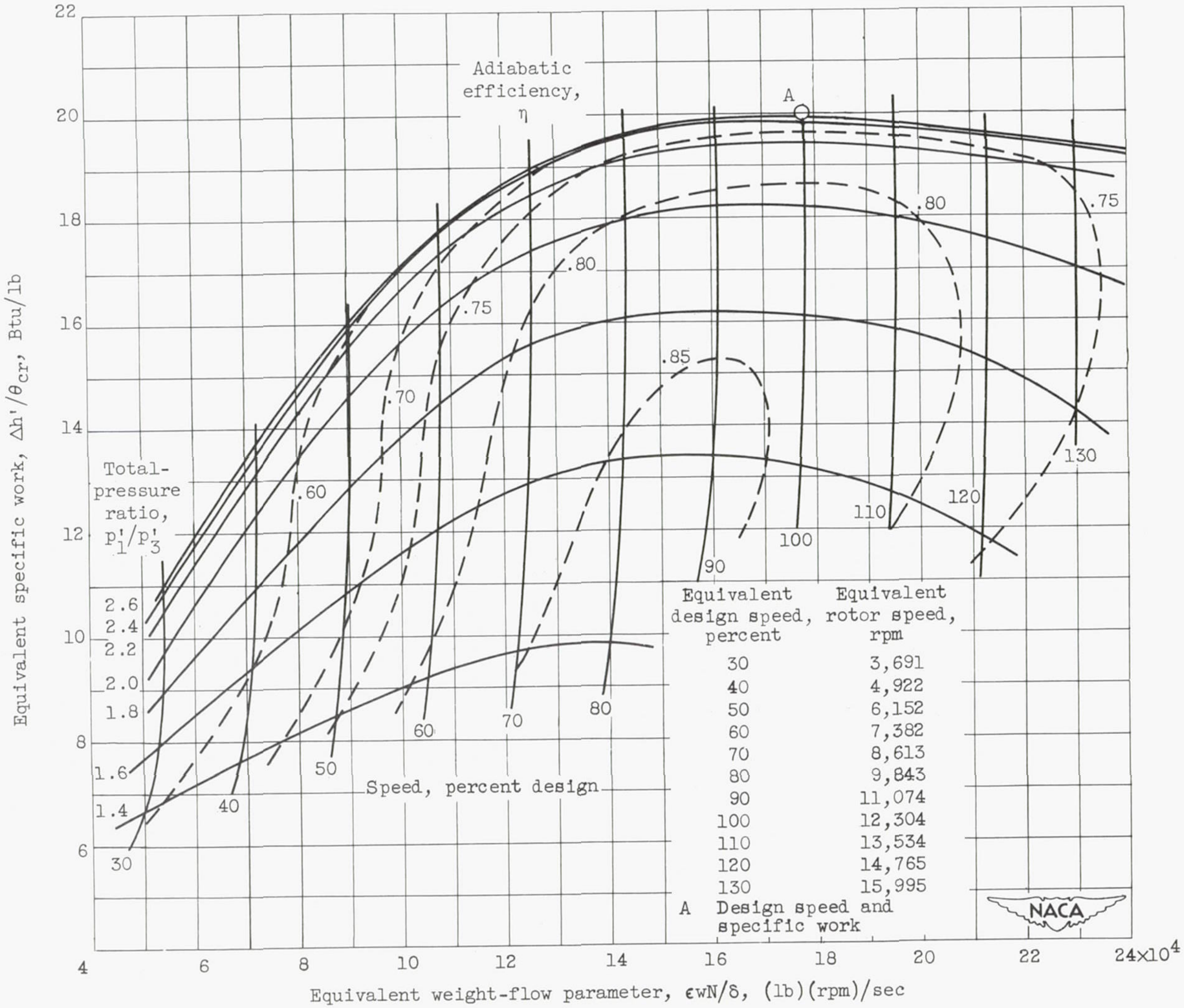
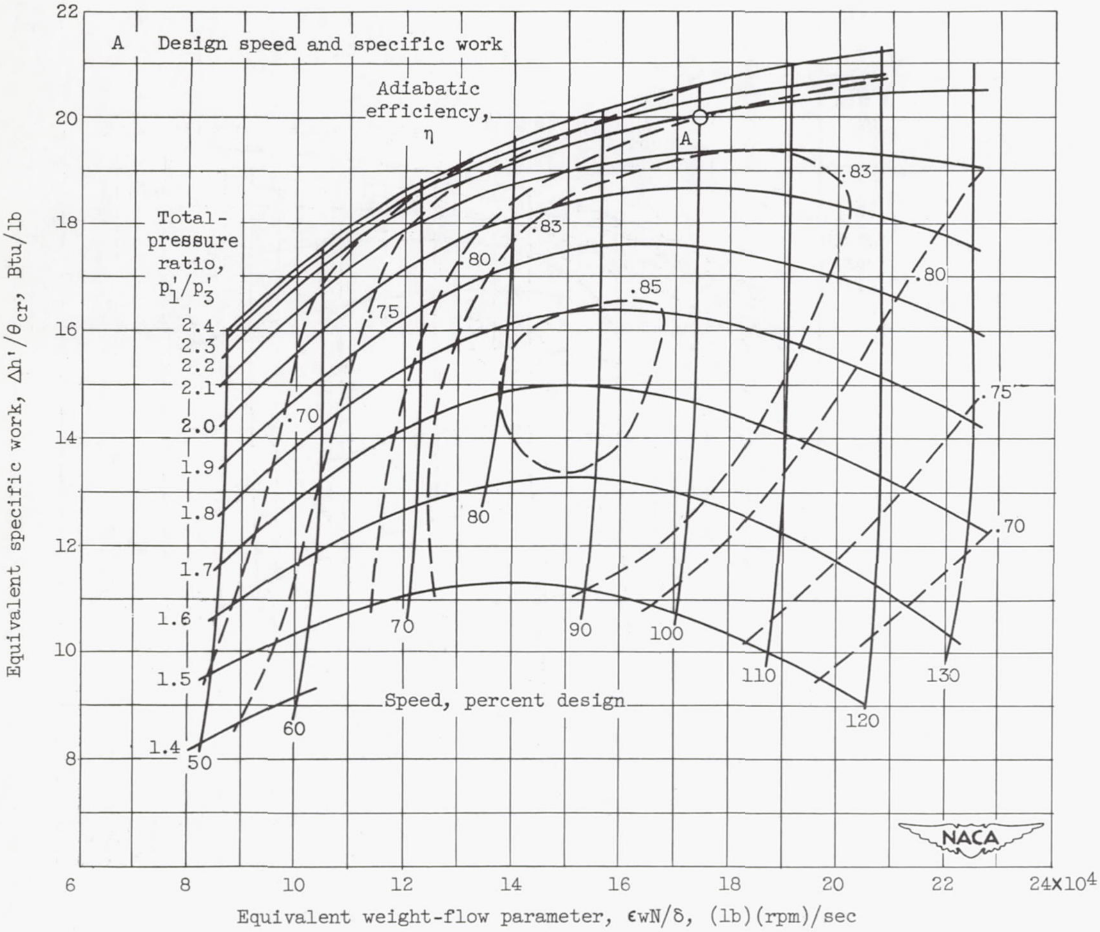


