SECURITY INFORMATION



[redacted]

Copy
RM E52B22

NACA RM E52B22

TECH LIBRARY KAFB, NM
0143224

[redacted]

NACA

# RESEARCH MEMORANDUM

6729

## PERFORMANCE OF AN IMPULSE-TYPE SUPERSONIC COMPRESSOR WITH STATORS

By John F. Klapproth, Guy N. Ullman
and Edward R. Tysl

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Classification cancelled (or changed to Unclassified)
By authority of Nasa Tech Pub Announcement #125
(OFFICER AUTHORIZED TO CHANGE)
By 18 Mar. 58
NK
(GRADE OF OFFICER MAKING CHANGE)
27 Mar. 61
DATE

[redacted]

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
April 28, 1952

PERMANENT RECORD

319.98/13

[redacted]

TECH LIBRARY KAFB, NM
0143224



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

# PERFORMANCE OF AN IMPULSE-TYPE SUPERSONIC COMPRESSOR WITH STATORS

By John F. Klapproth, Guy N. Ullman, and Edward R. Tysl

2489

## SUMMARY

An impulse-type supersonic compressor rotor with stators was tested in Freon-12 over a range of equivalent tip speeds and weight flows. A stage pressure ratio of 1.83 and an efficiency of 84.7 percent were obtained at 69.1 percent of the design speed of 1604 feet per second in air. Efficiency decreased rapidly with increasing tip speed to a value of 66.8 percent at a pressure ratio of 2.6 at 96.6 percent design speed.

Diffusion to stator exit Mach numbers below 0.6 was obtained with the stators set at a negative angle of attack for design speed operation. For this stator setting angle, all speeds except 110.6 percent design gave continuous operation as the shock was forced from stator alone to shock in both rotor and stator. Stator exit Mach numbers below 0.57 were obtained for all speeds. Pressure recoveries above 90 percent were obtained across the stators for stator entrance Mach numbers up to 1.2, with recovery decreasing rapidly for Mach numbers above 1.4.

The limiting ratio of the flow area entering the stators to the stator minimum section area apparently depends largely on the mixing losses between the rotor and the stator and on the boundary layer at the stator minimum section. On the basis of limited data, additional restrictions required for starting the supersonic flow through the stators appear to be less critical than those computed by one-dimensional theory for a diffuser having a normal shock ahead of the inlet prior to starting.

## INTRODUCTION

Theoretical considerations based on a one-dimensional analysis of several different configurations for supersonic compressors (reference 1) indicated possible high stage pressure ratios for the impulse or shock-in-stator type compressor. The supersonic compressor utilizes a high axial inlet Mach number (approximately 0.7) and a relatively high tip speed to give supersonic velocities relative to the rotor. The rotor passages of the impulse-type compressor are designed for a large turning with supersonic flow throughout, avoiding strong shocks. The flow enters the stators with supersonic velocities where it is decelerated through sonic velocity and turned to the axial direction.

To investigate the characteristics of the impulse-type supersonic compressor, a rotor was designed, built, and tested at the NACA Lewis laboratory. The rotor was designed for a moderate pressure ratio of approximately 3:1, assuming an 85 percent efficiency with an air equivalent tip speed of 1604 feet per second and an average turning of 47° in the rotor passage. The performance characteristics of the rotor as a separate component, tested in Freon-12 (dichlorodifluoromethane), a commercial refrigerant, are reported in reference 2.

A set of stators was built for the design discharge conditions of the impulse-type supersonic compressor rotor of reference 2, and the performance in Freon-12 of the compressor as a complete stage is presented herein. An analysis of the performance of the stators is made for the stator blade setting angle where stator exit Mach numbers below 0.6 were obtained for all speeds.

2489

## STATOR DESIGN

The design of the stators was based on the estimated rotor exit conditions. The design vector diagram for the rotor pitch section is shown in figure 1(a). With a 10 percent loss of the total pressure relative to the rotor assumed, the computed exit Mach number at the mean radius was 1.79 at an angle of 27°. Since the estimated angle entering the stators varied only from 29° to 25° from root to tip and the Mach number varied from 1.55 to 1.79, the stators were designed on a two-dimensional basis using conditions at the mean radius.

The stator passages were designed such that the flow entered parallel to the suction surface at the leading edge (fig. 1(b)), with a leading-edge wedge angle of 10°. The wave pattern was contained inside the blade passage with the flow turned supersonically to the axial direction. The minimum section area was determined from the entrance area and the Kantrowitz contraction ratio for air (reference 3) at the design entrance Mach number (1.79). After a short constant-area minimum section, the subsonic portion of the blade diverged such that the passage area increased at a rate corresponding to a 5° diffuser cone having an equivalent minimum area. The estimated exit Mach number, when a 10 percent boundary layer and wake allowance and normal shock losses at the minimum section Mach number were assumed, was 0.48.

The blade height was constant at 1.02 inches, with a chord length of 5.29 inches. The 25 blades at a mean diameter of 15 inches resulted in a solidity of 2.8. The leading edge of the stators was placed approximately 2 inches downstream of the trailing edge of the rotor. A photograph of the rotor and stators being installed in the test unit is shown in figure 2.

## APPARATUS AND INSTRUMENTATION

The rotor and stator combination was investigated in Freon-12 using the variable component test rig described in reference 2 and shown schematically in figure 3. The compressor was driven by a 3000 horsepower variable-frequency motor with a speed control of ±0.5 percent. A recirculating system was used in which the Freon inlet temperature was maintained by passing the hot gases through twin cooler assemblies.

2489

The over-all rating of the compressor was obtained as recommended in reference 4 using the instrumentation in the entrance tank and that at station 5 (about 8.75 in. downstream of the rotor or 1.5 in. downstream of the stators). The exit temperature at station 5 was measured by two calibrated 3-point total-temperature rakes.

Total-pressure measurements at station 5 were obtained by 15 shielded total-pressure probes. The annular segment behind a single stator passage was divided into 15 equal areas by five circumferential and three radial increments with the total-pressure probes located at the area centers. The probes were spaced around the annulus in corresponding positions behind the stator passages such that a maximum of two probes fell behind any one passage. Total-pressure measurements at station 4 between the rotor and stators were made by 3 shielded probes located at the center of three equal annular areas, 3/4-inch downstream of the rotor. Total-temperature and total-pressure instruments were set at an average angle as determined by tests and were insensitive to angle over the range encountered.

A probe actuator with a cone-type combination probe (reference 2) was used at station 4 to determine the rotor discharge conditions. Wall static pressures were measured on the inner and outer housings at the instrument stations and along the stator passage.

The weight flow was measured by static pressures on the inlet fairing nozzle, which was calibrated against a known adjustable orifice.

## PROCEDURE

Over-all performance data in Freon-12 for the rotor and stator combination were obtained over a range of back pressures from open throttle to stall at seven wheel speeds from 110.6 percent to 55 percent of the design equivalent speed (1604 ft/sec tip speed in air). For these data the inlet stagnation pressure was maintained between 30 and 32 inches of mercury absolute, and the inlet temperature was maintained between 100° and 130° F. Frequent measurements of the test-gas purity were made during the runs, with the purity being maintained at 97 percent or better. The computation methods are similar to those used in appendix B of reference 2, where they are considered in more detail.

Compressor rotor speed in Freon-12. - The design speed in Freon-12 was computed so as to obtain the design relative entrance Mach number at the rotor tip (fig. 4). The resulting design equivalent speed $U_t/\sqrt{\theta}$ in Freon-12 is then 772 feet per second compared with 1604 feet per second for standard upstream conditions in air. (The symbols used herein are defined in the appendix.) With the guide vane turning producing a spanwise variation in the absolute entrance velocity, it was impossible to match exactly for Freon-12 the relative inlet Mach numbers at all other radii because of the slight variation in the velocity of sound arising from the different values of $\gamma$ for air and Freon-12.

2489

Weight flow. - The weight flow of Freon-12 was calculated by use of the standard nozzle equations (reference 5) and static pressures measured in the inlet section. The approximate air equivalent weight flow was calculated as described in appendix B of reference 2 and is used in presenting the experimental results.

