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RESEARCH MEMORANDUM

EFFECT OF COMPRESSOR-INLET AREA BLOCKAGE ON PERFORMANCE OF AN EXPERIMENTAL COMPRESSOR AND A HYPOTHETICAL ENGINE

By Richard E. Filippi and James G. Lucas

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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Page 12, REFERENCES: The following references should be added to the list:

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RESEARCH MEMORANDUM

EFFECT OF COMPRESSOR-INLET AREA BLOCKAGE ON PERFORMANCE OF AN EXPERIMENTAL COMPRESSOR AND A HYPOTHETICAL ENGINE

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SUMMARY

An investigation was conducted to determine the effects of inlet-annulus blockage on compressor performance and its corresponding effect on the computed performance of a hypothetical engine. The hypothetical engine performance was calculated from the over-all compressor performance and assumed component performance characteristics. Blockage consisted of hub baffles blocking 15 and 26.3 percent of the inlet annulus and a sector baffle covering 12.5 percent of the inlet annulus. Data obtained from a previous investigation of a hub baffle blocking 20.5 percent of the inlet annulus are also included.

Use of the hub baffles blocking 26.3 and 20.5 percent of the inlet annulus completely eliminated periodic rotating stall over the entire speed range examined, while the hub baffle blocking 15 percent of the inlet annulus eliminated periodic rotating stall over the entire range examined except at the surge point at 50-percent design speed. The sector baffle blocking 12.5 percent of the inlet annulus was not investigated at speeds higher than 65 percent of design speed because of large rig vibrations. The results obtained, however, indicated no improvement in compressor part-speed performance. The absolute rotation of the inlet stall still existed and was not contained entirely behind the sector.

The analysis for the hypothetical engine with no inlet blockage indicated that acceleration to design speed is impossible if auxiliary devices are not used, because of the poor part-speed performance of the test compressor. No equilibrium operating point existed at 75 percent of design speed. However, with the addition of the hub baffles, equilibrium operating points were determined for each speed investigated, which indicated that acceleration to design speed could be obtained. These results are inconclusive, however, indicating only that hub baffles could be an aid for an engine using the test compressor, which has poor part-speed performance characteristics. Use of hub baffles for an engine with good compressor part-speed performance might be disadvantageous.

The hypothetical engine calculations indicated that hub blockage may be used effectively as a thrust-control device. At static sea-level conditions and operation with design jet nozzle area, a thrust reduction of approximately 46 percent of design thrust was calculated at design speed from the use of the hub baffle blocking 26.3 percent of the inlet annulus. This thrust is equivalent to a speed reduction of 16 percent of design for the hypothetical engine with no blockage. The turbine-inlet temperature required by using the three hub baffles never exceeded the turbine-inlet temperature at the design point.

INTRODUCTION

One of the major problems arising in the use of high-pressure-ratio axial-flow compressors in turbojet engines has been that of part-speed operation. The part-speed problems are principally associated with the compressor component and may be separated into two main categories: (1) engine acceleration problems resulting from poor compressor efficiencies and surge-line characteristics, as discussed in references 1 to 3, and (2) blade vibration problems resulting from rotating stall at low and intermediate speeds, as discussed in reference 4. In general, both the acceleration and blade vibration problems can be attributed to stalling of the inlet stages of the compressor due to their mismatching at part-speed operation.

Adjustable inlet guide vanes and interstage bleed have both been used to improve stage matching during part-speed compressor operation. The two-spool type of engine is another approach toward improving part-speed matching of compressor stages by having the front and rear stages operating at different rotational speeds. In addition, compressor-discharge bleed has been used to alter the matching of the compressor and turbine and thereby improve engine acceleration.

Inlet-annulus blockage, as discussed in reference 5, is another approach toward solving the part-speed blade vibration problem. The investigation of reference 5, which was conducted on a 15-stage high-pressure-ratio axial-flow research compressor, considered complete circumferential blockage at both the hub and tip of the inlet annulus just ahead of the inlet guide vanes. This investigation indicated that hub blockage was more effective than tip blockage for the compressor investigated. A hub blockage, referred to as a hub baffle, completely eliminated the periodic rotating stall and thus eliminated one potential source of blade vibration. These preliminary results also indicated improvement in the potential acceleration characteristics of an engine using this compressor with the hub baffle or blockage. The possibility of using a retractable baffle as a means of thrust control at high engine speeds was also suggested.

In order to study further the effectiveness of inlet blockage as a solution to the part-speed compressor operating problems and as a means of thrust control, additional experiments were made with hub baffles having inlet area blockages of 15 and 26.3 percent of the total inlet-annulus area. Data were taken over a speed range of 50 to 100 percent of design rotational speed for the 15-percent blockage and over a speed range of 65 to 100 percent for the 26.3-percent blockage.

Inasmuch as the application of inlet blockage to an engine would require development of a retracting mechanism, it was considered that a sector or segment blockage plate would be more simple mechanically than the complete circumferential hub baffle. Therefore, tests at 50 and 65 percent of design speed were made with a sector blockage covering 45° or 12.5 percent of the inlet annulus.

In order to evaluate the effect of the hub baffle on engine acceleration as well as to evaluate the potential of the inlet blockage as a thrust-control device, the compressor performance data obtained were analytically matched with a hypothetical turbine, and a resultant engine performance was computed for static sea-level conditions operating entirely with design exhaust-nozzle area. The results of the experiments and analysis are reported herein. For completeness, the data of reference 5 for a hub blockage of 20.5 percent are also included.

APPARATUS AND INSTRUMENTATION

A 15-stage high-pressure-ratio axial-flow compressor was used in this investigation. The installation and instrumentation of the test compressor are the same as reported in reference 5, except that no compressor insulation was used.

Two types of blockage were used upstream of the inlet guide vanes to reduce the inlet-annulus area. The first type of blockage was an annular plate covering the inlet annulus from the hub outward toward the tip, as shown in figure 1. Hub baffles blocking 15, 20.5 (ref. 5), and 26.3 percent of the inlet-annulus area were investigated. The second type of blockage considered was a plate covering a 45° sector of the inlet annulus from the hub to the tip, as shown in figure 2.

Hot-wire anemometers were used to determine flow fluctuations and frequency of periodic rotating stall. Three hot wires were used in radially traversing probe actuators, two in the first-stage stator blade row and one in the fourth-stage stator blade row.

EXPERIMENTAL PROCEDURE

The range of equivalent speeds investigated with the corresponding inlet blockage is shown in the following table:

Baffle	Blockage, percent annulus	Speed, percent design
Annular	15.0	50, 65, 75, 80, 100
	20.5 (ref. 5)	50, 65, 75, 80
	26.3	65, 80, 100
Sector	12.5	50, 65
No blockage	----	30, 50, 65, 75, 80, 85, 100

The area reductions of the compressor inlet, as shown in the above table, are geometric reductions and do not account for the additional decrease of inlet flow area that would be caused by the vena contracta. Therefore, the effective area reductions would probably be greater than represented in the table.

The stall data were analyzed according to the method described in reference 6. All compressor performance parameters were measured and evaluated by the procedure suggested by the NACA subcommittee on compressors (ref. 7).

CALCULATION PROCEDURE

The compressor performance data obtained, with and without inlet-annulus blockage, were analytically matched with a hypothetical turbine, and the resultant engine performance was computed. It was assumed that, for all speeds investigated, the turbine was operating with the turbine nozzles choked. The turbine adiabatic efficiency was assumed to be constant at a value of 85 percent. Since the turbine stators tend to be unchoked at low engine speeds, an equilibrium operating point determined for any one speed in this region by assuming the turbine stators choked would have a higher compressor equivalent weight flow than would be obtained by using the actual turbine flow. The assumption that the turbine stators are choked along the operating line is generally accurate near design speed but may induce some error at the lower speeds. This error at low speeds, however, will not seriously affect the comparison of the calculated operating lines. The effect of this assumption on the use of blockage to control thrust is insignificant, because the range of primary importance is in the high-speed region from 80 to 100 percent of design speed.

The hypothetical engine design point was arbitrarily taken at a compressor pressure ratio of 7.0 at an equivalent weight flow of 161 pounds per second. Design turbine-inlet temperature was assumed to be 2080° R. The ratio of burner-outlet to burner-inlet total pressure was assumed to be 0.95. The total-pressure loss between the turbine outlet and jet nozzle outlet was assumed to be proportional to the dynamic pressure leaving the jet nozzle. The ratio of turbine-outlet to jet nozzle-outlet total pressure was assumed to be 1.05 at a jet nozzle-exit Mach number of 1.0. Thrust was calculated according to the method described in reference 8, with a complete-expansion nozzle assumed.

