NACA

RESEARCH MEMORANDUM

EFFECT OF BLADE-SURFACE FINISH ON PERFORMANCE OF A SINGLE-STAGE AXIAL-FLOW COMPRESSOR

By Jason J. Moses and George K. Serovy

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
April 16, 1951

2096

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF BLADE-SURFACE FINISH ON PERFORMANCE OF A SINGLE-STAGE AXIAL-FLOW COMPRESSOR

By Jason J. Moses and George K. Serovy

SUMMARY

An investigation was made to determine the effect of blade-surface finish on the performance of a single-stage axial-flow compressor having a tip diameter of 14 inches and a hub-tip diameter ratio of 0.8 at the rotor-blade leading edge. A set of modified NACA 5509-34 rotor and stator blades was investigated with rough-machined, hand-filed, and highly polished surface finishes. Over-all total-pressure ratio and adiabatic efficiency were determined for a complete range of weight flows at six equivalent tip speeds from 672 to 1092 feet per second. A range of relative inlet Mach numbers from 0.36 to 0.85 at the rotor mean radius was covered; the approximate Reynolds number based on blade chord varied from 222,000 to 470,000.

Over-all total-pressure ratio and adiabatic efficiency for the highly polished blades were not measurably different from those for the hand-filed blades. When the rough-machined blades were used, both the total-pressure ratio and the adiabatic efficiency were reduced from that obtained with the smoother finishes for tip speeds below 1050 feet per second and at weight flows above those for peak pressure ratio. The change in peak efficiency was 0.03 at a tip speed of 672 feet per second and decreased to zero at a tip speed of 1025 feet per second and above.

Although this investigation does not define an upper limit of blade-surface roughness, no improvement in stage performance could be obtained by using blade finishes smoother than 40 microinches root mean square. In general, finishing blade surfaces below the roughness that may be considered aerodynamically smooth on the basis of an admissible roughness formula will have no effect on compressor performance. The use of blade-surface finishes of sufficient roughness that they cannot be considered aerodynamically smooth will affect compressor performance only at operating points where the blade friction losses are a significant portion of the total losses. If blade finishes not considered aerodynamically smooth are used in a multistage compressor,

consideration must be given to insure proper stage matching throughout the compressor at the reduced stage efficiency.

2096

INTRODUCTION

In order to make an intelligent compromise between axial-flow compressor-blade manufacturing costs and compressor performance, the effect of blade-surface finish on performance must be known. Although some work has been done to determine surface-finish effects, the applicability of the results to axial-flow-compressor design is questionable. Experiments indicate (references 1 and 2) that there is no object in finishing a surface beyond a certain degree of smoothness because no further decrease in frictional losses will be obtained. Attempts have been made to predict surface-finish effects on the basis of analyses of isolated laminar-flow airfoil data. Because surface-finish effects predicted from these data may be due primarily to a shift in the location of the point of transition from laminar to turbulent boundary layer, the same effect may not be noticeable in a compressor because of the high turbulence level. Some effect of stator-blade surface finish on compressor performance was noted in a three-stage experimental compressor (reference 3). The blade finishes used in this investigation were not specified, however, and the actual surface-finish effect may have been hidden by stage-matching effects.

In order to study more completely the effects of blade-surface finish on axial-flow compressor performance, an investigation was made at the NACA Lewis laboratory on a 14-inch-diameter single-stage compressor representative of an intermediate stage of a multistage compressor.

The compressor blading consisted of a row of inlet guide vanes, a row of rotor blades, and a row of stator blades. A modified NACA 5509-34 airfoil section was used for the rotor and the stator blades. A comparison was made of the compressor performance for three different rotor- and stator-blade finishes. Compressor performance was determined over a range of weight flows for equivalent rotor tip speeds from 672 to 1092 feet per second.

SYMBOLS

The following symbols are used in this report:

C_L lift coefficient

2096

k_s equivalent sand grain height, (ft) (reference 1)

M' relative inlet Mach number, ratio of relative inlet velocity to local velocity of sound

P total pressure, (lb/sq ft absolute)

R Reynolds number

U_t velocity of blade at tip, (ft/sec)

$U_t/\sqrt{\theta}$ equivalent tip speed, (ft/sec)

v local velocity over blade, (ft/sec)

W weight flow, (lb/sec)

$W\sqrt{\theta}/\delta$ corrected weight flow, (lb/sec)

δ ratio of inlet total pressure to standard sea-level pressure

η_{ad} adiabatic efficiency

θ ratio of inlet total temperature to standard sea-level temperature

σ solidity ratio, $\frac{\text{blade chord}}{\text{blade spacing}}$

ν kinematic viscosity, (sq ft/sec)

Subscripts:

1 depression tank

2 stator outlet

APPARATUS

Blade-Surface Finish

Compressor performance was compared for three degrees of blade finish on the rotor and stator blades (the guide-vane finish was unaltered). The first finish was produced by rough-machining the blade blank, which left chordwise tool marks in the metal (fig. 1).

The second finish was obtained through a hand-filing operation. The final finish was obtained by hand-polishing with fine abrasive paper until a high degree of polish resulted. For these operations, care was exercised not to alter the original blade profile. Photographs of the three finishes and comparable standard surface-finish specimens magnified nine times are shown in figure 2. 2096

Profilometer measurements were taken of the three surface finishes that gave the surface roughness in terms of the root-mean-square deviation from a mean line measured in microinches (reference 4). Representative measured values of the blade roughness for the three finishes are given in table I. The finish of approximately 63 microinches on the inside wall of the casing was not changed throughout the investigation.

Compressor Design

The airfoil section used for both the rotor and stator blades was an NACA 5509-34 section, slightly modified to reduce velocity peaks over the blades. The rotor blades were steel and the stator blades aluminum. Guide vanes were used that were formed with circular-arc surfaces faired into an elliptical nose section. The design procedure used for these blades is similar to that described in reference 5 with the exception that the σC_L limitation was raised from 0.77 to 0.99 at the rotor hub.

The blading was installed in a variable-component axial-flow compressor having a constant tip diameter of 14.00 inches and a hub-to-tip diameter ratio of 0.8 at the rotor inlet. Static rotor-tip clearance was approximately 0.020 inch and stator-hub clearance approximately 0.015 inch. Approximate axial distance between the trailing edge of the inlet guide vanes and the leading edge of the rotor blades was 0.43 inch and the distance between the trailing edge of the rotor blades and the leading edge of the stator blades was 0.70 inch.

Compressor Installation and Instrumentation

The compressor installation is shown schematically in figure 3 and is similar to that described in reference 5.

