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RESEARCH MEMORANDUM

DESIGN AND PERFORMANCE OF AN EXPERIMENTAL AXIAL-DISCHARGE MIXED-FLOW COMPRESSOR

III - OVER-ALL PERFORMANCE OF IMPELLER AND SUPERSONIC-DIFFUSER COMBINATION

By Ward W. Wilcox and William H. Robbins

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Cleveland, Ohio

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RESEARCH MEMORANDUM

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SUMMARY

An axial-discharge impeller, in combination with a 16-vaned supersonic diffuser cascade, was investigated over a range of flow conditions at equivalent tip speeds varying from 800 to 1600 feet per second. Diffuser-entrance Mach numbers were in the low supersonic range, that is, less than 1.4; and the 0.030-inch-thick straight blades were placed at an angle of 65° with the compressor axis. Each pair of blades constituted a convergent-divergent supersonic diffuser wherein primary emphasis was placed on deceleration through a Mach number of 1 with minimum loss. Such a diffuser, when started, would be expected to have a single value of weight flow at each speed, and the maximum pressure ratio and adiabatic efficiency would be expected to occur simultaneously at the peak of a vertical characteristic curve.

At all tip speeds covered by this investigation, the requirements for starting of the cascade were not met because effective contraction ratio was increased by the presence of boundary layer, blade wakes, and separation. At no speed was the design value of weight flow attained, because of choking in the diffuser passages. Peak values of diffuser efficiency occurred at weight flows lower than the choking value at each speed. Thus, the indications are that a diffuser with an external shock configuration would perform as well as or better than the convergent-divergent type in this range of Mach numbers, with the additional benefit of operating over a range of weight flows.

The application of flow bleedoff between the impeller and the diffuser to the extent of 9 percent of the actual weight flow was insufficient to allow starting of the diffuser. The net weight flow through the diffuser was not increased by the use of bleedoff.

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INTRODUCTION

Prime requisites for the compressor component of modern aircraft engines include the characteristics of compactness, dependability, and structural simplicity, as well as the customary demand for high flow capacity per unit of frontal area, high pressure ratio, and relatively high adiabatic efficiency. The axial-discharge centrifugal-type impeller was designed at the NACA Lewis laboratory as a particular compromise in which maximum flow capacity per unit frontal area was sought at a predetermined pressure ratio. The design theory and the impeller performance are discussed in references 1 and 2.

Air is discharged from this impeller with a high rotational component of velocity at resultant Mach numbers that are in the low supersonic range, that is, less than 1.4. It was expected that the necessary turning could be accomplished without great difficulty through separate conventional subsonic airfoil cascades after the shock to subsonic velocities. In the design of the diffuser considered herein, primary emphasis was placed on deceleration through a Mach number of 1.0 with minimum loss. At the diffuser-inlet Mach numbers encountered in this design, the loss through a single normal shock is not excessive. The subsonic axial-velocity component necessitates blades for precipitation of the shock.

A cascade of sheet-metal blades was designed on the basis of two-dimensional-flow theory, each pair of blades constituting a convergent-divergent supersonic diffuser. Flow Mach numbers and angles were chosen from impeller-outlet flow-distribution data obtained from unreported previous design-speed investigations at an equivalent weight flow of 16.5 pounds per second. At this operating point a uniform flow angle existed across the discharge annulus. A system for bleeding off air between the impeller discharge and the diffuser was incorporated in this design to assist in starting the diffuser.

Over-all performance of the impeller-diffuser combination was obtained over a range of weight flows and tip speeds. In addition, an indication of the trends of the flow processes within the diffuser cascade was obtained from total-pressure surveys upstream and downstream of the diffuser and from static-pressure readings on the outside wall along a single passage.

DIFFUSER DESIGN

On the basis of two-dimensional performance, the convergent-divergent supersonic diffuser was chosen to decelerate the impeller absolute velocity through a Mach number of 1. Problems of starting, stability, and general operation of two-dimensional diffusers of this type are discussed in detail in reference 3. A serious complication arose from the application of convergent-divergent diffuser principles to an annular cascade because of the necessity for flow spillage when the operation is in the "unstarted" condition. In free-stream operation, at supersonic Mach numbers below the starting value, some of the air in a stream filament of the size of the projected area of the diffuser passage must flow around the diffuser. Obviously this condition is impossible in an infinite cascade. As a result, some flow adjustment must be made upstream of the diffuser, either in the annulus or within the impeller itself.

In the application of convergent-divergent-diffuser design principles to the flow conditions at the discharge of this impeller, a two-dimensional design was made for the hub, tip, and mean-radius locations. If the starting requirements are met at all radii and the flow enters the passages supersonically, the peak pressure ratio, adiabatic efficiency, and weight flow are expected to occur simultaneously at design speed.

When the diffuser-inlet Mach number is below the starting value, an external shock configuration forms in front of the cascade. Both radial and axial turning may take place through these shock waves. At design speed, the unstarted operation is accompanied by positive angles of incidence, as shown in figure 1.

A photograph of the supersonic diffuser cascade is presented in figure 2. The design value of weight flow for this cascade was 16.5 pounds per second, an operating point where the distribution of flow angle was uniform from hub to tip at an average value of 65°. Sixteen straight blades of 0.030-inch thickness were used, with a 5° wedge on both ends. For this geometry the highest contraction ratio, 1.030, occurs at the hub, and the corresponding minimum Mach number for shock entry is 1.252. The design Mach number was assumed to be 1.3 to allow for viscous effects. The minimum length of the blade was determined by the intersection of an oblique shock wave from the 5° wedge with the adjoining blade. At the tip, the minimum length was 3.17 inches for a 60° oblique shock. An additional 1/2 inch of straight section was added for stability. At the blade hub a common trailing edge was prescribed, which further lengthened the blade at this radius. This diffuser cascade was placed 7/8 inch behind the impeller.

In an effort to ease the starting problem at low Mach numbers, a number of bleedoff holes were installed between the impeller discharge and the diffuser throat (fig. 2). In each blade passage, six 1/4-inch holes were placed on the outside wall in this region with an additional hole slightly downstream of the throat. On the inside wall five 1/4-inch holes and four 1/8-inch holes were used in front of the throat.

APPARATUS

For this series of investigations, several alterations were made to the original test rig described in reference 2. Changes that affected the flow characteristics are limited to the following:

1. Replacement of the cantilevered inner cylinder and bearing support required the presence of six airfoil-shaped struts downstream of the diffuser measuring station. These struts reduced the maximum obtainable weight flow without stators from a value of 18.7 (reference 2) to 17.6 pounds per second.

2. Provisions were made to withdraw and measure a quantity of air between the impeller and the diffuser throat on both the outer and inner walls (fig. 2).

3. Different inlet guide vanes were placed in the same location in front of the impeller. These blades produced essentially the same average flow distribution but were fabricated to closer tolerances to reduce circumferential flow variations.

INSTRUMENTATION

For over-all performance of the impeller-diffuser combination, the instrumentation was essentially the same as that reported in reference 2. Inlet weight flow was measured by a calibrated variable-area orifice in the inlet system. Total temperature and pressure and static pressure were obtained at a station in the inlet pipe that was 4 diameters upstream from the impeller and was preceded by 12 diameters of straight pipe. At a station about 0.80 inch downstream from the diffuser discharge and on an extension of the passage center line, total pressure, static-pressure flow angle, and total temperature were surveyed at 1/10-inch radial intervals. Four equally spaced wall taps on both inner and outer walls were used to determine static pressure in the transonic range of Mach numbers where the survey probe was unreliable. Total pressures at each radius were arithmetical averages of readings from a nine-tube rake. A cylindrical yaw tube was found to be satisfactory for angle measurement at all Mach numbers. For static-pressure surveys a wedge of about 8° included angle was used. At Mach numbers between 0.98 and 1.3, laboratory test facilities for calibrating the probe were inadequate, but indications were that a very high correction would be necessary. Interpolation between wall-tap static pressures was utilized for this range of Mach numbers.

Flow characteristics within the diffuser passages were estimated from readings of 20 static taps placed on the outside casing in three rows equally spaced across a single passage. No attempt was made to introduce instruments into the passage because the presence of the instruments would have completely altered the flow.

In addition to the surveys downstream of the diffuser, a survey of total pressure and flow angle was made at a station 1/2 inch in front of the diffuser.

For runs with flow bleedoff, the flow from the individual holes was drawn off into two ducts. Sharp-edged orifices in these ducts were used to measure the air flow.

