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RESEARCH MEMORANDUM

INVESTIGATION OF REYNOLDS NUMBER EFFECT ON PERFORMANCE OF AN EIGHT-STAGE AXIAL-FLOW RESEARCH COMPRESSOR WITH LONG- AND MEDIUM-CHORD LENGTHS IN THE TWO TRANSONIC INLET STAGES

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

The chords of the first two stages of an eight-stage axial-flow compressor with two transonic inlet stages were doubled, and the effects of Reynolds number on the over-all performance were investigated and compared with those of the original compressor. This investigation was conducted at an inlet-air temperature of approximately 400° R (with the compressor casing insulated with 4 in. of Fiberglas) over a range of equivalent weight flow at 90 and 100 percent of equivalent design speed for Reynolds numbers relative to the first rotor tip ranging from 195,000 to 2,265,000. At design speed, the peak adiabatic efficiency decreased from 0.82 to 0.78, the maximum equivalent weight flow from 71.5 to 66.4 pounds per second, and the stall pressure ratio from 10.8 to 9.4 as the chord Reynolds number was decreased from 2,155,000 to 255,000. At 90-percent design speed, the efficiency decreased from 0.83 to 0.73, the weight flow from 61.3 to 51.6 pounds per second, and the stall pressure ratio from 8.0 to 6.6 as the chord Reynolds number was decreased from 2,265,000 to 195,000.

In comparing the over-all performance characteristics of the long- and medium-chord compressors at design speed, the percent decrease in stall pressure ratio and maximum equivalent weight flow with decreasing Reynolds number index was found to be approximately the same for both configurations. The long-chord compressor is more efficient than the medium-chord compressor at low values of Reynolds number index, the relative improvement in efficiency increasing with decreasing Reynolds number index. At a Reynolds number index of 0.40, the peak efficiency of each configuration is approximately 0.82; at a Reynolds number index of 0.054, the peak efficiency of the long-chord compressor is about 0.78 as compared with 0.73 for the medium-chord compressor.

INTRODUCTION

The component of a turbojet powerplant most adversely affected by low Reynolds numbers encountered at very high altitudes is the compressor. In order to study the performance problems of multistage compressors with high-pressure-ratio, high Mach number stages, an eight-stage axial-flow compressor having two long-chord transonic inlet stages was designed, fabricated, and tested at the NACA Lewis laboratory. The object of the study reported herein was to evaluate the influence which increasing the chords of the first two stages has on low Reynolds number effects. The testing of this compressor is a continuation of a previous investigation (ref. 1) of the effects of low Reynolds numbers on compressors. The difference between the compressor of this report (long-chord) and that of reference 1 (medium-chord) is that the chord lengths of the rotor and stator blades of both transonic inlet stages are approximately doubled. The aerodynamic design details are given in references 2 to 4. The over-all performance characteristics of the medium-chord compressor at high and low Reynolds numbers are given in references 1, 5, and 6.

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This report presents the over-all performance characteristics of the long-chord compressor over a range of weight flow from maximum flow to incipient stall at 90 and 100 percent of equivalent design speed for a series of inlet-air pressures ranging from 11.1 to 1.0 inch of mercury absolute at an inlet-air temperature of approximately 400° R. The present report also contains a comparison with some of the results given in reference 1.

SYMBOLS

A frontal area, sq ft

c chord length at tip of first rotor, ft

P absolute total pressure, in. Hg

Re Reynolds number relative to first rotor tip, $\rho V'c/\mu$

T total temperature, °R

V' velocity relative to first rotor tip, ft/sec

w weight flow, lb/sec

δ ratio of inlet total pressure to NACA standard sea-level pressure of 29.92 in. Hg abs

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$\frac{\delta}{\varphi\sqrt{\theta}}$ Reynolds number index

η adiabatic temperature-rise efficiency

θ ratio of inlet total temperature to NACA standard sea-level temperature of 518.7° R

μ viscosity based on total temperature at tip of first rotor, lb/(ft)(sec)

ρ static density at tip of first rotor, lb/cu ft

φ ratio of inlet absolute viscosity to viscosity at NACA standard sea-level conditions

Subscripts:

0 inlet depression-tank station

1 compressor-inlet measuring station

20 compressor-discharge measuring station

APPARATUS AND INSTRUMENTATION

Compressor

A cross-sectional view of the compressor, the inlet bellmouth nozzle, and the discharge collector is shown in figure 1. The aerodynamic design details for this compressor are presented in references 2 to 4. The over-all performance characteristics at high Reynolds number are presented in reference 4. A photograph of the first-stage rotor is shown in figure 2.

The major compressor design values are:

Total-pressure ratio	10.26
Equivalent weight flow, lb/sec	72.4
Equivalent tip speed, ft/sec	1218
Relative tip Mach number	1.25
Inlet hub-tip diameter ratio	0.46
Tip diameter at inlet to first rotor, in.	20.86

The compressor of this report will be referred to as the long-chord compressor. The compressor of reference 1 will be referred to as the medium-chord compressor because the blade chord lengths of the first two stages are longer than those found in typical present-day compressors.

Installation

The compressor was driven by a 15,000-horsepower variable-frequency electric motor. The speed was maintained constant by an electronic control and was measured by both an electric chronometric tachometer and an electronic frequency-period counter. Air entered the compressor through a submerged thin-plate orifice, a butterfly inlet throttle for controlling inlet pressure, and a depression tank 6 feet in diameter and approximately 10 feet long. Screens in the depression tank and a bellmouth faired into the compressor inlet were used to obtain a uniform distribution of air entering the compressor. Air was discharged from the compressor into a collector connected to the laboratory altitude exhaust system. Air weight flow was controlled by a butterfly valve located in the exhaust ducting.

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Instrumentation

The axial locations of the instrument measuring stations are shown in figure 1. The inlet depression-tank station and the compressor-discharge station had axial locations that were in accordance with reference 7. The radial distribution of outlet total temperature was obtained from multiple-probe rakes located at the area centers of equal annular areas. The discharge static pressure was obtained from six wall static taps. The instruments used at each station are similar to those illustrated in reference 5. The methods of measurement were as follows:

(1) Temperature measurement: self-balancing potentiometers

(2) Pressure measurement: mercury manometers referenced to atmosphere for inlet pressures greater than 3 inches of mercury absolute, dibutylpthalate manometers referenced to pressure measured with a 0 to 100-millimeter pressure gage for inlet pressures less than 3 inches of mercury absolute, and mercury manometers referenced to atmosphere for all compressor-discharge pressures

(3) Weight-flow measurement: a thin-plate submerged orifice that was changed depending on inlet volume flow so that the pressure drop across the orifice was generally maintained between 20 and 80 inches of water

PROCEDURE

This investigation of over-all compressor performance at low Reynolds numbers was carried out as follows: The long-chord compressor was insulated with 4 inches of Fiberglas, an inlet-air temperature of approximately 400° R (-60° F) was maintained, and the Reynolds number relative to the tip of the first rotor was varied from approximately 195,000 to 2,265,000 by varying inlet-air pressure from 1.0 to 11.1 inches of mercury absolute. The compressor was operated at 90 and 100 percent of equivalent design speed, a range of airflows being investigated at each inlet pressure from maximum flow to incipient stall.

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The over-all compressor performance characteristics were calculated from the orifice measurements, the drive-motor speed, the inlet total pressure and temperature, and the discharge static pressure and total temperature. The discharge total pressure was calculated by the procedure recommended in reference 7 and used in references 1, 4, 5, and 6.

RESULTS AND DISCUSSION

Long-Chord-Compressor Performance

High Reynolds number. - Reference 4 discusses the over-all performance characteristics of the long-chord compressor obtained at a constant Reynolds number of approximately 2,250,000. These performance characteristics are presented in figure 3. The over-all total-pressure ratio is plotted as a function of equivalent weight flow at various values of equivalent speed, with contours of constant adiabatic efficiency and the stall-limit line indicated. This performance is discussed in detail in reference 4.