RESULTS AND DISCUSSION

Compressor Performance with No Inlet Blockage

The over-all performance of the 15-stage compressor without inlet-annulus blockage is shown in figure 3 as a plot of over-all total-pressure ratio and adiabatic temperature-rise efficiency against compressor equivalent weight flow for constant values of equivalent speed. Design-speed weight flow was approximately 161 pounds per second at a surge total-pressure ratio of about 8.8. A discontinuity exists in the surge-limit line in the intermediate-speed region. In this region multiple-branched operating curves were found, as described in reference 9 (at 78.5-percent equivalent design speed), and a unique surge-limit line could not be ascertained. On increasing speed, with the exhaust throttles wide open, rotating stall was observed between 50 and 84 percent of design speed. On reducing speed, with the exhaust throttles wide open, rotating stall occurred at 74 percent of design speed and was present at all lower speeds investigated. Peak pressure ratio at 75 percent of design speed is 2.85 at an adiabatic efficiency of approximately 0.60, the peak efficiency at this speed. At speeds below approximately 65-percent design, the peak adiabatic efficiencies are approximately 52 percent.

Effect of Hub Blockage on Compressor Performance and Stall Characteristics

Compressor performance. - The effect of inlet-annulus hub blockage on the over-all performance characteristics of the test compressor is presented in figures 4(a), (b), and (c) for area blockages of 15, 20.5, and 26.3 percent of the inlet annulus, respectively. For all speeds investigated, the maximum weight flow, surge weight flow, and surge pressure ratio were decreased by blocking the inlet annulus (except at the surge point at 50 percent of design speed with 15 percent of the inlet annulus blocked).

The effect of inlet area blockage on maximum weight flow at each speed is presented in figure 5. It is apparent that increasing the blockage results in decreased flow, especially at the high speeds. At design speed, the maximum weight flow was reduced approximately 27 percent with the baffle blocking 26.3 percent of the inlet annulus; while at 65 percent of design speed, the weight flow was reduced approximately 13 percent. At low speeds the rear stages choke and limit inlet weight flow. Therefore, changing the inlet area by introducing blockage of this order of magnitude does not have much effect on compressor equivalent weight flow.

By introducing various amounts of compressor-inlet blockage at the hub, it was hoped that the rematching of the front and rear stages might improve part-speed performance. Introducing inlet-annulus blockage at the hub of the compressor directs the air toward the highly loaded tip and mean regions of the blade, unloads these critical stalled areas, and thus tends to raise the adiabatic efficiency of these blade elements. The attainment of this improved performance required sacrifices in the efficiency of the hub region behind the hub baffles. Consequently, peak over-all adiabatic efficiency does not vary appreciably in the low-speed region, as may be seen in figure 4. At 50 and 65 percent of design speed, the adiabatic-efficiency level is relatively constant. However, at higher speeds, where the inlet stages are operating unstalled, introducing hub blockage reduces the efficiency level of the hub regions without an appreciable variation in the efficiency of the tip and mean regions of the blade. Thus over-all compressor efficiency is reduced, as may also be seen in figure 4. The 26.3-percent blockage reduced the peak over-all adiabatic efficiency from approximately 0.75 to 0.64 at design speed.

Stall characteristics. - Since rotating-stall regions occurring in a compressor, usually in the intermediate- and low-speed ranges, are areas of very low flow, the areas comprising the stall may be considered, in effect, a blockage. By installing an inlet blockage of sufficient magnitude, the location and configuration of these regions may be controlled by establishing the stalled region behind the blockage. As compressor speed or weight flow is reduced and the compressor-inlet area necessary for efficient operation decreases, a larger inlet stall area results. Hence, at low speeds a larger blockage would be required to rematch the inlet stages in order to maintain the inlet stall behind this blockage than would be required at intermediate speeds.

The results of reference 5 indicate that a hub baffle would be more advantageous in the elimination of periodic rotating stall than a tip blockage, because the hub baffle unstalls the critical tip region of the blade. An annular blockage would also be necessary to eliminate the harmful effect of separated stall zones on blade vibration. Preliminary results (reported in ref. 5) indicate that proper inlet-annulus blockage could eliminate periodic rotating stall for the speed range investigated, as shown by blocking the annulus by 20.5 percent at the hub. The present investigation included two additional hub baffles, blocking 26.3 percent and 15 percent of the inlet annulus.

Because the compressor-inlet area is too large for efficient operation at part speed, as evidenced by the appearance of rotating stall, use of inlet blockage rematches the front stages at part speed by reducing the inlet area. Since the baffle blocking 20.5 percent of the annulus rematched the front stages sufficiently to eliminate periodic rotating stall, it may be expected that a larger baffle would also eliminate the periodic rotating stall. This was found to be true with the baffle blocking 26.3 percent of the inlet annulus; no periodic rotating stall was encountered in the speed range investigated. However, the hub baffle blocking 15 percent of the inlet annulus was not of sufficient area to contain all the inlet-stage stall while operating at 50-percent design speed at the surge point, and periodic rotating stall was encountered. This point is distinguished on figure 4(a) as a slight increase in pressure ratio and efficiency and is designated as point A. Point B evidenced no periodic rotating stall.

Effect of Sector Blockage on Compressor Performance

Since it was considered to be simpler to retract a sector baffle instead of a complete annular ring, an investigation was also made by blocking 45° of the inlet annulus or 12.5 percent of the annulus area. If the stall zone could be isolated behind the sector plate, and not rotate, then the speed at which resonance would occur between the blade frequency and the frequency with which a blade crosses the stall zone could be definitely established. Such a scheme would enable the determination of a safe operating range with regard to blade vibration resulting from rotating stall. When the stall zone behind the sector plate is isolated, however, blade vibration problems due to a nonuniform circumferential flow pattern are still present.

A calculation was made to determine the engine speed at which resonance would be attained between the blades in the first rotor row and an exciting force caused by the stall zone behind the sector plate. Blade vibrations resulting from a frequency equal to half the natural frequency of the first-rotor blades would be possible when compressor mechanical speed was approximately 71 percent of design. This was equal to a compressor equivalent speed of 76 percent of design for the inlet temperature run; and, therefore, experimental investigations were to be avoided in this speed region. In an attempt to determine the surge point at 65 percent of design speed, however, rig vibration became excessively high, and further investigations were not made. The over-all performance results obtained are shown in figure 6. Over-all performance was hardly affected by the sector blockage, and the absolute rotation of the stall zones still existed over the range examined. The radial penetration of the tip stall, measured from the tip inward, varied between 25 and 45 percent of the blade passage height. Therefore, the sector plate blocking 12.5 percent of the inlet annulus was not of sufficient area to isolate the inlet-stage stall. Larger sector plates may be beneficial; but, for comparable annulus area blockage, the hub baffle would be more effective. This difference in effect of blockage is due to the fact that the hub baffle unloads more of the critical blade sections. A sector blockage would unload part of the tip and mean region but would also unload the hub sections, which are not highly loaded blade elements.

Effect of Hub Blockage on Computed Engine Performance

The engine performance resulting from hub blockage covers a wide range of speeds. For convenience, the results are discussed in two general classifications, namely (1) engine acceleration potential in the off-design low-speed range and (2) thrust control at speeds near design.

Engine acceleration potential. - The effect of inlet-annulus blockage on the operating line of the compressor installed in the hypothetical engine is shown in figure 7. The location of the operating line on the compressor over-all performance map without any inlet blockage is given in figure 7(a). The operating line is not continuously drawn through the intermediate-speed region. A calculation revealed that an equilibrium operating point did not exist on the 75-percent-speed curve. Consequently, some compressor variable geometry such as bleed or adjustable guide vanes would be required in order to accelerate to design speed.

By installing the baffle blocking 15 percent of the inlet annulus, equilibrium operating points were determined for all the speeds investigated, as may be seen on figure 7(b). Inasmuch as the surge-limit line was undetermined between 80- and 100-percent design speed, which involves a large weight-flow increment, the equilibrium operating line is indicated by a dashed line. It is believed that the surge-limit line will not dip and intersect the equilibrium operating line in this speed region, since the dip in the surge-limit line is attributed to discontinuities in stage performance as a result of inlet-stage stall. These discontinuities will probably not exist for operation with hub baffles. It is felt, therefore, that acceleration to design speed could be accomplished with the 15-percent baffle. Use of the baffle in the high-speed region reduces compressor efficiency; and, consequently, it would be desirable to remove the baffle as soon as possible to permit quicker acceleration. In figure 7(a), a continuous equilibrium operating line exists between 80 and 100 percent of design speed; and in figure 7(b), between 50 and 80 percent of design speed. Therefore, it is obvious that, by using the hub baffle from 50- to 80-percent design speed and then slowly retracting the baffle, acceleration to design speed would be possible. Thus, for an engine using this compressor, inlet-annulus blockage would be a possible means to permit acceleration through the intermediate-speed region. Equilibrium operating points determined for the hypothetical engine configurations with the hub baffles blocking 20.5 and 26.3 percent of the inlet-annulus area indicated that engine acceleration to design speed would also be possible with these configurations.