Pressure ratio. - The over-all pressure ratios were computed using the inlet stagnation conditions measured in the inlet depression tank and an area weighted average of the total-pressure probes downstream of the stators (station 5). Only conditions of subsonic velocities leaving the stators were used in plotting the over-all performance map.

The average total pressure between the rotor and stator (station 4) was obtained by correcting the averaged readings of the shielded probes for normal shock losses. The average Mach number was determined from the averaged inner and outer wall static pressures and the observed total pressures using the relation for the Mach number as a function of the static pressure upstream of the shock to the total pressure behind the shock.

Adiabatic efficiency. - The total conditions at the entrance and exit were used to determine the enthalpy rise for a constant entropy process and for the actual process, using the thermodynamic tables of reference 6. The ratio of the enthalpy rise under these two conditions was used as the adiabatic efficiency. When compared with the efficiency obtained using the observed total-pressure ratio and temperature ratio, and an average $\gamma$, the efficiency using the thermodynamic tables was about 2 points lower. The adiabatic efficiency and total-pressure ratio are reported as measured in Freon-12.

## RESULTS AND DISCUSSION

### Stators at Design Angle

The stators were installed at the design angle and performance was obtained over a range of speeds. With the design stator setting angle, diffusion from Mach number $M_4$ of 0.75 to $M_5$ of 0.55 was obtained

across the stators at 55 percent design speed. Supersonic velocities entering the stators were not obtained until 89.6 percent design speed, where diffusion from a Mach number of 1.13 to 0.74 occurred. At this speed, as well as the lower speeds, the compressor weight flow could be varied with changes in throttle setting.

For a rotor tip speed of 96.6 percent design, a supersonic Mach number of 1.5 was obtained entering the stators. At the open throttle (low back pressure) condition, supersonic velocities were obtained throughout the stators. As the back pressure was increased a shock pattern could be forced into the diverging portion of the stator passage, as evidenced by static pressures measured on the inner and outer casings. This shock pattern could be forced upstream into the stator passage until the increased back pressure was felt in the stator minimum section. Any further increase in back pressure caused the compressor to surge. The minimum stator exit Mach number $M_5$, obtained with the entrance Mach number of 1.5, was 0.84. At a rotor tip speed of 104.4 percent design, the stator entrance Mach number was 1.63, with supersonic velocities occurring throughout the stator passage. For this rotor speed, a shock could not be forced into the diverging portion of the stators, with the minimum obtainable exit Mach number being 1.41 in the free stream. Any attempt to reduce this exit Mach number by increasing the back pressure resulted in compressor surge.

Thus, with the stators at the design blade setting angle, diffusion to the estimated exit Mach number of 0.48 was not approached for rotor speeds near design. Comparison of the blade setting angle with the observed flow angles leaving the rotor indicated that while the low pressure surface was within $2^{\circ}$ of the measured midstream flow direction at design speed, the angle of attack at the root and tip sections was approximately $+8^{\circ}$.

As the rotor speed was reduced from design, the rotor exit Mach number decreased. Supersonic flow into the stators could not be obtained at these lower Mach numbers and a shock was formed ahead of the stators, thereby imposing a back pressure on the rotor. This back pressure forced a shock to occur in the rotor, which increased the density level and decreased the axial velocity at the rotor discharge, resulting in large absolute discharge angles $\beta_4$ with a correspondingly large angle of attack on the stators.

To reduce the angle of attack on the stators, the blade setting angle was increased by $7^{\circ}$ and $12^{\circ}$. The configuration with the stator angle increased by $12^{\circ}$ yielded the best observed performance and permitted diffusion to reasonable subsonic velocities. The over-all performance of the compressor and an analysis of the stator performance at the $12^{\circ}$ increase in angle are presented.

## Performance at Increased Stator Angle

Total-pressure ratio and efficiency. - The total-pressure ratio as measured in Freon-12 over a range of equivalent speeds is shown in figure 5 plotted against the approximate equivalent weight flow in air. The pressure ratio is shown in figure 6 plotted against efficiency. The efficiency increased with back pressure until it reached a maximum value, then decreased with a further increase in back pressure for all except 110.6 and 104.4 percent design speed, where the maximum efficiency occurred at maximum back pressure. In general the efficiency decreased rapidly with rotor speed, for example, from 84.7 percent at a pressure ratio of 1.83 for the 69.1 percent design speed to an efficiency of 66.8 percent at a pressure ratio of 2.6 at 96.6 percent design speed. The increase in pressure ratio was very slight in going from 96.6 percent to 110.6 percent design speed. 2489

Stator exit Mach numbers. - The Mach numbers observed at the stator exit $M_5$ based on an average total pressure and an average static pressure at station 5 are shown in figure 7 plotted against the stage pressure ratio. For the speeds investigated, supersonic stator exit velocities could be obtained at open throttle; however, the data are presented only for conditions of subsonic exit velocities. Stator discharge Mach numbers below 0.57 were obtained at all operating speeds.

Rotor discharge angles. - The rotor discharge angles measured in the midspan position 3/4-inch downstream of the rotor are shown in figure 8 plotted against weight flow. The limiting line of minimum discharge angle is shown for operation with the stators as well as for the rotor alone (reference 2). The stator setting angle measured tangent to the low pressure surface at the stator blade leading edge is also indicated.

For 96.6, 104.4, and 110.6 percent design speed the minimum rotor discharge angle (which occurs at low back pressures) remained fairly constant. For these speeds the compressor operated with supersonic flow throughout the rotor passages, as indicated by the static pressure on the outer casing and the measured conditions at station 4. The discharge angles were within $1^{\circ}$ of the observed angles without stators.

For speeds lower than 96.6 percent design, the presence of the stators appreciably reduced the rotor discharge angle from that observed when operating without stators. As anticipated in reference 7, when the rotor speed was reduced, the Mach number entering the stators was decreased and the area restriction of the stators forced a shock pattern to form at the exit of the compressor in order to increase the density level and the rotor discharge angle. As the rotor speed was further reduced, the stator restriction caused the shock pattern to move upstream through the rotor passage. At 69.1 percent design speed, where

the maximum weight flow is slightly less than that obtained in tests of the rotor alone, the shock configuration occurred just at the entrance to the rotor passage. (The relative Mach number at the rotor entrance $M_3'$ for this speed was approximately 1.24.) A reduction in maximum weight flow from 20.5 to 18.1 pounds per second was observed at 55 percent speed.

2489

The stator is seen to operate at a negative angle of attack for speeds above 89.6 percent design. For this angle setting, a 10° compression wave forms at the low pressure surface of the stators. This compression wave for near design speeds falls just inside the stator passage. Thus a substantial reduction in Mach number is obtained just at the stator passage entrance, as recommended in reference 7. However, the flow was observed to be steady for a range of Mach numbers (1.6 to 1.8) and could be established without the use of a variable geometry stator.

Stator performance. - The effectiveness of the stators must take into account the amount of diffusion obtained across the blade row as well as the total-pressure recovery. In order to indicate both of these factors, the stator entrance Mach number is plotted against the stator discharge Mach numbers for each of the rotor speeds (fig. 9). The total-pressure recovery across the stators (ratio of downstream total pressure to upstream total pressure) is then indicated by recovery contours. For 55 percent and 69.1 percent design speed, the recovery was very good even for the condition of low weight flow where the angle of attack entering the stators (measured tangent to low pressure surface at the leading edge) is up to 15°.

For rotor speeds of 82.8 percent design and higher, the Mach number entering the stators is supersonic. The stator entrance Mach number remains constant with increasing back pressure (decreasing $M_5$) until the shock is forced upstream of the stators. This reduces the stator entrance Mach number by altering the shock pattern already existing in the rotor for 82.8 percent and 89.6 percent design speed, or by forcing a shock into the rotor passage for the higher speeds. A reduction in the stator entrance Mach number could be obtained for all speeds except 110.6 percent design speed. Thus the shock pattern could be controlled by the downstream throttle to exist in the stator alone or in both the rotor and the stator with no break in the performance. Forcing the shock upstream of the stators improved the stator recovery (principally by reducing the Mach number entering the stators), but the drop in performance of the rotor at this condition (reference 2) caused a net decrease in the over-all efficiency. In general, the recovery was above 90 percent in diffusing from Mach numbers up to 1.2, but the recovery decreased very rapidly for Mach numbers above 1.4 (fig. 9).