Variation with inlet pressure. - The variation of compressor over-all total-pressure ratio with equivalent weight flow is shown in figure 4(a) for compressor speeds of 90 and 100 percent of equivalent design speed (13,380 rpm), an inlet-air temperature of approximately 400° R, and inlet-air pressures ranging from 11.1 to 1.0 inch of mercury absolute. The stall limit obtained at high inlet pressures (from fig. 3) is also indicated. It can be seen that the incipient stall points obtained at the various inlet pressures (Reynolds numbers) at 90 and 100 percent of equivalent design speed approximately coincide with the stall-limit line obtained at high inlet pressures. This result is the same as the trend discussed in reference 1. The variation of adiabatic temperature-rise efficiency with over-all total-pressure ratio at an inlet-air temperature of 400° R is shown in figure 4(b) for design speed and in figure 4(c) for 90-percent equivalent design speed. Figures 4(b) and (c) show that decreasing the inlet-air pressure decreases the compressor over-all total-pressure ratio at which the peak adiabatic temperature-rise efficiency occurs.

Effect of Reynolds Number on Compressor Performance

Adiabatic efficiency. - Figure 5 shows the variation of peak adiabatic temperature-rise efficiency with Reynolds number based on first-rotor-tip chord and relative flow conditions at the tip of the first rotor, at an inlet-air temperature of approximately 400° R at 90 and 100 percent of equivalent design speed for the long-chord compressor. At design speed (fig. 5(a)), the peak adiabatic efficiency decreases from approximately 0.82 at a Reynolds number of 2,155,000 to 0.78 at a Reynolds number of 255,000. At 90 percent of equivalent design speed (fig. 5(b)), the variation follows a similar trend. The peak adiabatic efficiency decreases gradually from approximately 0.83 at a Reynolds number of 2,265,000 to 0.82 at a Reynolds number of 800,000 and then decreases more rapidly to 0.73 at a Reynolds number of 195,000.

Equivalent weight flow. - Figure 6 shows maximum equivalent weight flow as a function of Reynolds number at an inlet-air temperature of approximately 400° R at 90 and 100 percent of equivalent design speed. At design speed, the maximum equivalent weight flow decreases gradually from 71.5 pounds per second at a Reynolds number of 2,155,000 to 70.8 pounds per second at a Reynolds number of 740,000 and then decreases more rapidly to 66.4 pounds per second at a Reynolds number of 255,000. At 90 percent of equivalent design speed, the trend is similar. The weight flow decreases gradually from 61.3 pounds per second at a Reynolds number of 2,265,000 to 61.0 pounds per second at a Reynolds number of 990,000 and then decreases more rapidly to 51.6 pounds per second at a Reynolds number of 195,000.

Stall limit. - Figure 7 shows the variation of stall pressure ratio with Reynolds number at an inlet-air temperature of approximately 400° R at 90 and 100 percent of equivalent design speed. The design-speed stall pressure ratio decreases gradually from 10.75 at a Reynolds number of 2,155,000 to 10.28 at a Reynolds number of 900,000 and then to 9.36 at a Reynolds number of 255,000. At 90 percent of equivalent design speed, the stall pressure ratio again decreases gradually from 8.00 at a Reynolds number of 2,265,000 to 7.83 at a Reynolds number of 900,000 and then to 6.60 at a Reynolds number of 195,000.

Comparison of Long- and Medium-Chord Compressor Performance

High Reynolds number. - The long- and medium-chord compressors are compared in detail at high Reynolds number in reference 4. Figure 8 gives a comparison of the performance characteristics of the two compressor configurations at high Reynolds numbers. The increased stable operating range of the long-chord compressor at intermediate speeds indicates that the first two stages are able to operate over a wider flow range. Increased range due to increased chord length is discussed in the single-stage investigation of reference 8.

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Variation with Reynolds number index. - Reynolds number index is commonly used as a parameter in comparing the relative altitude performance of turbojet engine components. Figure 9 shows the variation of stall pressure ratio, peak adiabatic temperature-rise efficiency, and maximum equivalent weight flow of both compressor configurations with Reynolds number index at design speed and an inlet-air temperature of approximately 400° R.

In order to make the following discussion readily interpreted on the basis of altitude, Reynolds number index is plotted against flight Mach number with altitude as a parameter in figure 10. The Reynolds number index used is based on measured data at the tip of the first rotor.

Figure 9(a) shows the variation of stall pressure ratio with Reynolds number index for both compressors. The decrease in stall pressure ratio with decreasing Reynolds number index is approximately the same for both compressors, the long-chord compressor showing a slight improvement in stall pressure ratio at the low values of Reynolds number index.

The variation of peak adiabatic temperature-rise efficiency with Reynolds number index is given in figure 9(b) for both compressors. The long-chord compressor is the more efficient at low values of Reynolds number index, the relative improvement in efficiency increasing with decreasing Reynolds number index. At a Reynolds number index of 0.40, the peak efficiency of each configuration is approximately 0.82; at a Reynolds number index of 0.054, the peak efficiency of the long-chord compressor is about 0.78 as compared with 0.73 for the medium-chord compressor.

The variation of maximum equivalent weight flow with Reynolds number index is shown in figure 9(c) for both compressors. The decrease in maximum equivalent weight flow with decreasing Reynolds number index is approximately the same for both compressors, the long-chord compressor showing a slight improvement in weight flow at the low values of Reynolds number index.

Although the improvement in altitude performance was not proportional to the increase in chord length of the first two stages, improved performance was obtained at altitude by increasing the chord lengths. In order to give an example of the difference in altitude performance of the two compressors, a flight Mach number of 1.5 and a compressor efficiency of 0.79 were arbitrarily chosen. Figure 9(b) shows that a compressor efficiency of 0.79 corresponds to a Reynolds number index of 0.07 for the long-chord compressor and 0.16 for the medium-chord compressor. Using these values of Reynolds number index and a flight Mach number of 1.5, figure 10 shows that this corresponds to an altitude of approximately 85,000 feet for the long-chord compressor as compared with approximately 68,000 feet for the medium-chord compressor.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effect of Reynolds number on the over-all performance of an eight-stage axial-flow compressor with two long-chord transonic inlet stages:

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1. With the compressor insulated and with an inlet temperature of 400° R, the design-speed peak adiabatic efficiency decreased from approximately 0.82 at a Reynolds number of 2,155,000 to 0.78 at a Reynolds number of 255,000, and the 90-percent-speed peak adiabatic efficiency decreased from approximately 0.83 at a Reynolds number of 2,265,000 to 0.73 at a Reynolds number of 195,000.

2. The maximum equivalent weight flow decreased from 71.5 to 66.4 pounds per second at design speed and from 61.3 to 51.6 pounds per second at 90-percent design speed for the range of Reynolds numbers covered.

3. The stall pressure ratio decreased from 10.75 to 9.36 at design speed and from 8.00 to 6.60 at 90-percent design speed for the range of Reynolds numbers covered.

4. The decrease in stall pressure ratio and maximum equivalent weight flow with decreasing Reynolds number index at design speed is about the same for the long-chord and medium-chord compressors. The long-chord compressor is more efficient than the medium-chord compressor at all values of Reynolds number index below 0.40.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 31, 1957

REFERENCES

1. Geye, Richard P., and Lucas, James G.: Investigation of Effects of Reynolds Number on Over-All Performance of an Eight-Stage Axial-Flow Research Compressor with Two Transonic Inlet Stages. NACA RM E56L11a, 1957.

2. Voit, Charles H.: Investigation of a High-Pressure-Ratio Eight-Stage Axial-Flow Research Compressor with Two Transonic Inlet Stages. I - Aerodynamic Design. NACA RM E53I24, 1953.

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3. Geye, Richard P., and Voit, Charles H.: Investigation of a High-Pressure-Ratio Eight-Stage Axial-Flow Research Compressor with Two Transonic Inlet Stages. IV - Modification of Aerodynamic Design and Prediction of Performance. NACA RM E55B28, 1955.

4. Sievers, Gilbert K., Geye, Richard P., and Lucas, James G.: Preliminary Analysis of Over-All Performance of an Eight-Stage Axial-Flow Research Compressor with Two Long-Chord Transonic Inlet Stages. NACA RM E57H14, 1957.