SYMBOLS

The following symbols are used in this report:

M	Mach number
P	total pressure, pounds per square foot
p	static pressure, pounds per square foot
U	tip speed, feet per second
W	weight flow, pounds per second
γ	ratio of specific heats
δ	ratio of impeller-inlet total pressure to standard sea-level pressure
η_{ad}	adiabatic efficiency
η_s	supersonic efficiency
η_{st}	static-pressure efficiency

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θ	ratio of impeller-inlet total temperature to standard sea-level temperature
$U/\sqrt{\theta}$	equivalent tip speed, feet per second
$W\sqrt{\theta}/\delta$	equivalent weight flow, pounds per second

Subscripts:

1	impeller-inlet measuring station
2	diffuser-inlet measuring station
3	diffuser-discharge measuring station

OPERATING PROCEDURE

Compressor performance data were taken over the obtainable range of equivalent weight flow $W\sqrt{\theta}/\delta$ at constant values of equivalent tip speed $U/\sqrt{\theta}$ varying from 800 to 1600 feet per second. Inlet-air conditions were maintained at 15 inches of mercury absolute and inlet temperature was approximately -20° F for all runs except at an equivalent tip speed of 1600 feet per second, where -60° F air was used.

The desired tip speed and inlet pressure were established with the outlet throttle wide open. The outlet throttle was then closed to position the shock waves in the diffuser. Further closing of the outlet throttle caused the disturbances to move upstream of the diffuser, and closing of the inlet throttle was then necessary to maintain the assigned inlet pressure. This operation resulted in a lower value of equivalent weight flow. The routine was continued until surging was observed.

ANALYSIS OF RESULTS

Over-all performance of impeller-diffuser combination. - A standard compressor-performance characteristic curve is shown in figure 3 for this impeller-diffuser combination. Mass-weighted average total-pressure ratio P_3/P_1 is plotted against equivalent weight flow $W\sqrt{\theta}/\delta$ at intervals of equivalent tip speed $U/\sqrt{\theta}$ from 800 to 1600 feet per second. Contours of constant adiabatic efficiency η_{ad} are given by dashed lines.

From a comparison of this plot with the impeller plot in reference 2, it is immediately apparent that the introduction of the diffuser cascade was responsible for severe reductions in pressure ratio and efficiency. A range of weight flow exists at all operating speeds; however, this type of diffuser cascade, if performing as designed, for a started supersonic flow with a shock wave contained in the blading would be expected to have a unique value of weight flow for each tip speed. On the other hand, an unstarted cascade with an external shock configuration can operate at various values of impeller weight flow.

Adiabatic efficiency peaks at a low tip speed and is generally similar to that of the impeller alone (reference 2). The surge line is not clearly indicated in these investigations because surging was not violent at any speed.

Starting of diffuser cascade. - The existence of a range of operation at all tip speeds is, in itself, an indication of failure to start. In addition, as shown by figure 4, a plot of the maximum diffuser-inlet Mach number M_2 against radius for design speed, when compared with the design minimum value as limited by contraction ratio alone, shows Mach numbers too low for starting to occur, even disregarding boundary layer, wakes, and mixing losses (reference 3, pp. 183-187). The boundary layer and possibly a separated region resulting from positive angles of incidence caused the diffuser to reach a weight-flow limit (choking) at a value below design. As a result, design Mach number and flow angle were unobtainable.

Use of flow bleedoff to aid starting. - In an effort to circumvent the starting problem, bleedoff holes were installed between the impeller and the diffuser. The geometry of the test rig limited the amount of air that could be withdrawn. At design speed, the removal by suction of some 9.06 percent of the actual weight flow allowed the impeller to operate at an equivalent-weight-flow condition 7 percent higher than the previous limit. As shown in figure 4, the resulting Mach number distribution at the diffuser entrance was barely in excess of the theoretical minimum for starting. This increase in Mach number was actually insufficient to allow starting, however, and the net weight flow through the diffuser was unimproved.

The over-all performance-characteristics curves are presented in figure 5 for operation with bleedoff between impeller and diffuser. The value of equivalent weight flow given is the net value that flows through the diffuser. Pressure ratio and adiabatic efficiency are improved somewhat as a result of more favorable impeller operation. This improvement is more marked at a tip speed of 1600 feet per second where pressure ratio is increased 9 percent near the maximum-flow point than at lower speeds.

Radial distribution of flow angle. - An examination of the measured flow angles at the inlet and the discharge of the diffuser cascade (fig. 6) reveals considerable change from previously measured impeller-discharge flow angles (reference 2). At the maximum weight flow, the observed angle of incidence just in front of the diffuser is 2° or less; at lower weight flows the maximum is 6°. In previous tests of the impeller alone, the much higher flow angles at comparable weight flows indicated large angles of incidence with the blades. The shock configuration in front of the diffuser is probably responsible for this change in measured flow angle.

At the maximum-flow condition with the diffuser in place, the dependence of the diffuser-discharge flow angle on the back pressure indicated an expansion wave off the blade trailing edge. At lower values of weight-flow little turning takes place.

Flow characteristics within diffuser. - Measurements of flow conditions within a diffuser passage were impractical because the presence of the instruments alters the flow. An estimate of the flow processes at representative flow conditions at design speed is presented in figure 7. Static-pressure readings were obtained at 20 locations arranged in three rows along the outside wall of a single passage. When used in conjunction with the measured total pressure just outside the boundary layer at the diffuser discharge, a minimum value of Mach number was determined for each station. Similarly, by using the total pressure in front of the cascade a maximum Mach number was established. In general, minimum values of Mach number were considered to be more nearly correct at all positions downstream of the first shock wave, which, for an unstarted cascade, must occur ahead of the throat section.

In figure 7(a), the choking flow condition at wide-open outlet throttle is given ($W\sqrt{\theta}/\delta = 14.23$ lb/sec). Near the blade tip the air entrance angle closely approximates the blade angle (see fig. 6) and the Mach number barely exceeds the theoretical minimum for starting (fig. 4). At other radii, however, the Mach number was lower, and starting did not take place. Tabulated values of Mach number show that both maximum and minimum values exceed unity in the region in front of the throat and the maximum values are considered more likely. Because the flow could not enter supersonically, at this contraction ratio for the remainder of the wall-tap locations, the minimum values of Mach number were chosen. At this flow condition, these values show a region of high subsonic velocity, followed by a transition to sonic flow and an expansion wave off the blade trailing edge, which resulted in discharge Mach numbers exceeding those at the diffuser inlet. Although the return to sonic velocity after the shock is undoubtedly aided by the lack of area divergence of the straight blades, any area divergence after a normal shock at these Mach numbers must be treated with great care. The optimum area increase required to maintain and decelerate subsonic flow would require empirical determination.

As the outlet throttle is closed to increase back pressure, a second strong shock wave, previously downstream of the instrument station, was forced up to the diffuser blades. This flow condition is shown in figure 7(b) for virtually the same weight flow $(W\sqrt{\theta}/\delta = 14.13 \text{ lb/sec})$. Flow Mach numbers are the same as for the wide-open throttle condition in the upstream part of the blading, and again an expansion wave forms off the trailing edge. In this instance, however, the back pressure forces a normal shock to occur at the blade exit, which cancels the growth of the expansion wave. At the downstream measuring station, the flow velocity is subsonic and the discharge angle is only slightly lower than the blade angle.

As the back pressure is increased further, the second shock moves upstream until it disappears at the diffuser throat. The inlet-flow configuration remains unaltered until the subsonic flow exists everywhere in the diffuser passage and then a further increase in back pressure results in an upstream displacement of the detached waves at the diffuser inlet and a reduction of impeller weight flow. This flow condition is demonstrated by figure 7(c) for a weight flow of 11.34 pounds per second.

Efficiency of diffuser cascade. - The efficiency of the supersonic diffuser is presented in terms of two parameters, η_s and η_{st}.

The supersonic efficiency (reference 3) is based on inlet total and static pressures and outlet total pressure and is given the form

$$\eta_s = 1 - \frac{2}{\gamma-1}\frac{1}{M_2^2}\left[\left(\frac{P_2}{P_3}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

This parameter gives an indication of the loss in total pressure across the diffuser cascade.

The customary relation for total-pressure ratio across a normal shock may be substituted for P_2/P_3,

$$\frac{P_2}{P_3} = \left(\frac{2\gamma}{\gamma+1} M_2^2 - \frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \left(\frac{1 + \frac{\gamma-1}{2} M_2^2}{\frac{\gamma+1}{2} M_2^2}\right)^{\frac{\gamma}{\gamma-1}}$$

A curve showing the theoretical relation of η_s to Mach number is given in figure 8. At a Mach number of 1.3, the highest obtained with the diffuser installed, the theoretical value of η_s is above 98 percent. Thus, the loss through a single normal shock at these Mach numbers is not excessive.