Instrumentation for determination of over-all compressor performance was similar to that of reference 5 and was located at the stations indicated in figure 3.

PROCEDURE AND METHOD OF CALCULATION

For each blade finish, compressor performance was determined at 80, 100, 110, 120, 125, and 130 percent of design speed, which covered a range of equivalent tip speeds from 672 to 1092 feet per second. At each speed, the weight flow was varied from an approximate maximum to the region of unstable operation. A constant pressure of 25 inches of mercury absolute was maintained in the depression tank for all speeds and weight flows.

The methods of reference 5 were used to calculate the total-pressure ratio and adiabatic efficiency of the compressor. The total-pressure ratio was obtained from a mass-flow weighted average of the isentropic energy input integrated across the flow passage. The adiabatic efficiency was calculated from a mass-flow weighted average of the total-temperature rise across the compressor and a mass-flow weighted average of the isentropic temperature rise obtained from the calculated pressure ratio.

RESULTS

Total-pressure ratio and adiabatic efficiency. - A comparison of over-all compressor performance for the three blade-surface finishes at each of six equivalent tip speeds is shown in figure 4. Changing the surface finish from the hand-filed to the highly polished condition did not affect the compressor performance. When the surface finish was changed from the rough-machined to the hand-filed condition, however, increases in both total-pressure ratio and adiabatic efficiency were observed. Surface-finish effects were largest on the high-weight-flow portion of the curves. At a compressor tip speed of 672 feet per second (80 percent of design speed), the efficiency was improved by approximately 0.17 (fig. 4(a)); at 840 feet per second (design speed), the maximum increase in total-pressure ratio of approximately 2.7 percent was obtained. As the weight flow was reduced, the curves gradually converged until they came together near the peak-pressure-ratio point. The effects of surface finish were observed at tip speeds from 672 to 1008 feet per second (80 to 120 percent of design). As the compressor speed was increased, the effect of surface finish diminished until at 1050 feet per second (125 percent of design speed) and above no effect was discernible.

Peak adiabatic efficiency. - Variation of peak adiabatic efficiency (obtained from fig. 4) with equivalent tip speed for the three blade finishes investigated is shown in figure 5. Because no difference in peak efficiency occurred between the hand-filed and highly polished finishes, one curve was used to represent both finishes. At the lowest tip speed, the difference in peak efficiency between the rough-machined and hand-filed finishes was approximately 0.03; this difference decreased to 0.02 at design speed (840 ft/sec). Above design speed, the curves converged more rapidly until they came together at a tip speed of approximately 1025 feet per second.

The rotor-inlet relative Mach number and Reynolds number at the mean radius for the minimum, peak efficiency, and maximum weight flows for each speed are shown in table II.

DISCUSSION AND APPLICATION OF RESULTS

The material presented in reference 1 is of interest in explaining the results obtained in the present investigation. An empirical formula is presented in reference 1 for the calculation of the admissible roughness of a surface in turbulent flow. This formula is based on data for flow parallel to artifically roughened flat plates. The admissible roughness refers to a limiting roughness below which a surface may be considered aerodynamically smooth and above which the skin friction drag is increased over that for a smooth surface. The data of reference 1 show that if

$$\frac{vk_s}{\nu} < 100 \text{ (approximately)}$$

the surface in question may be considered aerodynamically smooth; that is, the laminar sublayer of the boundary layer is of sufficient thickness to cover the protuberances of the surface in question.

Calculations using the preceding formula were made from data obtained in this investigation to check the agreement of the experimental results with the data of reference 1. The length dimension used was the predominant peak-to-valley height of the roughness determined by the method of reference 6 from the profilometer readings of table I. The peak-to-valley height was used instead of the equivalent sand grain height because peak-to-valley height determines the Reynolds number at which roughness effects first appear (reference 7). The velocities used were peak values estimated from cascade data for airfoils with a similar loading. The values of the roughness number are therefore considered not highly accurate, but the trends and general magnitudes are believed correct. Numerical values calculated from the preceding equation are summarized in the following table: (Because of the small change in the value of vk_s/ν with weight flow for each speed, single rounded-off values were used for the entire range of weight flows.)

Compressor tip speed (percent of design)	Finish					
	Rough machined		Hand filed		Highly polished	
	Spanwise	Chordwise	Spanwise	Chordwise	Spanwise	Chordwise
80	290	90	60	60	22	17
125	350	110	70	70	26	21

Because the values of vk_s/ν are well below the critical range for the hand-filed and the highly polished finishes, no difference in performance would be expected between the two finishes on the basis of this criterion. This expectation was verified in the experiments. Physically, therefore, in neither case was the blade surface sufficiently rough that the protuberances projected beyond the laminar sublayer of the boundary layer. The surfaces could therefore be considered aerodynamically smooth.

For the rough-machined surface, however, the values of vk_s/ν were well over the critical value for spanwise roughness and approached the critical value for the chordwise measurements. These values indicate a possible surface-finish effect on performance because the flow is not entirely in the chordwise direction. The results of this investigation showed a surface-finish effect on the stage performance for the rough-machined surface although it was observed only in the high-flow range of operation and at speeds below 1050 feet per second (125 percent of design speed).

The variation in the effect of blade-surface finish on stage performance appears reasonable when the nature of the flow at the various operating conditions is considered. At the low tip speeds in the high-flow operating range, the blade losses are low and are due largely to skin friction. Consequently, a change in blade-surface finish may have a large effect on compressor performance. At high tip speeds, the large adverse pressure gradients and the shock losses cause thicker boundary layers and earlier separation of the flow, which reduce the skin-friction proportion of the total blade losses. When the boundary layer is thick enough to cover the protuberances of all the roughnesses investigated, or when separation takes place, a change in roughness will not affect the skin friction. Hence, at high speeds the effects of surface finish are negligible. In the low-flow operating range at all tip speeds, high angles of attack on the blade cause earlier separation of the boundary layer. Thus the skin-friction portion of the losses and the surface-finish effects are reduced.

The admissible roughness formula of reference 1 was obtained for smooth flow over flat plates where the losses were essentially due to skin friction and no account was taken of boundary-layer thickening and separation due to high adverse pressure gradients and shock losses. In applying this criterion, therefore, no effect of surface finish should be noted at any compressor flow condition if the value of the admissible roughness number is somewhat less than 100. If the number is greater than 100, there may or may not be an effect, depending on the flow conditions. If skin-friction losses are a significant portion of the total losses (such as at low speeds and high flows), a noticeable surface-finish effect will occur. If the skin-friction losses are obscured by other losses (such as those occurring at high speeds and for low flows at low speeds), the surface-finish effects will be unnoticed.