Flow limitation imposed by stators. - An indication of the effect of the stators on the maximum mass flow at lower than design speed may

be obtained by considering the observed flow contraction ratio from upstream of the stators to the stator minimum section. By plotting the rotor discharge angles (fig. 8) against the exit Mach number $M_4$ (fig. 10), a curve of limiting angle against Mach number can be obtained. Up to 96.6 percent design speed, the minimum section of the stators imposes a limit on the rotor discharge conditions at maximum weight flow. At 96.6 percent design speed and above, the stators will pass the maximum weight flow of the rotor for the design condition of no increase in density through the rotor, and the rotor fixes the discharge angle.

2489

Since the minimum section area of the stator passage is known, the contraction of the stream tube of width $(2\pi r/N)\cos \beta_4$ upstream of the stators to the minimum section can be determined. The limiting curve of figure 10 is shown in figure 11 as a ratio of entrance to minimum area plotted against the stator entrance Mach number. The observed values shown in figure 11 are approximate since the computations are based on angle measurements made at the midspan position. A completely accurate solution would require a mass weighted average of the angle and Mach number distribution across the annulus and complete data for this computation were not available. For comparison purposes the isentropic contraction ratio to a Mach number of 1.0 and the Kantrowitz ratios (reference 3) for Freon-12 are also shown.

For Mach numbers up to 1.0, the difference between the isentropic and observed values shown in figure 11 reflects the mixing losses between station 4 and the minimum section and the boundary-layer displacement thickness in the minimum section. For supersonic velocities the difference reflects any shock losses that occur between station 4 and the minimum section, the mixing losses, and the minimum section boundary layer, as well as possible limitations on area ratios necessary for the starting of the supersonic flow through the stators. The observed contraction ratio is seen to diverge from the isentropic ratio with increasing Mach numbers; however, for Mach numbers between 1.0 and 1.6, the rate of divergence is less rapid than the Kantrowitz contraction ratio. Above a Mach number of 1.63 the flow angle into the stators was determined only by the rotor and the ratio of $A_{crt}/A_{min}$ remained nearly constant.

The data indicate that the limiting area ratio depends to a large extent on the mixing losses between the rotor and the stator and the boundary-layer thickness at the stator minimum section. The additional restrictions in the supersonic region for the starting of the supersonic flow through the stators do not appear to be so severe as that computed by one-dimensional theory for a diffuser having a normal shock ahead of the inlet prior to starting (reference 3).

## SUMMARY OF RESULTS

An impulse-type supersonic compressor (rotor and stators) was investigated in Freon-12 for a range of rotor speeds and back pressures, and the following results were obtained:

1. A stage pressure ratio of 1.83 with an efficiency of 84.7 percent was obtained at 69.1 percent design speed (design tip speed was 1604 ft/sec in air or 722 ft/sec in Freon-12). The efficiency decreased with increasing wheel speed to a value of 66.8 percent at a pressure ratio of 2.6 at 96.6 percent design speed.

2489

2. Mach numbers below 0.57 were obtained at the stator exit for all speeds. The Mach numbers entering the stators increased with rotor speed from 0.7 to 1.79. Total-pressure recoveries above 90 percent were obtained across the stators for stator entrance Mach numbers up to 1.2. The recovery, however, fell off rapidly for stator entrance Mach numbers above 1.4.

3. The limiting ratio of the flow area entering the stators to the stator minimum section depends to a large extent on the mixing losses between the rotor and the stator and on the boundary layer at the stator minimum section. Additional restrictions necessary for starting of the supersonic flow through the stators are apparently not so critical as those obtained by one-dimensional theory for a diffuser having a normal shock ahead of the inlet prior to starting.

4. For design speed operation, diffusion to Mach numbers below 0.6 was obtained with the low pressure surface of the stator blade alined so as to form a compression wave at the leading edge compressing the flow at the stator passage entrance. For all speeds except 110.6 percent design, continuous operation was obtained as the shock was forced from the stator only to shock in both the rotor and the stator.

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

## APPENDIX - SYMBOLS

The following symbols are used in this report:

$A$ area, sq ft

$M$ absolute Mach number, ratio of absolute fluid velocity to local velocity of sound

$M'$ relative Mach number, ratio of fluid velocity relative to rotor to local velocity of sound

$N$ number of blades

$P$ absolute total, or stagnation, pressure, lb/sq ft

$r$ compressor radius, ft

$T$ total temperature, $^{\circ}R$

$U$ velocity of rotor $(2\pi rN)$ at radius $r$, ft/sec

$W$ weight flow, lb/sec

$\beta$ angle between compressor axis and absolute fluid direction, deg

$\gamma$ ratio of specific heats

$\delta$ ratio of actual inlet pressure to standard sea-level pressure, $P_1/2116$

$\eta_{ad}$ adiabatic efficiency

$\theta$ ratio of actual inlet stagnation temperature to standard sea-level temperature, $T_1/518.2$

Subscripts:

1 entrance tank upstream of nozzle

2 ahead of guide vanes

3 rotor entrance

4 rotor exit

5 downstream instrument station

2489

t tip

z axial component

$\theta$ tangential component

2489

## REFERENCES

1. Wright, Linwood C., and Klapproth, John F.: Performance of Supersonic Axial-Flow Compressors Based on One-Dimensional Analysis. NACA RM E8L10, 1949.

2. Ullman, Guy N., Hartmann, Melvin J., and Tysl, Edward R.: Experimental Investigation of a 16-Inch Impulse-Type Supersonic Compressor Rotor. NACA RM E51G19, 1951.

3. Kantrowitz, Arthur, and Donaldson, Coleman duP.: Preliminary Investigation of Supersonic Diffusers. NACA ACR L5D20, 1945.

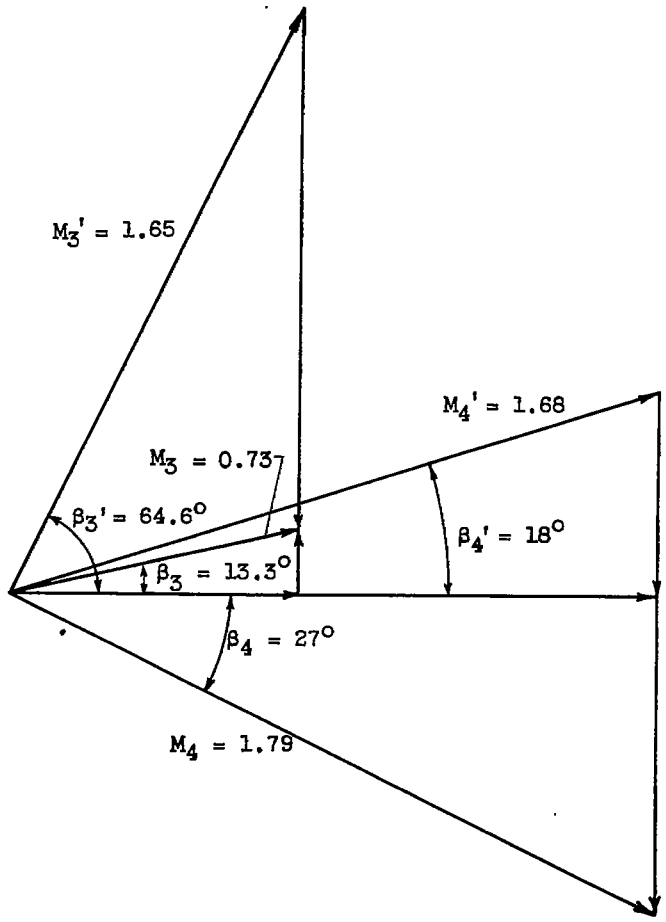
4. NACA Subcommittee on Compressors: Standard Procedures for Rating and Testing Multistage Axial-Flow Compressors. NACA TN 1138, 1946.