Figure 2. - Cold-air turbine test section.



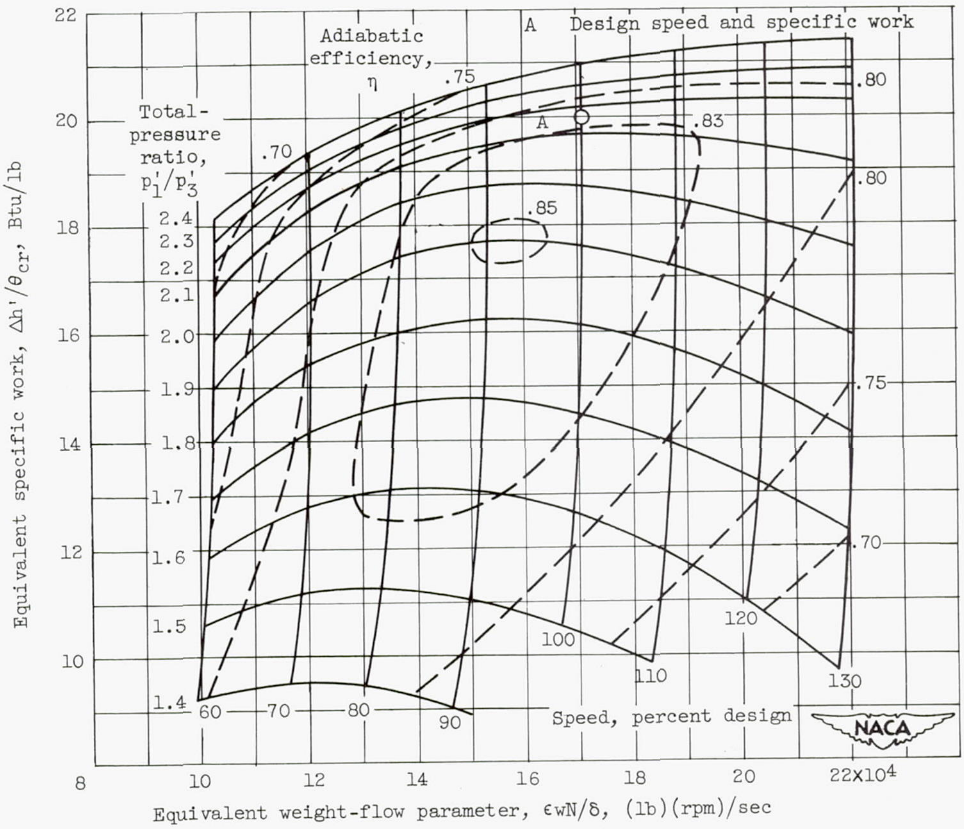
(a) Original nozzle setting 1A.

Figure 3. - Over-all performance of turbine.



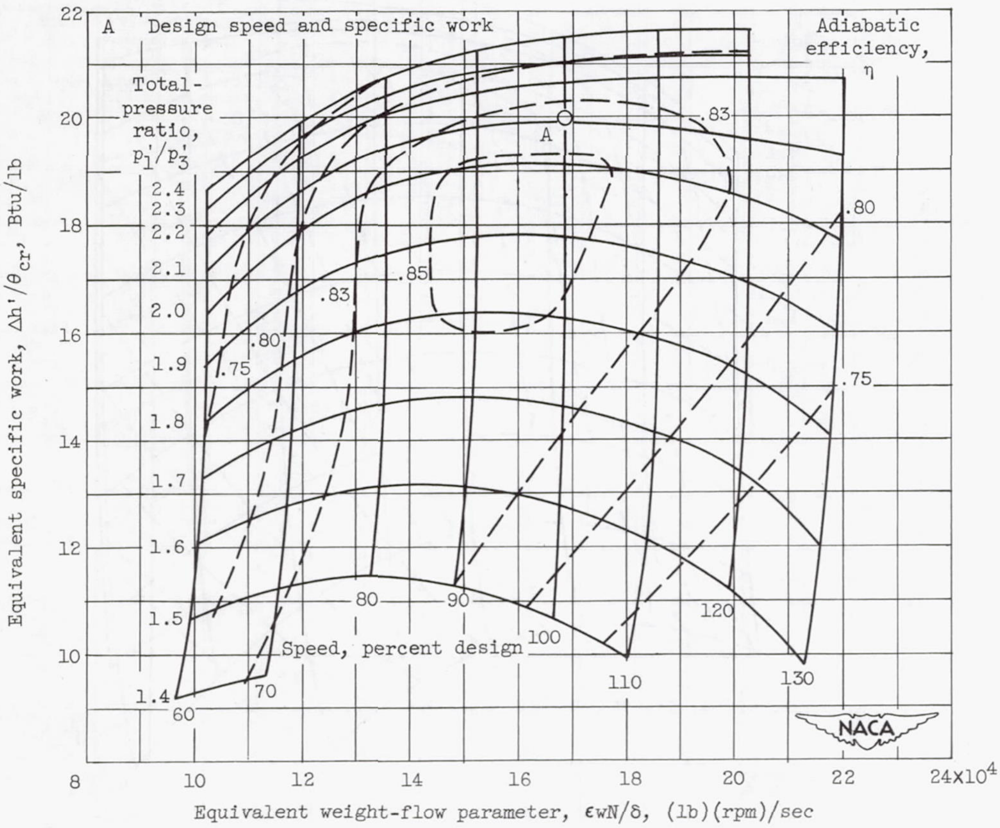
(b) Nozzle setting 1B.