A measure of the efficiency of the static-pressure gain in the diffuser may be obtained by substituting static pressure and temperatures in the standard equation for adiabatic efficiency. With some manipulation to convert static temperature to a function of Mach number, the following equation may be written:

$$\eta_{st} = \frac{\left(\frac{2}{\gamma-1} + M_3^2\right)\left[\left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{M_2^2 - M_3^2}$$

Both the supersonic efficiency and the static-pressure efficiency, obtained from experimental data, are plotted in figure 9 against equivalent weight flow for a number of values of equivalent tip speed. The values of supersonic efficiency are shown to be much lower than would be indicated by the presence of a single strong shock (fig. 8). A trend toward lower peak values of η_s exists at higher tip speeds and weight flows, which demonstrates a rise in losses at higher Mach numbers. Although the supersonic efficiency drops sharply at the choking-flow condition, absolute values still exceed 75 percent. The gradual drop in efficiency at lower values of weight flow at a given speed reflects the additional separation and mixing losses associated with successively higher angles of incidence.

The curves of static-pressure efficiency against weight flow show a sudden drop at the choking-flow condition. Because the flow reverts to the sonic state and then expands off the trailing edge of the blade, the discharge static pressure is lower than the inlet, and this efficiency goes to zero. As increasing back pressure causes the flow to become subsonic at the diffuser outlet, a pressure increase is established. The resulting value of static-pressure efficiency peaks at 62 percent at design speed and is only slightly higher at lower tip speeds. The absolute value of η_{st}, as presented, is probably too low because static pressure measured between the impeller and the diffuser may include some pressure gain from the external shock. The amount of this discrepancy, however, would be less than 6 percent.

The peak values of both supersonic and static-pressure efficiency are reached at weight flows lower than the maximum. An external shock configuration exists at all weight flows, and the indicated incidence angle is higher for the low-weight-flow operating point. Under these conditions the blades are operating as a pitot-type, or simple divergent, diffuser, with an external shock and subsonic flow through the blades. In this range of Mach numbers, a design specifically for this type of operation appears to be at least as efficient as the unstarted convergent-divergent diffuser (reference 4).

Comparison of over-all performance of impeller-diffuser combination with performance of impeller alone. - As a check on any possible changes in impeller operating characteristics resulting from (1) the installation of new guide vanes, (2) a slightly increased radial clearance, or (3) repair work on the impeller trailing edges, the impeller characteristic curve at design speed was obtained before installation of the diffuser cascade. At this time, a duplicate set of instruments was placed at the diffuser measuring station 3.75 inches downstream of the impeller. The standard-impeller characteristic curves for both instrument locations, as well as the over-all performance of the impeller-diffuser combination, are given in figure 10. Even without blades, a large loss in total pressure evidently exists in the annulus between the impeller and diffuser measuring stations. These losses result from dissipation of impeller wakes, other mixing losses, and wall friction. At a weight flow corresponding to the diffuser maximum-flow condition, the pressure ratio is reduced from 3.4 to 3.16 in the annulus alone. A good share of this loss represents energy unavailable for pressure conversion and should properly be charged against the impeller rather than the diffuser. This inherent loss would account for some, but not all, of the discrepancy in supersonic efficiency between the theoretical values for a single normal shock and the observed efficiencies.

Peak pressure ratio with the diffuser installed is 3.03 at design speed. The implication is not intended that only the loss in pressure ratio between 3.16 and 3.03 may be charged to the diffuser because the presence of blades may actually decrease mixing losses, and so forth. More than shock losses alone need to be considered, and other losses may be of the same order of magnitude as shock losses in this range of Mach numbers.

A similar comparison of adiabatic efficiency shows that failure to attain impeller design weight flow was very injurious to over-all efficiency. The diffuser-limited operating conditions cover a range of operation where the impeller efficiency is far from its peak value. This mismatching of compressor components cuts down the over-all adiabatic efficiency to undesirable values.

SUMMARY OF RESULTS

Experimental and analytical studies of the axial-discharge impeller combined with a supersonic diffuser cascade have indicated the following results:

1. Choking in the diffuser passages at values of weight flow lower than design prevented attainment of design flow conditions. The requirements for starting the supersonic flow in the diffuser were not met at any flow condition investigated because the effective contraction ratio was increased by the presence of boundary layer, blade wakes, and flow separation.

2. Flow angles, measured in front of the diffuser-cascade, differed materially from angles measured previously behind the impeller alone. The blade cascade appeared responsible for an adjustment of the flow that reduced the effective angle of incidence of the blade to the flow by several degrees.

3. At maximum weight flow the subsonic flow behind the first, or external, shock reverted to sonic flow farther downstream as a result of boundary-layer buildup. An expansion wave developed at the trailing edge of the diffuser blades, which resulted in discharge Mach numbers exceeding those at the diffuser inlet.

4. Bleeding off 9 percent of the impeller weight flow in front of the diffuser throat was insufficient to allow starting of the cascade or to increase the net weight flow through the diffuser.

5. Total-pressure losses resulting from poor flow distribution, mixing, and blade wakes assumed equal importance with the shock losses associated with the diffuser.

6. Peak values of diffuser efficiency occurred at weight flows lower than the choking value at each speed. Thus the indications are that a diffuser with an external shock configuration would perform as

well as or better than the convergent-divergent type in this range of Mach numbers with additional benefit of operating over a range of weight flows.

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REFERENCES

1. Goldstein, Arthur W.: Design and Performance of Experimental Axial-Discharge Mixed-Flow Compressor. I - Impeller Design Theory. NACA RM E8F04, 1948.

2. Wilcox, Ward W.: Design and Performance of Experimental Axial-Discharge Mixed-Flow Compressor. II - Performance of Impeller. NACA RM E8F07, 1948.

3. Ferri, Antonio: Elements of Aerodynamics of Supersonic Flows. The Macmillan Co., 1949, pp. 179-192.

4. Lukasiewicz, J.: Diffusers for Small Supersonic Mach Numbers. Design Data Tech. Note No. AERO.1973, S.D.84, British R.A.E., Sept. 1948.

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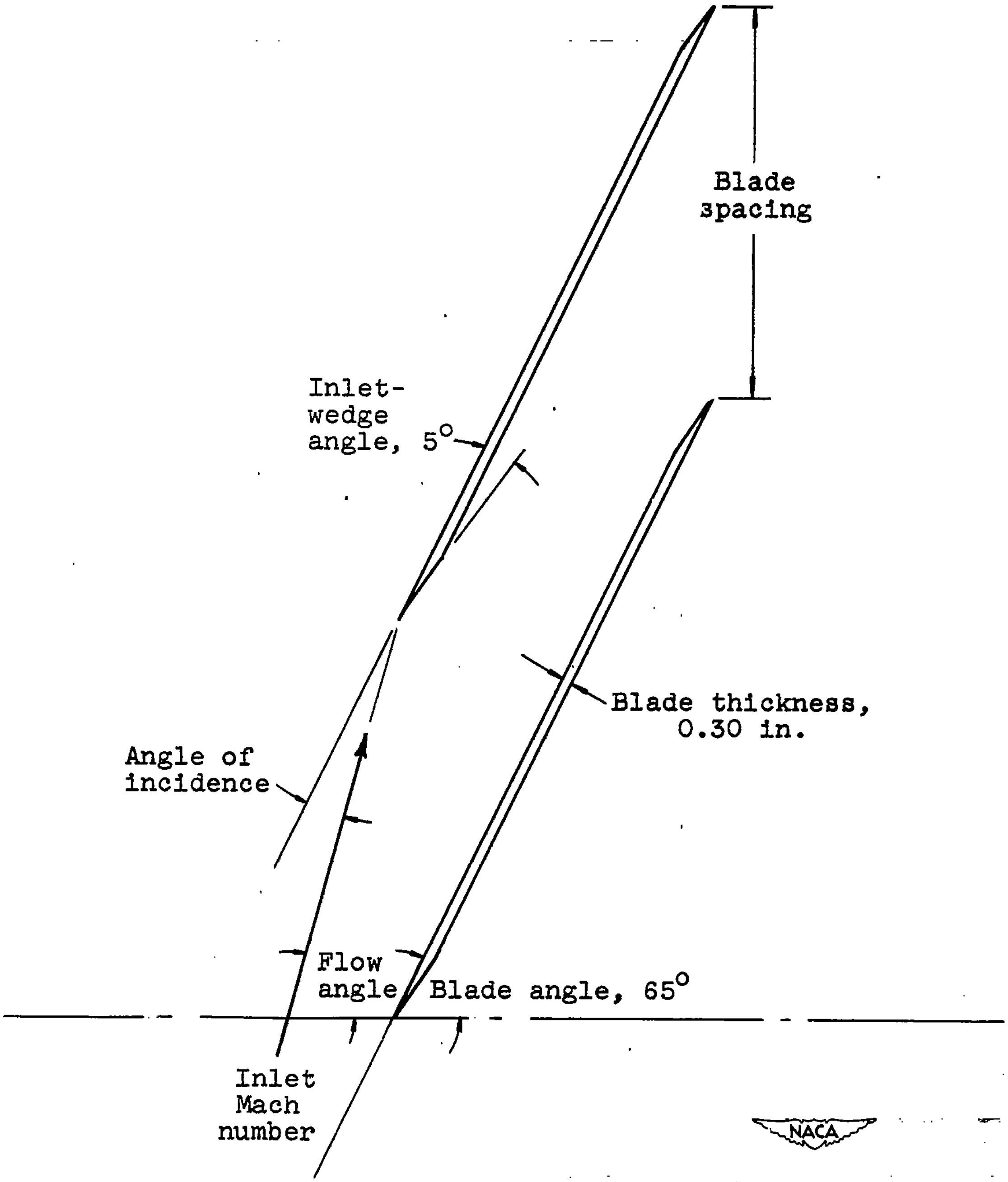

Figure 1. - Sketch of one diffuser passage.