5. Anon.: Flow Measurement by Means of Standardized Nozzles and Orifice Plates. Ch. 4, pt. 5, A.S.M.E. Power Test Codes, 1940.

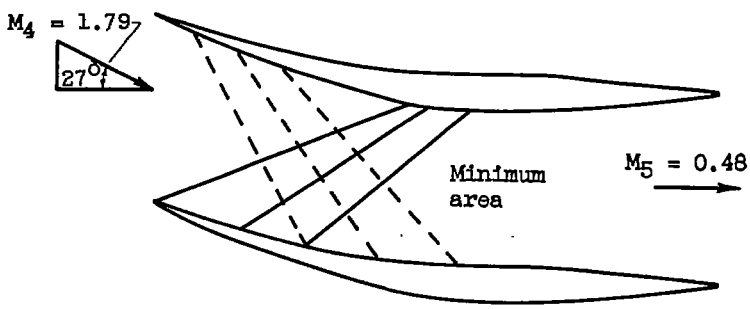
6. Perry, John H.: Chemical Engineers' Handbook. McGraw-Hill Book Co., Inc., 2nd ed., 1941, pp. 2577-2582.

7. Ferri, Antonio: Preliminary Analysis of Axial-Flow Compressors Having Supersonic Velocity at the Entrance of the Stator. NACA RM L9G06, 1949.

2489




(a) Design vector diagram for pitch section (U = 1400 ft/sec in air).




(b) Design stator passage.

Figure 1. - Compressor design.

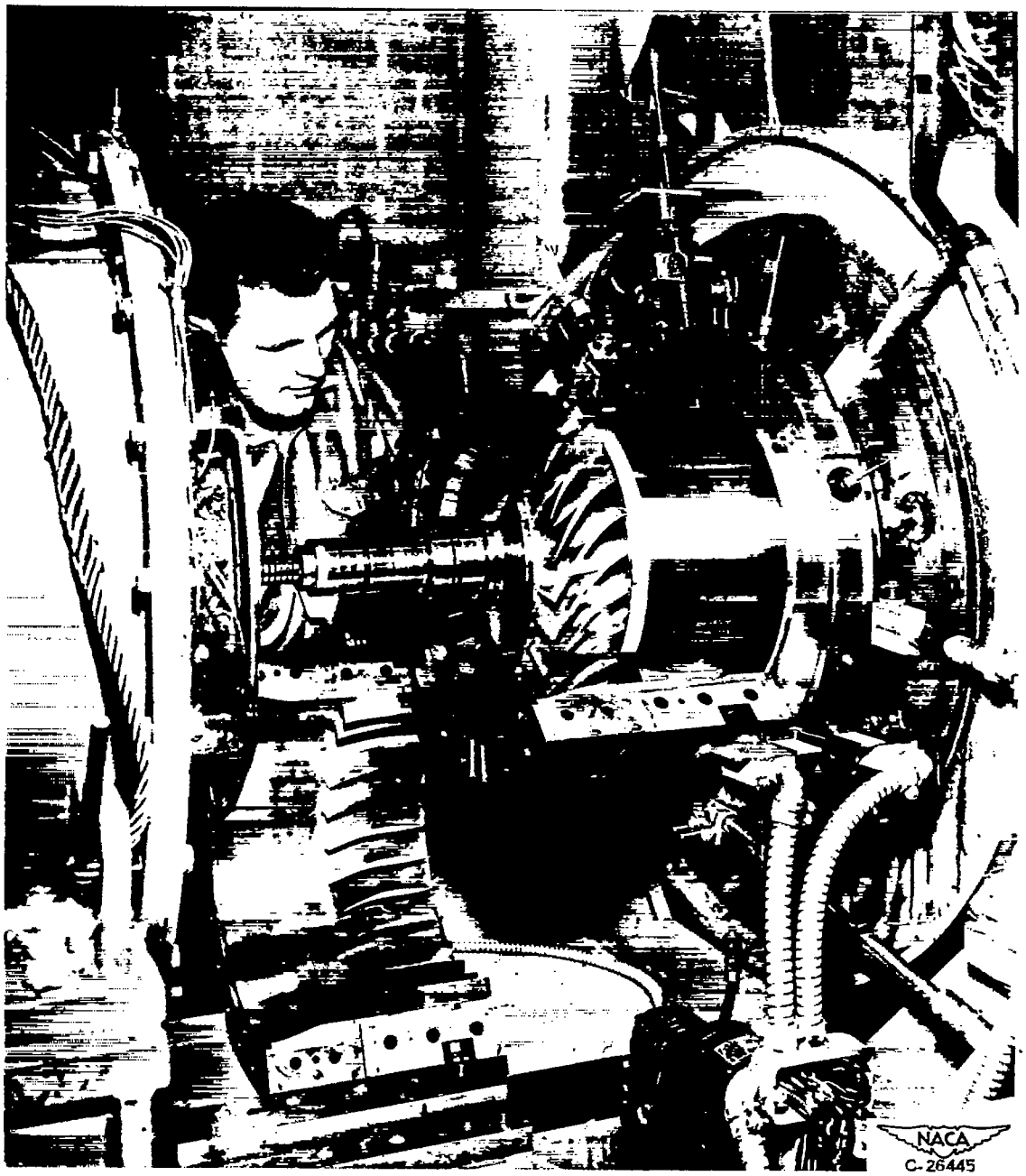



Figure 2. - 16-inch impulse-type supersonic compressor rotor and stators.