5. Standahar, Raymond M., and Geye, Richard P.: Investigation of a High-Pressure-Ratio Eight-Stage Axial-Flow Research Compressor with Two Transonic Inlet Stages. V - Preliminary Analysis of Over-All Performance of Modified Compressor. NACA RM E55A03, 1955.

6. Standahar, Raymond M., Hanson, Morgan P., and Geye, Richard P.: Investigation of a High-Pressure-Ratio Eight-Stage Axial-Flow Research Compressor with Two Transonic Inlet Stages. VI - Over-All Performance, Rotating Stall, and Blade Vibration at Low and Intermediate Compressor Speeds. NACA RM E55I13, 1955.

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

8. Kussoy, Marvin I., and Bachkin, Daniel: Comparison of Performance of Two Aerodynamically Similar 14-Inch-Diameter Single-Stage Compressor Rotors of Different Chord Length. NACA RM E57I03, 1957.

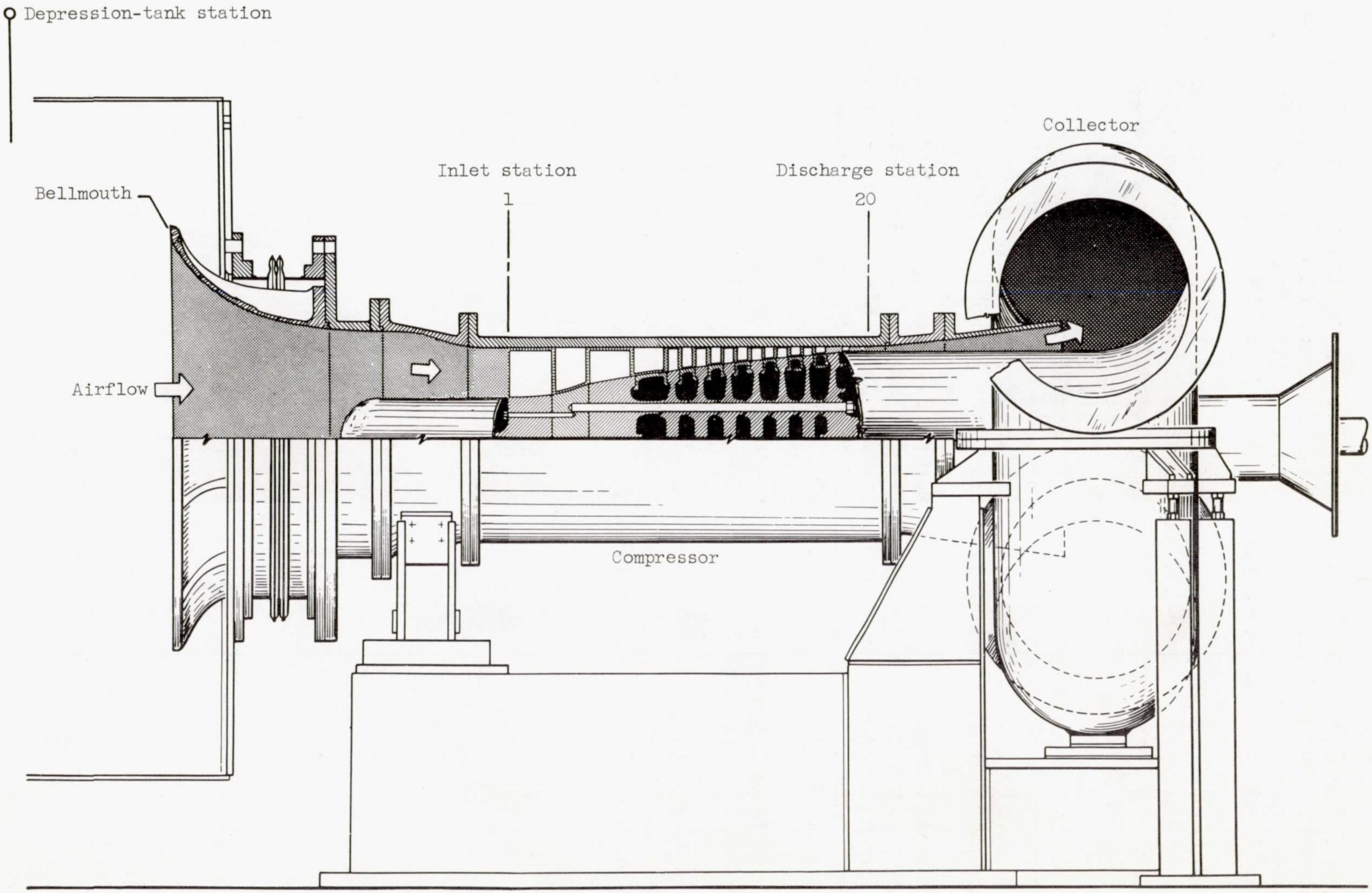

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Figure 1. - Cross section of long-chord eight-stage axial-flow compressor, inlet bellmouth, and discharge collector.

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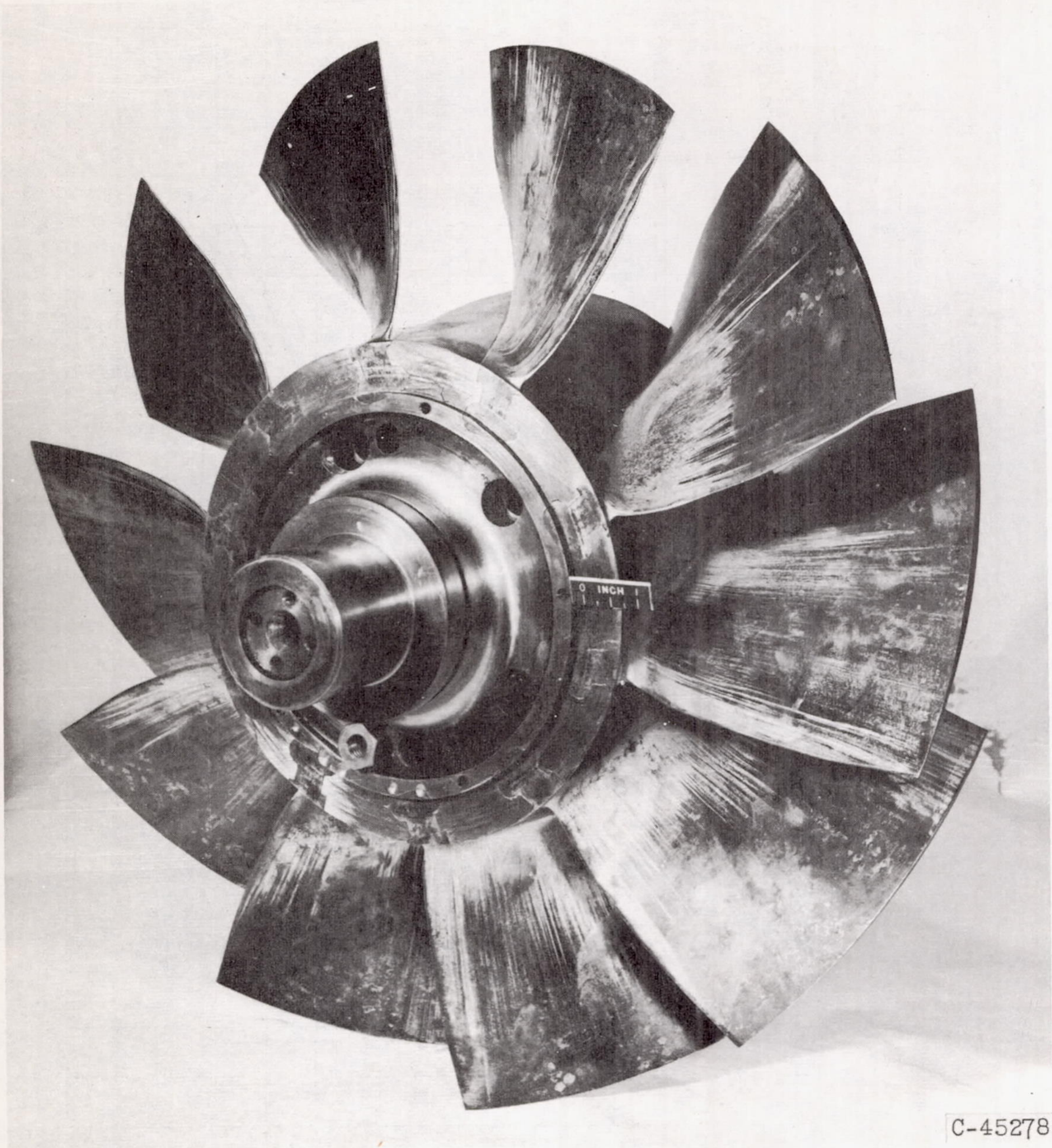

Figure 2. - First-stage rotor of long-chord compressor.