For compressors with good surge-line and efficiency characteristics at part speed, however, the advantages obtained for acceleration by using inlet-annulus blockage might not be as favorable as indicated with the test compressor. In fact, acceleration characteristics could possibly be reduced with the use of inlet blockage, considering a large decrease in compressor efficiency.

Engine thrust control. - The investigation of reference 5 indicated that inlet blockage could be used to control thrust in the high-speed regions. The calculated thrust in percent of design thrust is plotted against percent of design speed for various amounts of hub blockage in figure 8. In the high-speed region, thrust is reduced considerably by the use of the baffles. With 26.3 percent of the inlet area blocked, the thrust is decreased approximately 46 percent at design speed. Inasmuch as thrust reduction is usually accomplished by decreasing the engine speed, use of the baffle blocking 26.3 percent of the inlet annulus at design speed gives a thrust corresponding to an engine operating speed of approximately 84-percent design speed with no blockage. Since situations would be encountered where a quick thrust recovery would be needed, such as in an aircraft-carrier landing operation, a large speed reduction would be disadvantageous. Once engine speed has been reduced sufficiently to reduce thrust, inertia would delay a rapid thrust recovery. Rapid acceleration would necessitate large increases in turbine-inlet temperature, which, if allowed to surpass the limiting turbine-inlet temperature, would mean a reduction in turbine life. Therefore, for this thrust change, engine inertia and turbine overtemperature would not become a factor in thrust recovery if inlet blockage were used to control thrust.

One of the major limitations involved in using inlet blockage would be the effect on turbine-inlet temperature. Figure 9 shows the effect of the various hub baffles on the required turbine-inlet temperature for various engine speeds. None of the temperatures exceed the design temperature of 2080° R, and thus no difficulty would be encountered regarding excessive temperatures. If, however, the turbine-inlet temperature did become critical, some modulation could be made by opening the jet nozzle area, which would reduce the required turbine-inlet temperature.

Thus, there are two distinct advantages in using hub blockage as a means of controlling thrust:

(1) Large thrust variations may be achieved rapidly.

(2) Overtemperature effects on the turbine due to a necessity of rapid acceleration to recover thrust once it has been reduced by a speed change are not present.

Use of the hub baffles results in a decided increase in specific fuel consumption. If operation of the engine with the baffle in place is for a limited time, as, for example, in a landing operation or an acceleration, this is not considered a harmful effect. The high specific fuel consumption for operation with the baffle in place would make the use of the baffle undesirable as a means of reducing thrust for aircraft cruise or "loiter."

For larger thrust reductions, greater inlet-annulus blockage could be used or a combination of inlet blockage plus a small speed decrease. A small decrease in speed could be used without seriously increasing the time for thrust recovery, since acceleration time in the region near design without inlet blockage is small. When the baffle blocking 26.3 percent of the inlet annulus is combined with a 10-percent speed decrease, thrust is reduced approximately 67 percent. Additional thrust reduction may also be accomplished by opening the jet nozzle area. Thus, the combination of inlet blockage, jet nozzle-area adjustments, and small speed reductions would permit large reductions in thrust with rapid recovery if needed.

Design and Control Problems

The location of the hub baffles forward of the inlet guide vanes, as shown in figure 1, would present some difficulties. Obviously there would be an icing problem, and some means of protection must be provided. Since the operating mechanism for the hub baffles would probably be located in the compressor-inlet centerbody, the space available for accessory equipment would be reduced. The design problem will, of course, be aggravated for compressors with very small inlet hub-tip ratios.

The hub baffle will be used in the low- and intermediate-speed ranges to eliminate rotating stall and perhaps to aid in engine acceleration. However, once the engine is operating above this critical region, continued use of the baffle is undesirable. As stated previously, the use of the hub baffle increases specific fuel consumption, and the baffle must be fully retracted in the range of engine speeds normally encountered during flight. Furthermore, rapid removal of the hub baffle would result in undesired thrust discontinuities of large magnitude. Therefore, the control system must schedule the baffle position to meet these requirements.

If the hub baffle is used to decrease thrust at design speed (or slightly under design speed), during a landing approach, an additional control complexity will exist.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effects of compressor-inlet-annulus blockage on the performance of an experimental compressor and on the computed performance of a hypothetical engine. The inlet blockage consisted of three different sizes of annular hub blockages and one sector blockage.

1. Periodic rotating stall was eliminated over the entire speed range examined by using the hub baffles blocking 26.3 and 20.5 percent of the inlet annulus; while the hub baffle blocking 15 percent of the inlet annulus eliminated periodic rotating stall over the entire range examined, except at the surge point at 50-percent design speed.

2. The sector blocking 12.5 percent of the inlet annulus had no large effect on over-all compressor performance and did not eliminate the rotation of the inlet stall zones. Investigation was not carried past 65 percent of design speed because of excessive rig vibration.

3. Calculations indicated that acceleration to design speed was not possible for the hypothetical engine without inlet-annulus blockage if auxiliary devices are not used, since an equilibrium operating line in the intermediate-speed region did not exist. The analysis also indicated that acceleration to design speed was possible for the hypothetical engine by using any of the three hub baffles, inasmuch as equilibrium operating points were determined for all the speeds examined.

4. The improvement in acceleration characteristics for the hypothetical engine by using inlet blockage was obtained for a compressor with poor part-speed performance and might not be as great for a compressor with good part-speed performance.

5. Large thrust reductions were obtained through use of the hub baffles in the high-speed region. The computed thrust reduction was approximately 46 percent of design thrust at design speed with the hub baffle blocking 26.3 percent of the inlet annulus. This thrust reduction is equivalent to a speed change of approximately 16 percent of design speed for the hypothetical engine without blockage. Required turbine-inlet temperature did not become critical through the use of hub blockage.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 3, 1954

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3. Rebeske, John J., Jr., and Dugan, James F., Jr.: Acceleration of High-Pressure-Ratio Single-Spool Turbojet Engine as Determined from Component Performance Characteristics. II - Effect of Compressor Interstage Air Bleed. NACA RM E53E06, 1953.

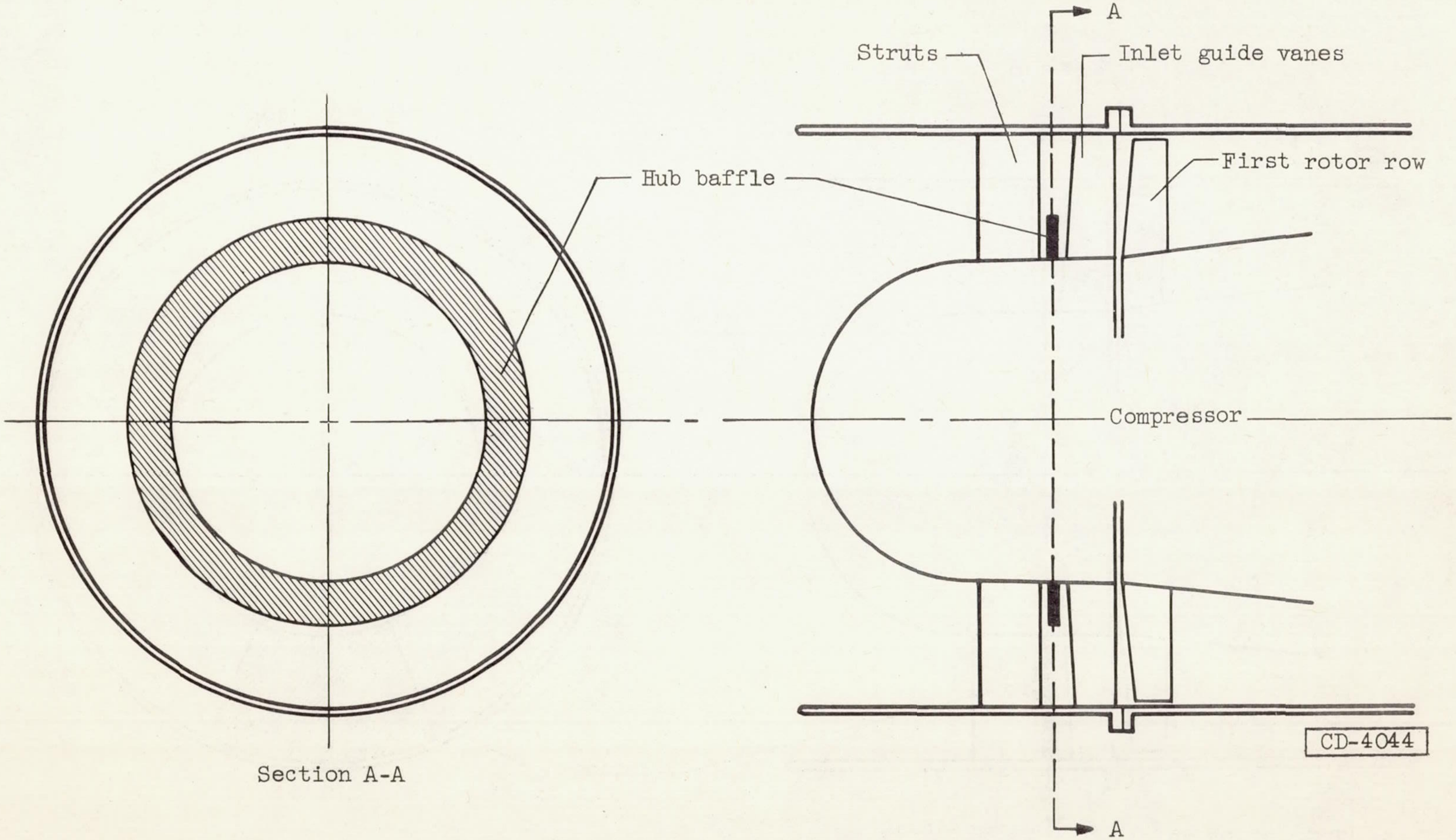


Figure 1. - Hub baffle area blockage.

