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RESEARCH MEMORANDUM

INVESTIGATION OF THE PERFORMANCE OF A TURBOJET ENGINE WITH VARIABLE-POSITION COMPRESSOR INLET GUIDE VANES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A 9000-pound-thrust turbojet engine with variable-position compressor inlet guide vanes was investigated in order to determine the effects of guide-vane angle changes on the compressor, compressor stage, and over-all engine performance.

The results of the investigation showed that increasing the inlet-guide-vane turning by closing the vanes decreased the compressor corrected weight flow, and pressure ratio, and at high speeds, slightly decreased the efficiency of this compressor along a steady-state engine operating line. Compressor surge also occurred at a lower value of total-pressure ratio and corrected weight flow at a constant speed with increased guide-vane turning. The changes in compressor performance at high speeds with guide-vane adjustment could be attributed primarily to the changes in performance of the first stage. Increasing the inlet-guide-vane turning shifted the first-stage performance curves toward lower values of flow coefficient, pressure coefficient, and temperature coefficient. Stages downstream of the first stage were essentially unaffected by guide-vane adjustment in the high-speed range of operation.

With the inlet guide vanes in the open position, the performance of the second-through-fourth-stage group indicated an abrupt stall in the region of compressor operation where poor engine acceleration characteristics were encountered. With the inlet guide vanes in the closed position, the abrupt stall characteristic of this stage group was eliminated and the engine acceleration characteristics were improved.

The over-all engine performance showed that increasing the compressor inlet-guide-vane turning at a constant value of corrected engine speed and exhaust-nozzle area decreased net thrust and exhaust-gas temperature, while specific fuel consumption was increased in the high-speed range of operation. The engine performance also showed that guide-vane adjustment could be used for thrust modulation at high engine speeds where quick thrust response is desired without the time lag associated with engine speed changes.

INTRODUCTION

In the development of more efficient engines, compressor pressure ratios have been consistently increased. With a fixed-geometry single-spool compressor, high design pressure ratios aggravate the part-speed operating problems and, thus, restrict the acceleration capabilities of the engine. Several solutions to these problems, such as interstage or discharge air bleed and inlet baffles have been suggested or used (refs. 1 to 3). Variable-position inlet guide vanes have also been used to improve the acceleration characteristics of high-pressure-ratio single-spool engines.

An investigation has been conducted in an altitude test chamber at the NACA Lewis laboratory to determine the engine, compressor, and compressor-stage performance of a 9000-pound-thrust axial-flow turbojet engine with variable-position compressor inlet guide vanes. This investigation was conducted at a simulated altitude of 35,000 feet and a flight Mach number of 0.8. A range of corrected engine speeds from approximately 65 to 100 percent of rated speed were investigated at three exhaust-nozzle areas and four inlet-guide-vane positions. The exhaust-nozzle area was varied from 97 to 119 percent of the rated area and the variable-position guide vanes were rotated through 30° from the open to the closed position. Engine performance, over-all compressor performance, and compressor-stage performance were determined at the various test conditions. In addition, a simplified flow analysis was made to estimate the effect of guide-vane angle changes on the flow distributions entering the first rotor-blade row.

APPARATUS

Engine. - The turbojet engine has a 12-stage axial-flow compressor, a two-stage turbine, and is in the 9000-pound-thrust class. The normal engine control was modified for this investigation to permit positioning the inlet guide vanes independently of speed. A variable-area jet exhaust nozzle was also installed in order to obtain a range of compressor pressure ratios at a constant value of corrected engine speed and guide-vane setting.

Compressor. - The 12-stage compressor had a constant tip diameter of 32 inches, an inlet hub-tip diameter ratio of 0.45, and a design tip speed of 1100 feet per second. The adjustable inlet guide vanes for this investigation were rotated through 30° from the open to the closed position. The open position represents an angle between the engine centerline and a tangent near the leading and trailing edge of the vanes (obtained by laying a straight-edge across the pressure surface) of zero at the root and 13° at the tip. The setting angle at the tip was used to define inlet-guide-vane position; hence 13° is open and 43° is closed.

The open, or 13° guide-vane setting, is the standard position for design speed operation of the engine.

INSTALLATION AND INSTRUMENTATION

Altitude test chamber. - A sketch of the altitude test chamber and some of its associated ducting is shown in figure 1. The test bed on which the engine was mounted is connected by a linkage to a balance diaphragm for thrust measurement. A screen and honeycomb are installed upstream of the test chamber to insure straight inlet air flow. A bell-mouth cowl was installed on the front bulkhead to obtain a uniform velocity profile at the inlet of the compressor.

Instrumentation. - The location of the engine and compressor instrumentation stations together with schematic sketches of the instrumentation at the engine inlet and exhaust nozzle inlet are shown in figure 2. A table is also inlcuded in figure 2 giving the number and types of measurements obtained at all instrument stations. The compressor interstage instrumentation located at stations 2a through 2d after the first, fourth, seventh, and tenth stage stator rows respectively (fig. 2) consisted of fixed radial rakes for measuring total pressure and total temperature. Each rake had five measuring tips which were located at area centers of equal annular areas. All pressures were measured with alkyazene or mercury manometers and photographically recorded. Temperatures were measured with iron-constantan and chromel-alumel thermocouples and were recorded by self-balancing potentiometers. Engine speed was measured by a chronometric tachometer and fuel flow with a calibrated rotometer.

PROCEDURE

The inlet-air total temperature and pressure and the static pressure in the test section surrounding the exhaust nozzle were maintained at values corresponding to an altitude of 35,000 feet and a flight Mach number of 0.8. The data were obtained along a steady-state operating line at a fixed value of exhaust-nozzle area. The engine was operated over a range of corrected speeds from approximately 65 to 100 percent of rated speed at three exhaust-nozzle areas for each of four inlet-guide-vane settings. The exhaust-nozzle areas were 97-, 108-, and 119-percent of the rated area and the guide vane settings at the tip were 13°, 20°, 30°, and 43°. A few preliminary data points were also obtained at a 5° guide-vane setting. However, the data indicated that compressor and engine performance decreased at this setting and, consequently, no further data were obtained.

The symbols and the methods of experimental data reduction are given in appendixes A and B, respectively.

OVER-ALL COMPRESSOR PERFORMANCE CHARACTERISTICS

The compressor performance maps are shown in figure 3 as pressure ratio plotted against percent of rated corrected weight flow with efficiency contours superimposed. These maps were determined by interpolation of the data obtained along steady-state engine operating lines for each combination of exhaust-nozzle area and guide-vane setting investigated.

Compressor performance characteristics at open (13°) guide-vane position. - At rated corrected weight flow and with the guide vanes in the design speed or open (13°) position, the compressor produced a total-pressure ratio of about 6.8 at an efficiency of 0.81 (fig. 3(a)). With the guide vanes in the open position, engine acceleration was possible but difficult (ref. 4). Consequently, engine acceleration time was excessive with the guide vanes in the open position. The poor compressor performance in the low and intermediate speed range at the open (13°) guide-vane position is not shown in figure 3(a) because of the limited amount of data obtained at low speeds during this investigation. However, a detailed compressor performance map at the open guide-vane position is presented for another engine of the same model in reference 5. The compressor performance in the low and intermediate speed region, as shown in reference 5, is affected by changes in compressor stall characteristics. At low speeds, the hot-wire-anemometer data presented in reference 5 indicated a complete ring stall of the compressor which was confined to the tip region. As speed was increased, the complete ring-type tip stall abruptly changed to a single rotating stall which was also confined to the outer one-half of the annulus. The single rotating stall decreased in circumferential extent while maintaining an approximately constant radial depth with further increases in speed. When the engine was accelerated to a corrected speed of approximately 85 percent of rated speed, all stall disappeared from the compressor. In the regions of engine operation where the compressor stall characteristics changed, double-valued performance was obtained. The poor engine acceleration characteristics with the guide vanes in the open position could probably be attributed to the poor and unstable nature of the compressor performance due to changes in compressor stall characteristics in the low and intermediate speed range.

Effect of guide-vane adjustment on compressor performance characteristics. - In the high-speed range of engine operation, increasing the guide-vane turning by successively closing the vanes from the 13° to the 43° setting resulted in a decrease in corrected weight flow, pressure ratio, and a slight decrease in efficiency at constant values of corrected engine speed and exhaust-nozzle area as shown in figure 3. The largest decrease in compressor performance occurs at design speed with progressively smaller decreases in performance being obtained as the engine speed is reduced. At design speed and closed exhaust-nozzle position, which is

97 percent of the rated nozzle area, the compressor corrected weight flow decreased to approximately 80 percent of rated weight flow, the pressure ratio decreased from 7.0 to 5.2, and the efficiency was decreased about five points in closing the guide vanes from the 13° to the 43° setting.

The constant corrected-speed lines shown in figure 3 are also affected by guide-vane adjustment. These lines tend to become vertical at lower values of corrected speed with increased guide-vane turning. The fact that only one value of mass flow can be obtained along the vertical constant corrected-speed lines indicates that the first rotor is choked. Consequently, it is apparent that increasing guide vane turning is reducing the compressor weight flow and speed at which flow separation and resultant local sonic Mach numbers are obtained in the first rotor.

Effect of guide-vane adjustment on compressor surge characteristics. - The results of an acceleration investigation of this engine (ref. 4) showed that closing the compressor inlet guide vanes improved the engine acceleration time. The data obtained for the present investigation did not extend into a low enough speed range to evaluate the source of improvement. The effect of inlet-guide-vane adjustment on the compressor surge line at high speeds as determined from transient data is shown in figure 4 as compressor pressure ratio at surge plotted against percent of rated corrected speed. Changing the inlet-guide-vane setting from 13° to 20° had no noticeable effect on the compressor surge pressure ratio in the range of speeds presented. Closing the guide vanes further to the 30° and 43° settings caused compressor surge to occur at a lower pressure ratio at a constant value of corrected speed. Since the maximum flow for a given characteristic curve in the high-speed range decreased with increased guide-vane turning, compressor surge must also occur at a lower value of corrected weight flow (fig. 3). An extrapolation of the characteristic curves of figure 3 to the surge pressure ratios given in figure 4 indicates that the compressor surge line in the high-speed range does not change appreciably with guide-vane adjustment when plotted against corrected weight flow. No surge data were available in the intermediate speed range, but, because of the improvement in engine acceleration characteristics (ref. 4), it is very probable that the shape of the surge line and, hence, pressure-ratio margin available for acceleration in this speed range were improved by guide-vane adjustment.

COMPRESSOR GUIDE-VANE-ADJUSTMENT ANALYSIS

A two-dimensional or mean line analysis of the effect of inlet-guide-vane adjustment shows that closing the guide vanes will reduce the mean value of angle of attack entering the first rotor. Consequently, on the basis of this type of analysis, sufficient guide-vane adjustment would appear to increase the stall-free range of the inlet stages and the attendant deterioration of compressor performance associated with stall in the low and intermediate speed range. Because this type of analysis neglects the effects of changes in the radial distribution of flow, a three-dimensional analysis was made assuming simple radial equilibrium after the guide vanes. The method for determining the velocity distribution downstream of the guide vanes is outlined in reference 6. This method requires a knowledge of the guide-vane turning angle and the weight flow. Since the guide-vane leaving angle was not measured, it was assumed that the design values of guide-vane turning angle existed at the design guide-vane setting. The turning angles at the four guide-vane settings from 13° to 43° were then determined by adjusting the design values of guide-vane turning angle by 0.9 of the change in setting angle. This 0.9 value was assumed to represent the slope of the cascade curve of turning angle against angle of attack. The radial distribution of guide-vane turning angles used for the simple radial equilibrium analysis are presented in figure 5. These turning-angle distributions will give a qualitative picture of the trends which might be expected with guide-vane adjustment. However, the 30° range of angle of attack on the inlet guide vanes considered in this analysis will affect the magnitude of the guide-vane losses as well as the turning angles and thus will affect the magnitudes of the velocities obtained in the analysis.

The radial distribusion of flow entering the first rotor was computed, satisfying the simple radial equilibrium condition at the corrected weight flow at design speed given in figure 3. The computed values of axial velocity, angle of attack, and relative inlet Mach number distributions at the four guide-vane settings are shown in figure 6. Increasing the guide-vane turning reduces the mean value of angle of attack and the inlet Mach number relative to the rotor, indicating unloading of the first rotor and, hence, a decrease in first-stage pressure ratio at design speed. The change in axial-velocity distribution in combination with the change in corrected weight flow at design speed resulted in higher angles of attack in the tip region of the first rotor with increased guide-vane turning (fig. 6). Since the tip region is normally quite critical as to stall, a similar analysis was conducted for the range of speeds investigated in order to obtain an indication of the effect of guide-vane setting angle on the tip angle of attack at speeds lower than design. The resulting tip angles of attack are presented in figure 7 as a function of corrected engine speed for the four guide-vane settings investigated. At all speeds investigated, the tip angle of attack entering the first rotor increased with increased guide-vane turning. Thus, it might appear that the tip blade sections are made more critical as the guide-vane turning angle is increased.