2096

Although this investigation does not define an upper limit of blade-surface roughness because of the limited number of finishes investigated, a surface finish of approximately 40 microinches was found to have no measurable effect on performance over the entire compressor operating range. It is possible, however, that a somewhat greater roughness could have been used without noticeable effect. For general application, a surface roughness that may be considered aerodynamically smooth on the basis of the admissible-roughness formula will apparently have no effect on compressor performance.

Caution must be used in applying the results of this investigation to other compressors. The effects of blade-surface roughness on compressor performance will depend not only on the microinch root-mean-square reading of the profilometer but on the type and the distribution of the roughness, amount of dirt accumulation, blade profile, and solidity. Some types of surface, such as those produced by vapor-blasting, tend to accumulate dirt rapidly, which will affect blade losses. Distribution of roughness is very important; roughness near the leading edge of the blade has more effect on blade losses than roughness near the trailing edge (reference 8). Leading-edge roughness has a compound effect on the blade losses; not only is the skin friction increased but the transition point from laminar to turbulent flow may be moved forward. As flow in compressors at high Reynolds numbers is generally turbulent enough to cause the transition point to be well forward on the blade whether the surface is rough or not, this combination of effects will be unnoticed except at low tip speeds.

In applying the results of this investigation to conventional multistage compressors, it may be stated that apparently nothing is to be gained by using finishes smoother than 40 microinches root mean square. For finishes that cause the admissible roughness number to exceed 100, there may be two effects of surface finish on compressor performance: (1) individual stage efficiency may be lowered;

(2) reduced stage efficiency may affect stage matching. Of the two effects, stage-matching is the most serious, especially for turbojet-engine compressors that have a large number of stages. Therefore, if finishes are to be used that cause the admissible roughness number to exceed 100, provision must be made throughout the compressor to permit all stages to be properly matched at the reduced stage efficiency.

SUMMARY OF RESULTS

An investigation was made to determine the effects of three blade-surface finishes on the performance of a single-stage axial-flow compressor using a modified NACA 5509-34 airfoil section for the rotor and the stator blades. A complete range of weight flows was covered at each of six equivalent tip speeds from 672 to 1092 feet per second. A range of relative inlet Mach numbers from 0.36 to 0.85 at the rotor mean radius was covered; the approximate Reynolds numbers based on blade chord varied from 222,000 to 470,000. For the rough-machined, hand-filed, and highly polished blade finishes investigated, the results are summarized as follows:

1. Over-all total-pressure ratios and adiabatic efficiencies for the highly polished blade finish were not measurably different from those for the hand-filed blades.

2. For tip speeds at which blade finish affected performance, the largest changes in total-pressure ratio and adiabatic efficiency occurred at high weight flows. No performance changes were noted at weight flows below those for peak pressure ratio.

3. No change in either adiabatic efficiency or total-pressure ratio was observed at tip speeds of 1050 and 1092 feet per second.

4. At the lowest speed investigated (672 ft/sec), peak adiabatic efficiency was about 0.03 higher for the hand-filed finish than for the rough-machined finish. This difference decreased to zero at an equivalent tip speed of approximately 1025 feet per second and above.

The results indicate that:

1. Blade-surface finish will affect compressor performance only at operating points where the blade friction losses are a significant portion of the total losses. Thus, surface-finish effects decrease with increasing compressor speed and with decreasing flow at a given speed.

2096

2. For conventional compressors, nothing is to be gained by using blade finishes smoother than 40 microinches root mean square. In general, it appears that a surface roughness that may be considered aerodynamically smooth on the basis of the admissible-roughness formula will have no effect on compressor performance.

3. If finishes are to be used in multistage compressors that cause the admissible-roughness number to exceed 100, provision must be made throughout the compressor to permit all stages to be properly matched at the reduced stage efficiency.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCES

1. Schlichting, H.: Lecture Series "Boundary Layer Theory." Part II - Turbulent Flows. NACA TM 1218, 1949.

2. Sörensen, E.: Wandrauhigkeitseinfluss bei Strömungsmaschinen. Forschung, Bd. 8, Heft 1, Ausg. A, Jan./Feb. 1937, S. 25-29.

3. Lindsey, W. H.: The Development of the Armstrong Siddeley Mamba Engine. Jour. Roy. Aero. Soc., vol. LIII, 1949, pp. 137-173.

4. Abbott, E. J., Bousky, S., and Williams, D. E.: The Profilometer. Mech. Eng., vol. 60, no. 3, March 1938, pp. 205-216.

5. Mankuta, Harry, and Guentert, Donald C.: Investigation of Performance of Single-Stage Axial-Flow Compressor Using NACA 5509-34 Blade Section. NACA RM E8F30, 1948.

6. Tarasov, L. P.: Relation of Surface-Roughness Readings to Actual Surface Profile. Trans. A.S.M.E., vol. 67, no. 3, April 1945, pp. 189-196.

7. Theodorsen, Theodore, and Regier, Arthur: Experiments on Drag of Revolving Disks, Cylinders, and Streamline Rods at High Speeds. NACA Rep. 793, 1944.

8. Relf, E. F.: Experiments on the Effects of Surface Roughness. Proc. Fifth International Congress Appl. Mech. (Cambridge, Mass.), 1938, pp. 410-415.

2096

TABLE I - MEASURED BLADE ROUGHNESS

Blade finish	Profilometer (microin. rms)	
	Spanwise	Chordwise
Rough-machined finish	100 - 200	40 - 60
Hand-filed finish	20 - 40	20 - 40
Highly polished finish	10 - 15	4 - 12

TABLE II - RELATIVE MACH NUMBER AND REYNOLDS NUMBER AT ROTOR INLET FOR MEAN RADIUS

Compressor speed		Corrected weight flow, $W\sqrt{\theta}/\delta$					
		Minimum		Peak efficiency		Maximum	
(percent of design)	Equivalent tip $U_t/\sqrt{\theta}$ (ft/sec)	Relative inlet Mach number M'	Reynolds number R	Relative inlet Mach number M'	Reynolds number R	Relative inlet Mach number M'	Reynolds number R
80	672	0.36	2.22×10^5	0.50	2.93×10^5	0.54	3.06×10^5
100	840	.49	2.88	.63	3.57	.66	3.70
110	924	.68	3.66	.69	3.80	.72	3.98
120	1008	.74	3.90	.75	4.04	.79	4.28
125	1050	.77	4.08	.79	4.20	.82	4.50
130	1092	.80	4.20	.83	4.29	.85	4.70