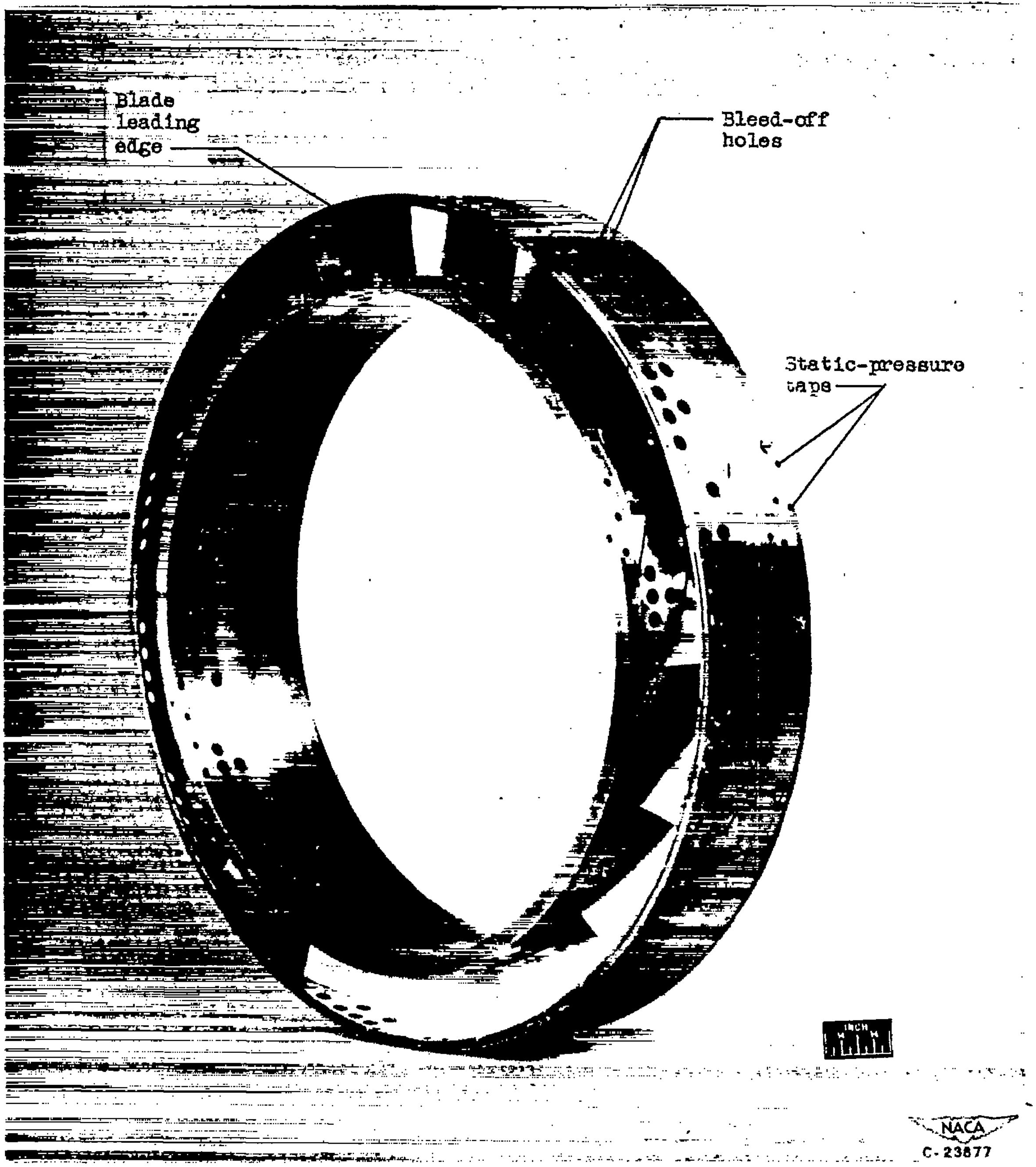

Figure 2. - Photograph of diffuser cascade.

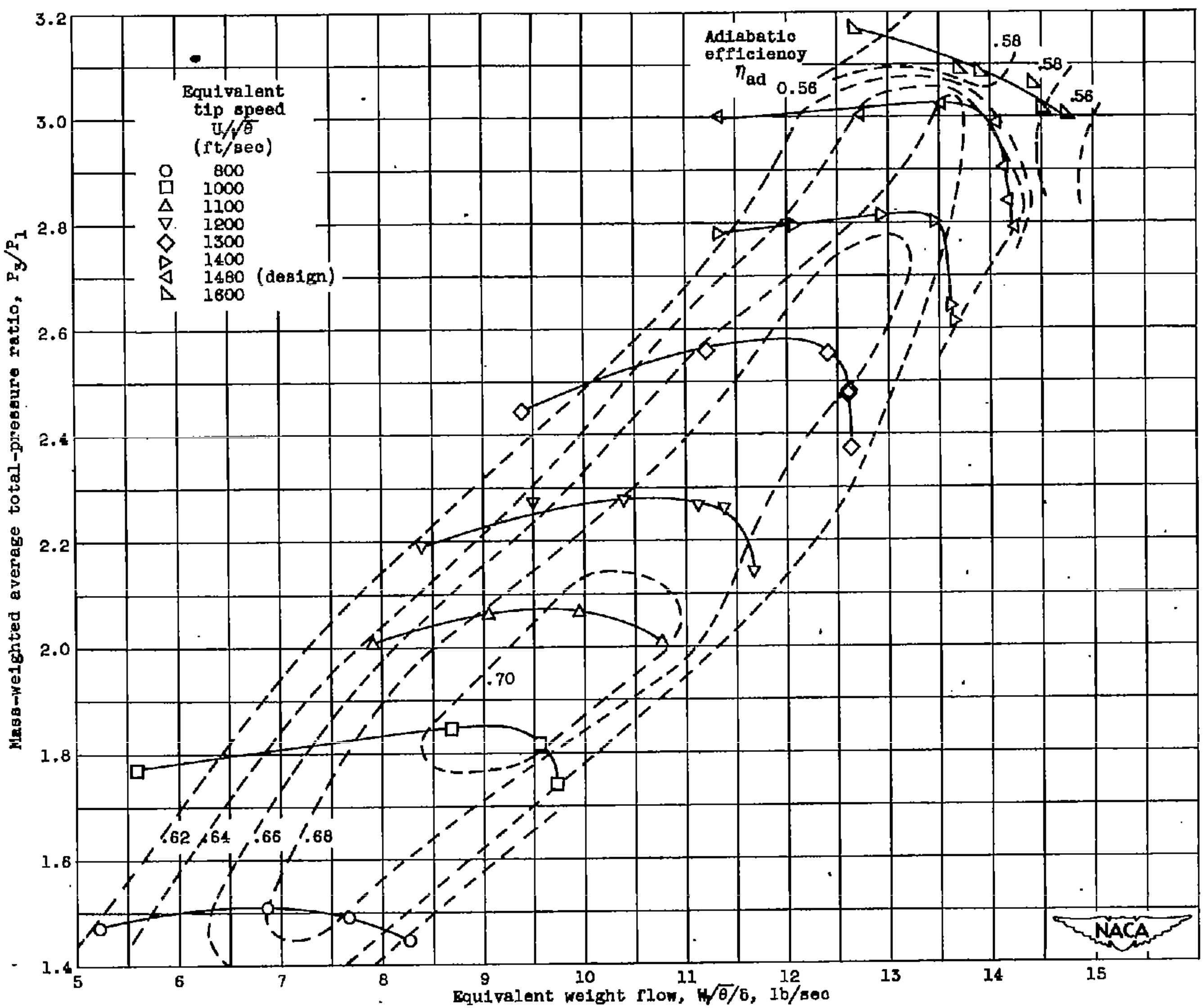

Figure 3. - Over-all performance of impeller-diffuser combination.