In addition to the angle of attack, the performance as determined by the loss and the angle-of-attack range at low loss of a blade section is a function of the blade loading. Therefore, in order to determine the effect of guide-vane adjustment on the first rotor loading, a simple radial equilibrium analysis was made downstream of the rotor. Carter's rule (ref. 7) for circular-arc mean-camber-line blading was used to determine the rotor-outlet relative flow angles. With these angles known and with simple radial equilibrium and continuity satisfied after the first rotor, the rotor-outlet flow distribution was determined by the method given in reference 6. The first rotor loading as defined by the rotor diffusion factor, a blade-loading parameter presented in reference 8, is shown in figure 8. This parameter indicates that the first rotor loading decreases across the entire blade span with increased guide-vane turning. The lower loading and also the lower values of relative inlet Mach number obtained with increased guide-vane turning will tend to increase the stall-free or efficient operating range of the first rotor. However, the higher tip angles of attack may use up all available range so that no net gain would be obtained in the tip region.

The axial velocity distribution at the outlet of the first rotor is also shown in figure 8 at design speed. The analysis shows that the magnitude and radial distribution of axial velocity at the outlet of the first rotor remain essentially unchanged with guide-vane adjustment except for a slight decrease in the magnitude of velocity at the 43° guide-vane setting. Since the magnitude and distribution of axial velocity are unchanged with guide-vane adjustment, the outlet flow coefficient from the first rotor will remain the same. Therefore, this analysis indicates that the performance of all blade rows downstream of the first rotor should not be affected to any great extent in the 30° range of guide-vane adjustment considered herein. However, the analysis must be qualified in that it merely represents trends because the effect of changes in guide-vane and rotor stall characteristics and attendant losses in addition to possible stage interaction effects associated with guide-vane adjustment are not considered.

In summary, the analysis showed that the change in axial-velocity distribution required to satisfy simple radial equilibrium after the guide vanes resulted in a decrease in angle of attack across all but the tip region of the first rotor with increased guide-vane turning. The decreased mean value of angle of attack and lower relative inlet Mach numbers obtained across the entire blade span resulted in decreased loading and, hence, decreased pressure ratio across the first rotor at design speed. The decrease in rotor pressure ratio compensated for the decrease in compressor corrected air flow with increased guide-vane turning so that the rotor-outlet axial velocity remained about the same both in magnitude and radial distribution. Therefore, the analysis indicated that at design speed the performance of blade rows downstream of the first rotor would not be appreciably changed by the range of guide-vane adjustment considered. The trends shown by the analysis are considered indicative of the effects of guide-vane adjustment; however, the magnitudes will be affected by changes in guide-vane and rotor losses and possible interaction effects, which could not be considered in the analysis.

COMPRESSOR-STAGE GROUP PERFORMANCE CHARACTERISTICS

The compressor interstage instrumentation made it possible to determine the performance of the following stage groups: first stage, second through fourth stages, fifth through seventh stages, eighth through tenth stages, and the eleventh and twelfth stages. The performance characteristics of these stage groups are presented in terms of dimensionless pressure coefficient, temperature coefficient, and adiabatic efficiency plotted against flow coefficient in figures 9 to 14 for the four inlet-guide-vane settings investigated. The dimensionless stage-performance parameters are defined in appendix B.

Performance characteristics of first stage. - The first-stage performance (fig. 9) shows that closing the inlet guide vanes shifts the stage curves toward lower values of pressure coefficient, temperature coefficient, and flow coefficient. This trend is the same as that exhibited by the first stage of the compressor reported in reference 9. The shift in the first-stage curves results from the fact that, in order to obtain the same mean value of angle of attack with increased guide-vane turning, the inlet flow coefficient must decrease. At any given speed, the reduction in the mean axial velocity required to obtain the same mean value of angle of attack will decrease the stage energy addition and, hence, will decrease the stage pressure and temperature coefficients.

The efficiency of the first stage (fig. 9) is abnormally low; having a peak value of approximately 0.67 at all guide-vane settings. The low efficiency of this stage may be attributed partly to the fact that the inlet-guide-vane losses were included in the performance evaluation of the first stage. With the guide vanes in the open position (13°), the previous analysis at design speed indicated a high rotor tip loading, which is indicative of a low tip efficiency as shown in reference 8. With the guide vanes in the closed position (43°), this loading parameter decreased in the tip region (fig. 8). However, the high guide-vane angle of attack at this setting probably causes flow separation and increased guide-vane losses, which will keep the first-stage efficiency low.

The vertical constant corrected speed lines exhibited by the compressor with the guide vanes in the closed position (43°), shown in figure 3(d), can be explained by the performance of the first stage (fig. 9). At the 43° guide-vane setting, all data points except those obtained at the lowest speeds lie on the vertical portion of the first-stage performance curve (fig. 9), thus indicating that the first stage is choked. Consequently, the first stage is operating at a constant value of flow coefficient and, therefore, only one value of compressor corrected air flow can be obtained at each speed. The negative pressure coefficients obtained across the first stage with the guide vanes in the closed (43°) position shown in figure 9 can probably be attributed to increased guide-vane and rotor losses. The increased losses are caused by high positive angles of attack entering the guide vanes and low negative angles of attack, particularly in the hub region entering the first rotor as indicated by the results of the analysis shown in figure 6.

Performance characteristics of stages two through four. - The performance of the second-through-fourth-stage group shown in figure 10 shows only a slight reduction in maximum flow coefficient due to closing the inlet guide vanes. The analysis of guide-vane adjustment at design speed which corresponds to the maximum flow portion of the inlet-stage curves indicated this effect. The analysis showed that the decrease in compressor corrected weight flow was compensated for by decreased loading or pressure ratio across the first rotor with increased guide-vane turning. Therefore, the flow coefficient at the inlet to the second stage is primarily a function of speed and not guide-vane position. The performance curves of the second-through-fourth-stage group (fig. 10) in the high flow-coefficient range (above approximately 0.4) indicates that closing the inlet guide vanes slightly decreases the pressure coefficient and temperature coefficient in addition to the decrease in maximum flow coefficient. However, the magnitude of the decreases in performance of this stage group in the designated flow range is slight in comparison with the changes in performance of the first stage.

In the low flow-coefficient range (below approximately 0.4), the pressure coefficient and adiabatic efficiency characteristics of the second-through-fourth-stage group (fig. 10) improve as the inlet guide vanes are closed. With the guide vanes in the open position (13°) there is an abrupt drop in pressure coefficient as indicated by the broken line in figure 10 which is indicative of an abrupt type of stall in this stage group. The data obtained in the low-speed range for the other three guide-vane positions do not indicate a similar stall characteristic. The change from the abrupt type of stall characteristic at the 13° guide-vane setting to a more gradual decrease in performance with increased guide-vane turning, as shown in figure 10, may be due to changes in stage interaction effects or to a change in radial distribution of angle of attack entering the first rotor as indicated in the analysis. The change in radial distribution of angle of attack shown in figure 6 indicates that the tip blade sections may be more critical as to stall with increased guide-vane turning thus causing stall to be concentrated in the tip region. The effect of a confined tip stall on the performance of the inlet stages with the guide vanes in the closed position would be less severe than the half-span stall which exists at the open guide-vane position (ref. 5).

Performance characteristics of stages one through four along a steady-state engine operating line. - The speed and flow range where stall is encountered in the second-through-fourth-stage group at the open (13°) guide-vane position corresponds to the region of operation where the compressor performance and engine acceleration characteristics are poor. In order to determine the effects of stall in the inlet stages at the open (13°) guide-vane position, the variation of stage performance along a steady-state operating line is presented in figure 11. The interstage data with measurements after the first stage were very limited in quantity in the low and intermediate speed range. Therefore, available data obtained on the same engine with measurements after the fourth stage were used to calculate the performance of stages one through four. The performance of the first four stages is plotted against percent of rated corrected engine speed at rated exhaust-nozzle area in figure 11 with the guide vanes in the open (13°) and closed (43°) positions. It is evident from figure 11 that the performance of the first four stages changes abruptly in the corrected speed range between approximately 65- and 85-percent of design at the 13° guide-vane setting. A hysteresis loop is indicated in figure 11; the steady-state data on the right side of the loop were obtained on an acceleration, and the data, on the left side of the loop on a deceleration of the engine. This hysteresis loop in the performance of stages one through four is probably the cause of the double-valued over-all compressor performance obtained in the intermediate speed range and discussed in reference 5. In this speed range, over one-third of the compressor work input is accomplished in the first four stages. Therefore, the compressor performance at the 13° guide-vane setting is penalized severely by the abrupt stall of the second-through-fourth-stage group. With the guide vanes in the closed position (43°), the performance of the first four stages varies uniformly along the steady-state operating line and no acceleration problems are encountered. The pressure coefficient at the closed guide-vane position does not attain a peak value in the range of speeds investigated for either the first stage or second-through-fourth-stage group as shown in figures 9 and 10. Therefore, stall in the inlet stages will occur at lower than approximately 65 percent of rated corrected speed with the guide vanes in the closed (43°) position. At the 20° and 30° guide-vane settings, the flattening out of the pressure coefficient curves in the low flow-coefficient range shown in figures 9 and 10 indicates that stall will be encountered on acceleration of the engine at these guide-vane positions. Because of changes in stage interaction effects and the fact that stall would occur at a lower speed and, hence, lower pressure ratio level, the effects of stall on compressor and engine performance at the 20° and 30° guide-vane settings would probably be less severe than at the 13° guide-vane setting.

Performance characteristics of stages five through twelve. - The performance of the remaining stage groups shown in figures 12 to 14 indicate that guide-vane adjustment has no effect on the performance of stages five through twelve. The flow coefficient range of the various stage groups decreased to a minimum value entering the eighth-through-tenth-stage group. This stage group operated essentially at a single point at all speeds, flows, and guide-vane positions investigated as shown in figure 13. The performance of the eleventh-and-twelfth-stage group (fig. 14) is typical of the performance of exit stages in multistage axial-flow compressors. The design passage taper in combination with the low pressure ratios of the inlet and middle stage at part speed causes high axial velocities and very low values of angle of attack in the exit stages thus producing negative values of pressure coefficient as shown in figure 14. Increasing the speed, rapidly decreases the axial velocity in the exit stages thus increasing the angle of attack and, hence, increasing the pressure coefficient of the last-stage group.

Summarization of effects of guide-vane adjustment on stage performance. - The performance characteristics of the individual stage groups showed that guide-vane adjustment primarily affects the performance of the first stage of the compressor. Closing the inlet guide vanes shifted the first-stage performance curves toward lower values of flow coefficient, pressure coefficient, and temperature coefficient. With the guide vanes in the open (13°) position, the performance of the second-through-fourth-stage group indicated an abrupt stall in the region of compressor operation where poor engine acceleration characteristics were encountered. Closing the inlet guide vanes to the 43° setting eliminated the abrupt stall characteristic of this stage group in the speed range investigated and improved the acceleration characteristics of the engine. The performance characteristics of stages five through twelve are unaffected by guide-vane adjustment.

OVER-ALL ENGINE PERFORMANCE CHARACTERISTICS

Over-all engine performance maps are presented in figure 15 for the four inlet-guide-vane positions investigated. The performance at the rated nozzle area presented in figure 16 was cross-plotted from figure 15. The experimental pressures and temperatures deviated slightly from the 35,000-foot altitude values. The data were corrected for these deviations.

An increase in inlet-guide-vane turning at constant engine speed and exhaust-nozzle area (fig. 15) decreased net thrust and exhaust-gas temperature, while specific fuel consumption increased. The exception to this trend was the speed range below which the inlet stages of the compressor were stalled with the guide vanes in the open (13°) position.

The fact that acceleration was possible at the 20° and 30° inlet-guide-vane settings might seem to indicate that closing the inlet guide vanes to 43° is excessive for avoiding stall in the compressor. Data from reference 4, an acceleration investigation on the same engine, however, show that stall of the inlet stages has merely been shifted to lower speeds and not eliminated by closing the inlet guide vanes. The use of increased guide-vane turning also reduces the engine acceleration time, as shown in reference 4. The data of the subject report did not extend into a low enough speed range to trace the stall characteristics of the inlet stages of the compressor as the inlet guide vanes were closed.

At high engine speeds, the best engine performance was obtained with the guide vanes in the open (13°) position. In order to determine if any performance benefits could be obtained by opening the guide vanes further, a few preliminary data points were obtained at a 5° guide-vane setting. The engine performance decreased when the guide vanes were opened from 13° to 5°, indicating that the 13° setting was about optimum for the high engine speeds.

As shown in figure 16, minimum specific fuel consumption at high thrust levels is obtained with the inlet guide vanes in the open (13°) position. At lower thrust levels, the minimum specific fuel consumption is obtained at the 20° inlet-guide-vane setting. Although steady-state operation at low speeds would probably be limited to "holding" or "loitering", lower specific fuel consumption could be obtained by operation at a 20° guide-vane setting instead of operating the engine with the guide vanes in the closed (43°) or acceleration position.

Variable-position inlet guide vanes could also be used for thrust modulation in a manner similar to a variable-area exhaust nozzle. Closing the inlet guide vanes at rated speed reduced the thrust 46 percent. A similar thrust reduction at the open (13°) guide-vane position would require a 15-percent decrease in engine speed. Although the magnitude of thrust modulation would be different at other flight conditions, there are situations such as landing where a quick thrust response is desirable without the time lag associated with engine speed changes.