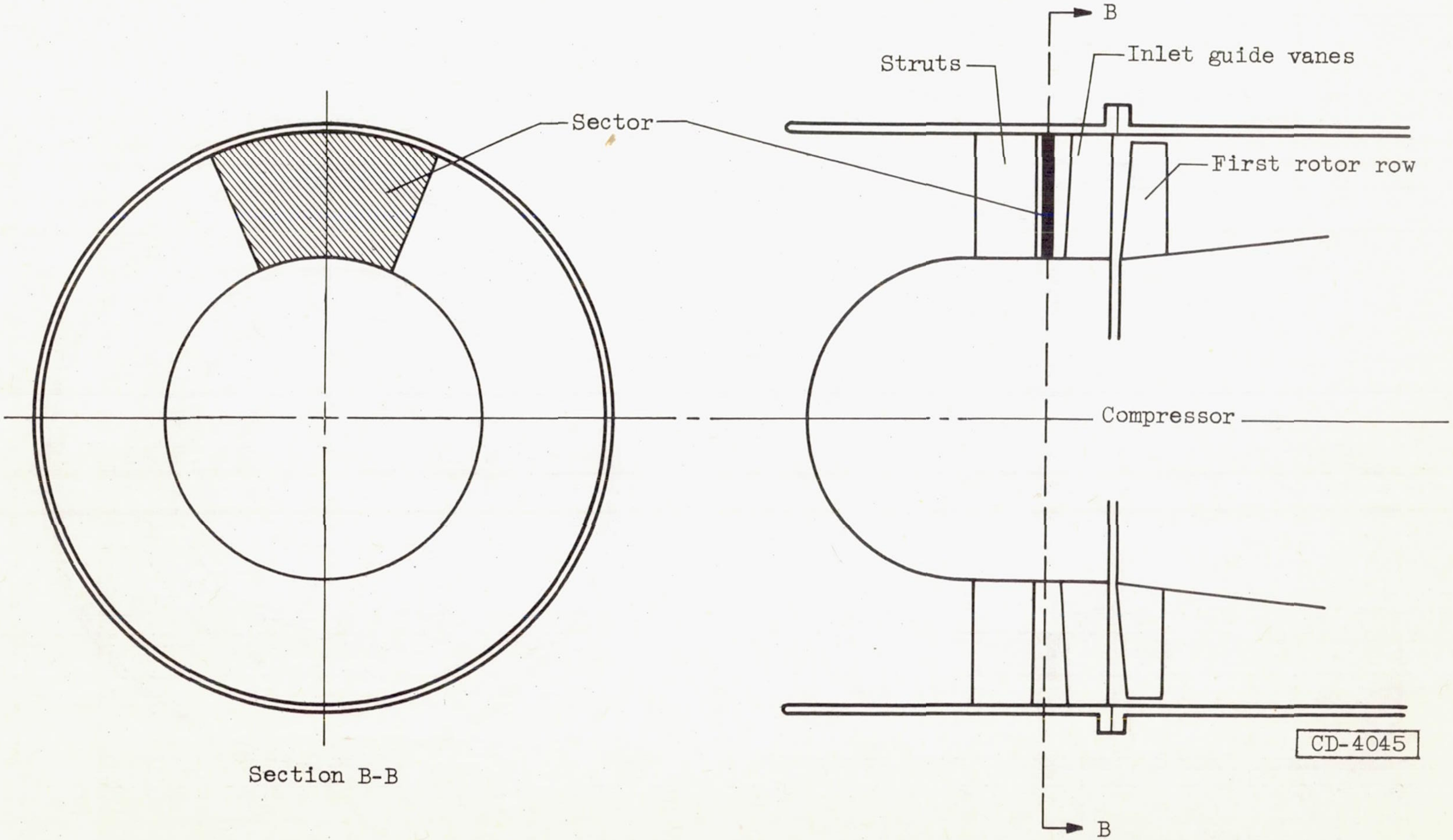


Figure 2. - Sector baffle.