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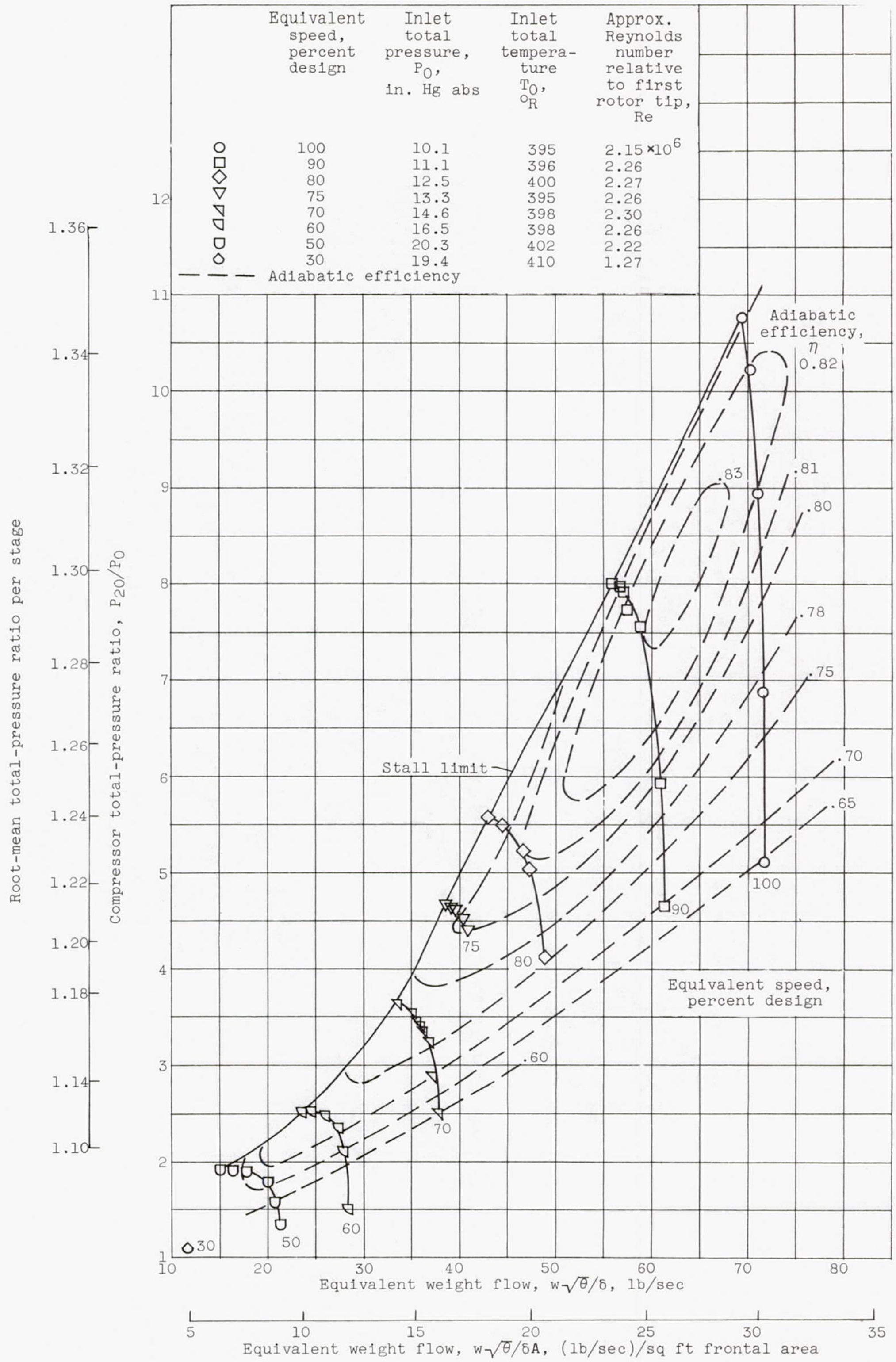
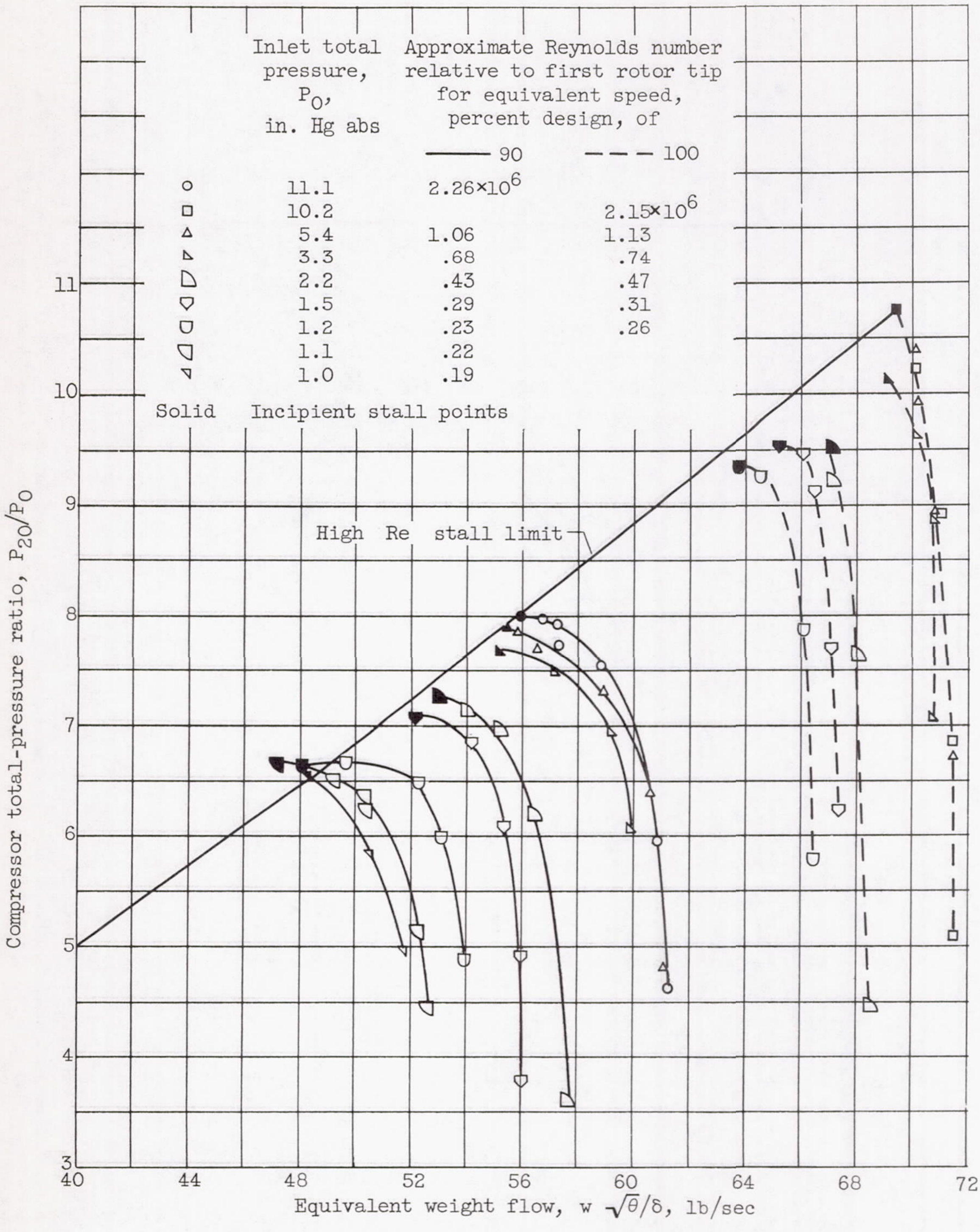


Figure 3. - Over-all performance characteristics of eight-stage axial-flow compressor with two long-chord transonic inlet stages.