SUMMARY OF RESULTS

The results of an investigation to determine the effect of variable-position compressor inlet guide vanes on the compressor, compressor stage, and engine performance may be summarized as follows:

1. Increasing the compressor inlet-guide-vane turning decreased the compressor corrected weight flow, and pressure ratio, and at high speeds slightly decreased the efficiency of this compressor along a steady-state engine operating line.

2. Compressor surge occurred at a lower value of pressure ratio and corrected weight flow with increased guide-vane turning at a constant value of corrected engine speed.

3. Guide-vane adjustment primarily affected the performance of the first stage for the range of setting angles studied in this investigation. Increasing the inlet-guide-vane turning shifted the first-stage performance curves toward lower values of flow coefficient, pressure coefficient, and temperature coefficient.

4. With the inlet guide vanes in the open (13°) position, the performance of the second-through-fourth-stage group indicated an abrupt stall in the region of compressor operation where poor engine acceleration characteristics were encountered. Closing the inlet-guide vanes to the acceleration position (43°) eliminated the abrupt stall characteristic of this stage group and improved the acceleration characteristics of the engine.

5. Increasing the compressor inlet-guide-vane turning at constant corrected engine speed and exhaust-nozzle area decreased net thrust and exhaust-gas temperature while specific fuel consumption was increased in the high speed range of operation.

6. A thrust reduction of 46 percent was accomplished at rated engine speed by closing the guide vanes from the 13° to the 43° setting. This same thrust reduction would require a 15 percent decrease in engine speed with the guide vanes in the open (13°) position.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 15, 1954.

APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	annulus area, sq ft
c_p	specific heat at constant pressure, Btu/(lb)(°F)
D	rotor diffusion factor
d_t	tip diameter, in.
F	thrust, lb
g	acceleration due to gravity, 32.17 ft/sec^2
J	mechanical equivalent of heat, 778.26 ft-lb/Btu
M'	relative Mach number
N	engine speed, rpm
n	number of stages
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
R	gas constant, 53.35 ft-lb/(lb)(°R)
T	total temperature, °R
U_m	mean wheel speed, ft/sec
V	velocity, ft/sec
W_a	air weight flow, lb/sec
W_f	fuel weight flow, lb/hr
W_g	gas weight flow, lb/sec
Y	pressure-ratio function

z radius ratio, ratio of any radius to tip radius

α angle of attack, deg

γ ratio of specific heats

$\Delta\beta$ turning angle, deg

δ ratio of inlet total pressure to NACA standard static sea-level pressure of 2116 lb/sq ft

η adiabatic efficiency

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

ρ density, $(lb)(sec^2)/ft^4$

φ flow coefficient

ψ_p pressure coefficient

ψ_t temperature coefficient

Subscripts:

c compressor

e exit

h hub

i inlet

ii inlet of preceding stage

j jet

n net

r rated

s standard

x axial

0 flight condition or free stream

APPENDIX B

METHOD OF EXPERIMENTAL DATA REDUCTION

Compressor performance. - The over-all compressor performance was determined from the arithmetically averaged values of measured total pressure and total temperature obtained from measurements at stations 1 and 3 as follows:

Air weight flow:

$$W_a = p_1 A_1 \sqrt{\frac{2\gamma g}{(\gamma - 1)\ RT_1} \left(\frac{P_1}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \left[\left(\frac{P_1}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{B1}$$

Adiabatic temperature-rise efficiency:

$$\eta_c = \frac{T_1\left[\left(\frac{P_3}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{T_3 - T_1} \tag{B2}$$

Stage performance. - The performance of the individual stage groups was determined in terms of dimensionless flow coefficient φ, pressure coefficient ψ_p, temperature coefficient ψ_t, and adiabatic efficiency η. These parameters were calculated from arithmetic radial averages of the total pressures and temperatures obtained from interstage rakes in the form of pressure and temperature ratios across each stage group. To facilitate the calculation procedure, the dimensionless stage performance parameters were defined in terms of corrected weight flow and corrected speed in addition to the pressure and temperature ratios as follows:

Flow coefficient:

$$\varphi = \frac{V_x}{U_m} = \frac{W_a\sqrt{\theta}/\delta}{U_m/\sqrt{\theta}}\ \frac{1}{(\rho_s\ g)A} \tag{B3}$$

Since the annulus area A and mean wheel speed U_m can be defined in terms of the compressor physical dimensions and rotative speed, the equation reduced to

$$\varphi = 1.098\times10^6\left[\frac{1}{(1 + z_h^2)(1 - z_h)\ d_t^3}\right]\frac{W_a\sqrt{\theta}/\delta}{N/\sqrt{\theta}} \tag{B4}$$

Pressure coefficient (per stage):

$$\psi_p = \frac{gJc_p\ T_s\left[\left(\frac{P_e}{P_i}\right)^{\frac{\gamma-1}{\gamma}} - 1.0\right]}{n(U_m/\sqrt{\theta})^2} \tag{B5}$$

which upon substituting for U_m and letting $Y = (P_e/P_i)^{\frac{\gamma-1}{\gamma}} - 1.0$ reduces to

$$\psi_p = 6.545\times10^{11}\left[\frac{1}{(1 + z_h)^2\ d_t^2 n}\right]\frac{Y}{(N/\sqrt{\theta})^2} \tag{B6}$$

Adiabatic efficiency:

$$\eta = \frac{Y}{\frac{T_e}{T_i} - 1.0} \tag{B7}$$

Temperature coefficient:

$$\psi_t = \frac{\psi_p}{\eta} \tag{B8}$$

The bracketed terms in the definitions of the flow and pressure coefficients (eqs. (B4) and (B6), respectively) are constants at the entrance to a stage for a given compressor and, consequently, it is only necessary to know the values of corrected weight flow and corrected speed at the inlet to the stage or outlet of the preceding stage in order to calculate the desired parameters. These corrected values can be calculated from the measured total-pressure and -temperature ratios as follows:

$$\frac{W_a\sqrt{\theta}/\delta}{N\sqrt{\theta}} = \left(\frac{W_a\sqrt{\theta}/\delta}{N\sqrt{\theta}}\right)_{ii}\left(\frac{T_i/T_e}{P_i/P_e}\right) \tag{B9}$$

and

$$\left(\frac{N}{\sqrt{\theta}}\right)^2 = \left(\frac{N}{\sqrt{\theta}}\right)_{ii}^2\left(\frac{1}{T_i/T_e}\right) \tag{B10}$$

Engine performance. - The engine performance data were calculated as follows:

Gas weight flow:

$$W_g = W_a + \frac{W_f}{3600} \tag{B11}$$

Net thrust:

$$F_n = F_j - \frac{W_a}{g} V_0 \tag{B12}$$

where

$$V_0 = \sqrt{\frac{2\gamma g R T_1'}{\gamma - 1}\left[1 - \left(\frac{p_0}{P_1'}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{B13}$$

and

$$F_j = B + \frac{W_a V_1'}{g} + A_1' (p_1' - p_0) + D \tag{B14}$$

where B is the thrust scale reading and D is the external drag of the installation. The subscript notation 1' is used to designate a measuring station just upstream of the compressor bullet-nose shown on figure 2.

Specific fuel consumption:

$$sfc = \frac{W_f}{F_n} \tag{B15}$$

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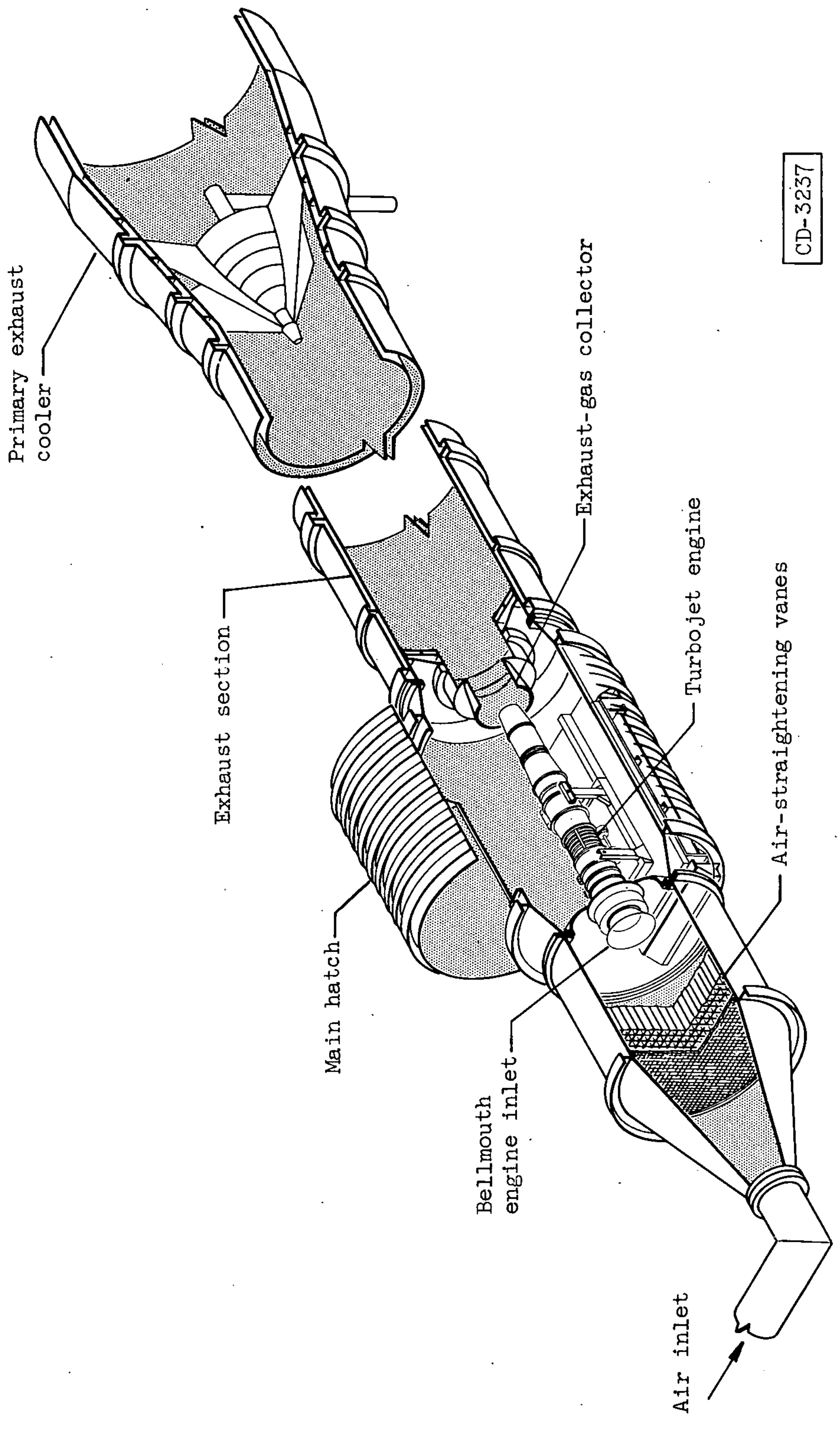
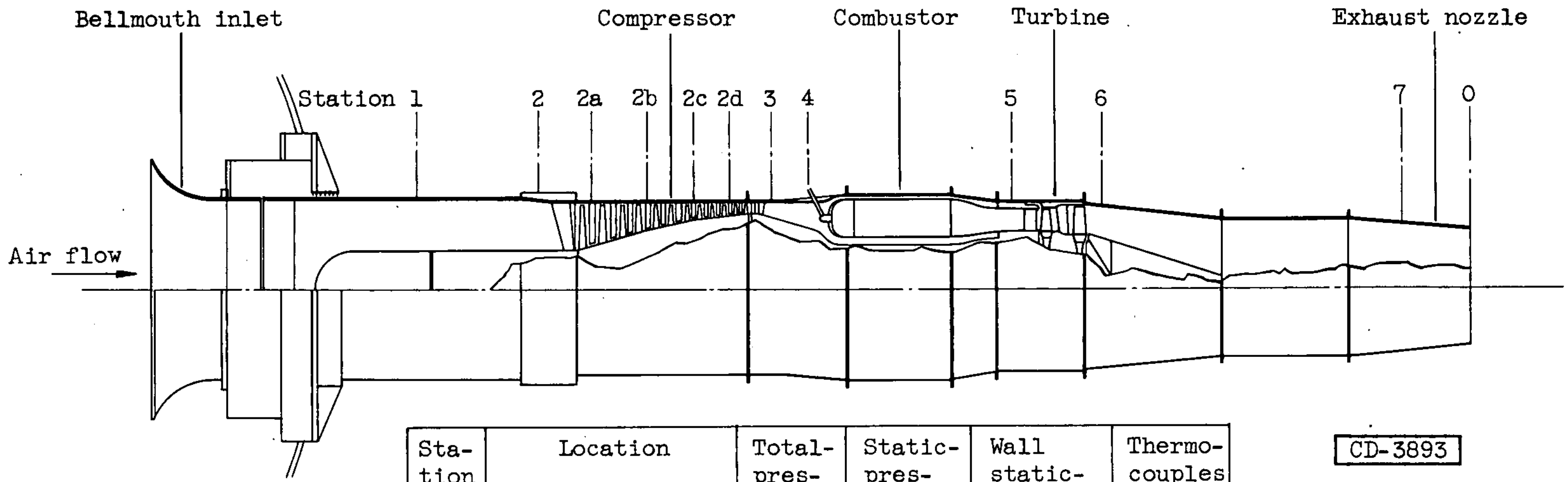
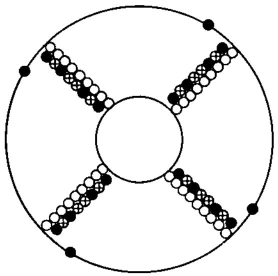


Figure 1. - Schematic diagram of altitude test chamber with engine installed in test section.