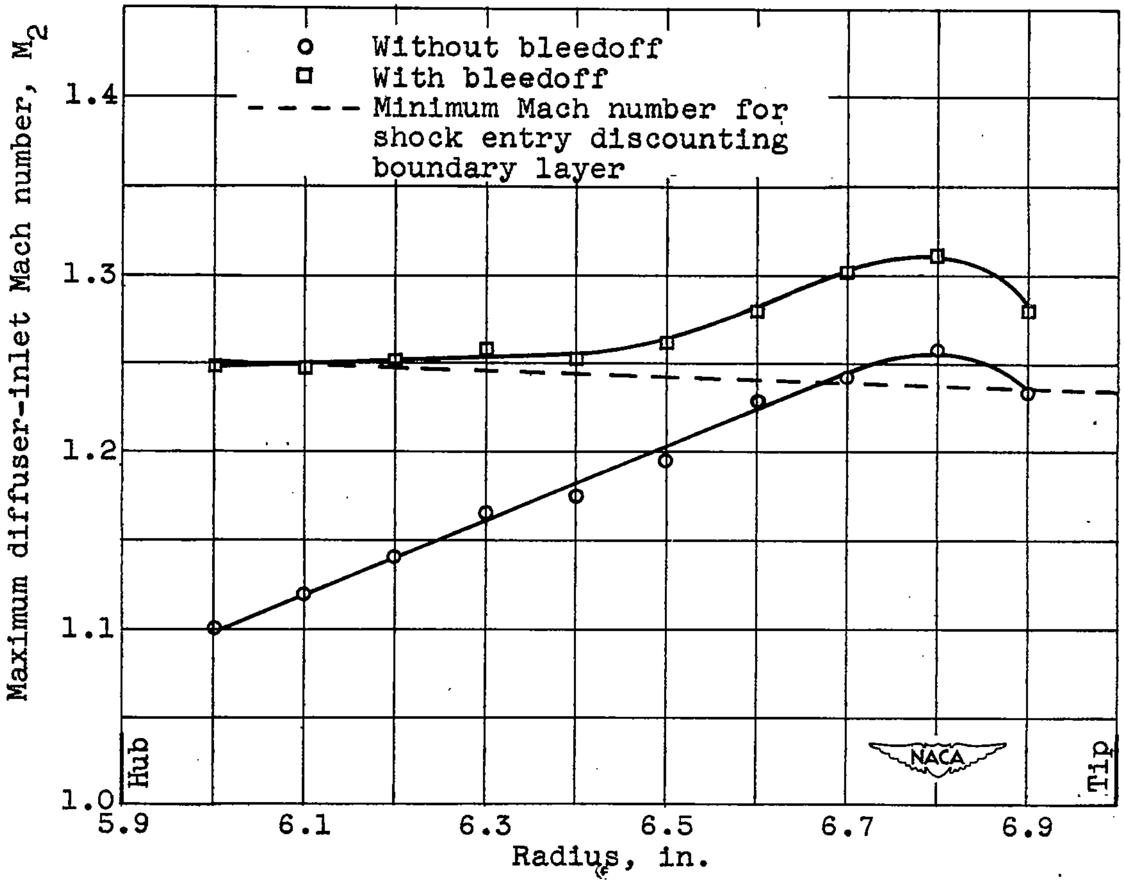

Figure 4. - Radial variation of maximum diffuser-inlet Mach number at maximum-flow condition at design speed ($U/\sqrt{\theta} = 1480$ ft/sec).

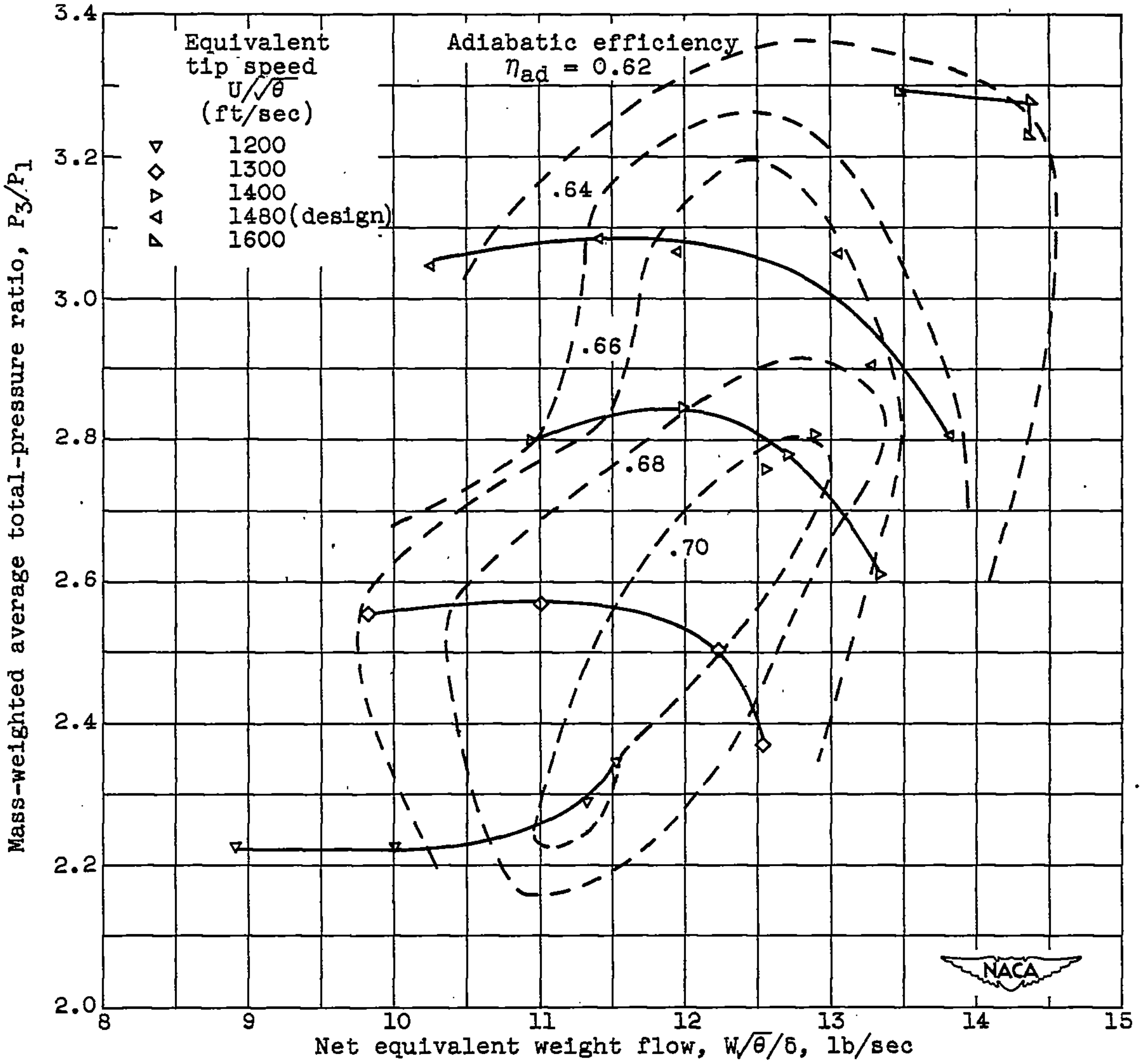

Figure 5. - Over-all performance of impeller and diffuser cascade with bleedoff.