Figure 3. - Continued. Over-all performance of turbine.



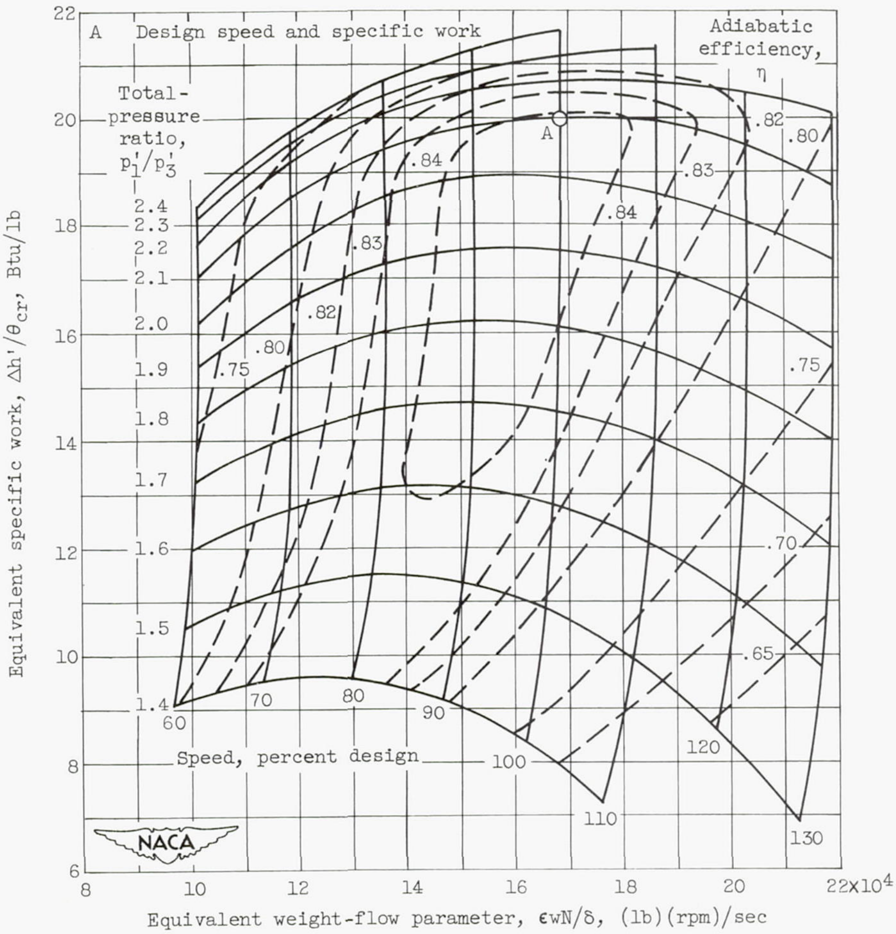
(c) Nozzle setting 1C.

Figure 3. - Continued. Over-all performance of turbine.



(d) Nozzle setting 1D.

Figure 3. - Continued. Over-all performance of turbine.



(e) Nozzle modification 1E.

Figure 3. - Concluded. Over-all performance of turbine.