Station	Location	Total-pressure tubes	Static-pressure tubes	Wall static-pressure orifices	Thermocouples
0	Tail-pipe region	0	4	0	0
1	Engine inlet	36	16	4	16
2	Compressor inlet	9	0	3	0
2a	1st stator	5	0	0	5
2b	4th stator	5	0	0	5
2c	7th stator	5	0	0	5
2d	10th stator	5	0	0	5
3	Compressor outlet	20	4	5	6
4	Combustor inlet	5	0	0	0
5	Turbine inlet	9	0	0	0
6	Turbine outlet	24	0	8	20
7	Exhaust nozzle	28	16	4	20



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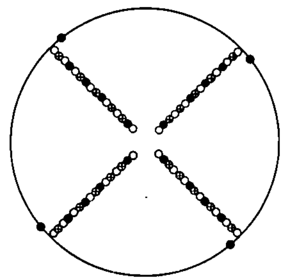
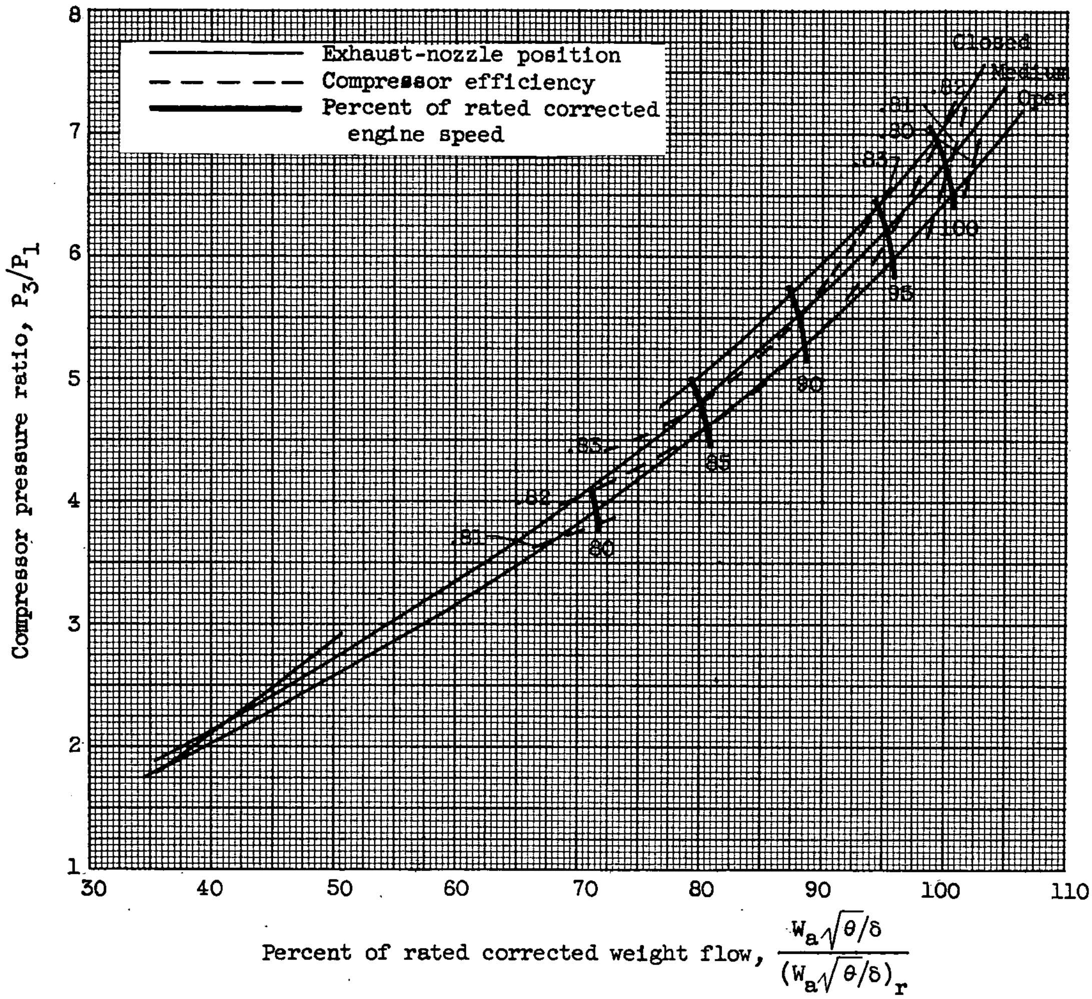
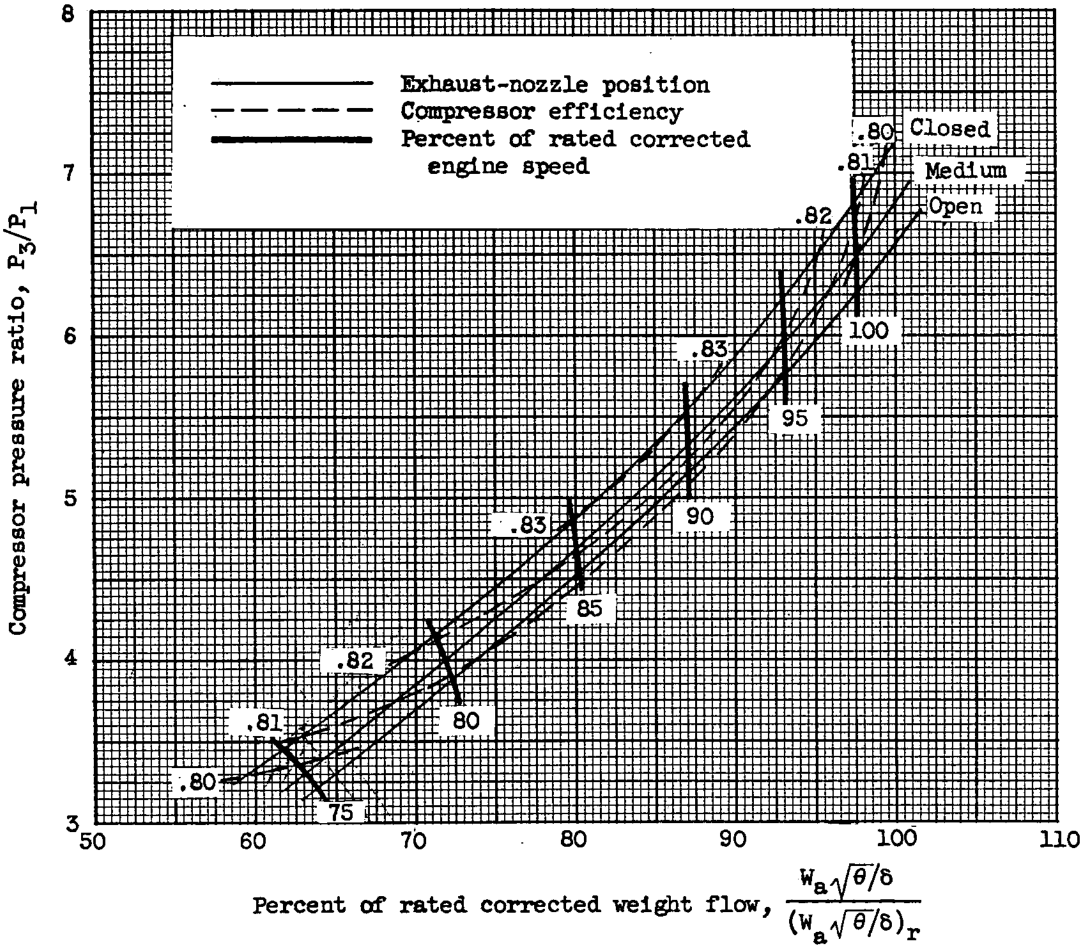


Figure 2. - Cross-sectional view of turbojet engine installation showing instrumentation stations.



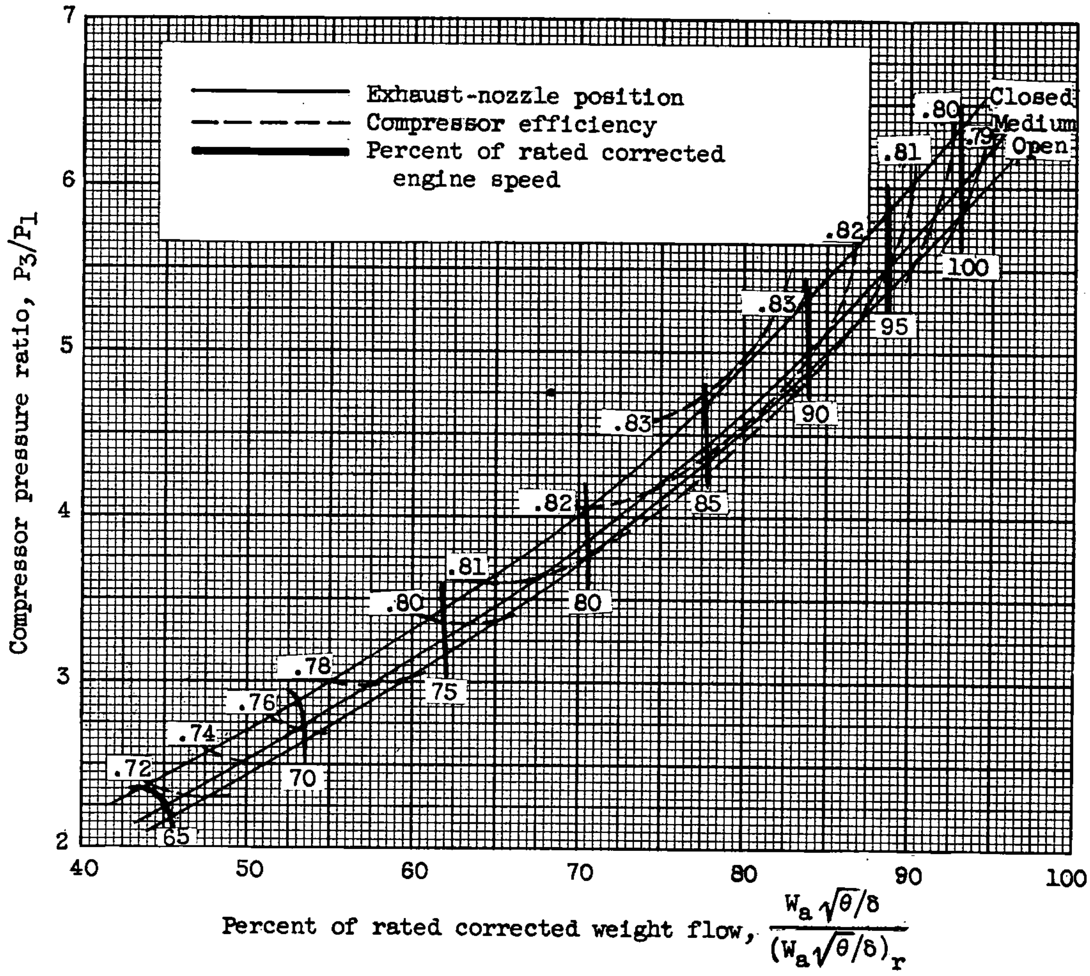
(a) Inlet-guide-vane setting, 13° (open).

Figure 3. - Compressor performance map.