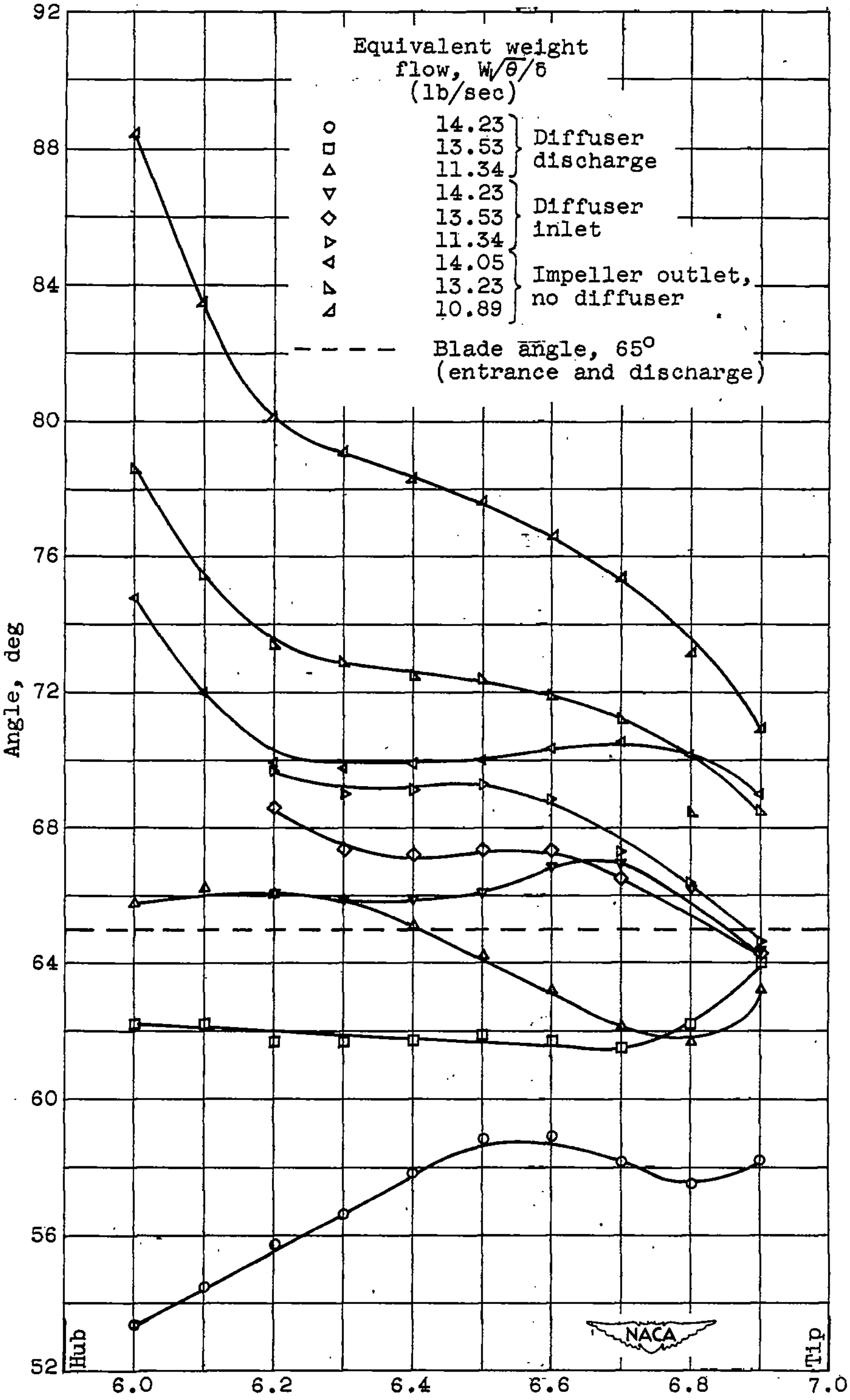

Figure 6. - Radial variation of inlet and discharge angles at design speed ($U/\sqrt{\theta}$ = 1480 ft/sec).

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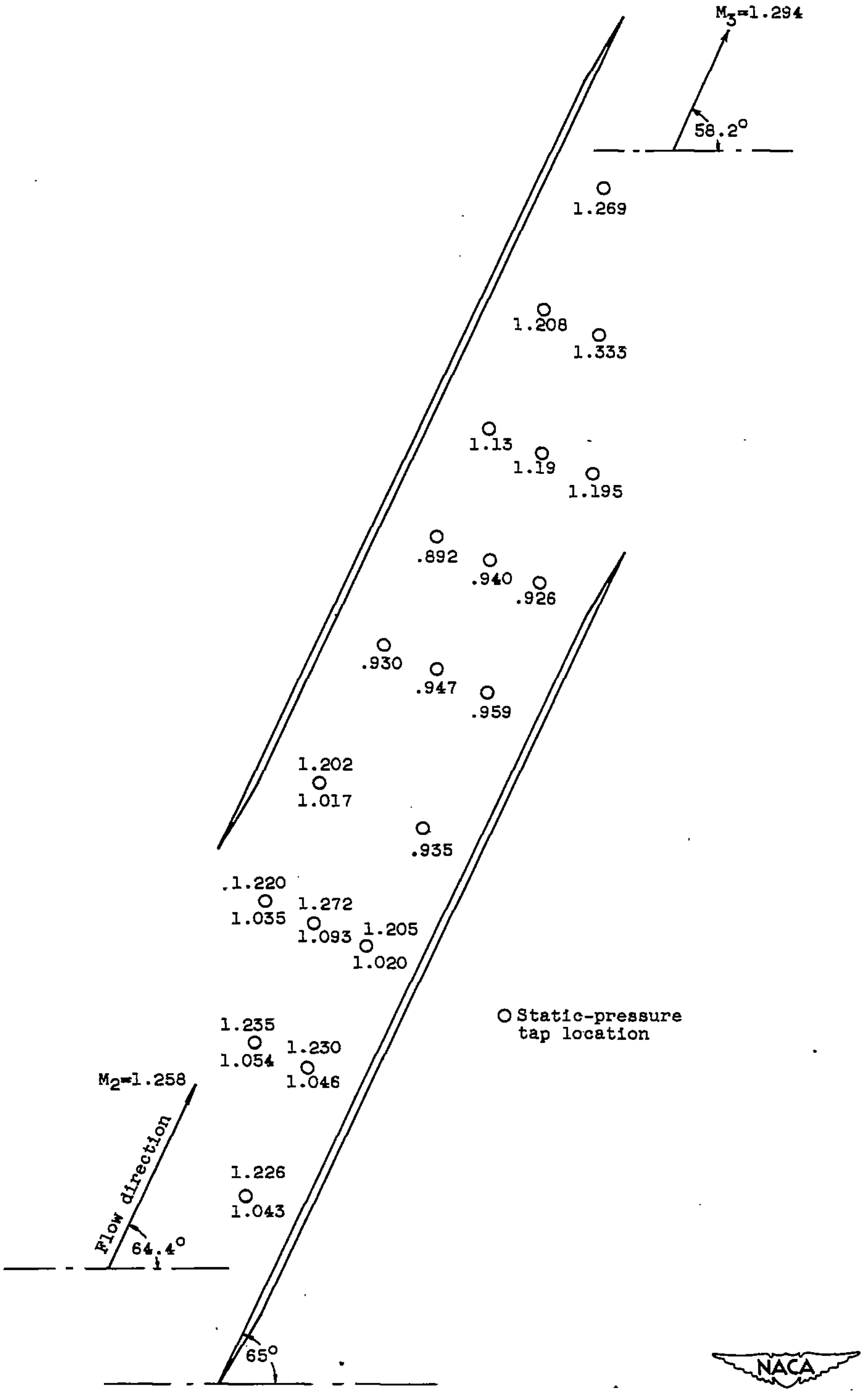

(a) Equivalent weight flow, $W\sqrt{\theta}/\delta$ = 14.23 pounds per second (wide-open throttle).

Figure 7. - Estimated Mach numbers at several locations in a diffuser passage. Values above tap location are maximum Mach numbers; values below are minimum Mach numbers. $U/\sqrt{\theta}$ = 1480 feet per second.

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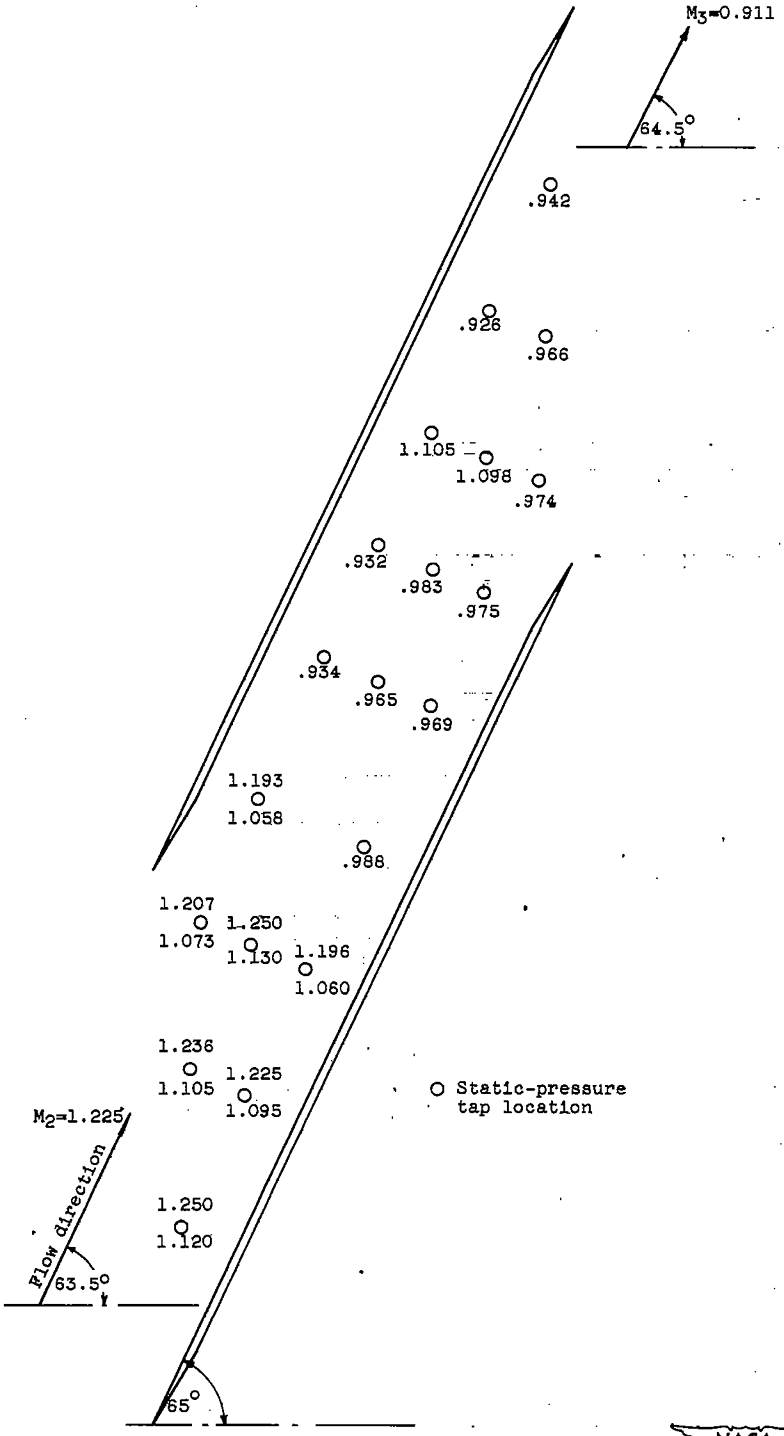