2096

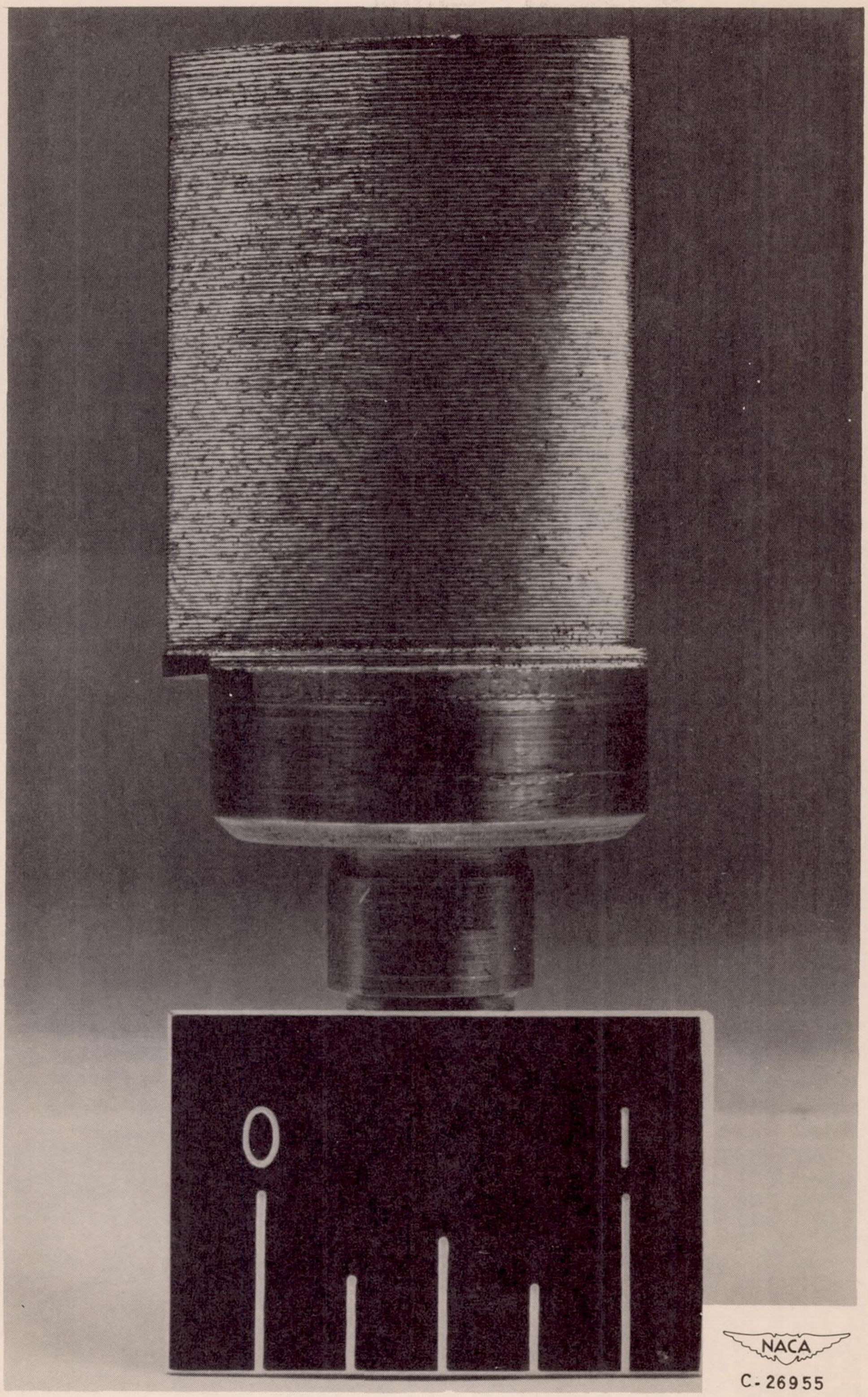
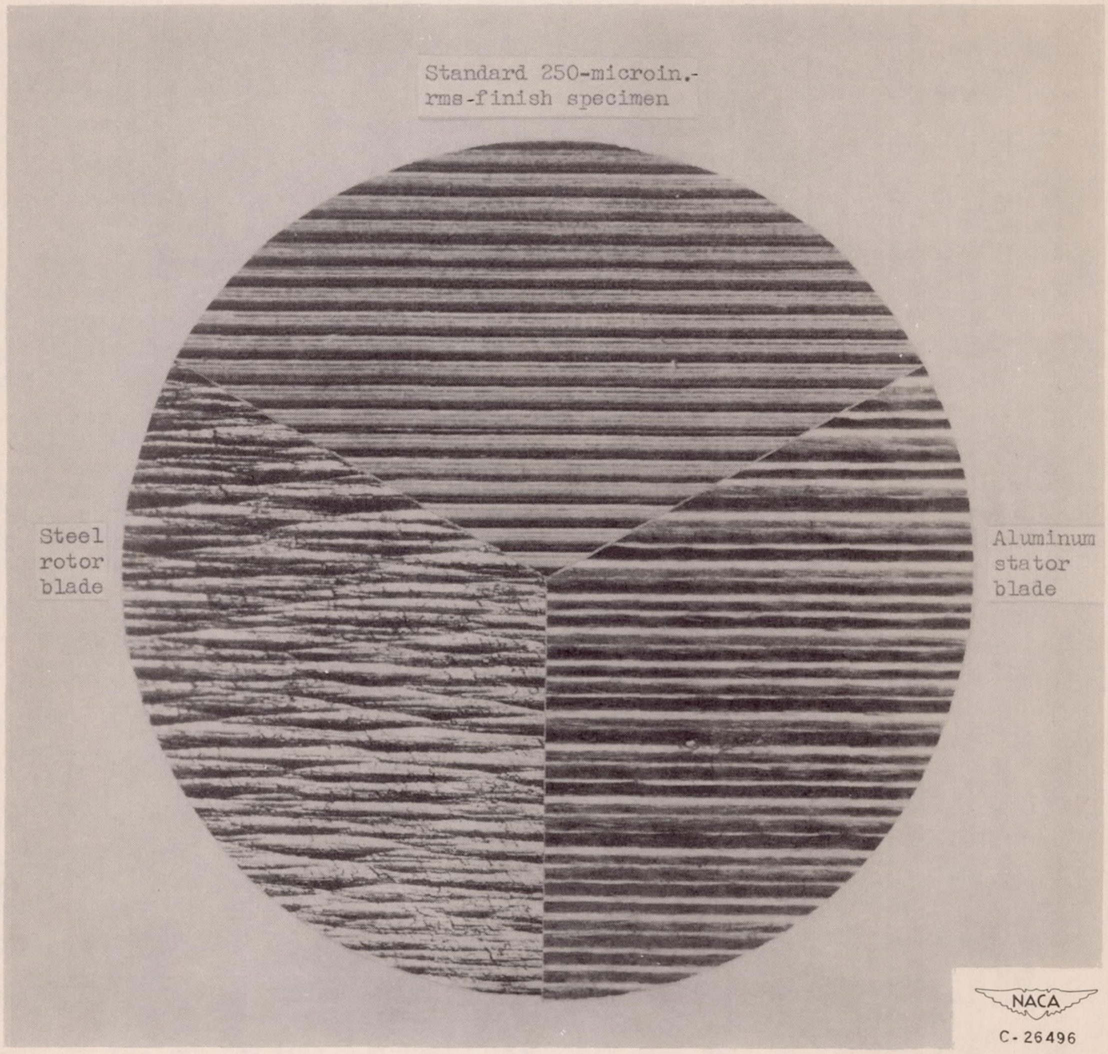