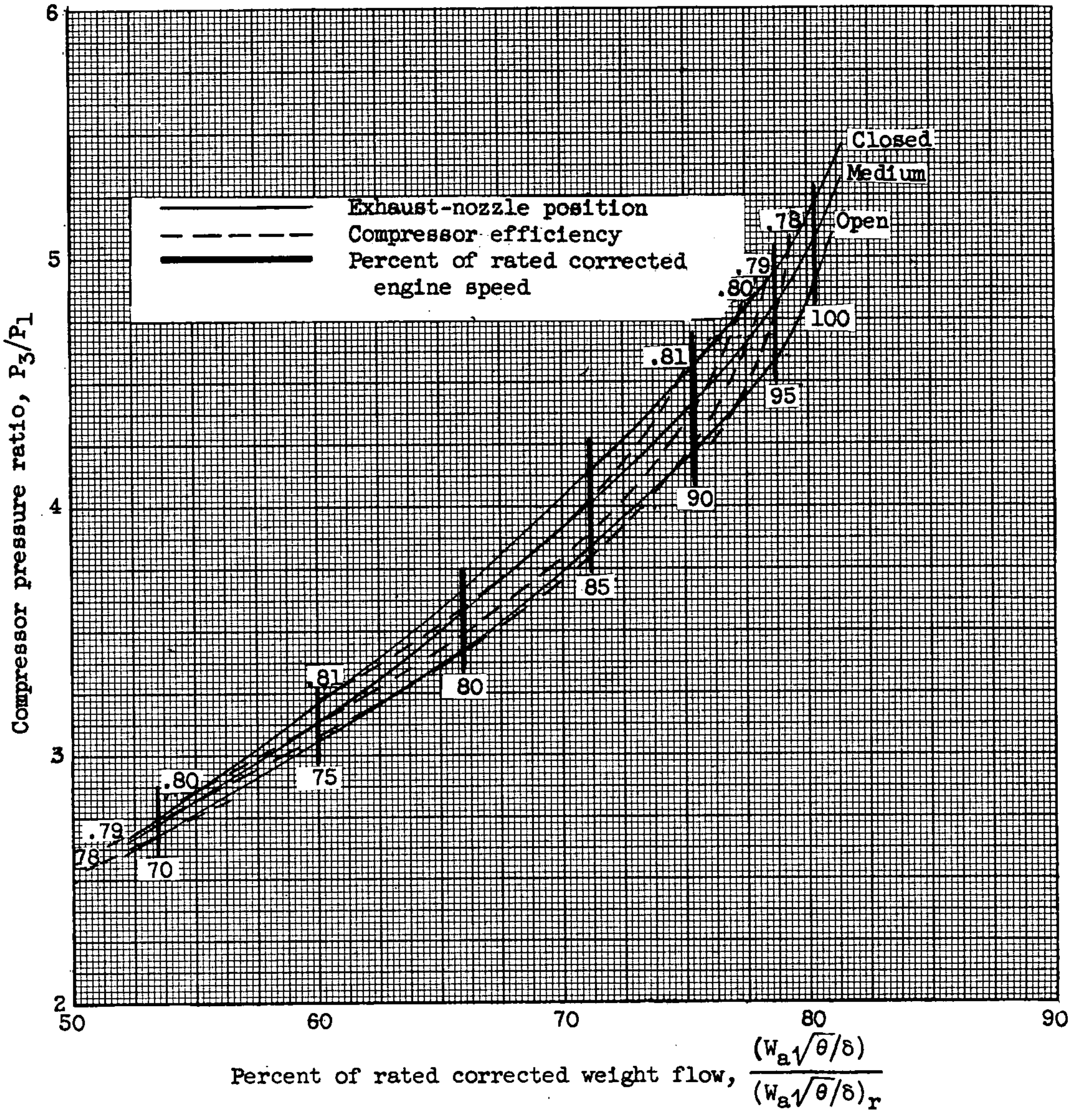
(b) Inlet-guide-vane setting, 20°

Figure 3. - Continued. Compressor performance map.



(c) Inlet-guide-vane setting, 30°.

Figure 3. - Continued. Compressor performance map.



(d) Inlet-guide-vane setting, 43° (closed).

Figure 3. - Concluded. Compressor performance map.

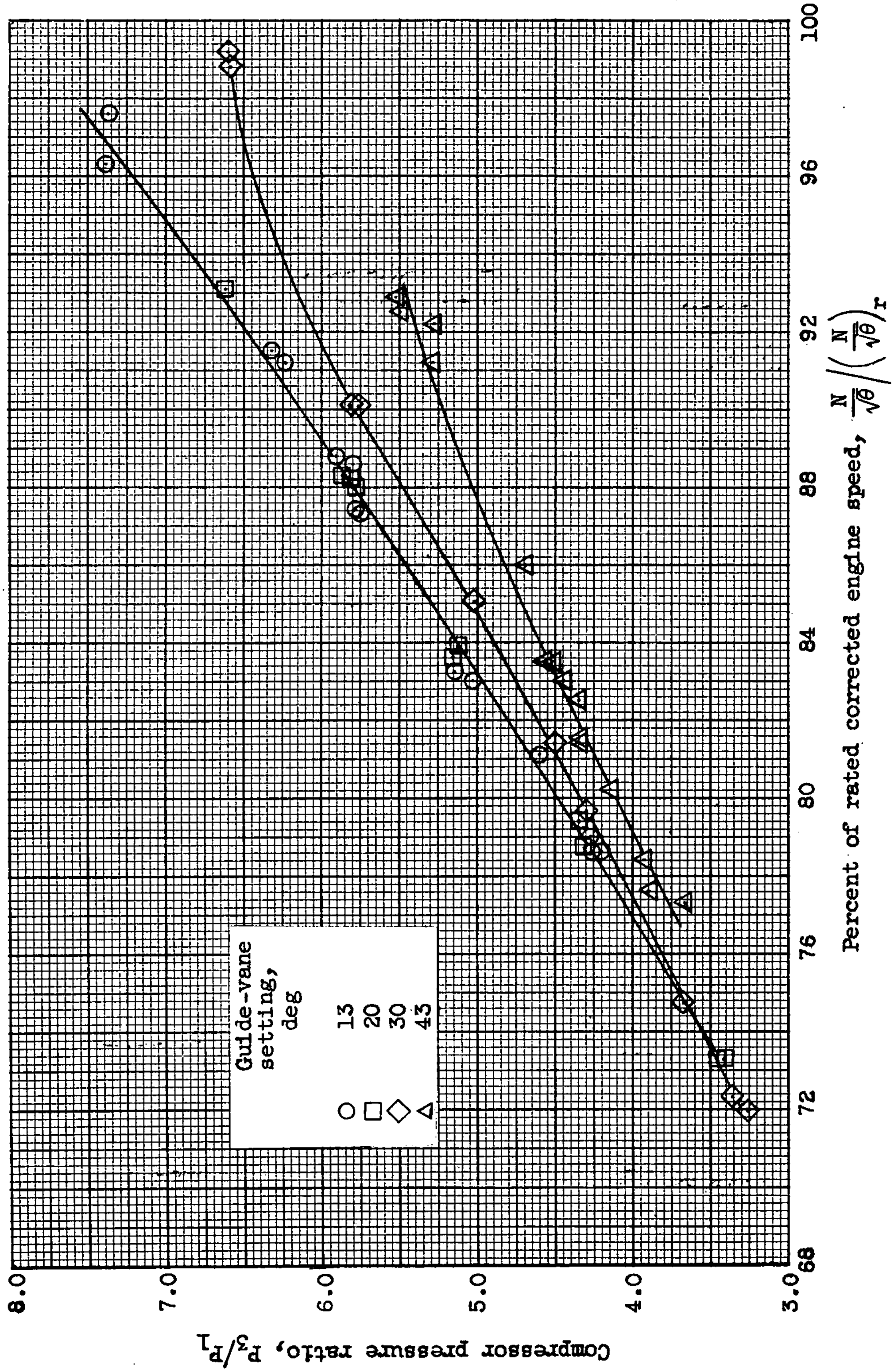


Figure 4. - Effect of inlet-guide-vane setting on compressor surge.

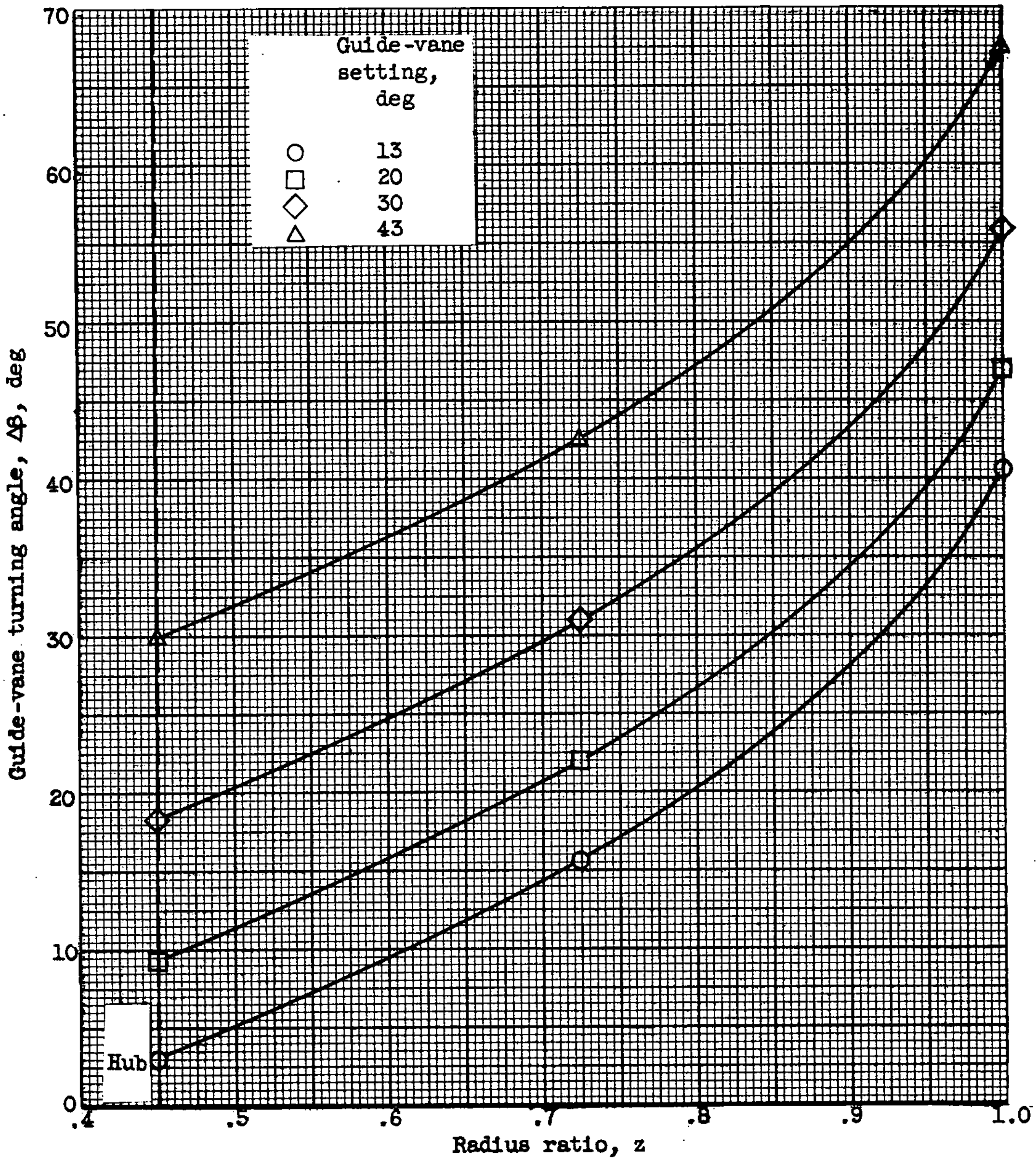


Figure 5. - Radial distribution of guide-vane turning angle.

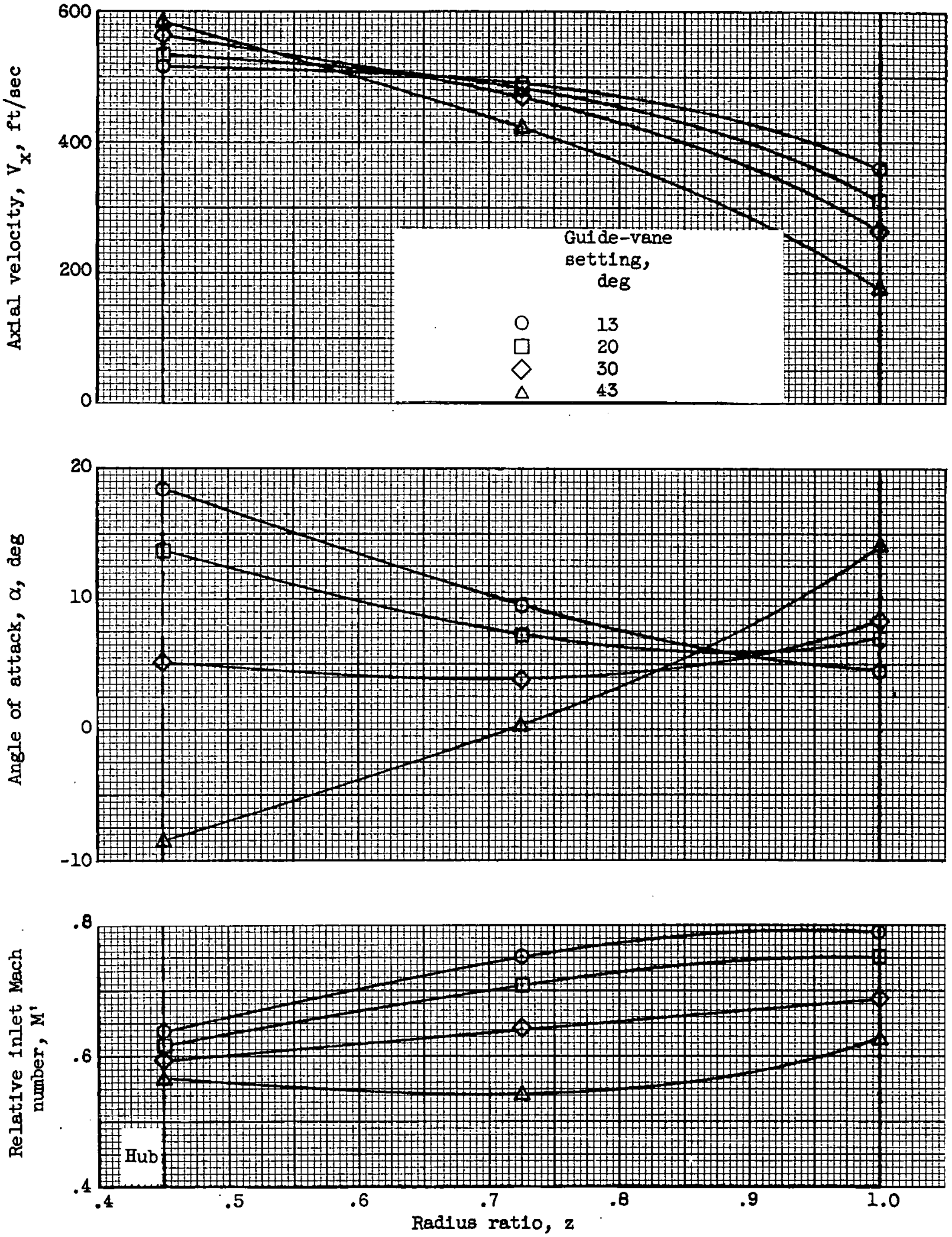


Figure 6. - Radial distribution of flow entering first rotor at design speed.