(b) Equivalent weight flow, $W\sqrt{\theta}/\delta$ = 14.13 pounds per second.

Figure 7. - Continued. Estimated Mach numbers at several locations in a diffuser passage. Values above tap location are maximum Mach numbers; values below are minimum Mach numbers. $U/\sqrt{\theta}$ = 1480 feet per second.

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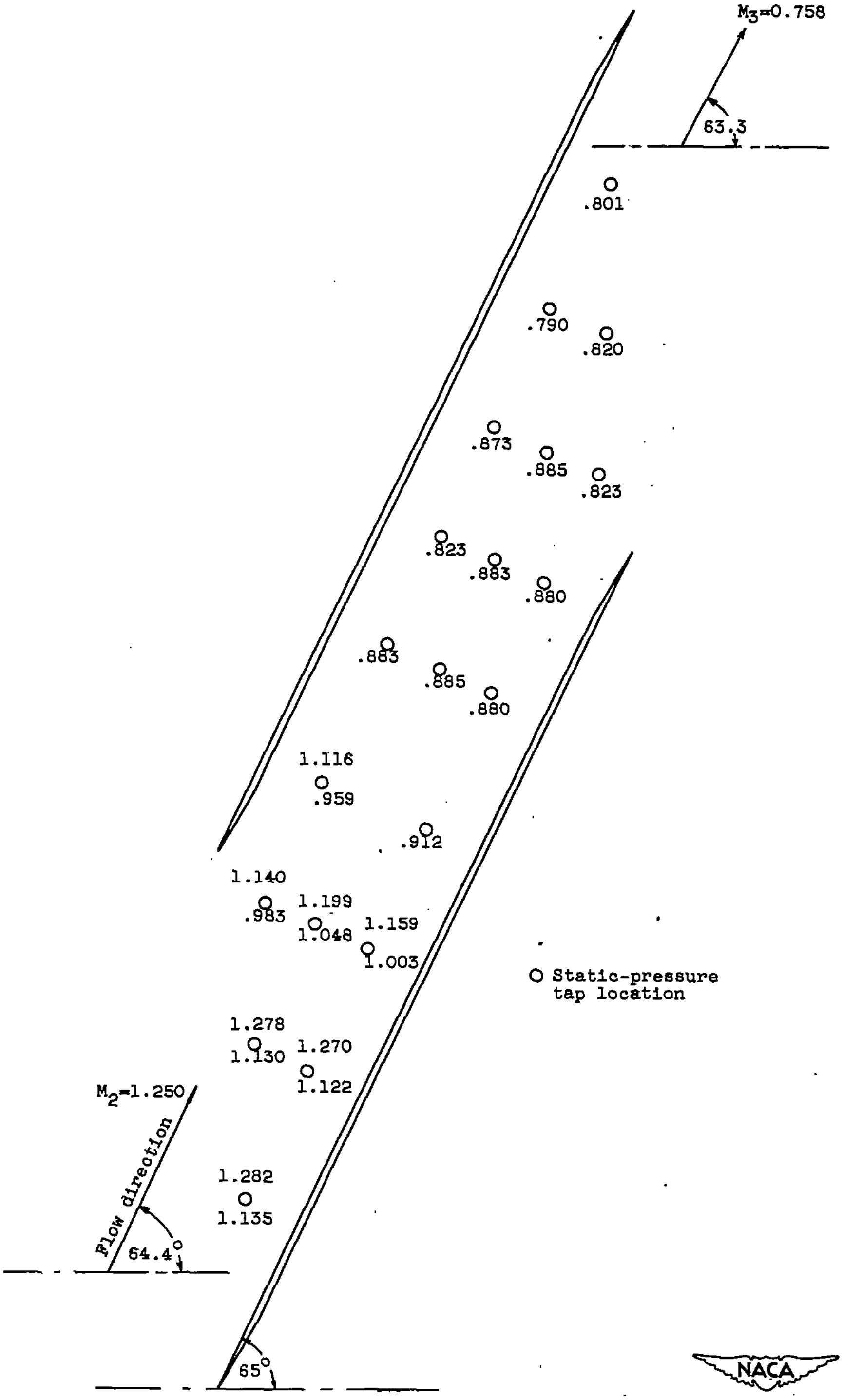


(c) Equivalent weight flow, $W\sqrt{\theta}/\delta$ = 11.34 pounds per second.

Figure 7. - Concluded. Estimated Mach numbers at several locations in a diffuser passage. Values above tap location are maximum Mach numbers; values below are minimum Mach numbers. $U/\sqrt{\theta}$ = 1480 feet per second.

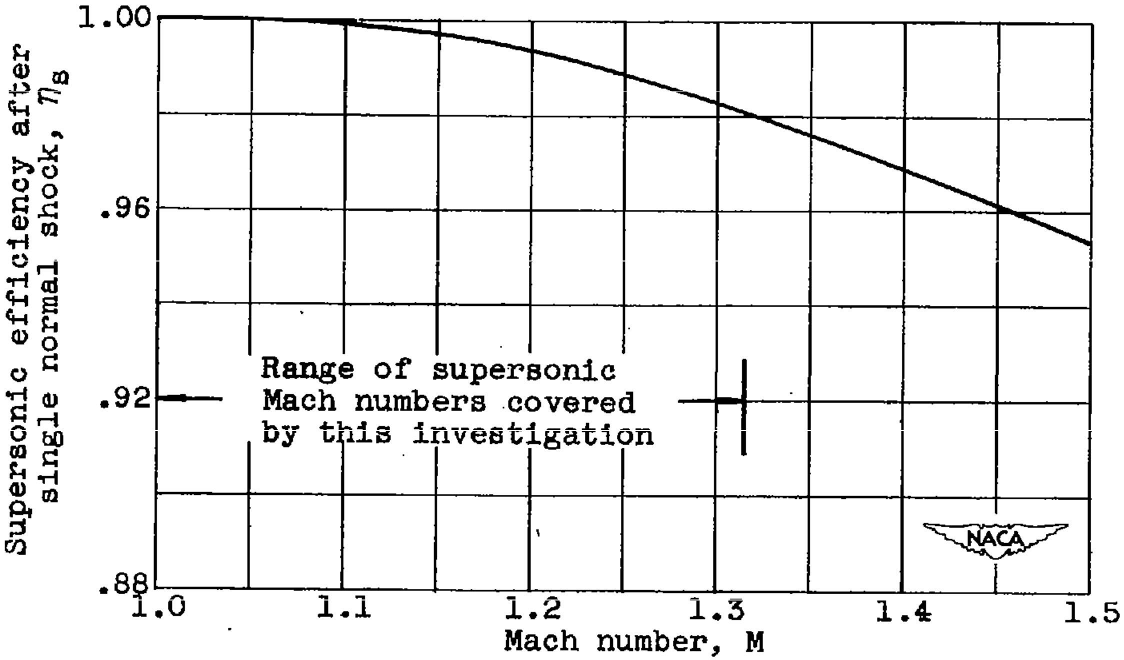


Figure 8. - Supersonic efficiency through single normal shock at various Mach numbers.