Figure 1. - Compressor blade in rough-machined condition.

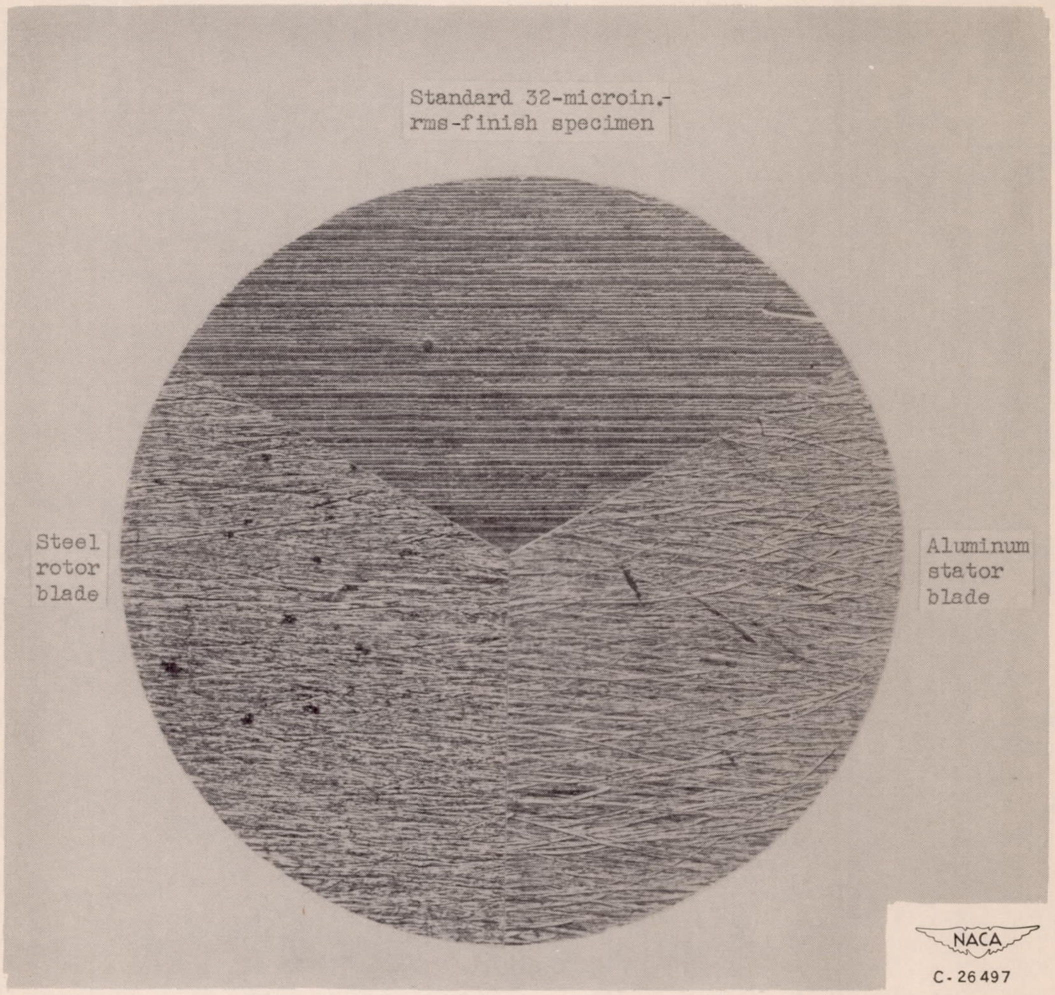
2096



(a) Rough-machined finish.

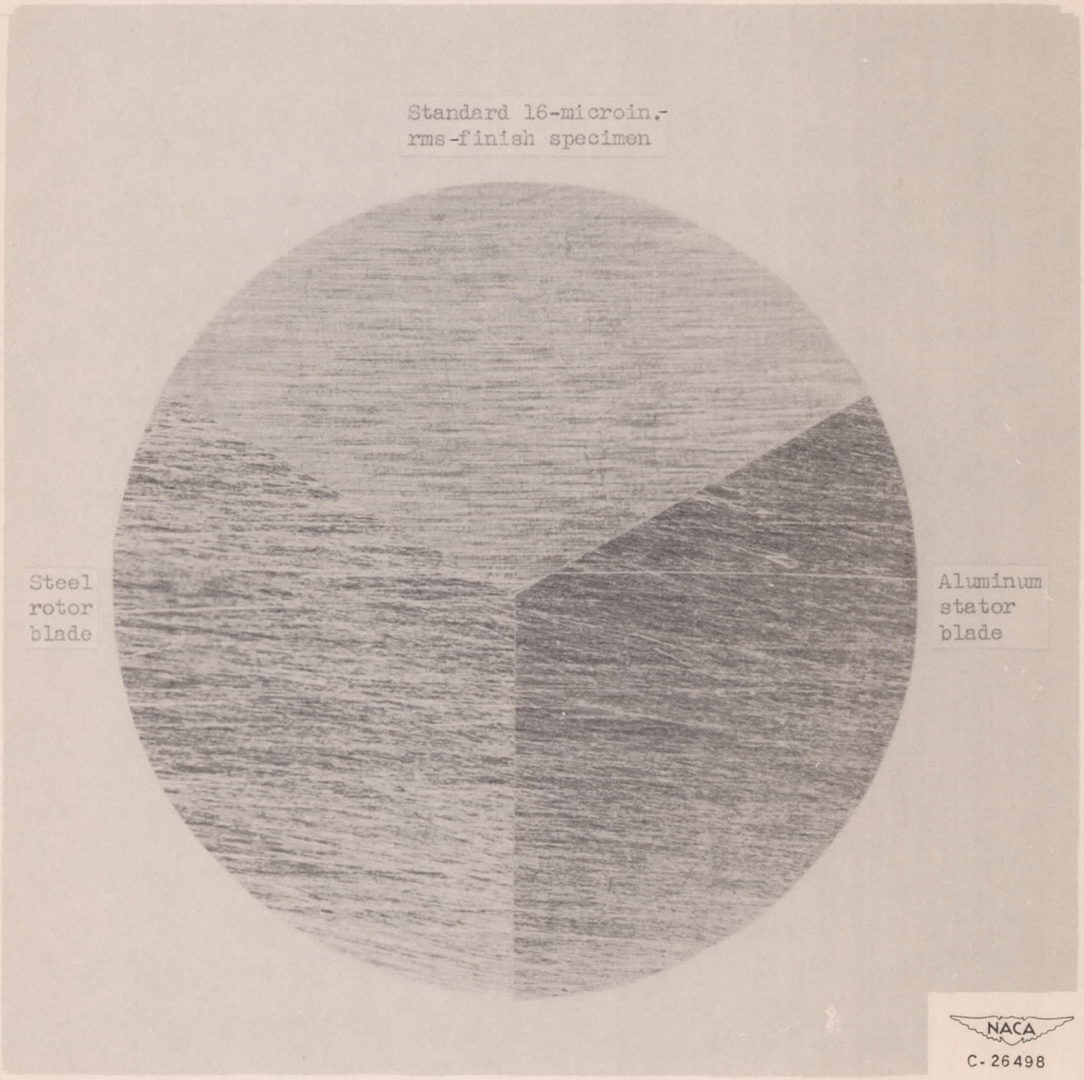
Figure 2. - Photographic comparison of rotor- and stator-blade finishes with standard specimens. X9.