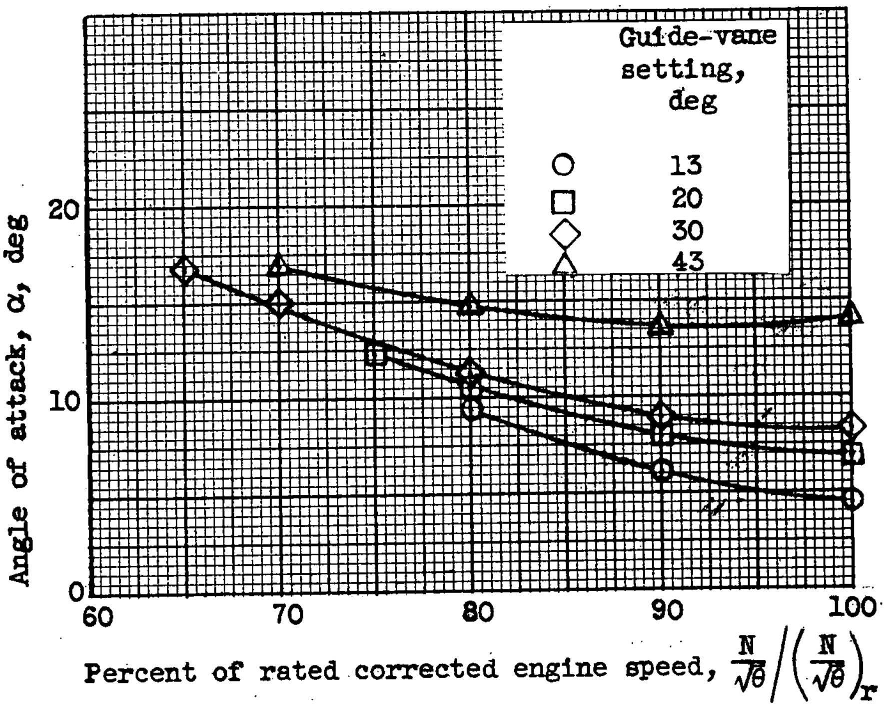


Figure 7. - Variation of angle of attack at tip of first rotor with speed.

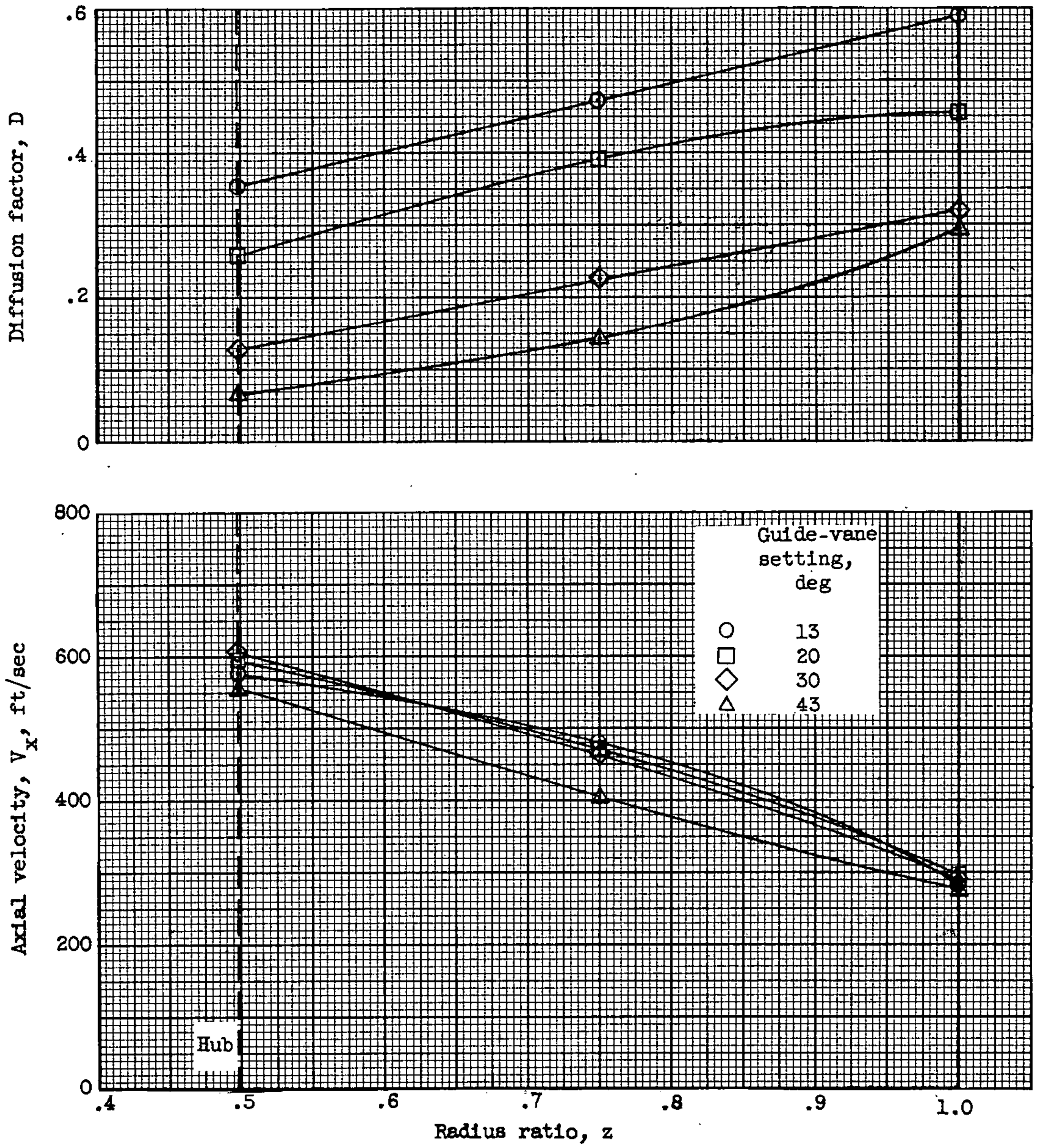


Figure 8. - Radial variation of diffusion factor and axial velocity after first rotor at design speed.

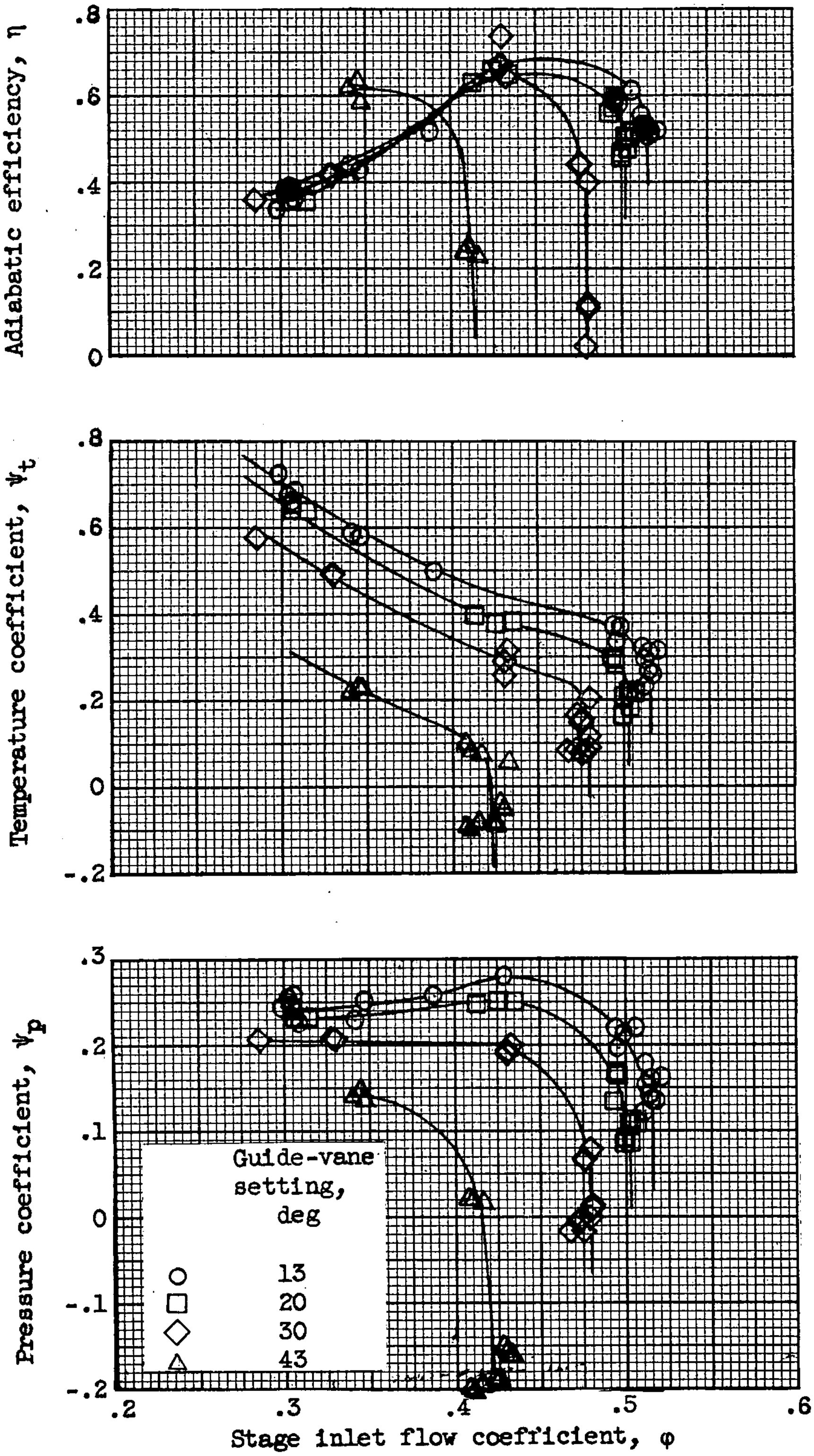


Figure 9. - First-stage performance.

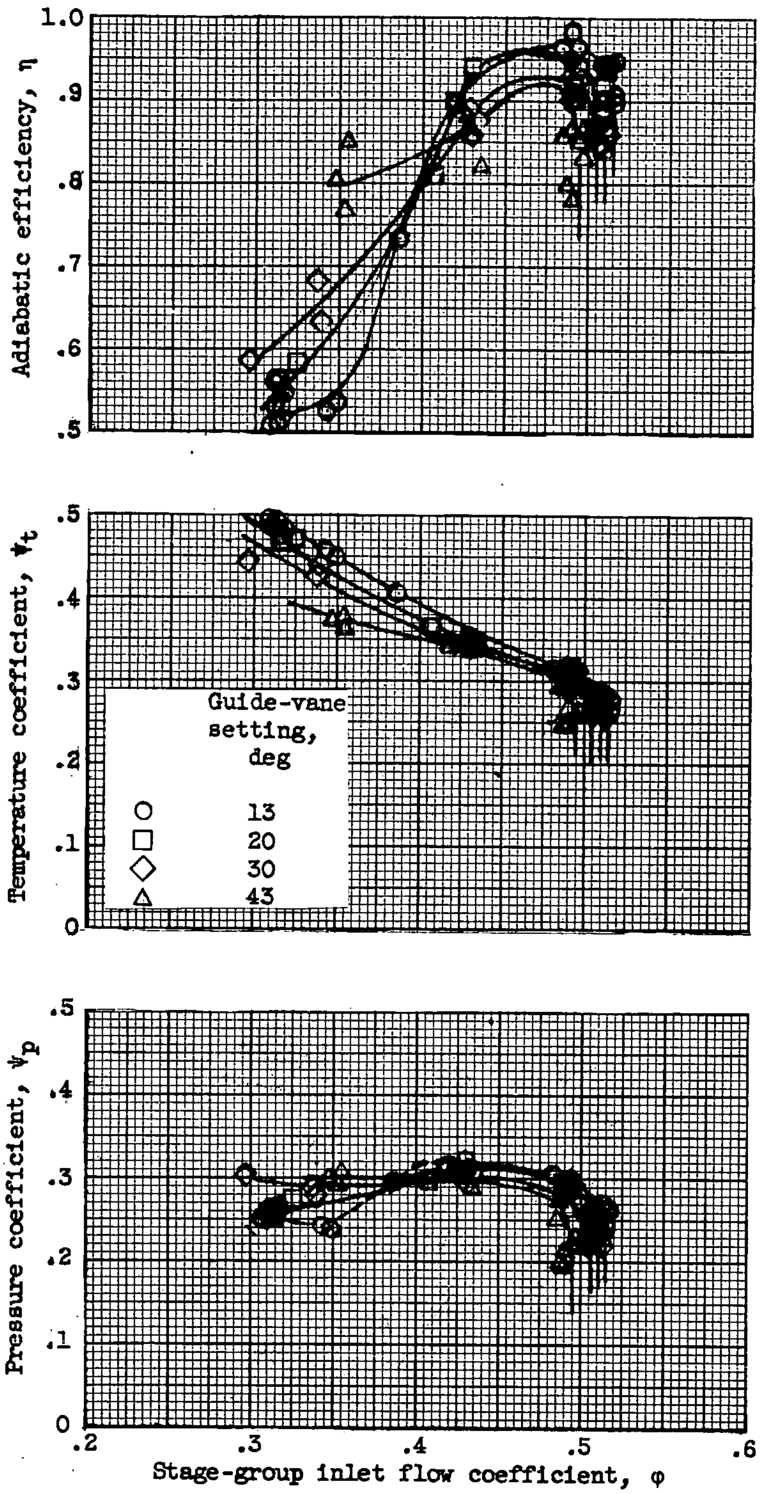


Figure 10. - Second-through-fourth-stage performance.