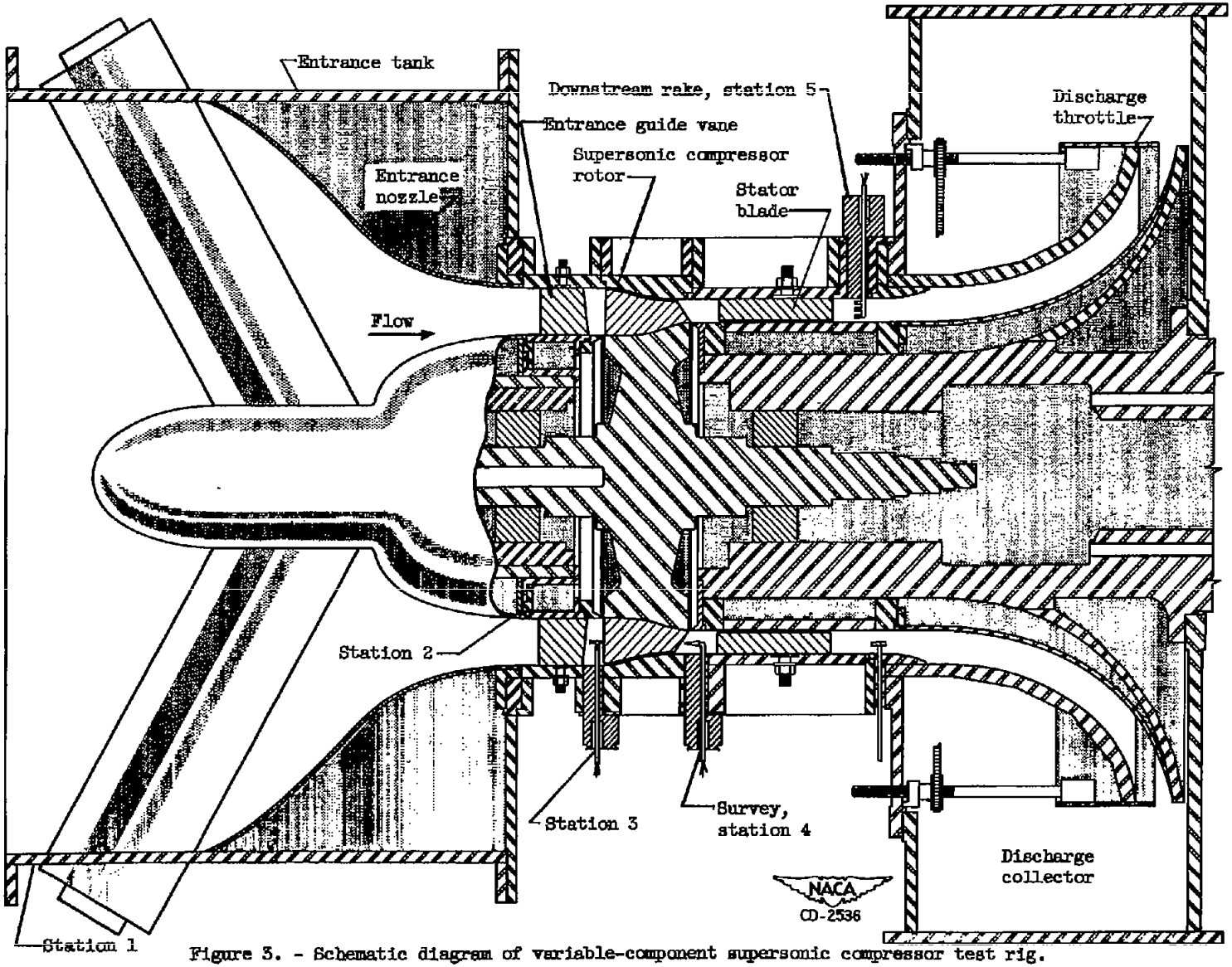
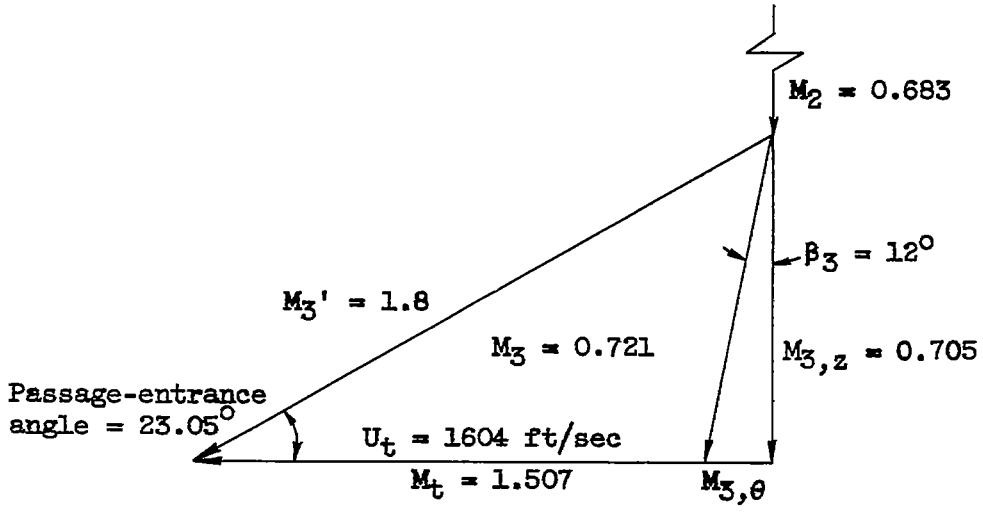
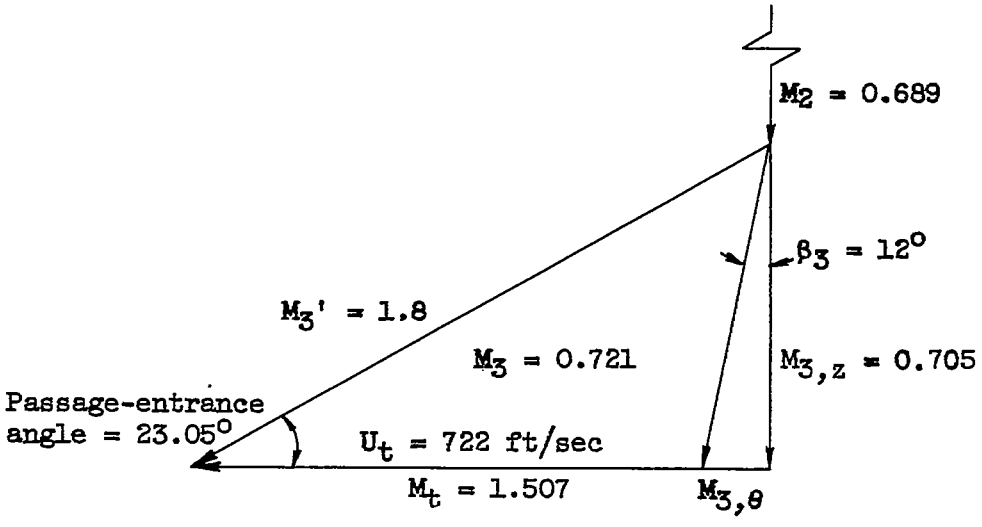



Figure 3. - Schematic diagram of variable-component supersonic compressor test rig.

2489




(a) Design for air.




(b) Computed for Freon-12.

Figure 4. - Design entrance tip vector diagram for 16-inch impulse-type supersonic compressor rotor in air and resulting changes for Freon-12.

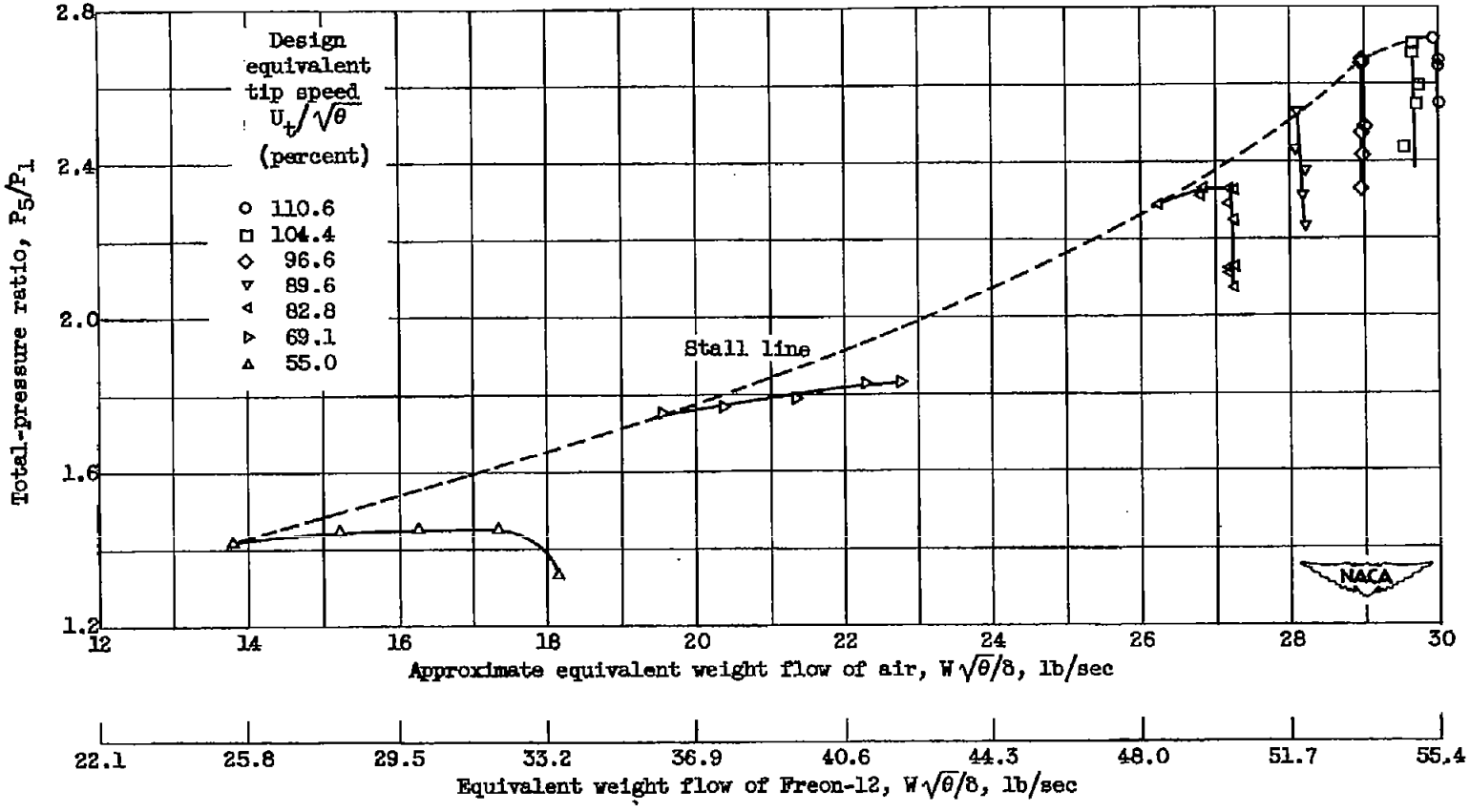



Figure 5. - Performance characteristics.