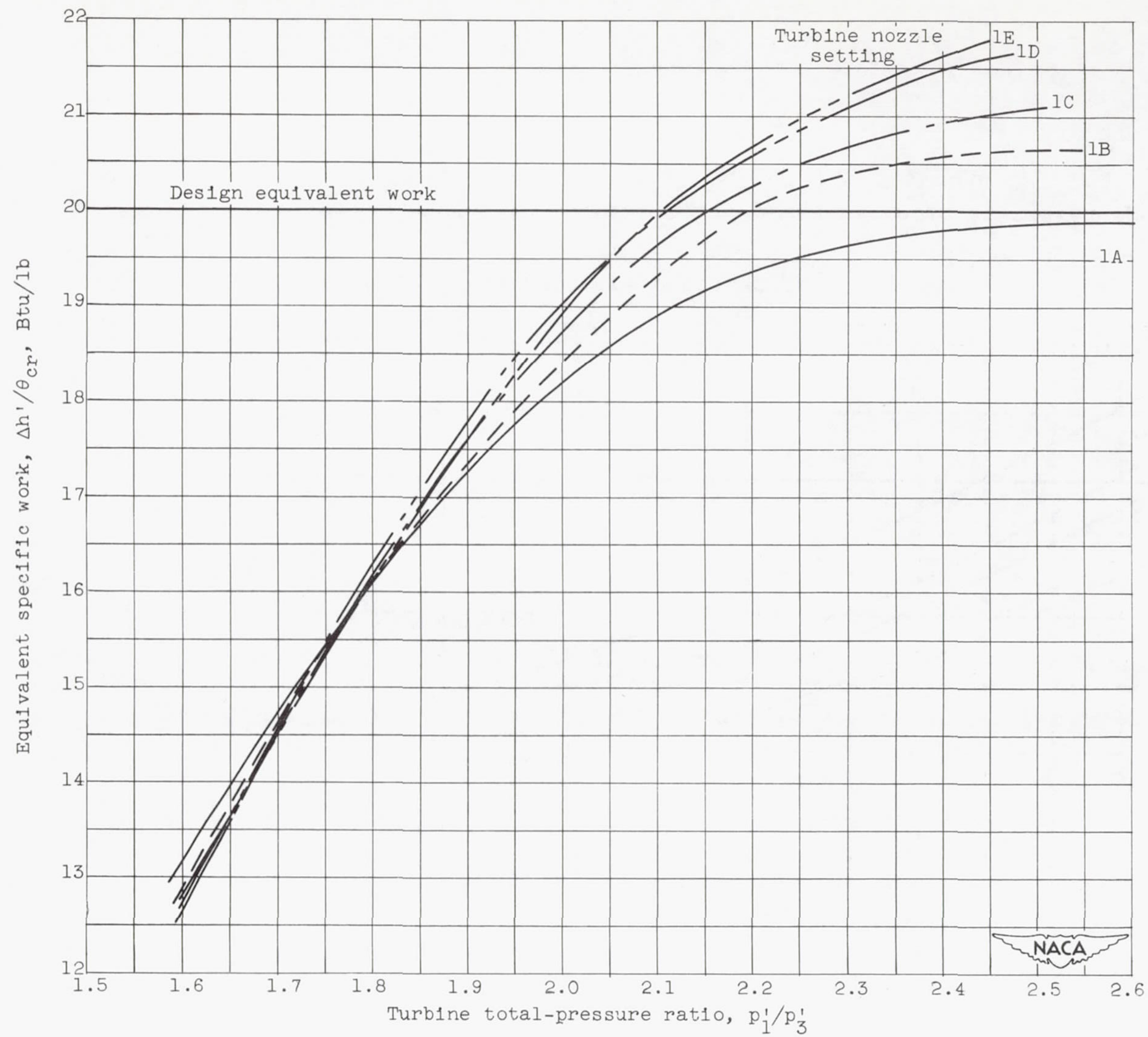


Figure 4. - Variation of equivalent specific work with turbine total-pressure ratio at design speed.

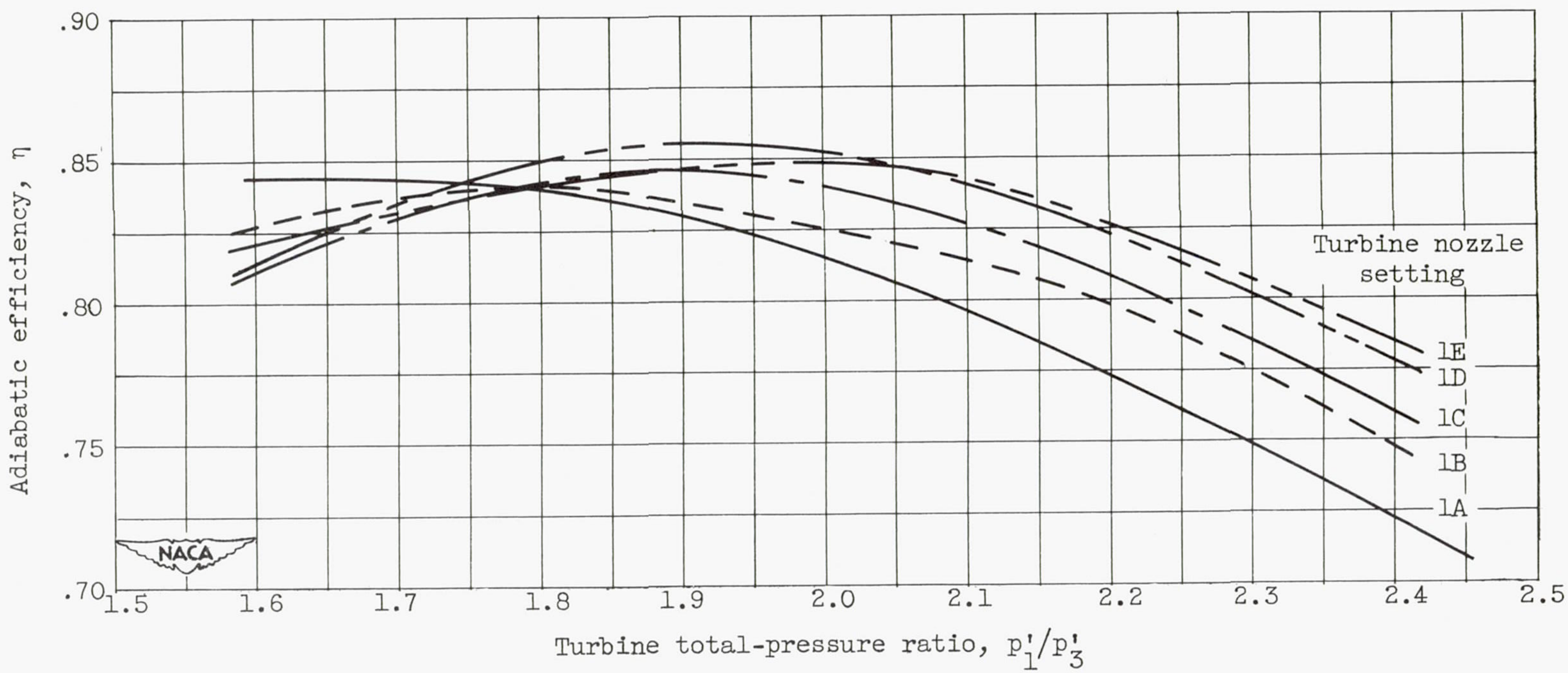


Figure 5. - Variation of efficiency with turbine total-pressure ratio at design speed.