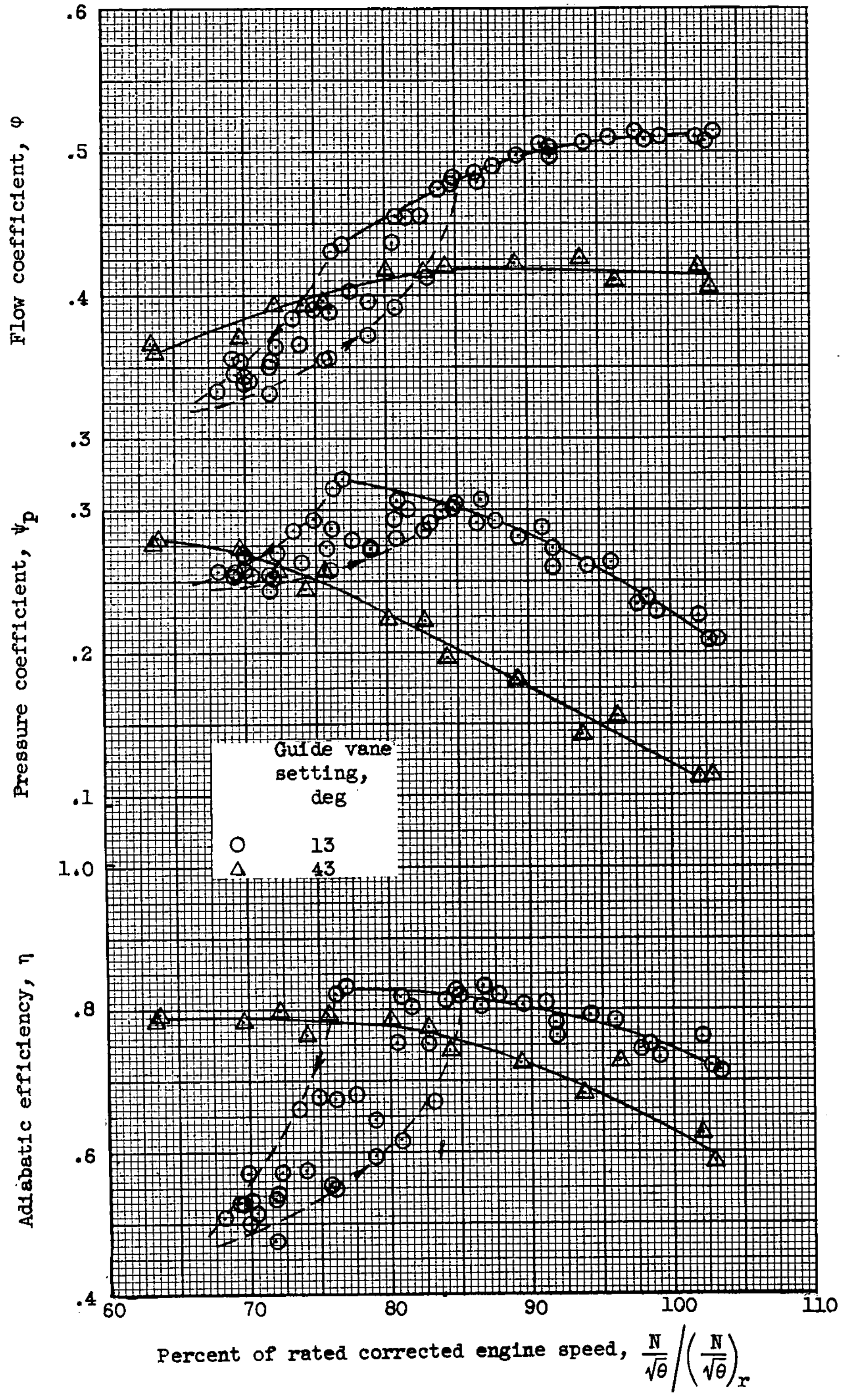


Figure 11. - Performance of first four stages with rated exhaust-nozzle area.

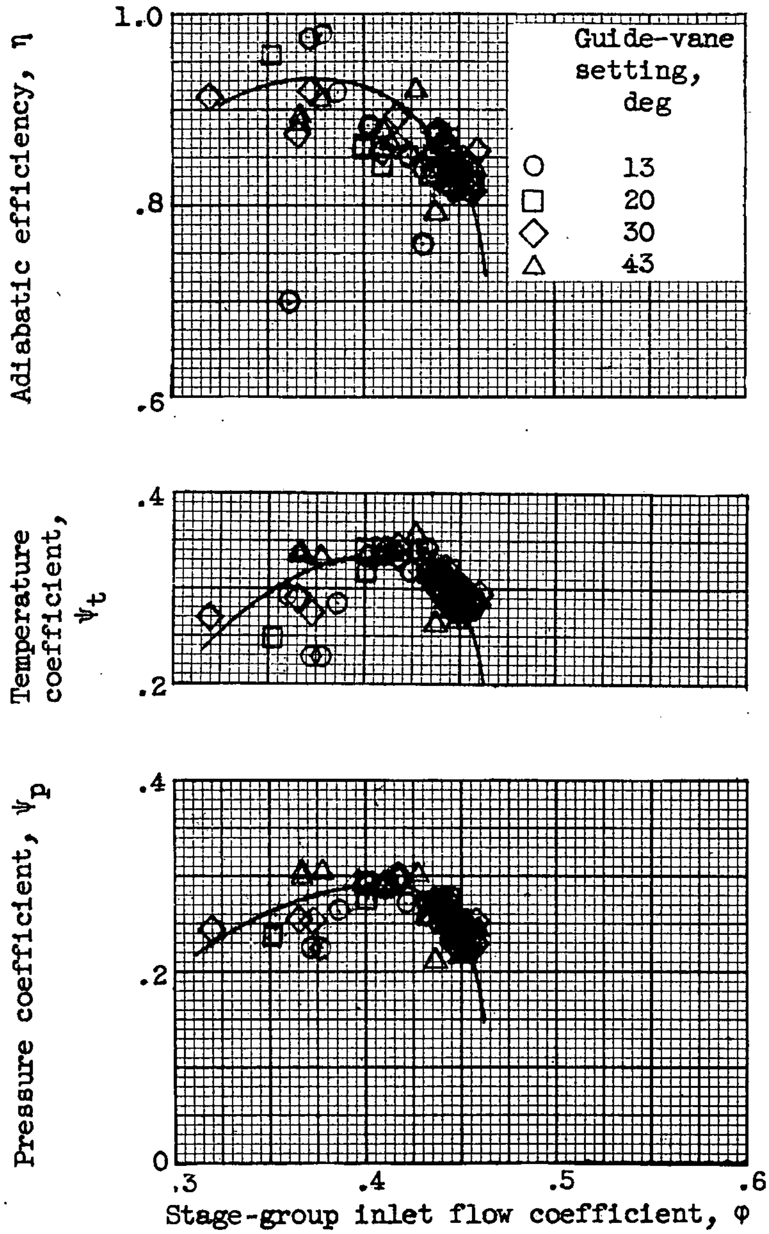


Figure 12. - Fifth-through-seventh-stage performance.

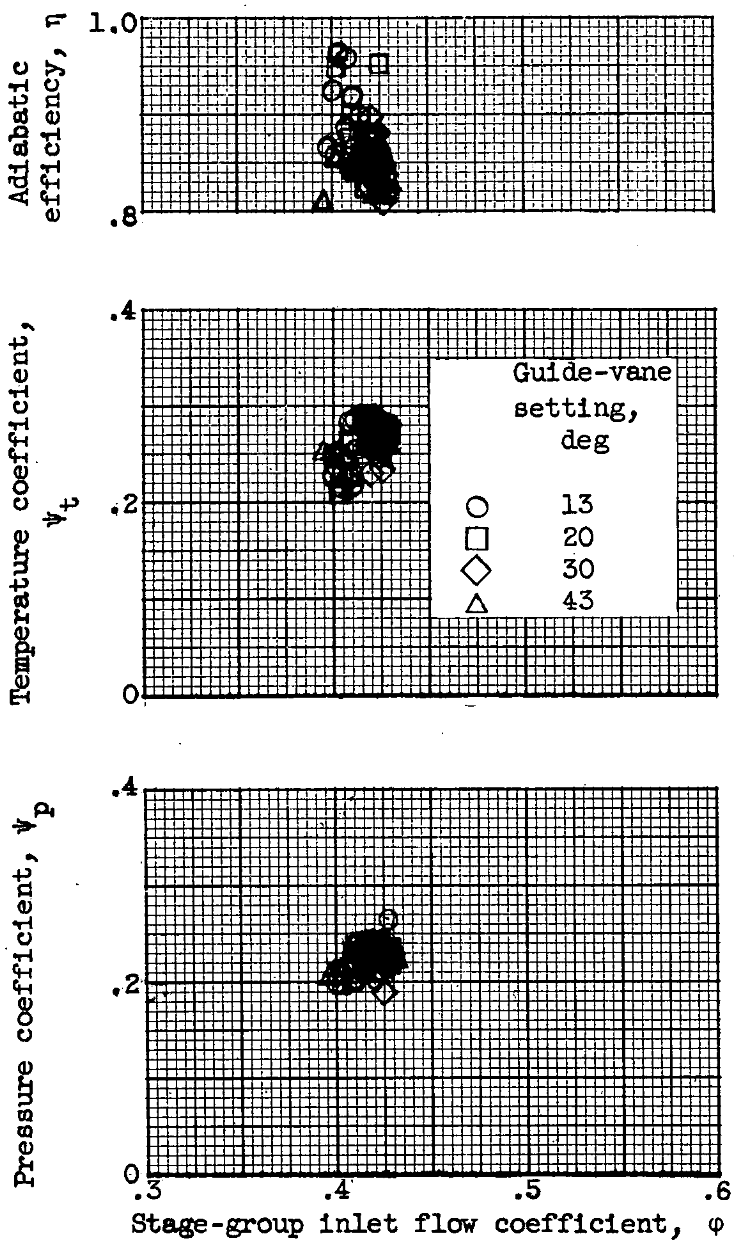


Figure 13. - Eighth-through-tenth-stage performance.