2096



(b) Hand-filed finish.

Figure 2. - Continued. Photographic comparison of rotor- and stator-blade finishes with standard specimens. X9.



(c) Highly polished finish.

Figure 2. - Concluded. Photographic comparison of rotor- and stator-blade finishes with standard specimens. X9.

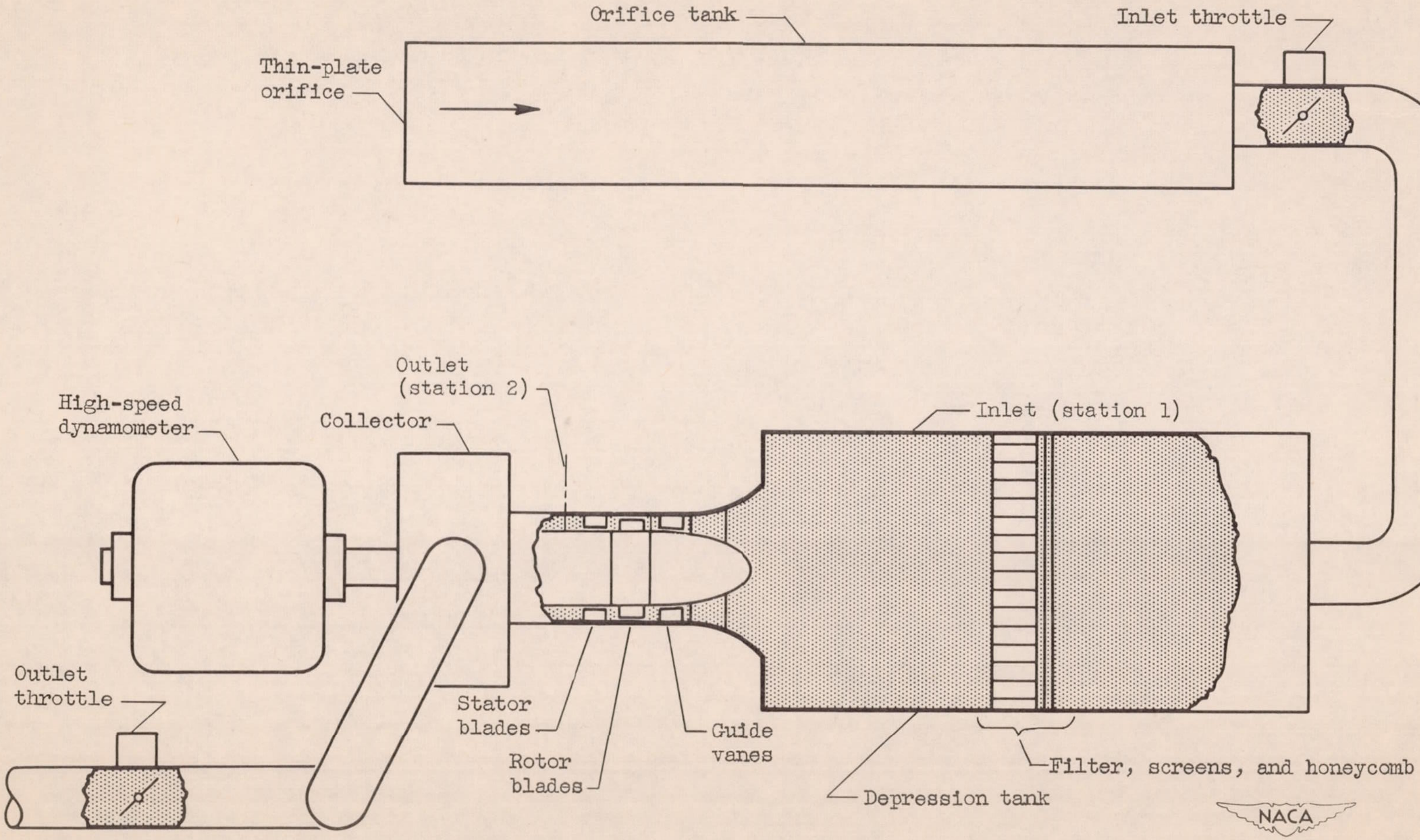
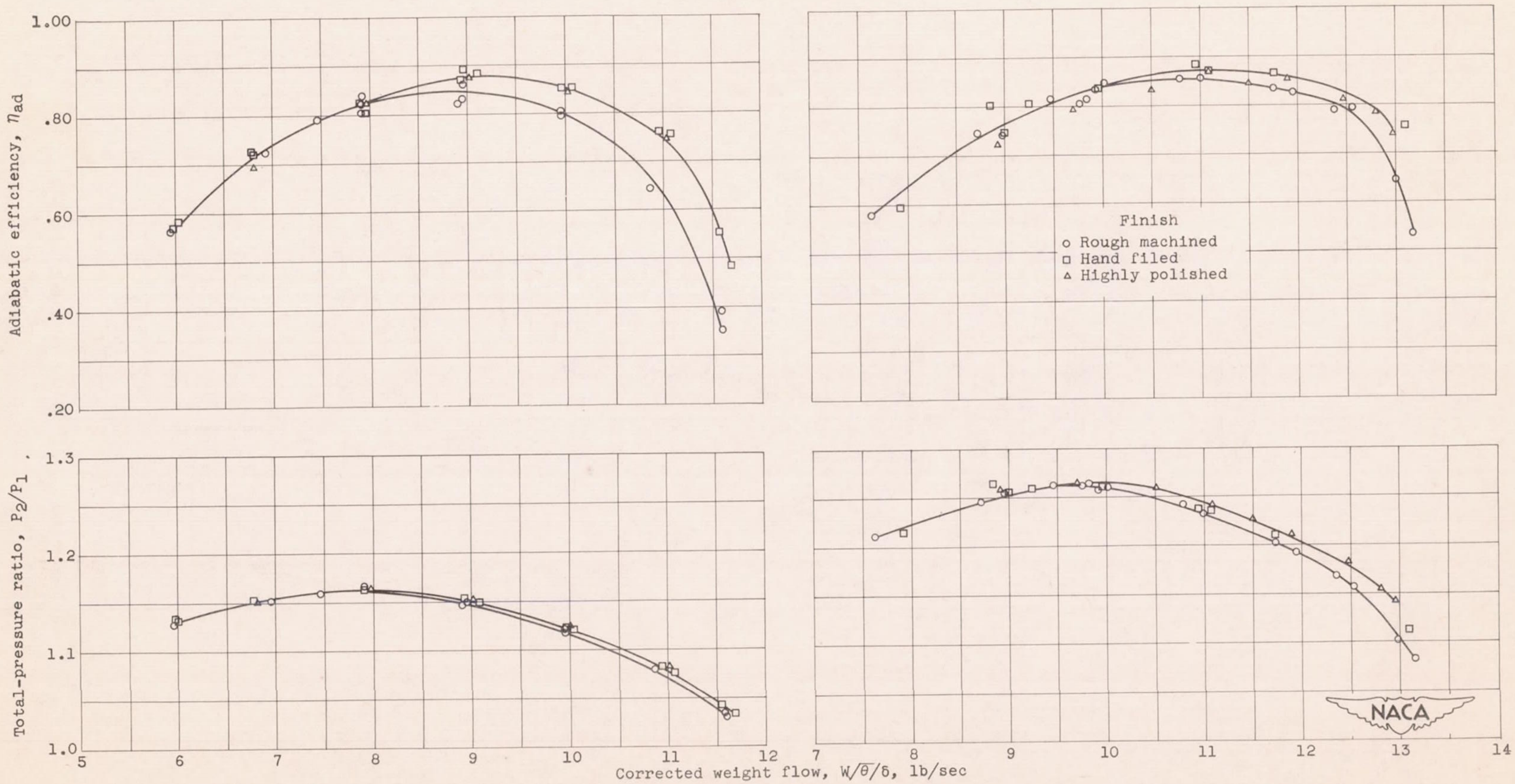