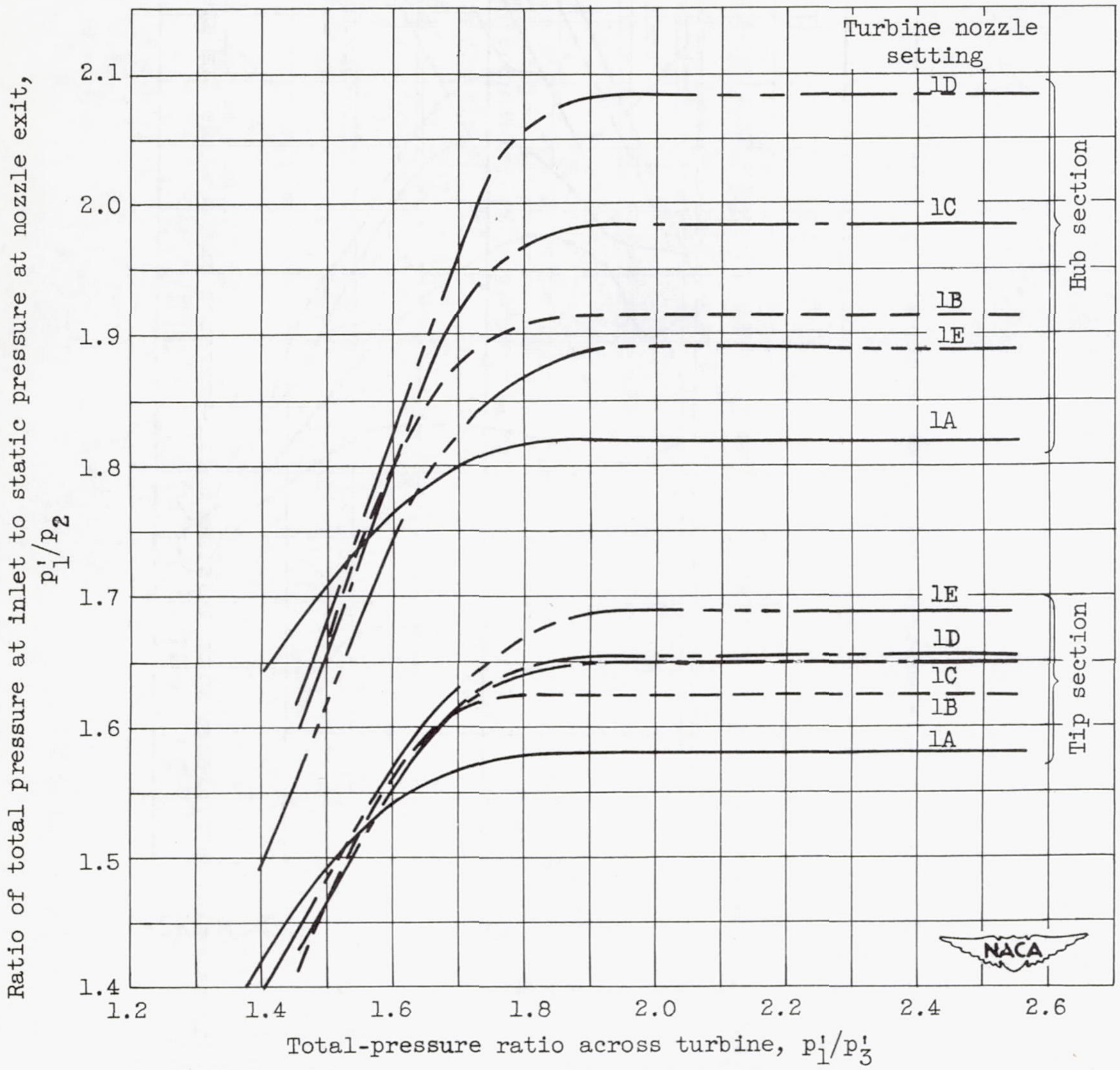
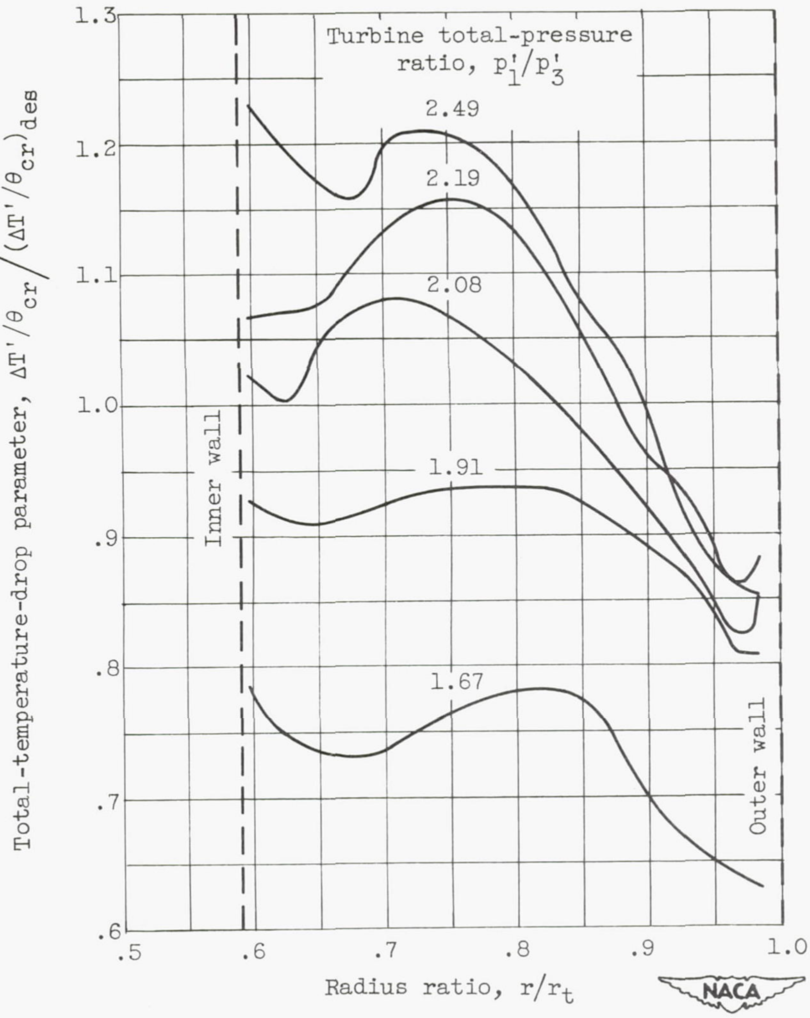