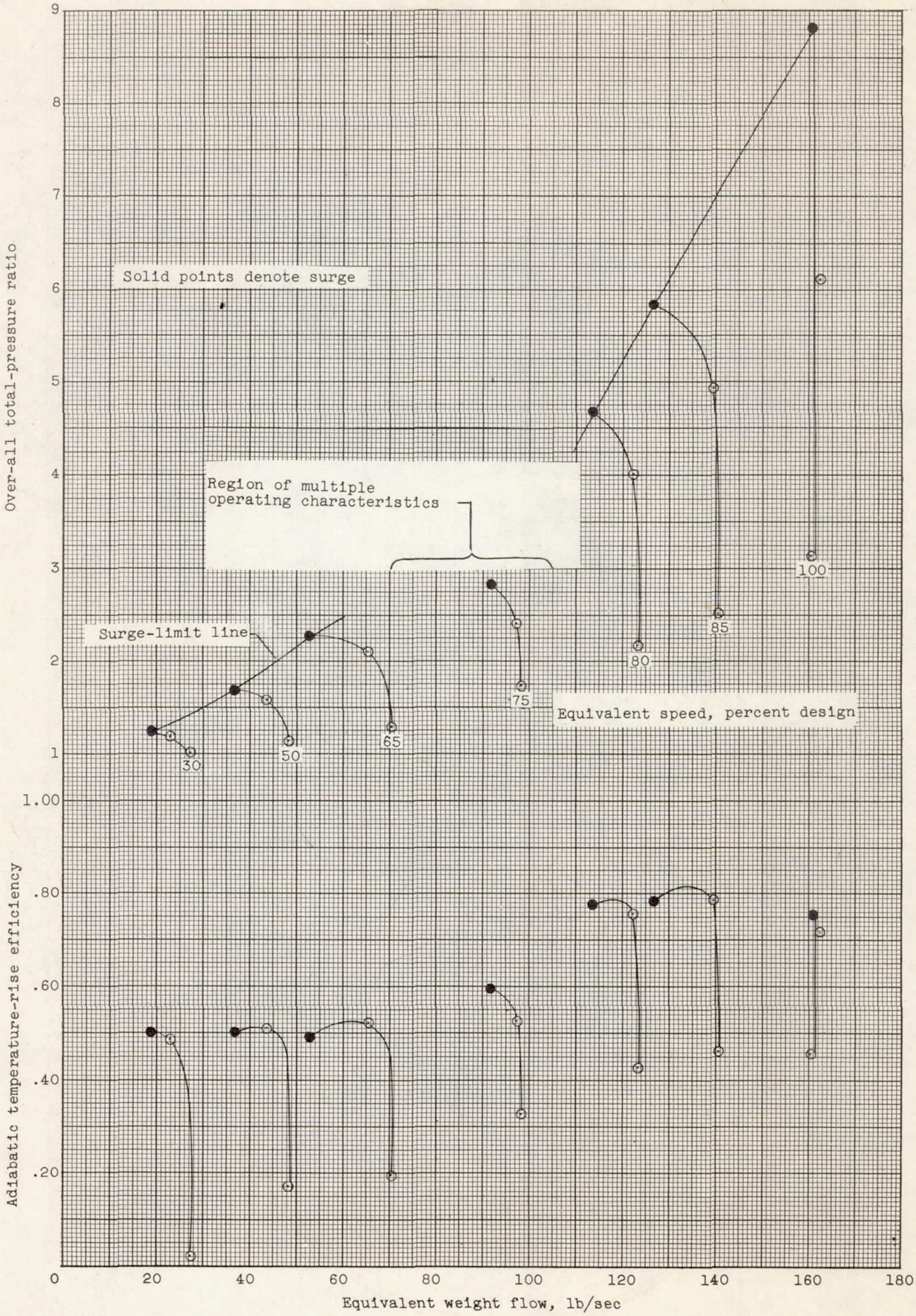
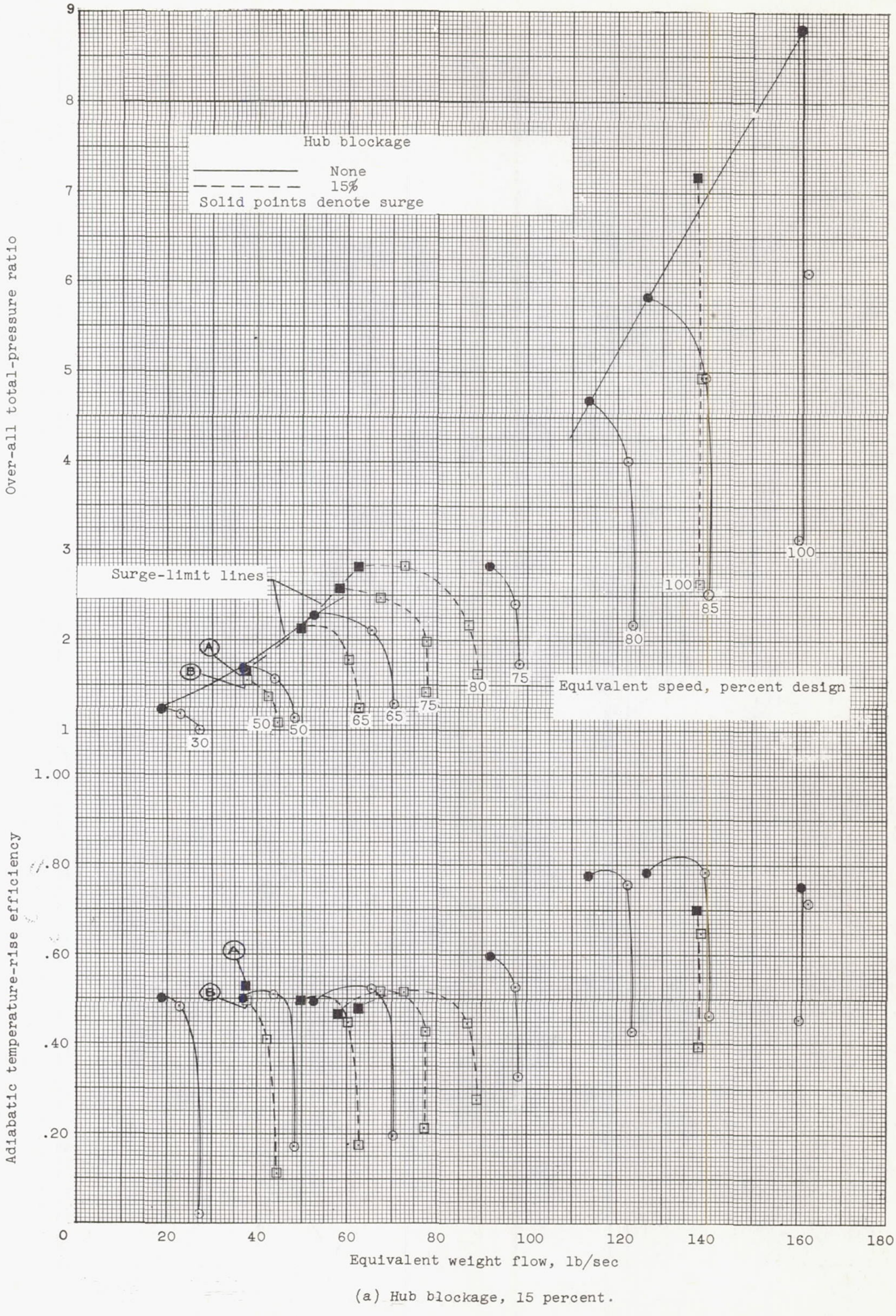
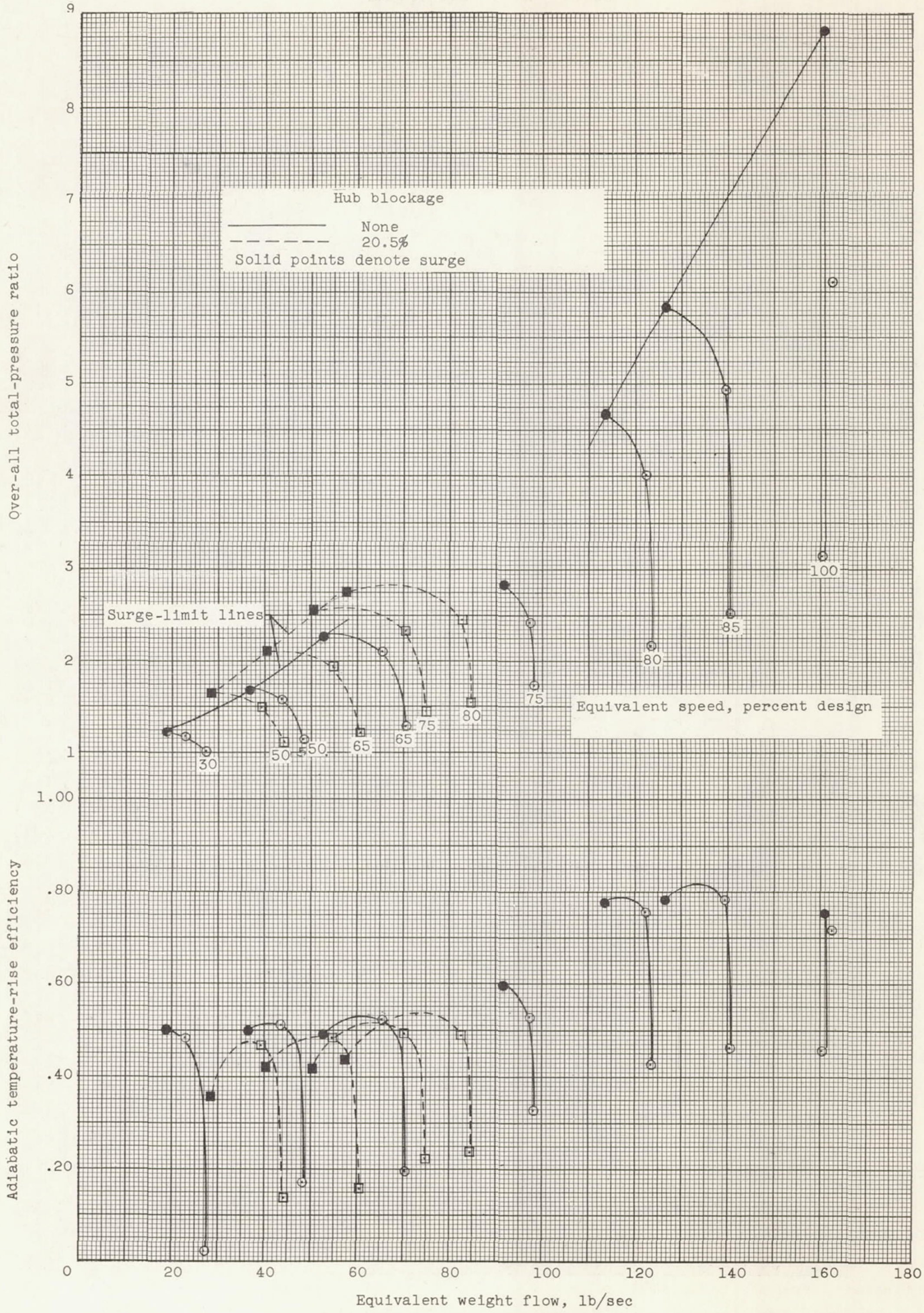


Figure 3. - Over-all compressor performance without inlet blockage.