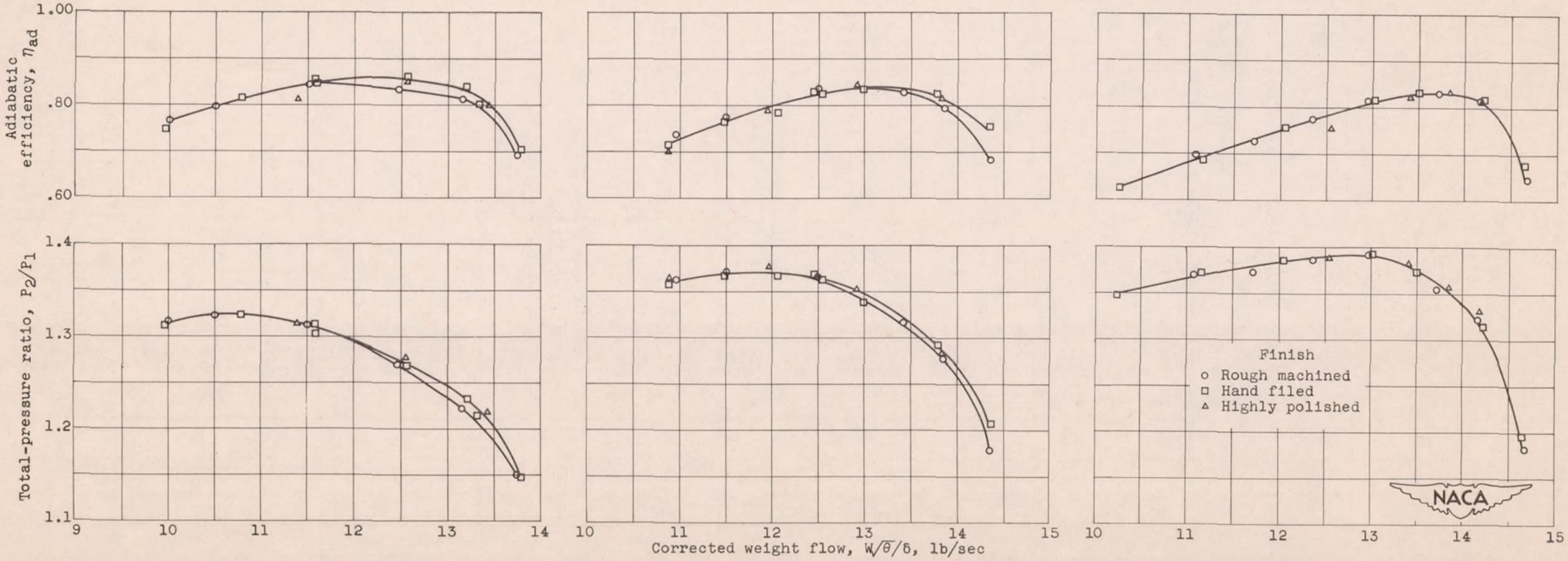
Figure 3. - Schematic diagram of compressor installation.



(a) Compressor tip speed, 672 feet per second (80 percent of design speed).

(b) Compressor tip speed, 840 feet per second (design speed).

Figure 4. - Variation of total-pressure ratio and adiabatic efficiency with corrected weight flow for three blade-surface finishes.