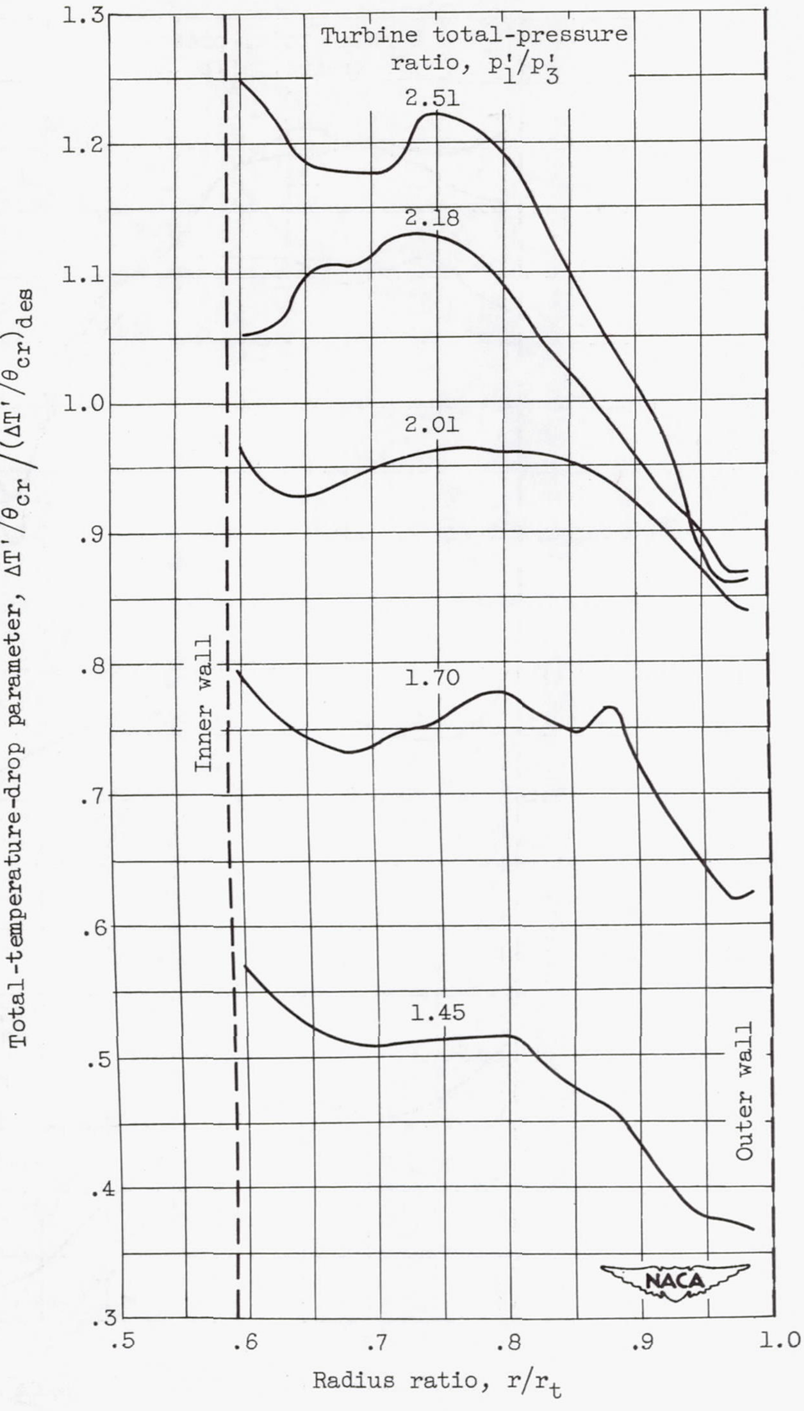