(a) Pressure-ratio and equivalent-weight-flow characteristics.

Figure 4. - Effect of inlet pressure on over-all performance. Long-chord compressor; inlet temperature, 400° R.

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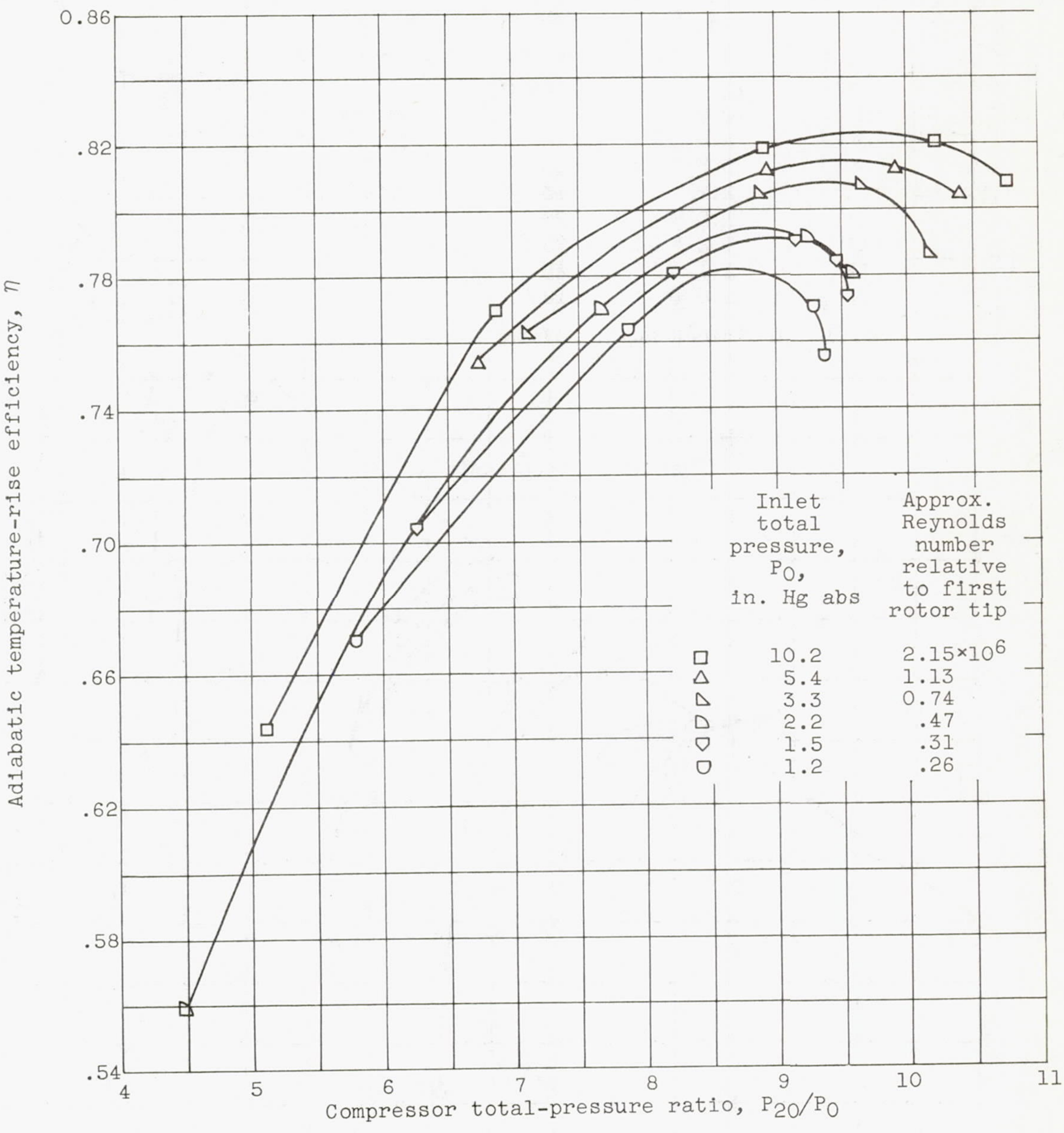

(b) Efficiency and pressure-ratio characteristics. Equivalent speed, 100-percent design.

Figure 4. - Continued. Effect of inlet pressure on over-all performance. Long-chord compressor; inlet temperature, 400° R.