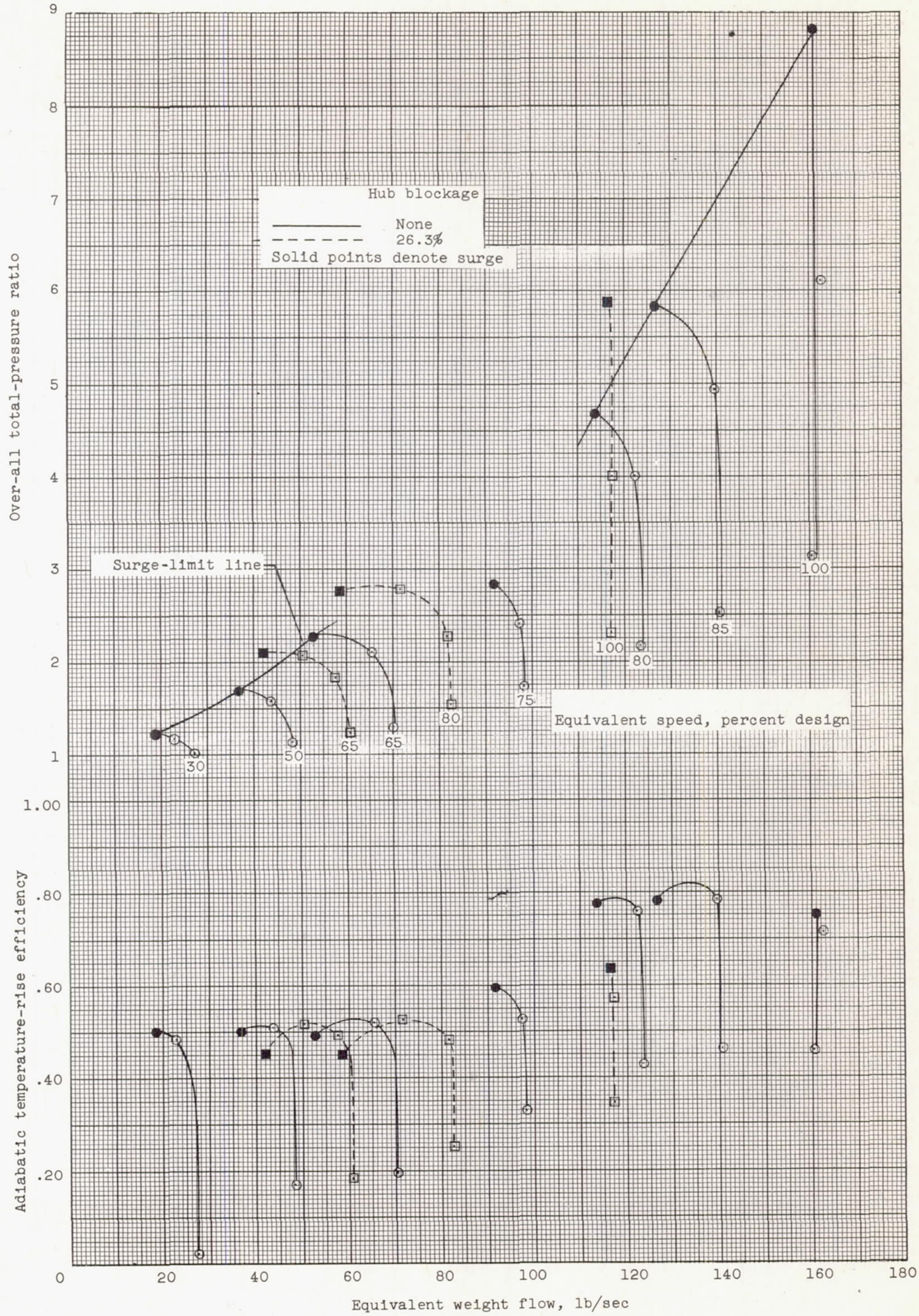
(a) Hub blockage, 15 percent.

Figure 4. - Effect of inlet-annulus hub blockage on compressor over-all performance.



(b) Hub blockage, 20.5 percent.

Figure 4. - Continued. Effect of inlet-annulus hub blockage on compressor over-all performance.



(c) Hub blockage, 26.3 percent.

Figure 4. - Concluded. Effect of inlet-annulus hub blockage on compressor over-all performance.

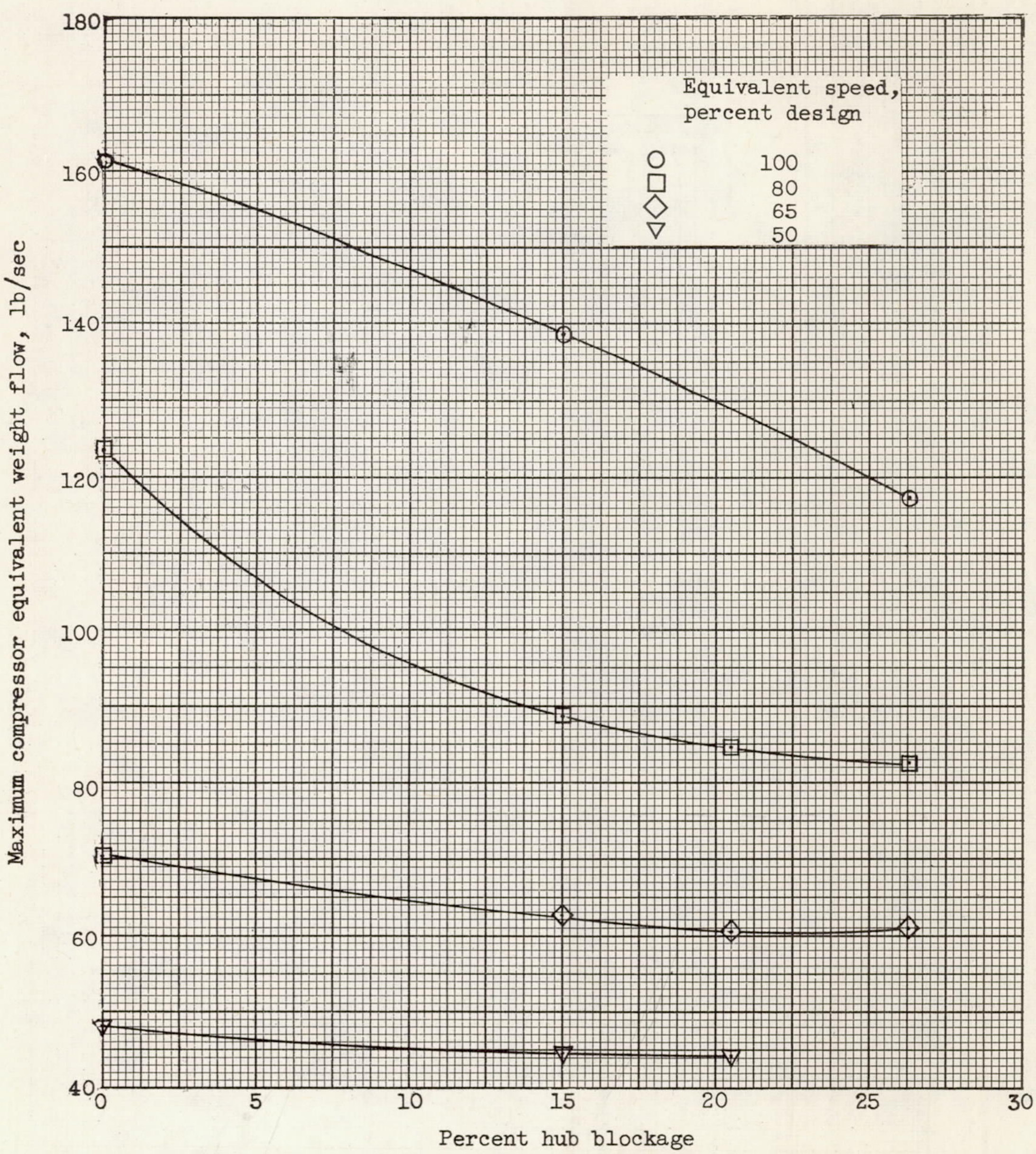


Figure 5. - Effect of inlet area blockage on maximum equivalent flow.