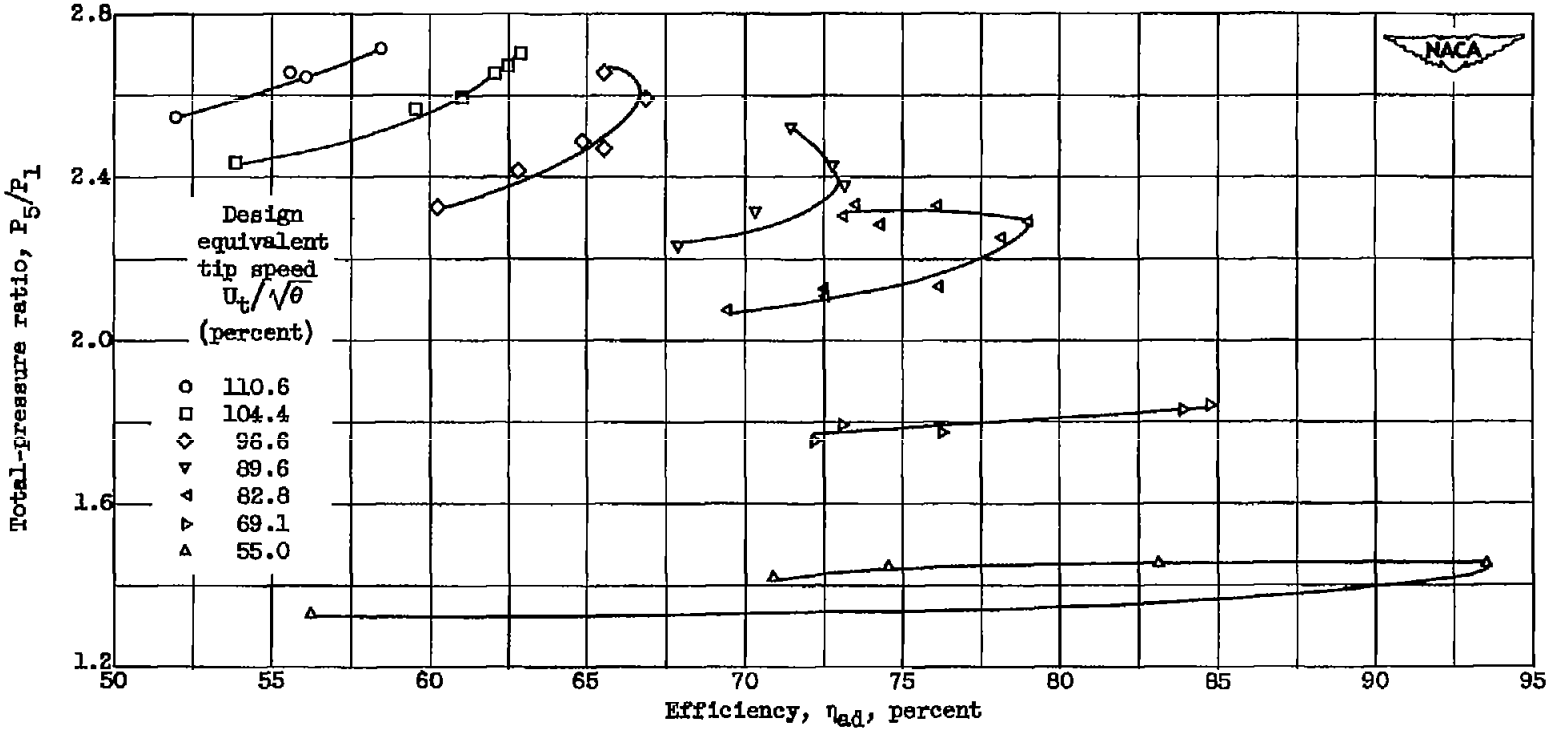



Figure 6. - Total-pressure ratio plotted against efficiency.

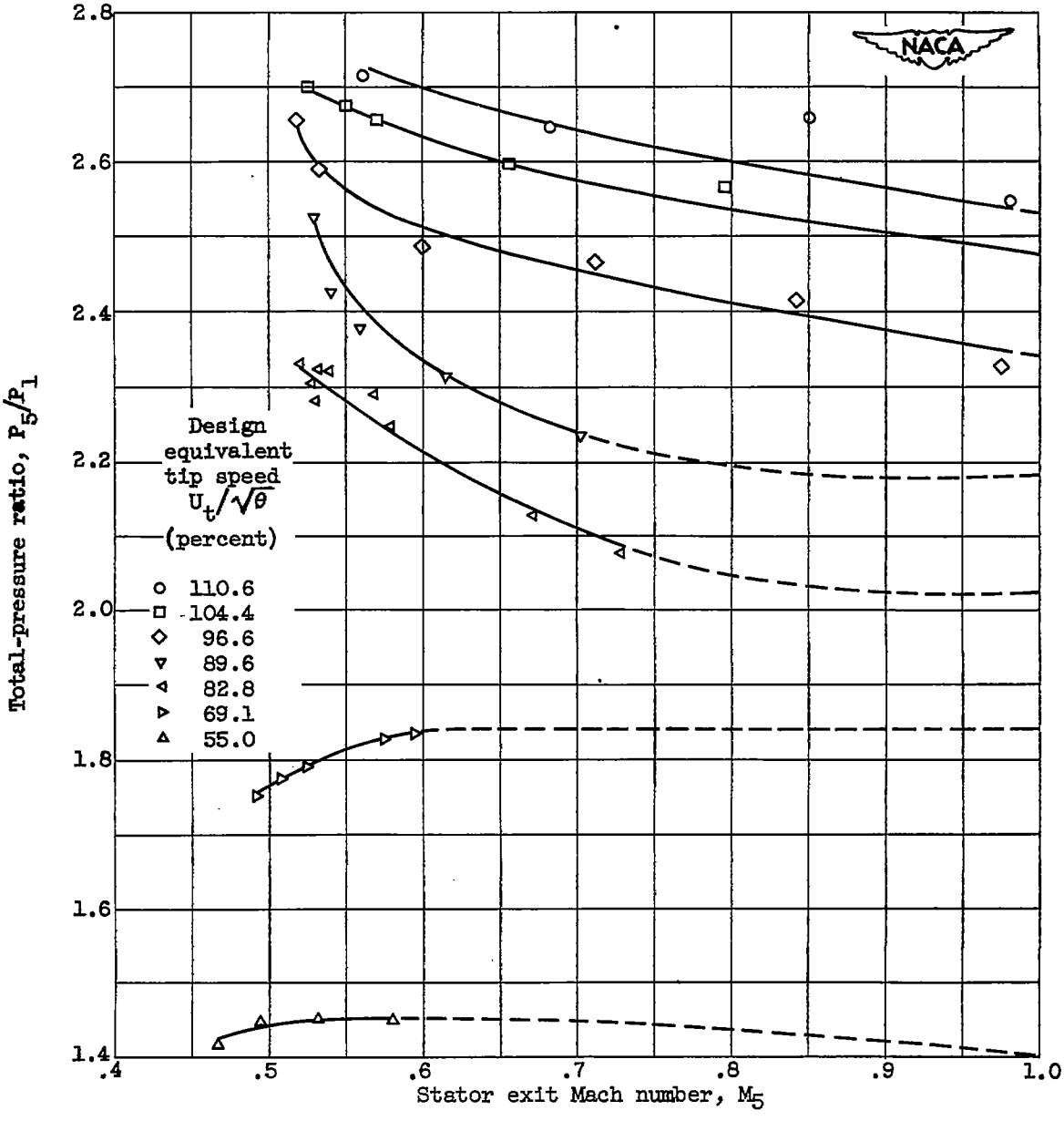



Figure 7. - Effect of pressure ratio on stator exit Mach number.