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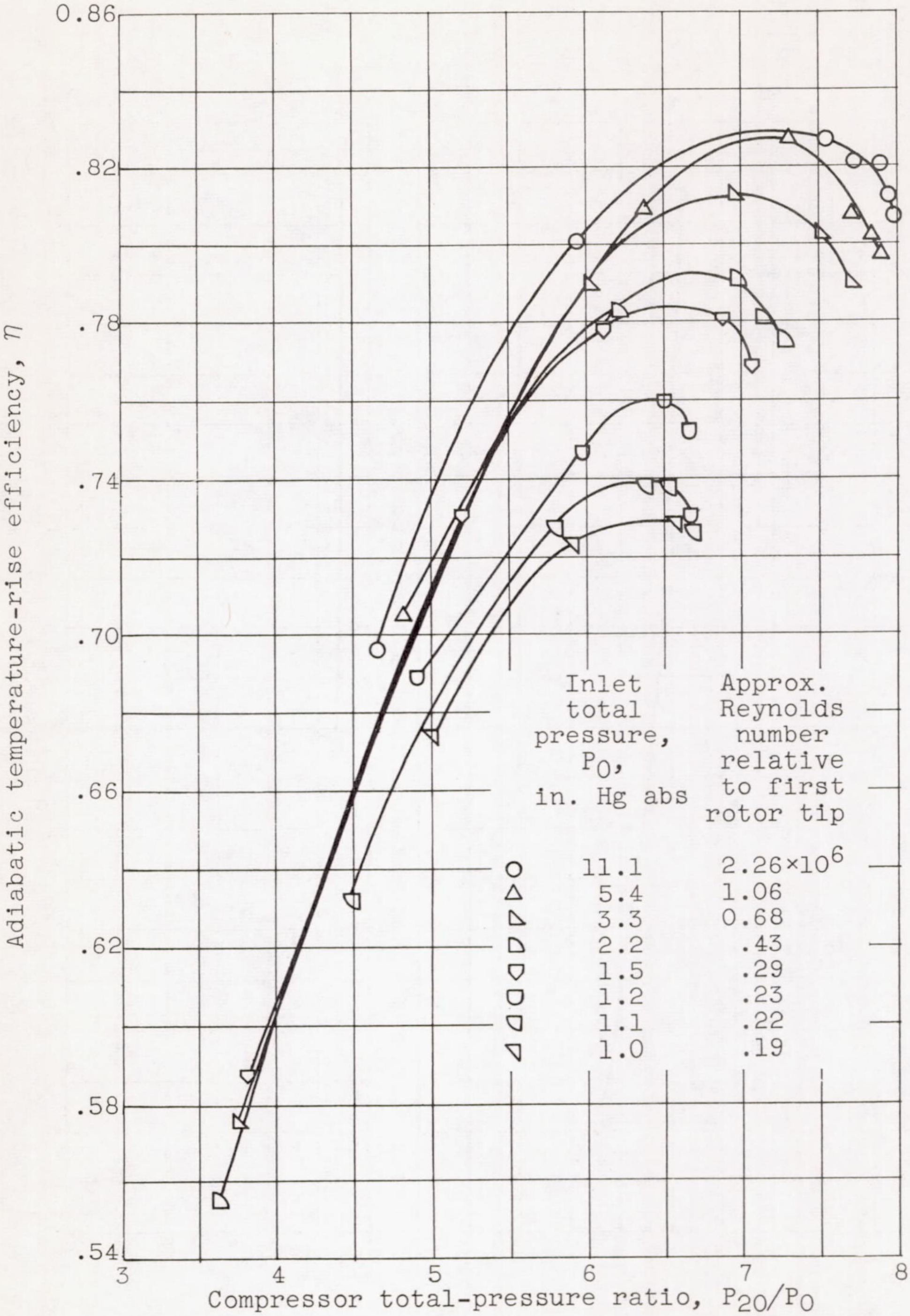
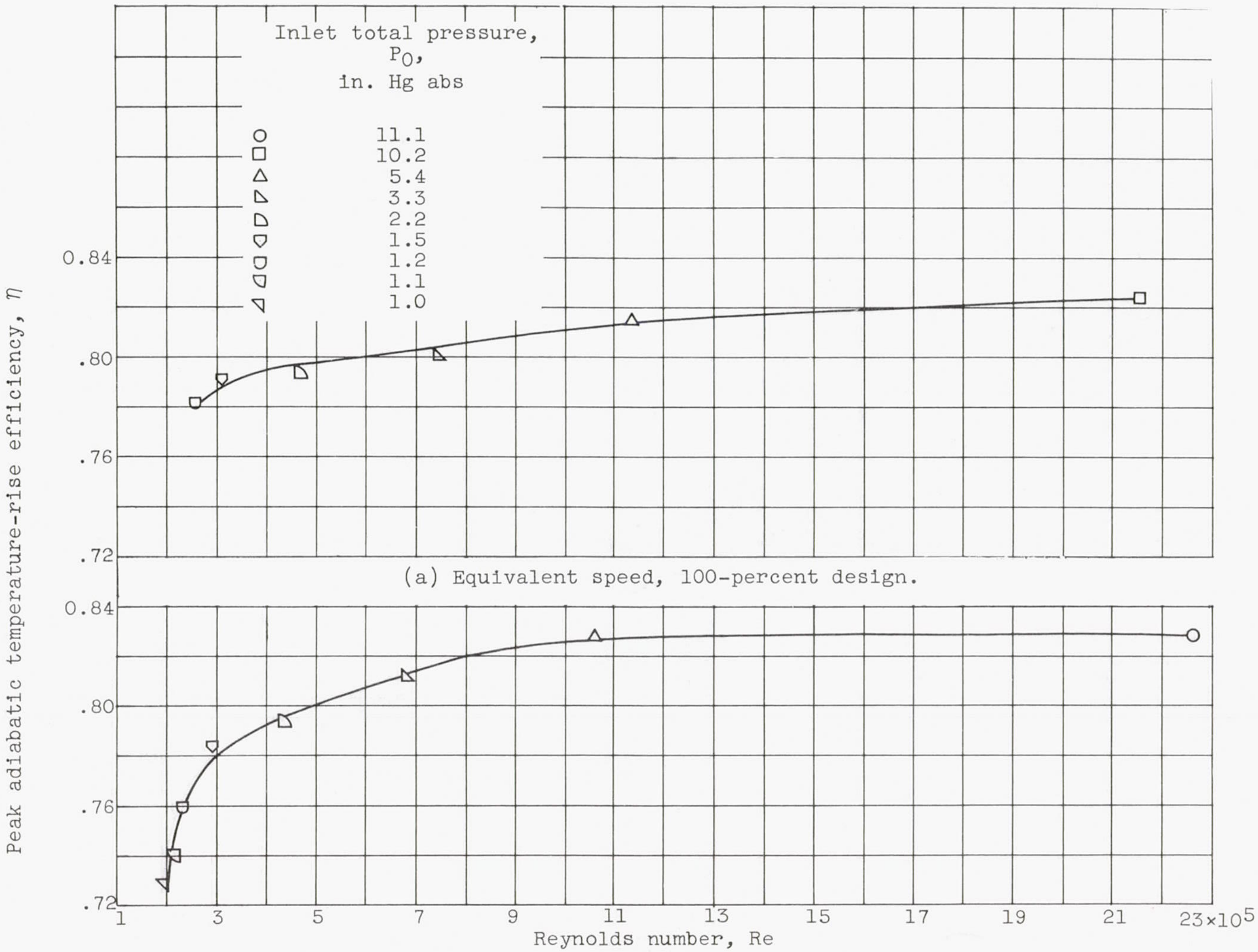


(c) Efficiency and pressure-ratio characteristics. Equivalent speed, 90-percent design.

Figure 4. - Concluded. Effect of inlet pressure on over-all performance. Long-chord compressor; inlet temperature, 400° R.



(b) Equivalent speed, 90-percent design.

Figure 5. - Variation of peak efficiency with Reynolds number. Long-chord compressor; inlet temperature, 400° R.

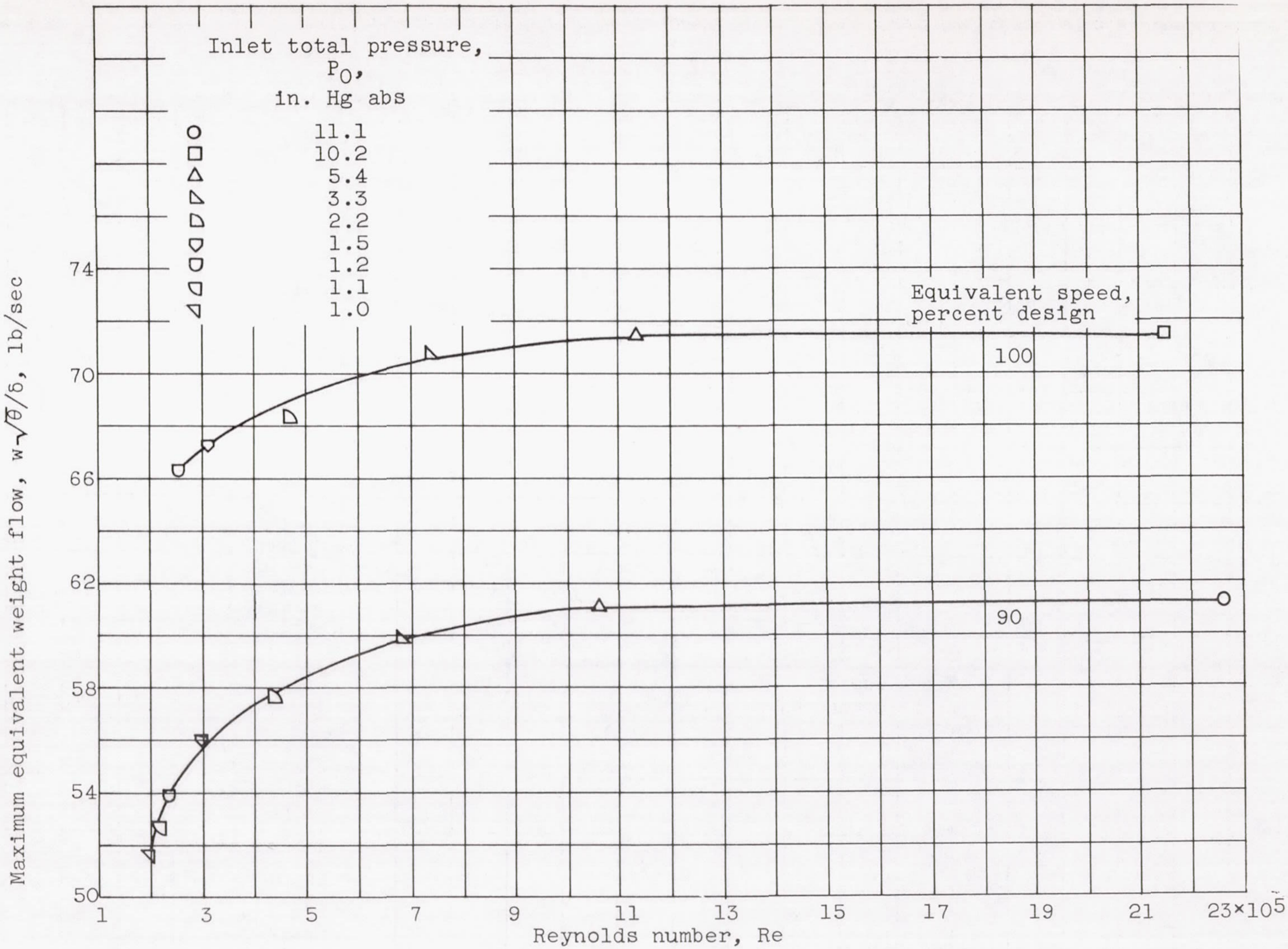


Figure 6. - Variation of maximum equivalent weight flow with Reynolds number. Long-chord compressor; inlet temperature, 400° R.