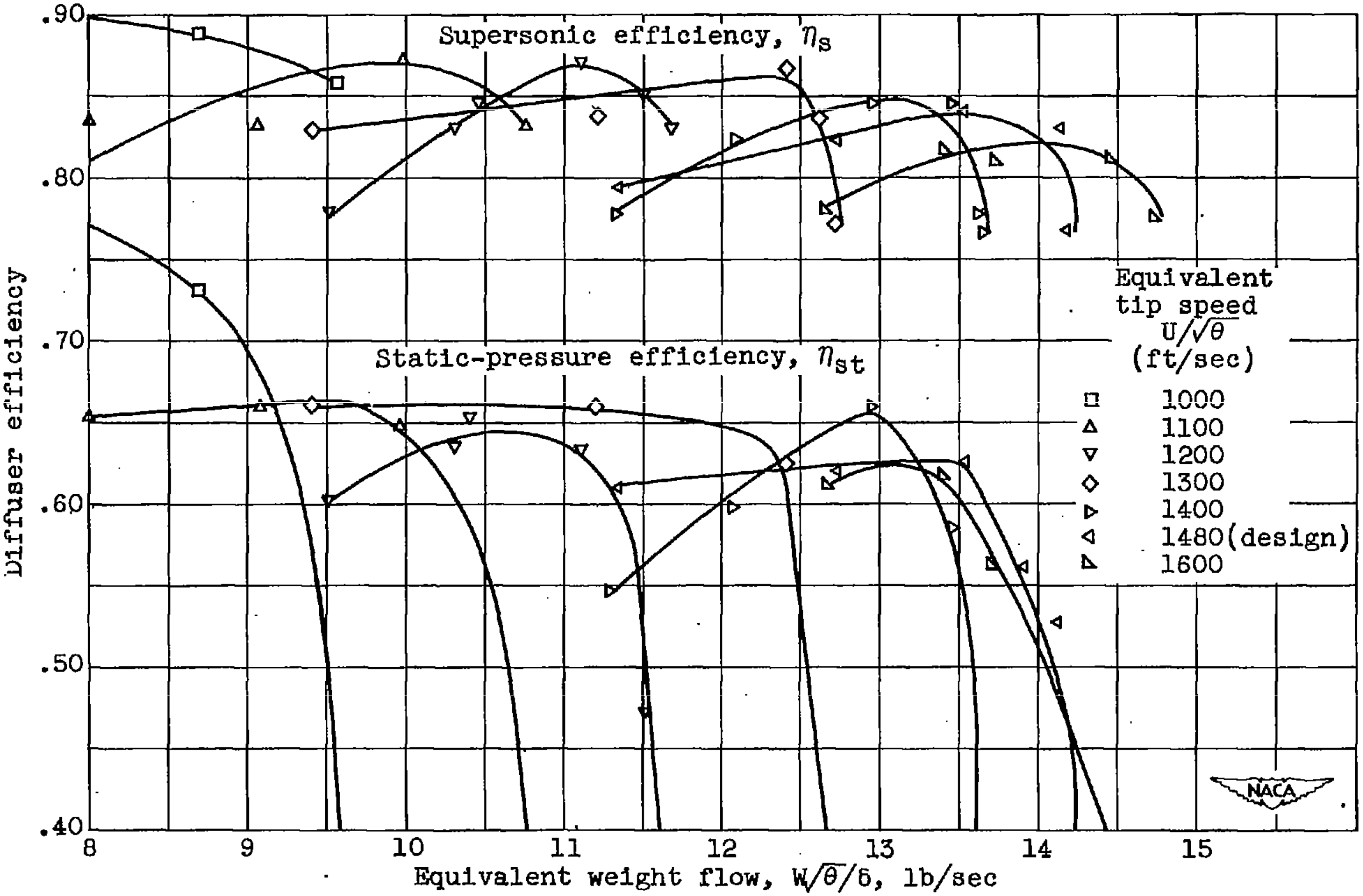
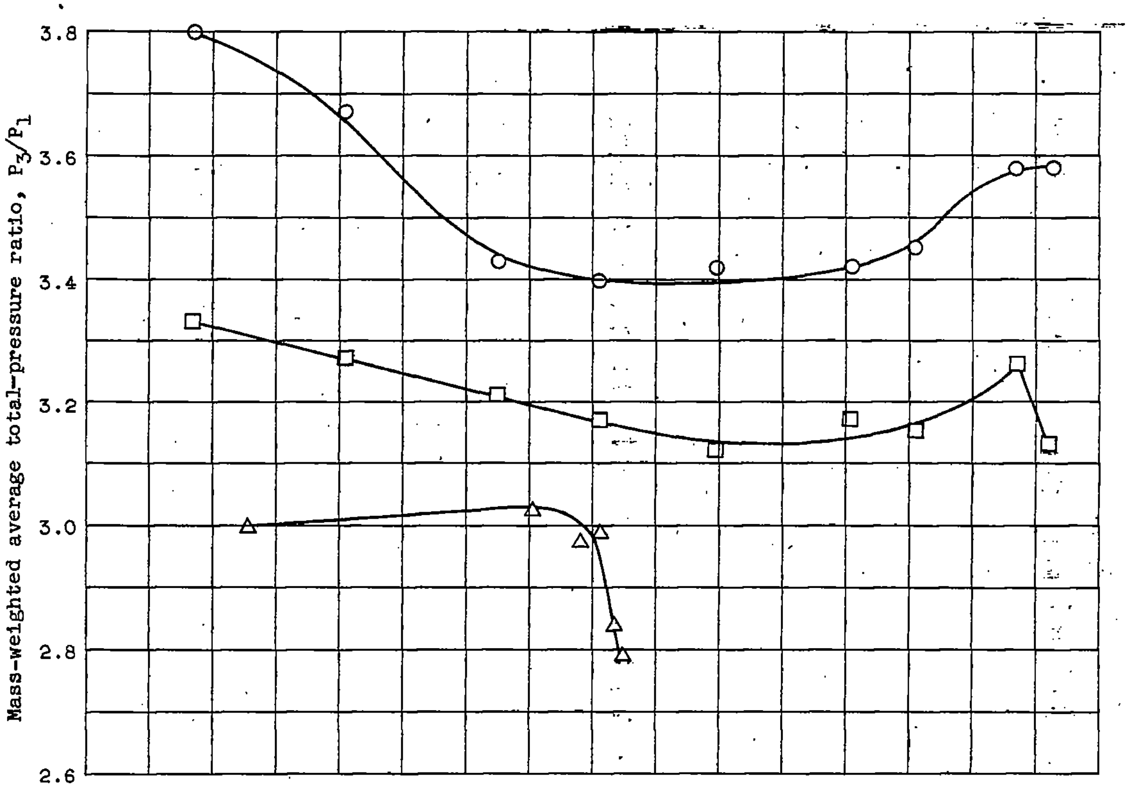
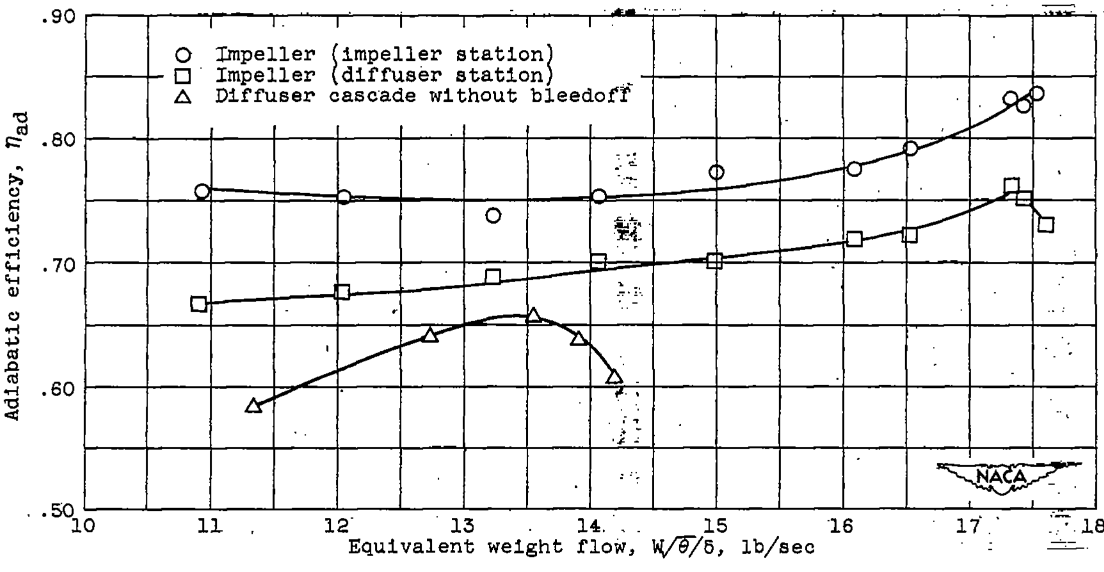


Figure 9. - Supersonic and static-pressure efficiencies for diffuser cascade without bleedoff.



(a) Pressure ratio.



(b) Adiabatic efficiency.

Figure 10. - Comparison of over-all performance of impeller alone and impeller with diffuser at design speed ($U/\sqrt{\theta}$ = 1480 ft/sec).

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