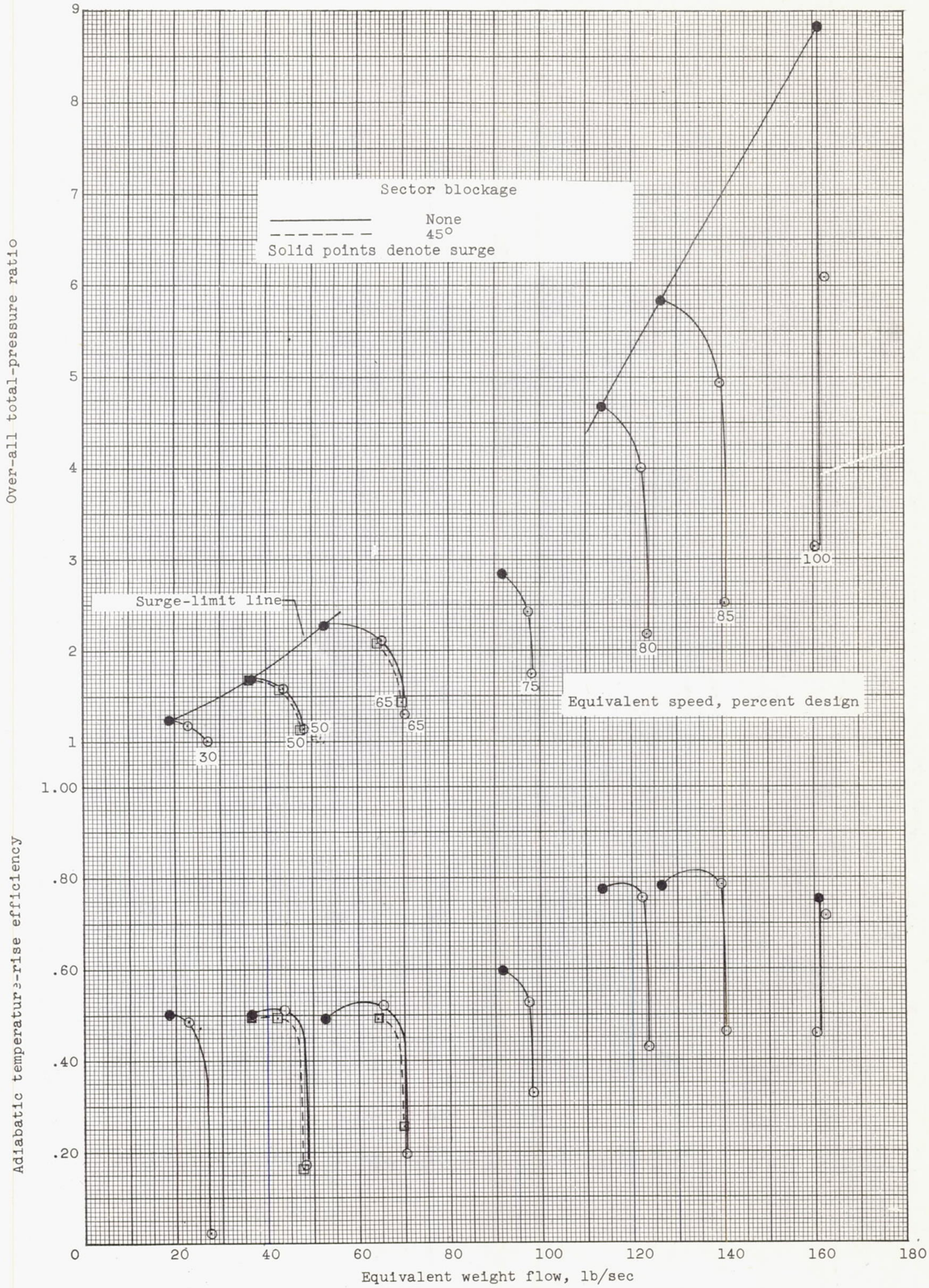
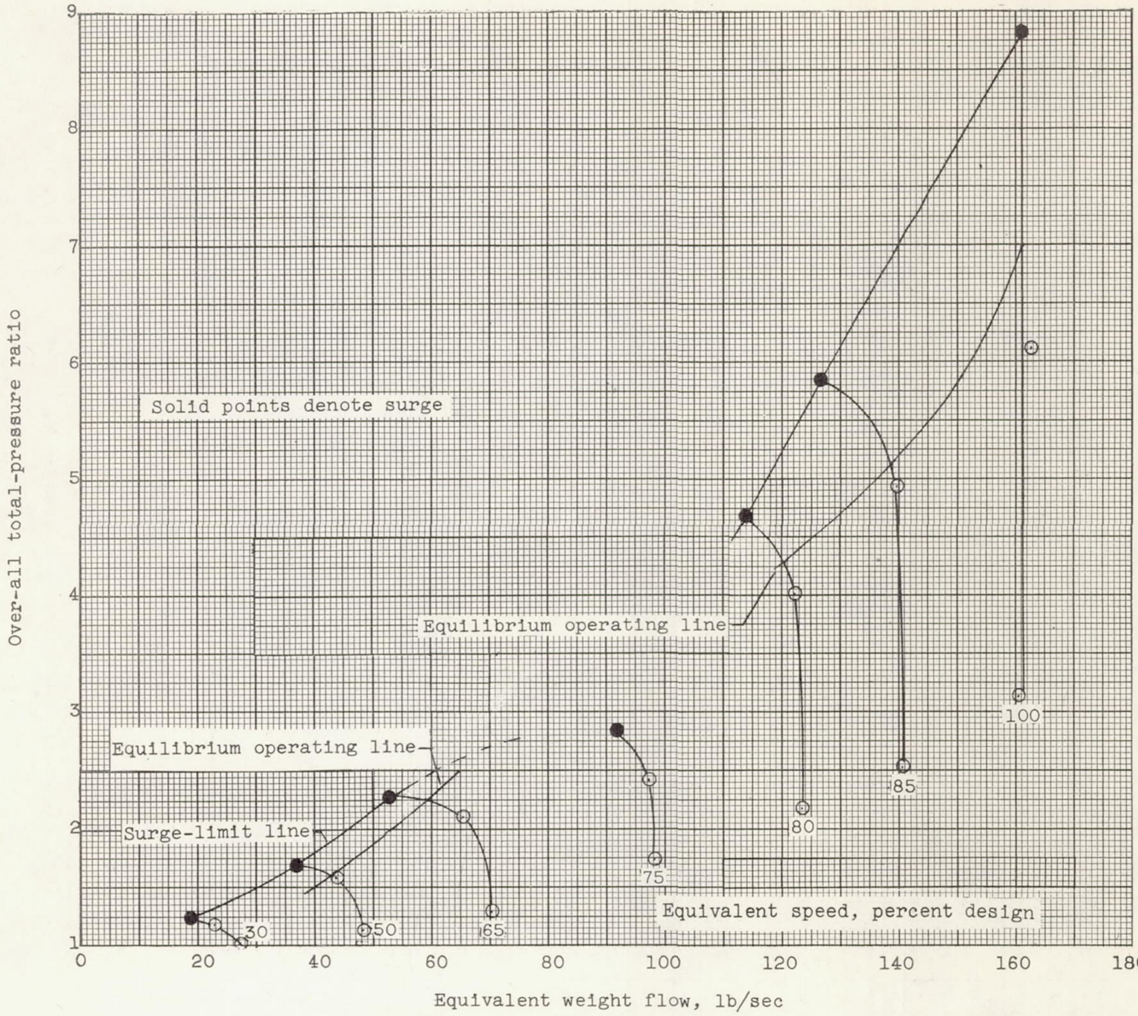
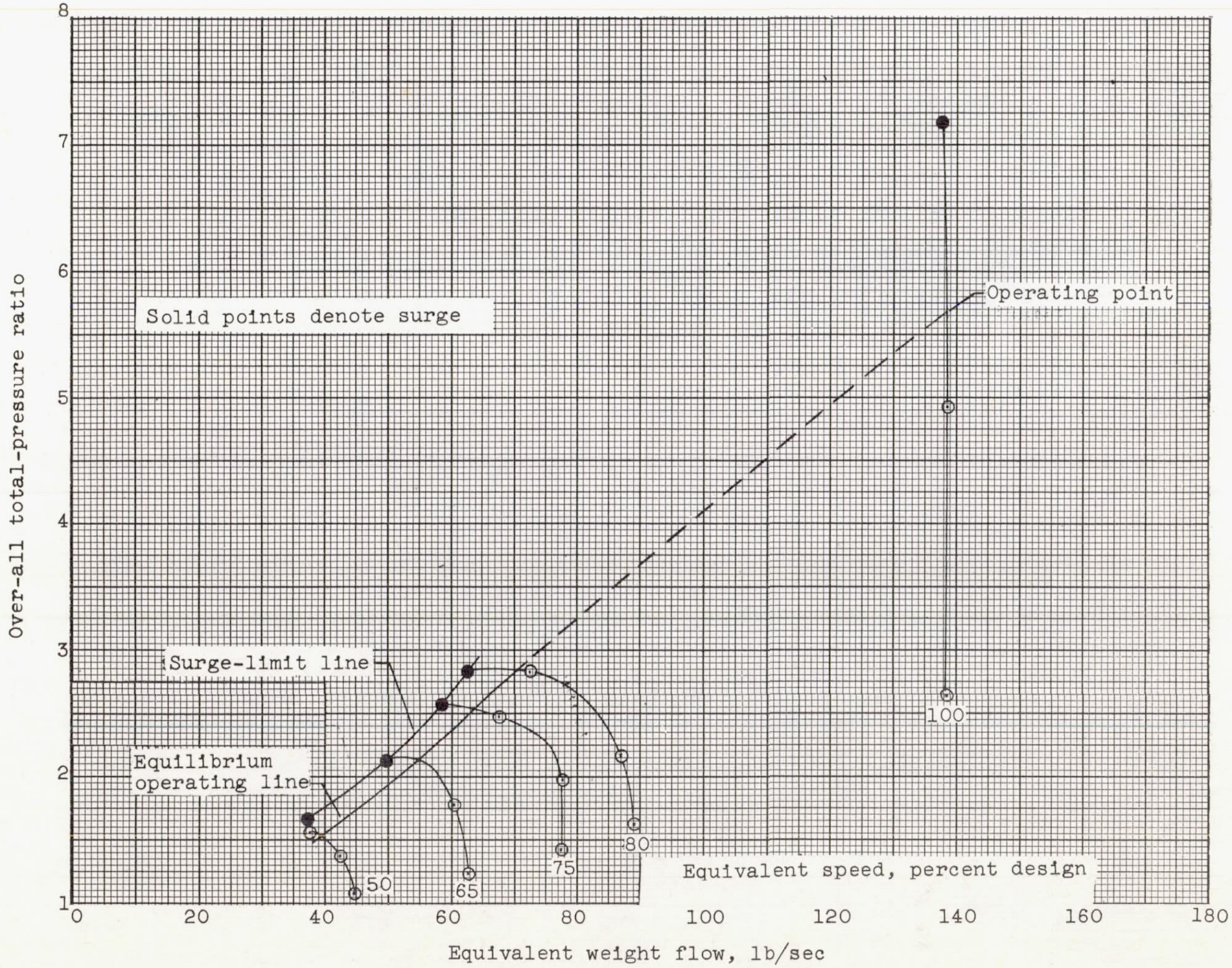


Figure 6. - Effect of 45° sector blockage on compressor over-all performance.