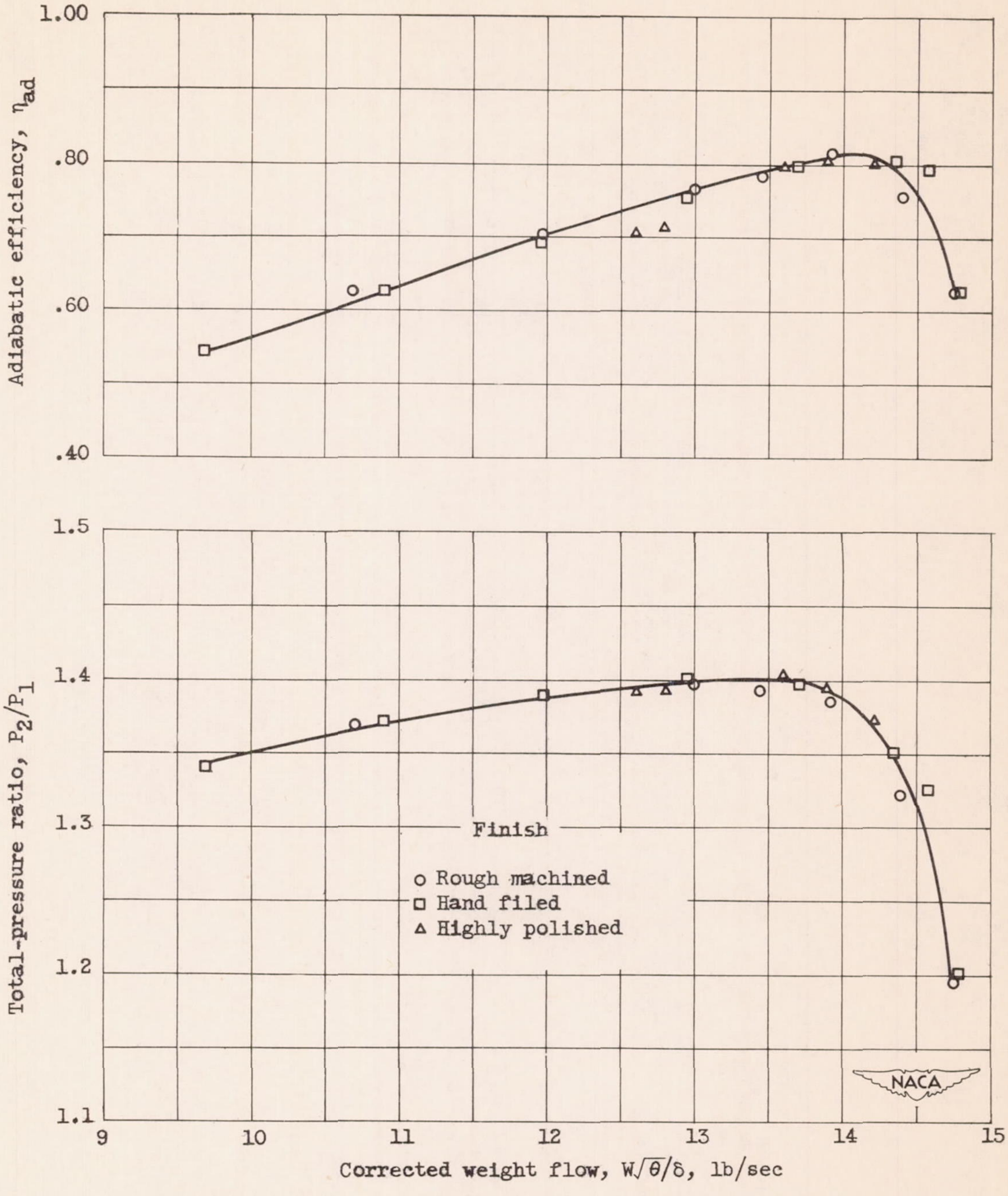


(c) Compressor tip speed, 924 feet per second (110 percent of design speed).

(d) Compressor tip speed, 1008 feet per second (120 percent of design speed).

(e) Compressor tip speed, 1050 feet per second (125 percent of design speed).

Figure 4. - Continued. Variation of total-pressure ratio and adiabatic efficiency with corrected weight flow for three blade-surface finishes.



(f) Compressor tip speed, 1092 feet per second (130 percent of design speed).

Figure 4. - Concluded. Variation of total-pressure ratio and adiabatic efficiency with corrected weight flow for three blade-surface finishes.

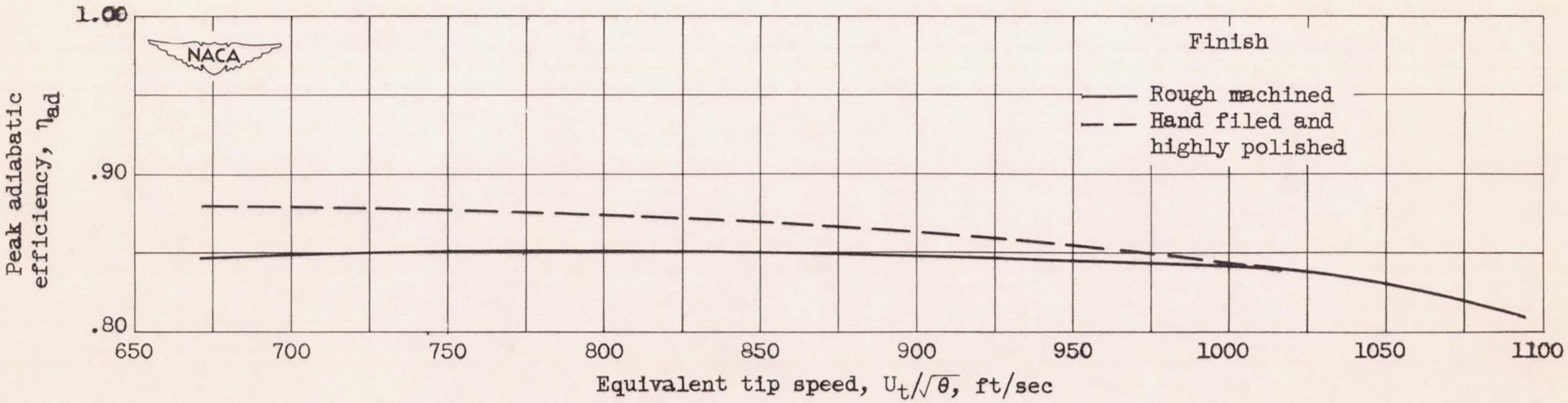


Figure 5. - Variation of peak adiabatic efficiency with equivalent tip speed for three blade finishes.