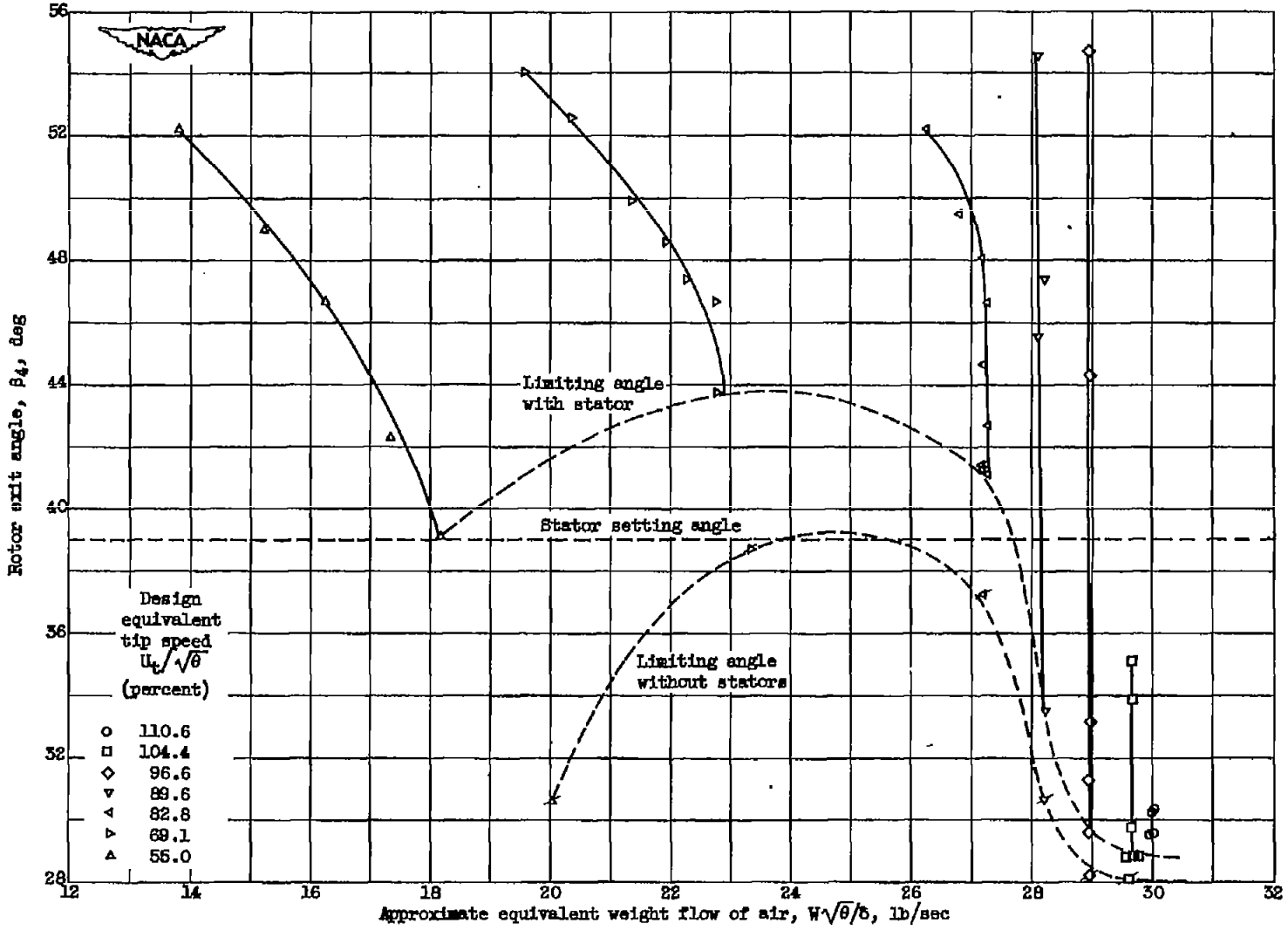



Figure 8. - Rotor exit angle plotted against approximate air equivalent weight flow.

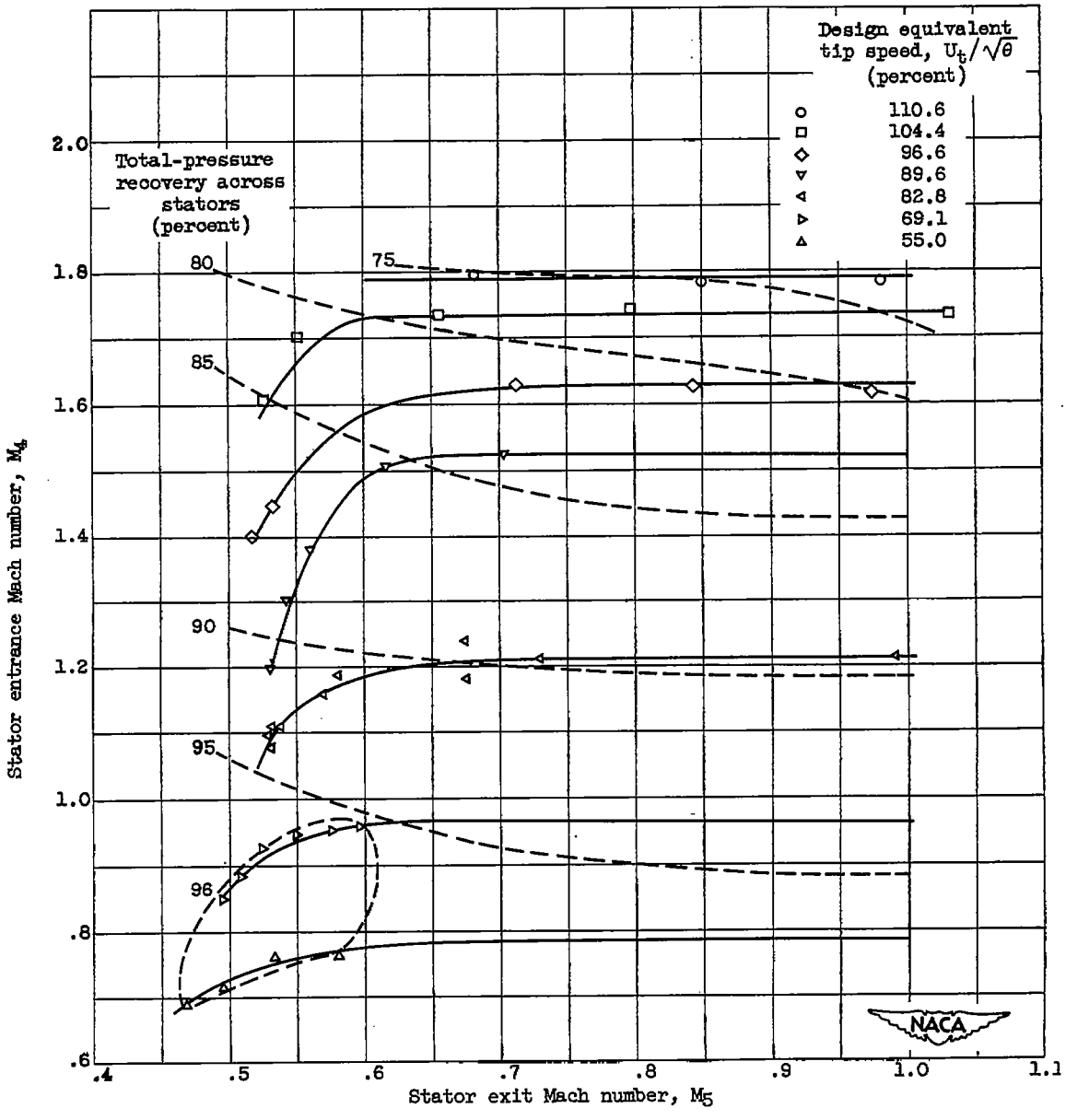



Figure 9. - Stator performance.