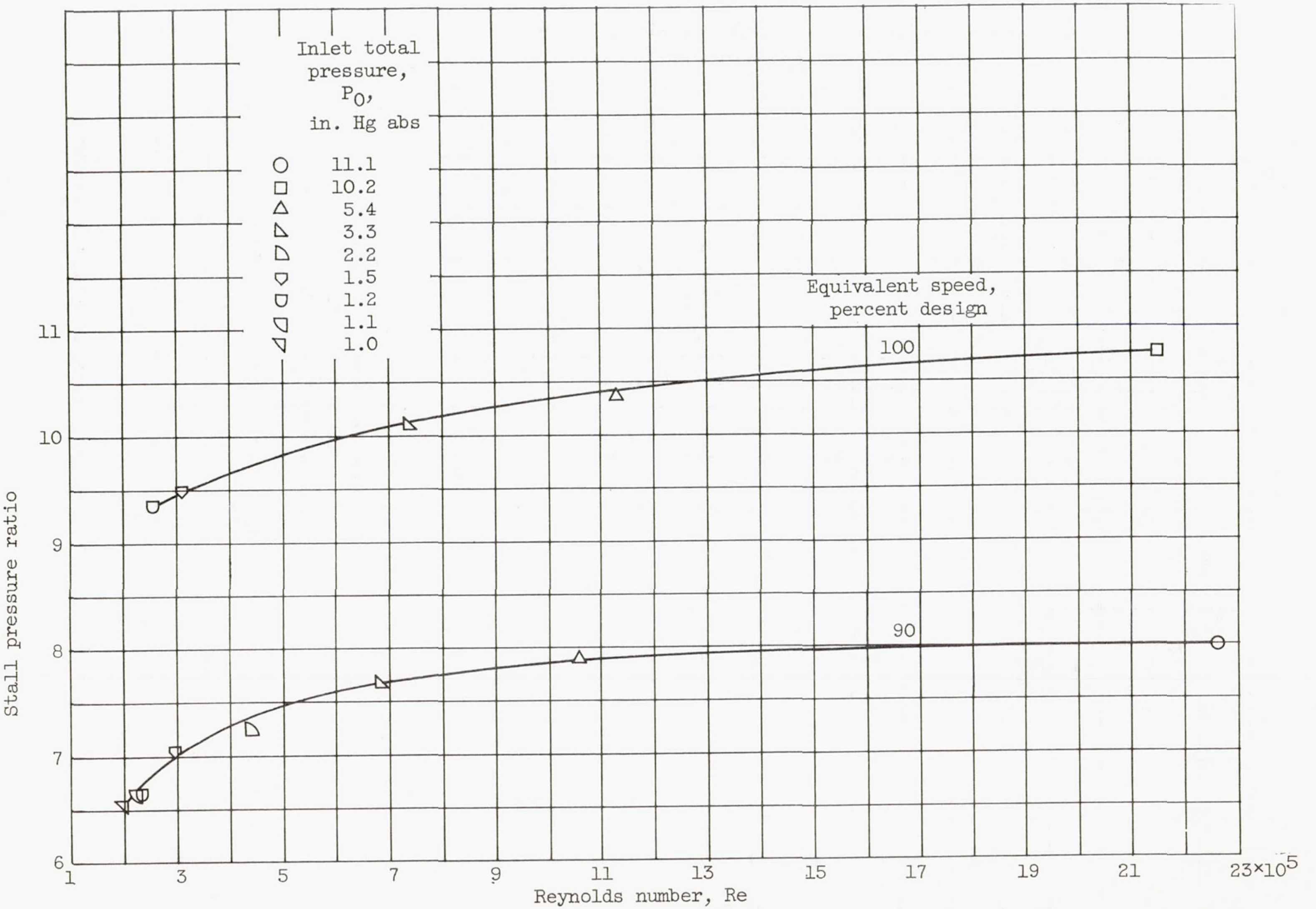


Figure 7. - Variation of stall pressure ratio with Reynolds number. Long-chord compressor; inlet temperature, 400° R.

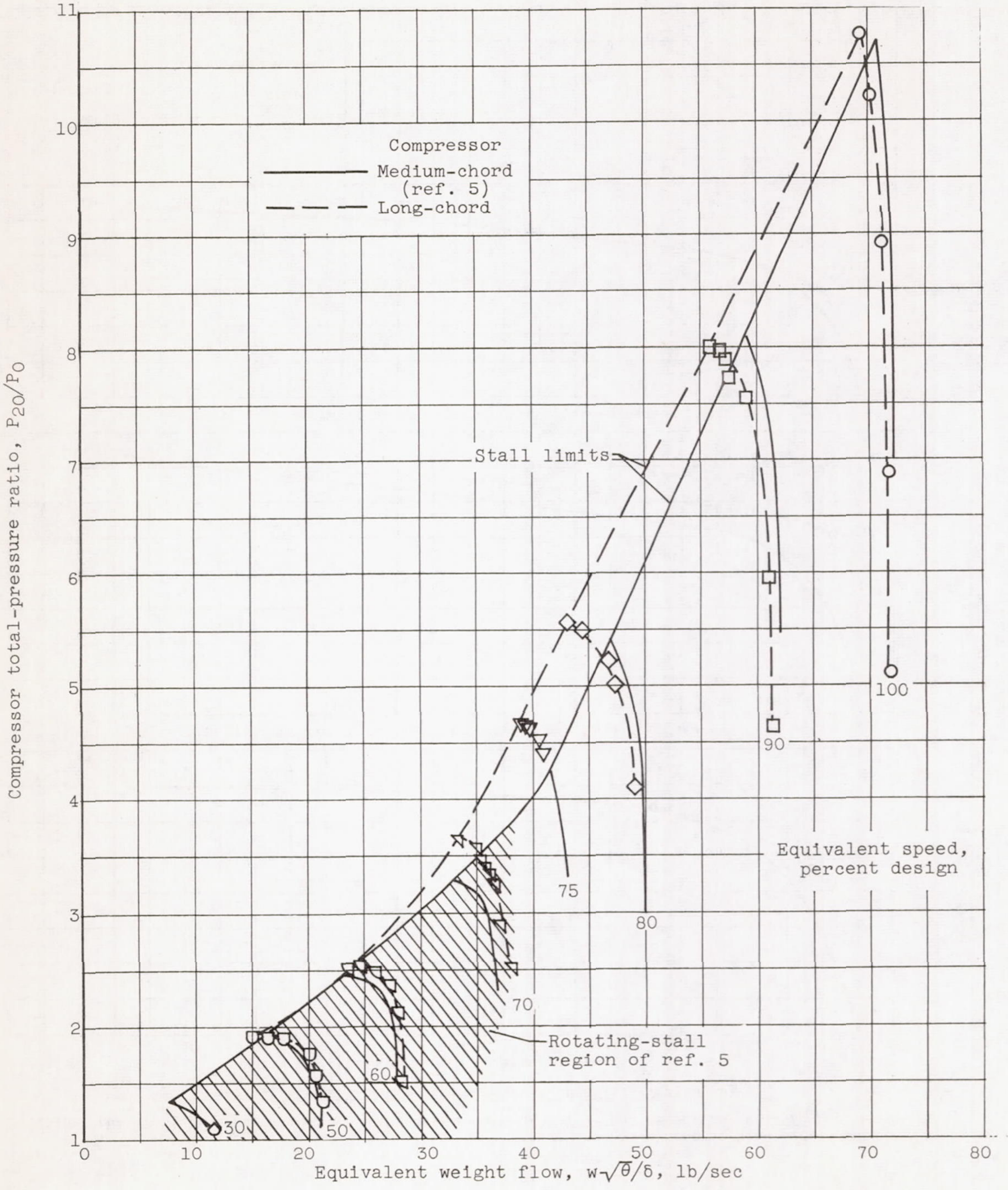
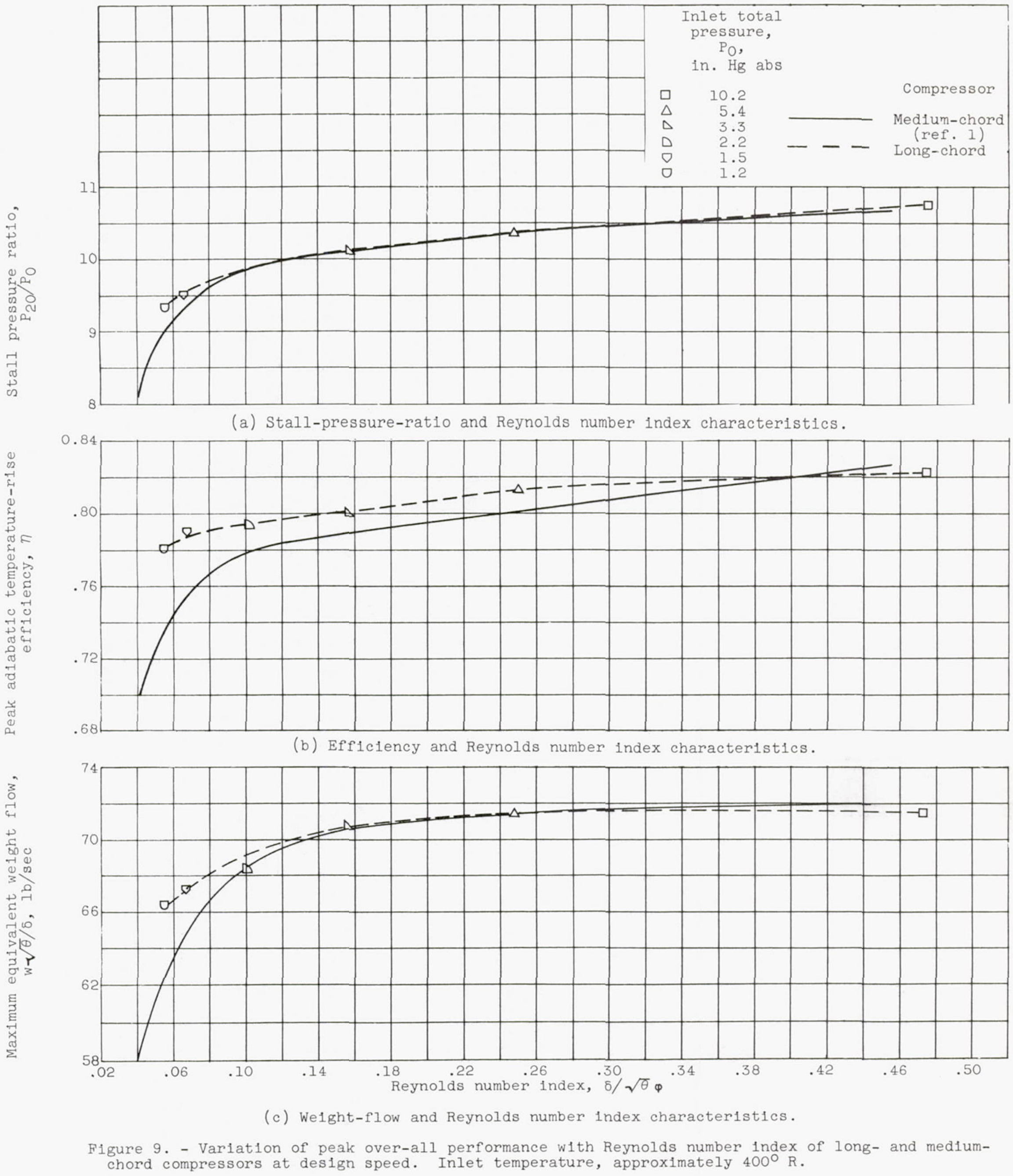