Figure 6. - Effect of total-pressure ratio across turbine on total-to-static pressure ratio across nozzles at design speed.



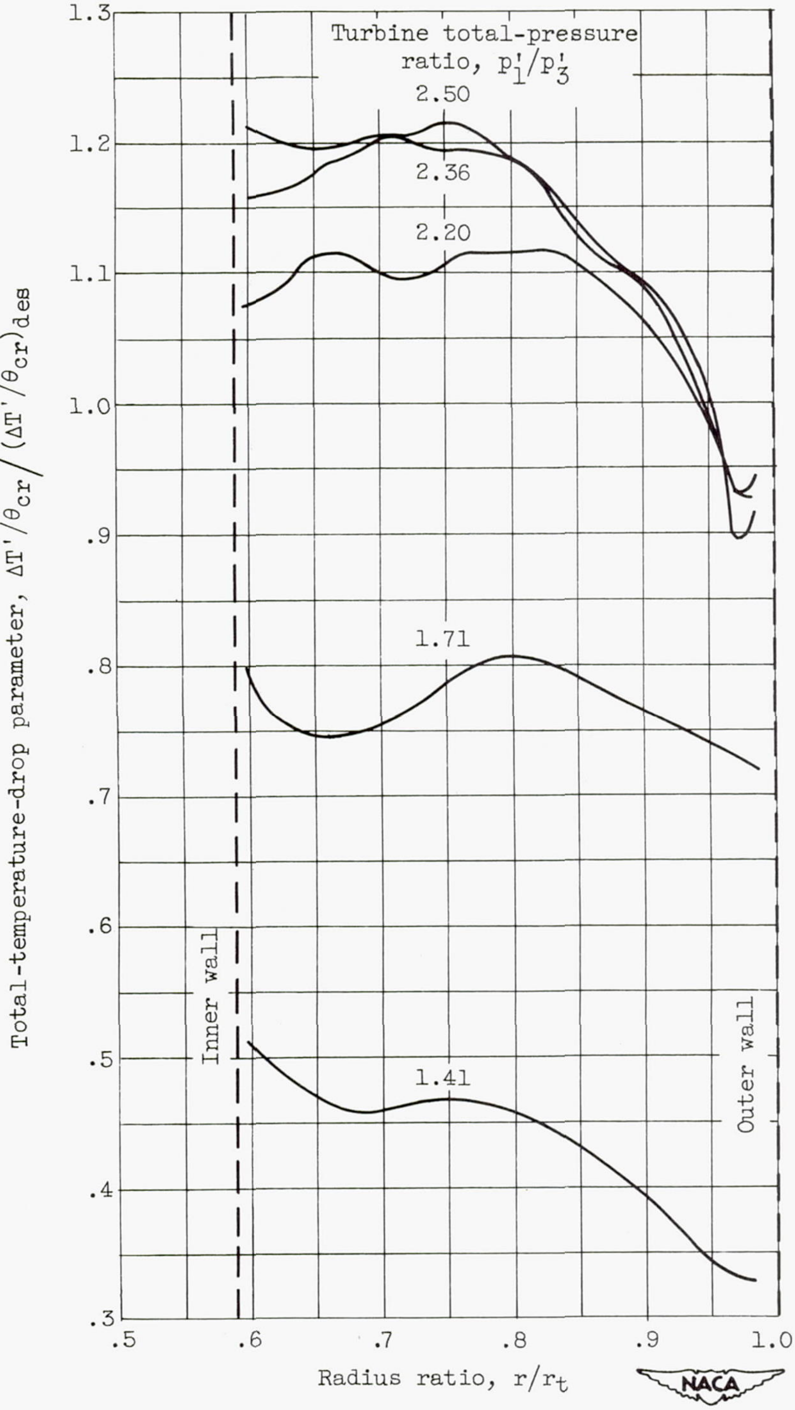
(a) Nozzle setting 1C.

Figure 7. - Radial variation of ratio of observed total-temperature drop to design total-temperature drop at design speed.



(b) Nozzle setting 1D.

Figure 7. - Continued. Radial variation of ratio of observed total-temperature drop to design total-temperature drop at design speed.



(c) Nozzle modification 1E.

Figure 7. - Concluded. Radial variation of ratio of observed total-temperature drop to design total-temperature drop at design speed.