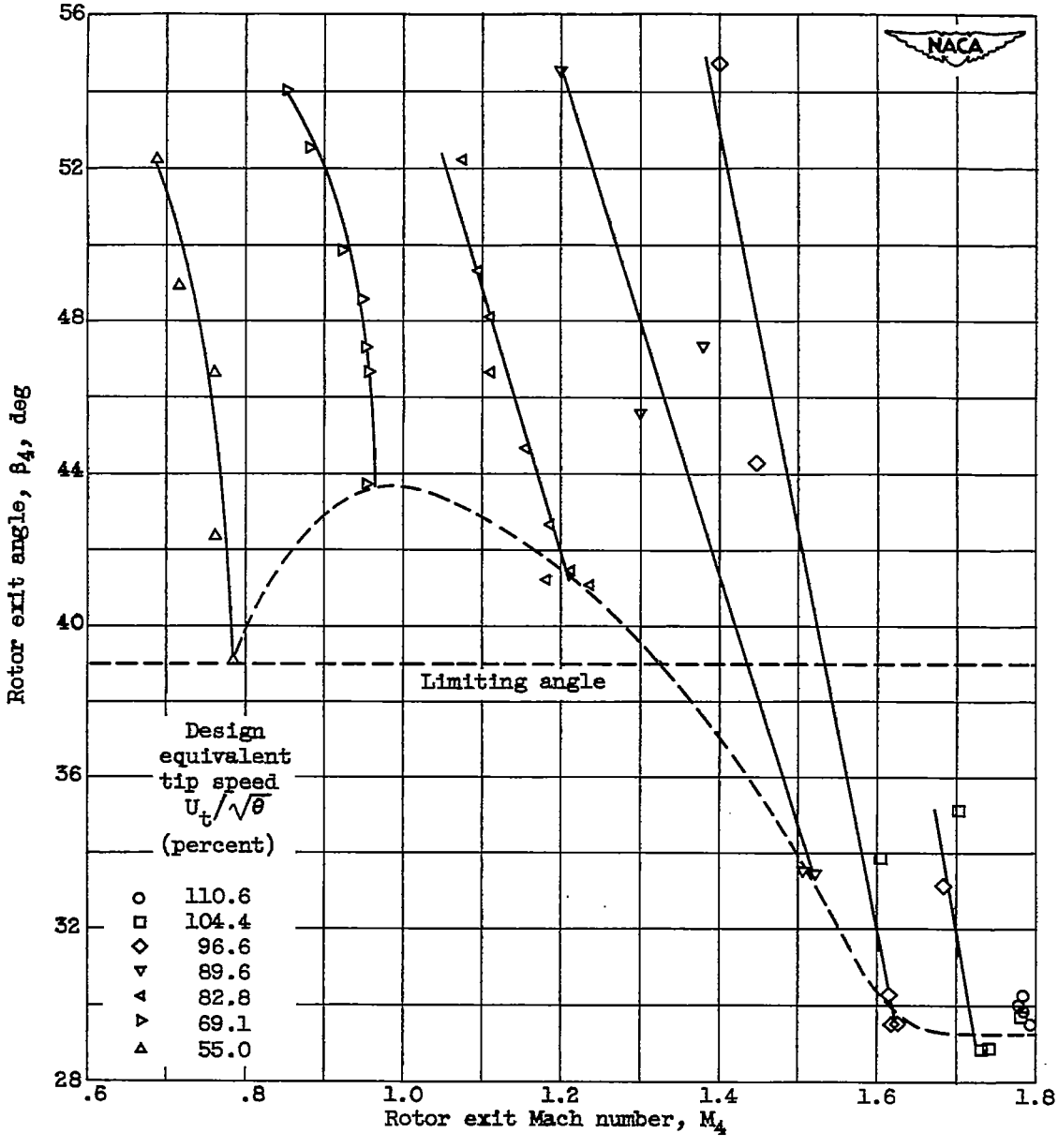



Figure 10. - Rotor exit conditions.

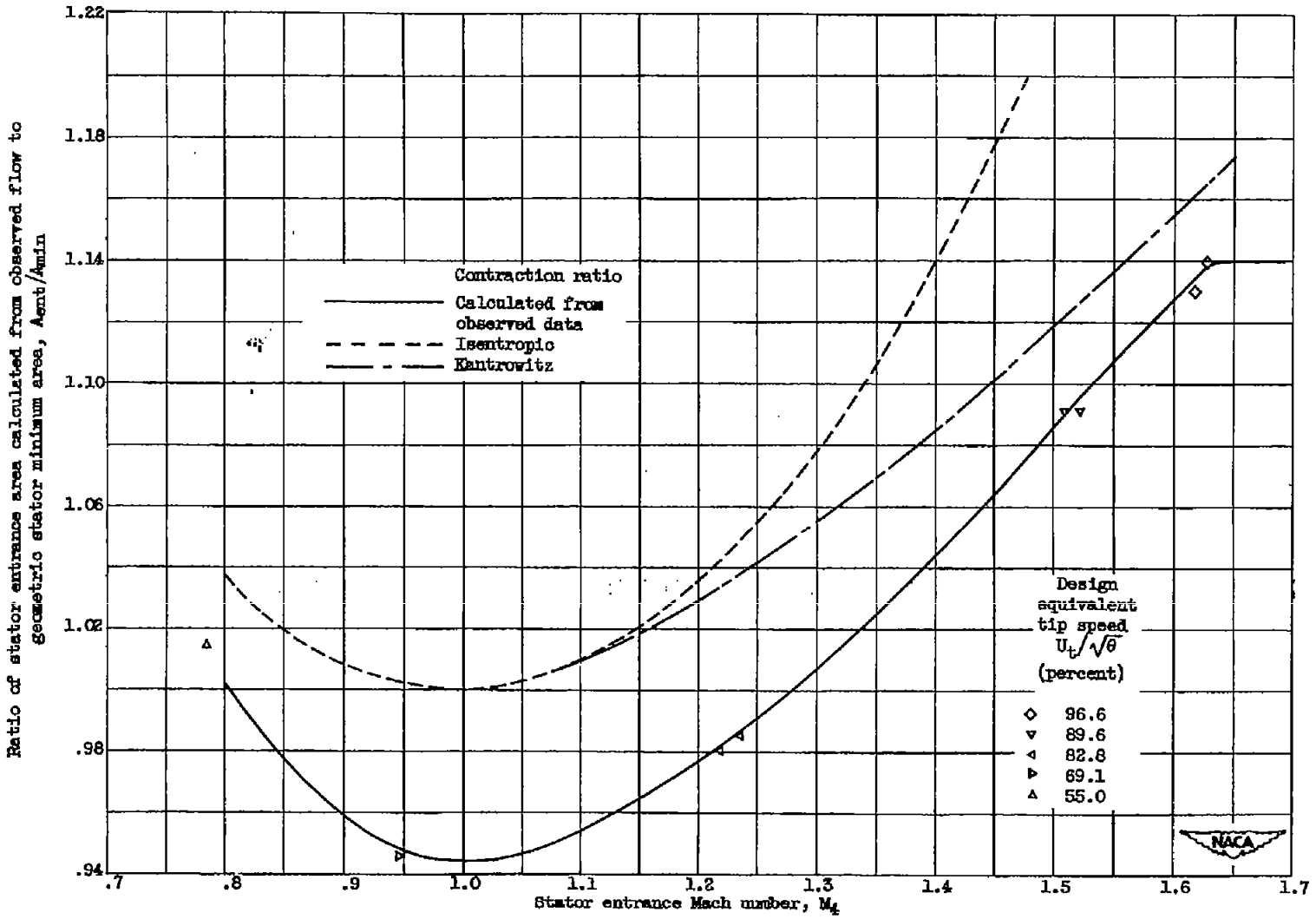



Figure 11. - Ratio of stator entrance area calculated from observed flow to geometric stator minimum area as function of stator entrance Mach number.