Figure 8. - Comparison of over-all performance characteristics of long- and medium-chord compressors.



(a) Stall-pressure-ratio and Reynolds number index characteristics.

(b) Efficiency and Reynolds number index characteristics.

(c) Weight-flow and Reynolds number index characteristics.

Figure 9. - Variation of peak over-all performance with Reynolds number index of long- and medium-chord compressors at design speed. Inlet temperature, approximately 400° R.

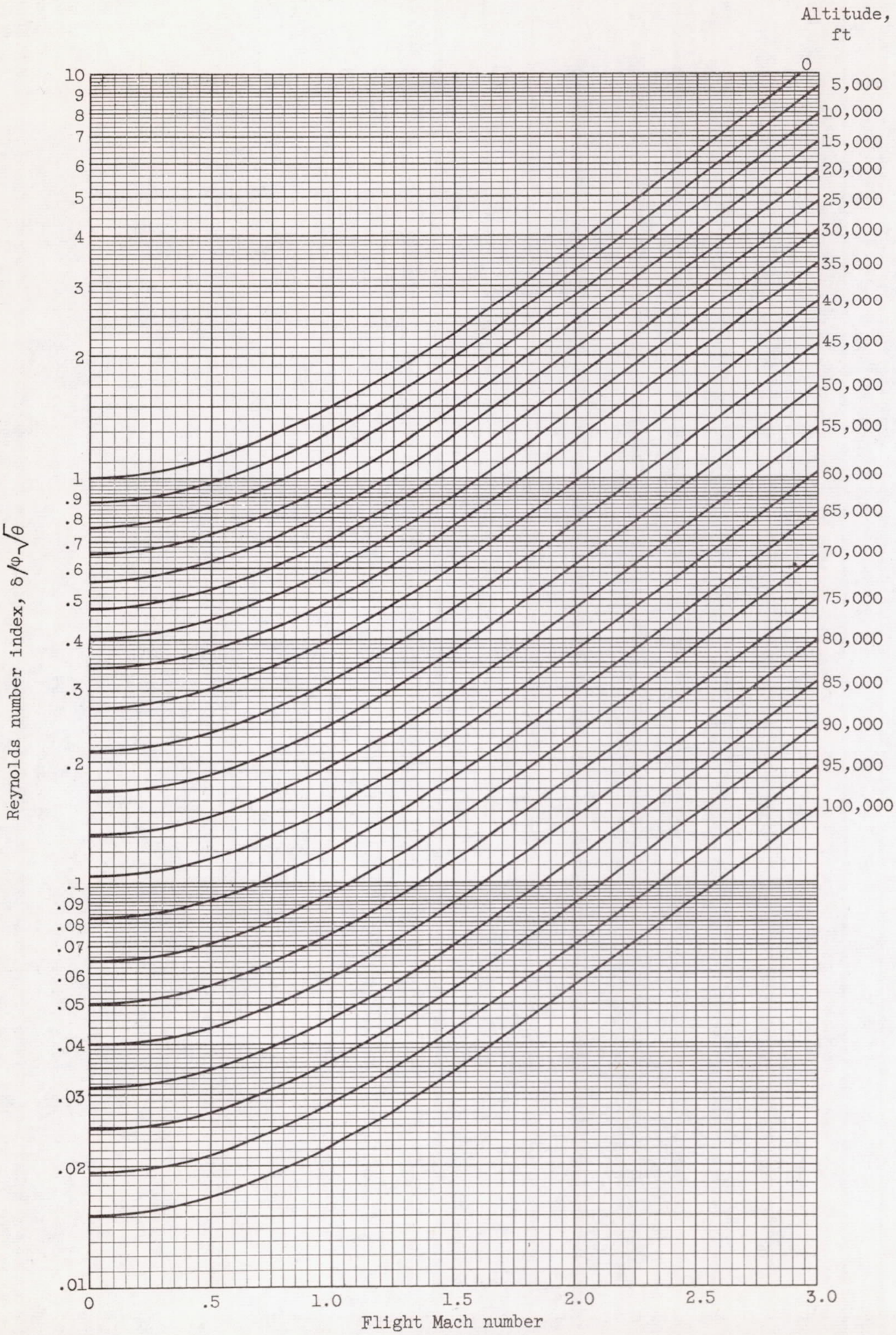


Figure 10. - Reynolds number index as a function of altitude and Mach number.