(a) No blockage.

Figure 7. - Effect of inlet-annulus hub blockage on compressor operating line.



(b) Hub blockage, 15 percent.

Figure 7. - Concluded. Effect of inlet-annulus hub blockage on compressor operating line.

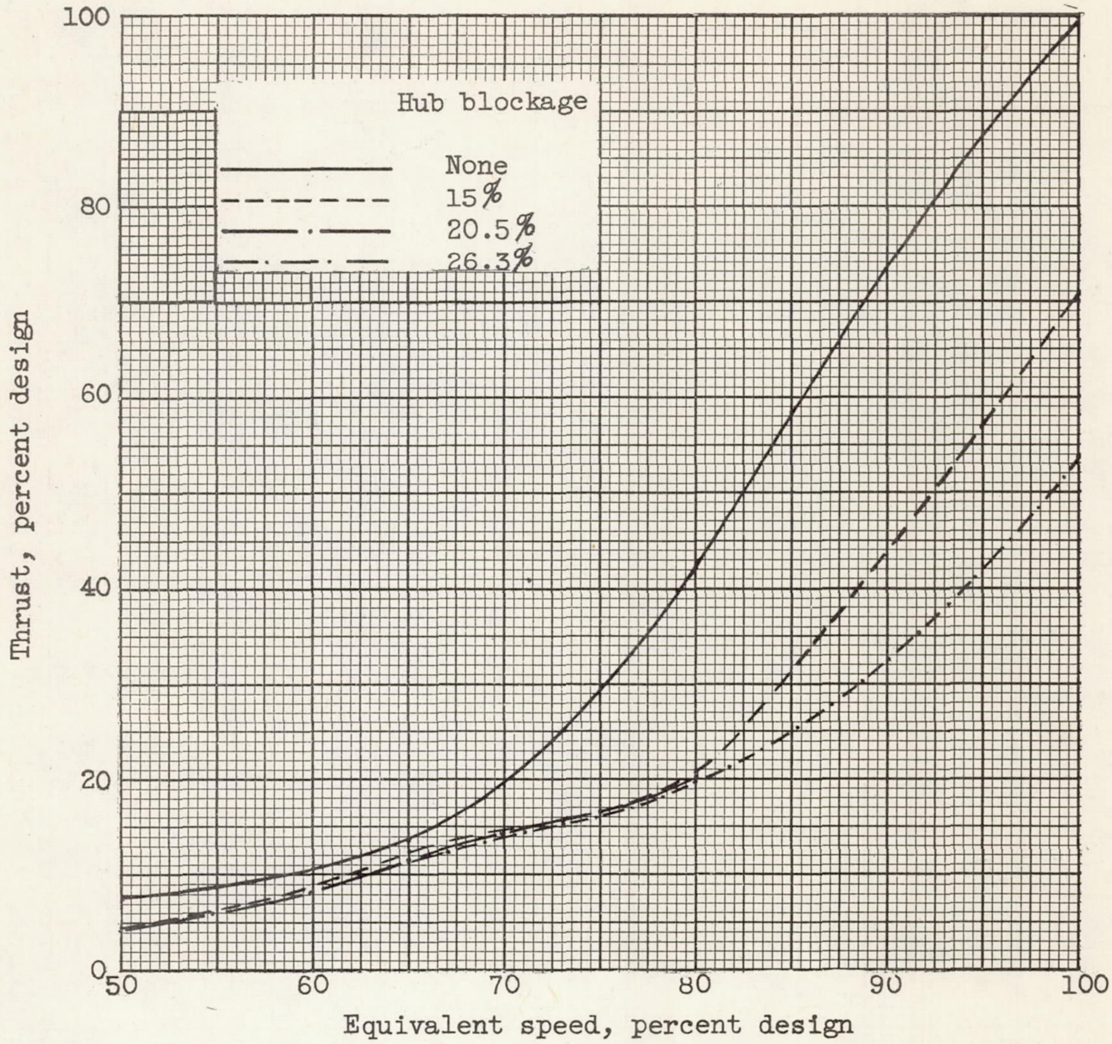


Figure 8. - Effect of inlet-annulus hub blockage on thrust.

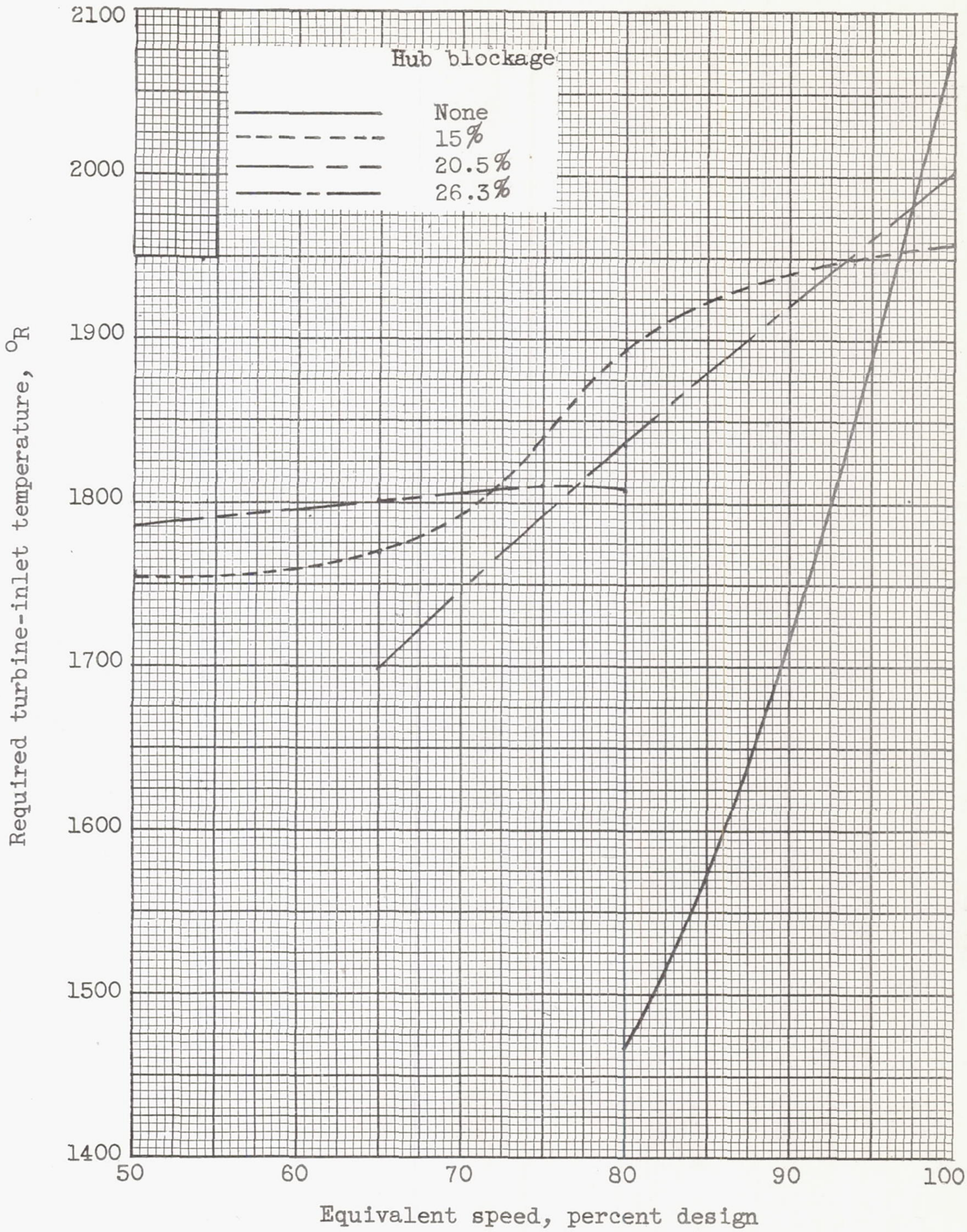


Figure 9. - Effect of inlet-annulus hub blockage on required turbine-inlet temperature.