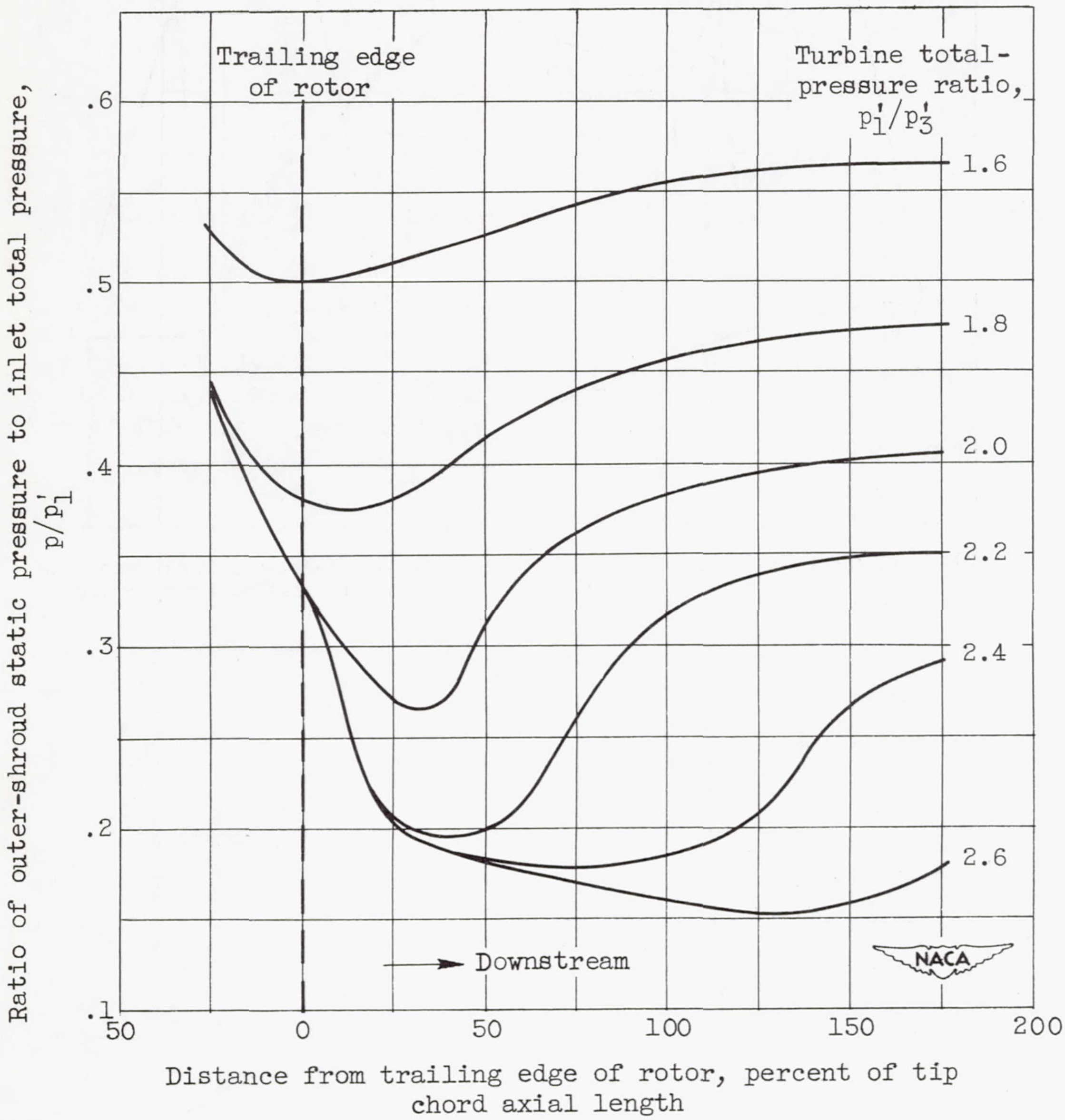
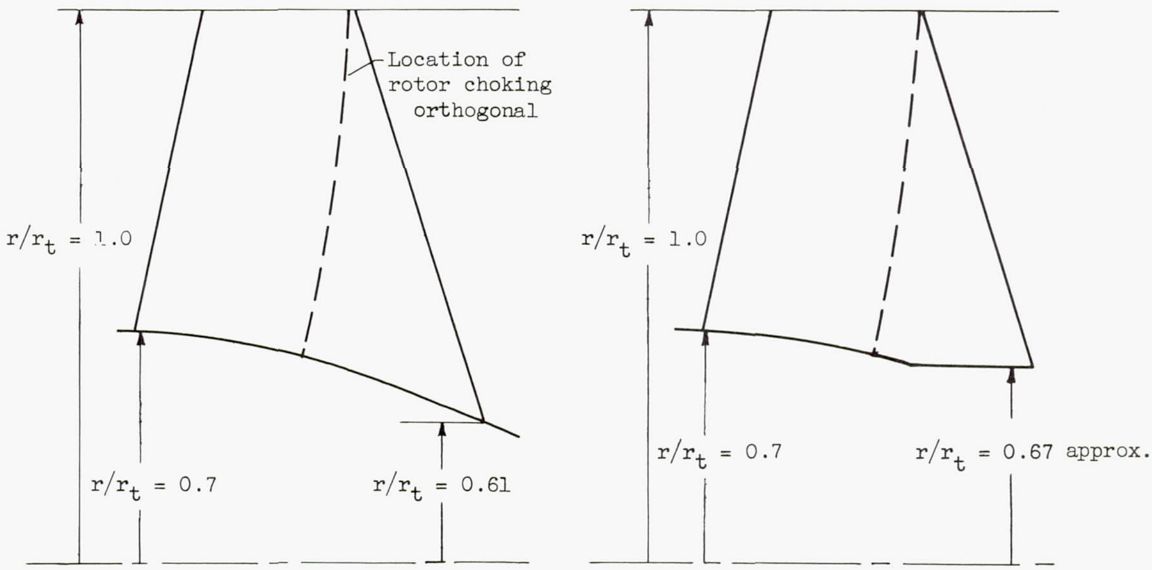
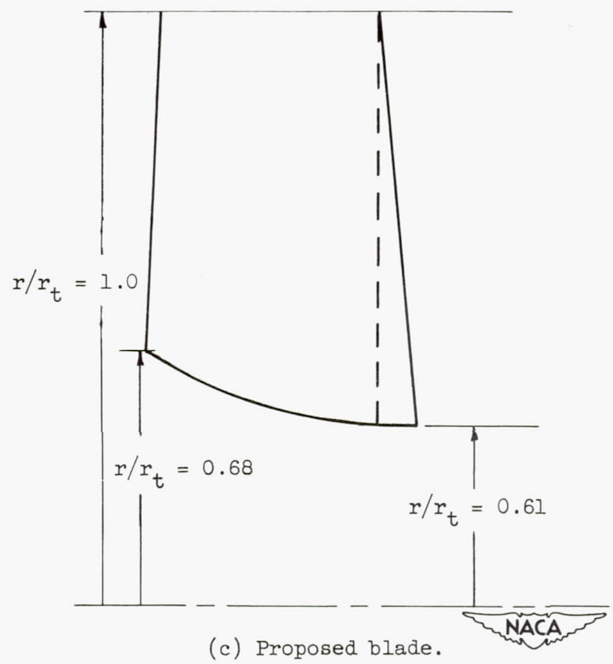


Figure 8. - Effect of total-pressure ratio on outer-shroud static pressure across the rotor tip for nozzle setting 1C at design speed.



(a) Subject turbine blade.

(b) Subject turbine blade modified to eliminate ineffective flow area.



(c) Proposed blade.

Figure 9. - Sketch of blading configurations used to illustrate discussion and recommendation on rotor choking and limiting loading.