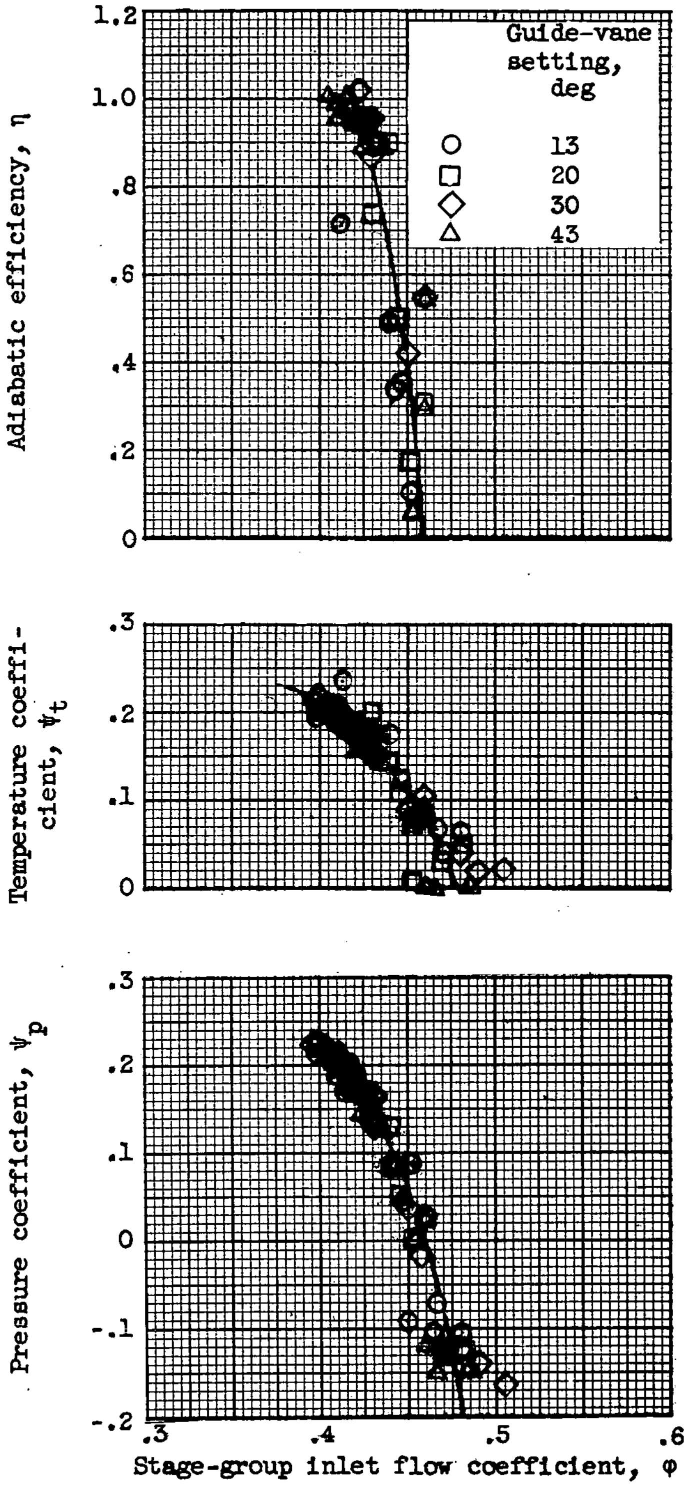
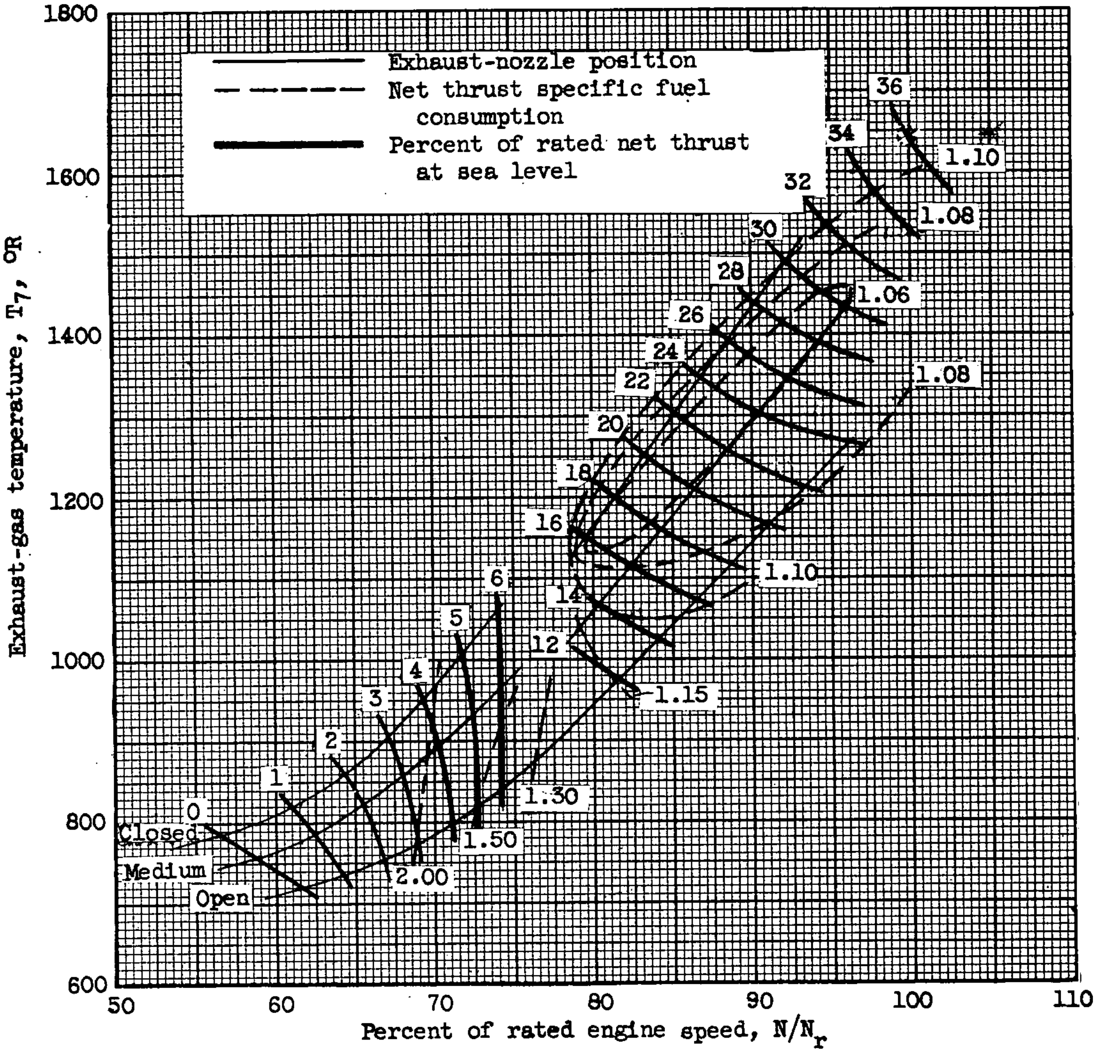
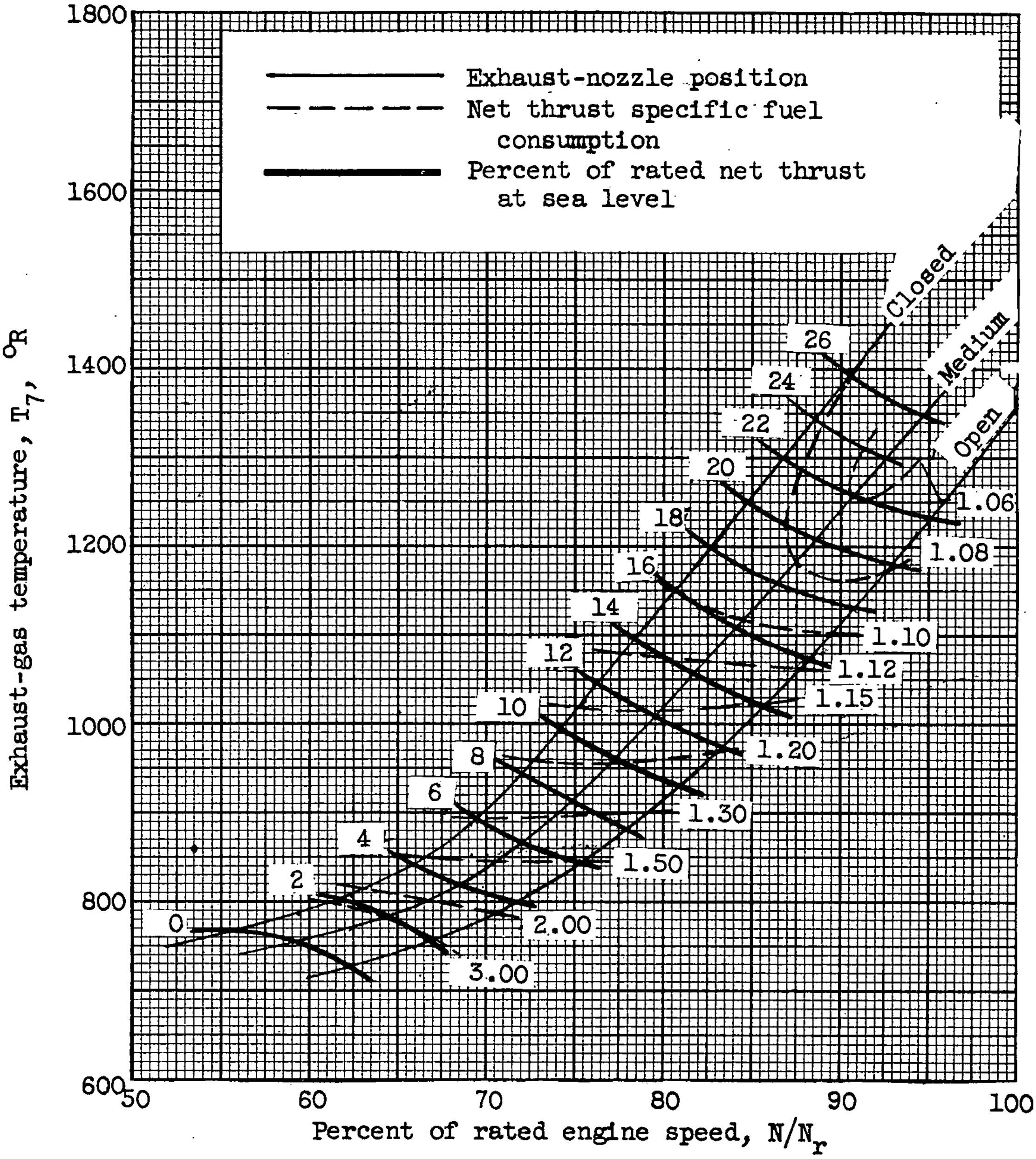


Figure 14. - Eleventh- and twelfth-stage performance.



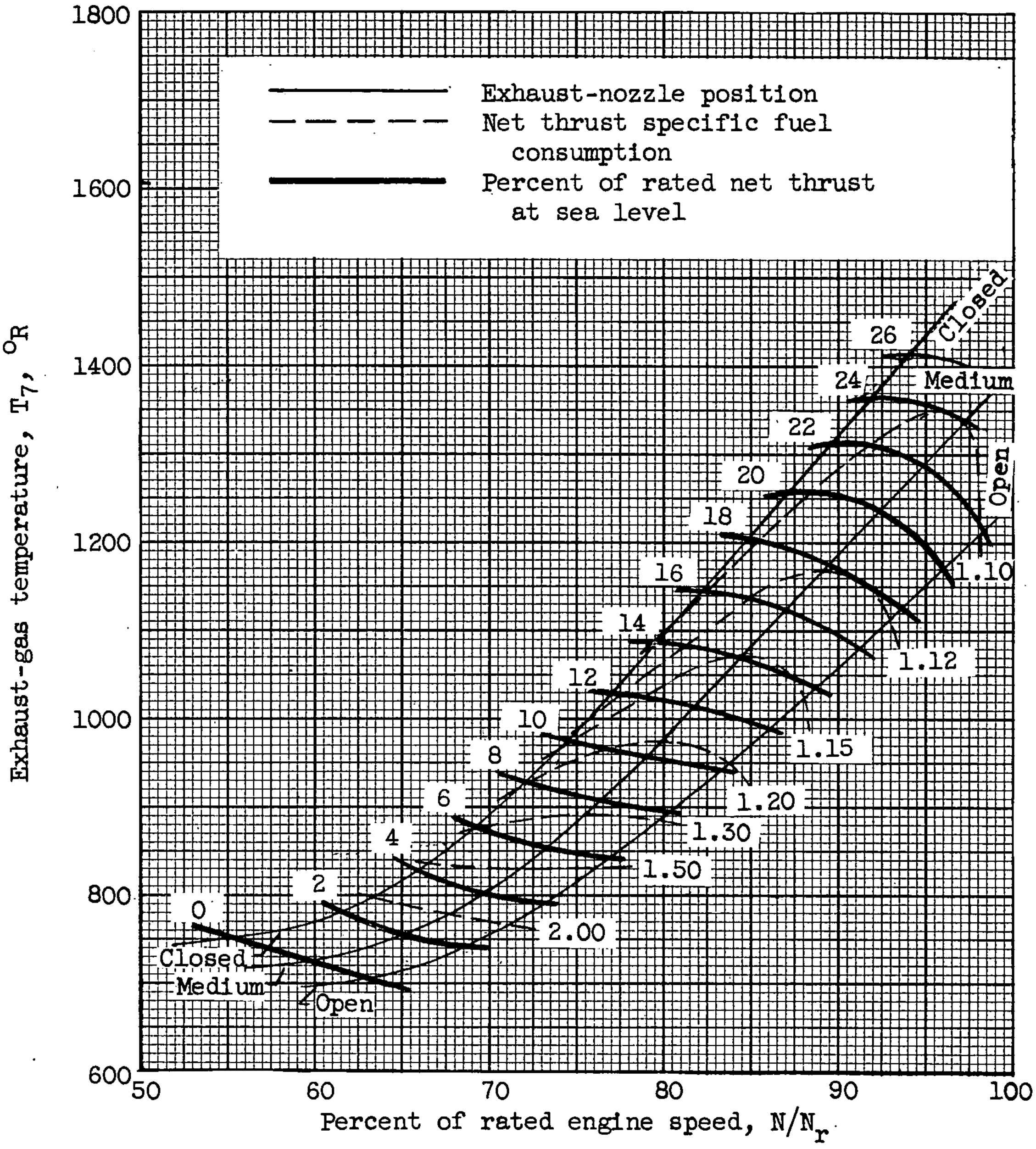
(a) Inlet-guide-vane setting, 13° (open).

Figure 15. - Engine performance maps at altitude of 35,000 feet and flight Mach number of 0.8.



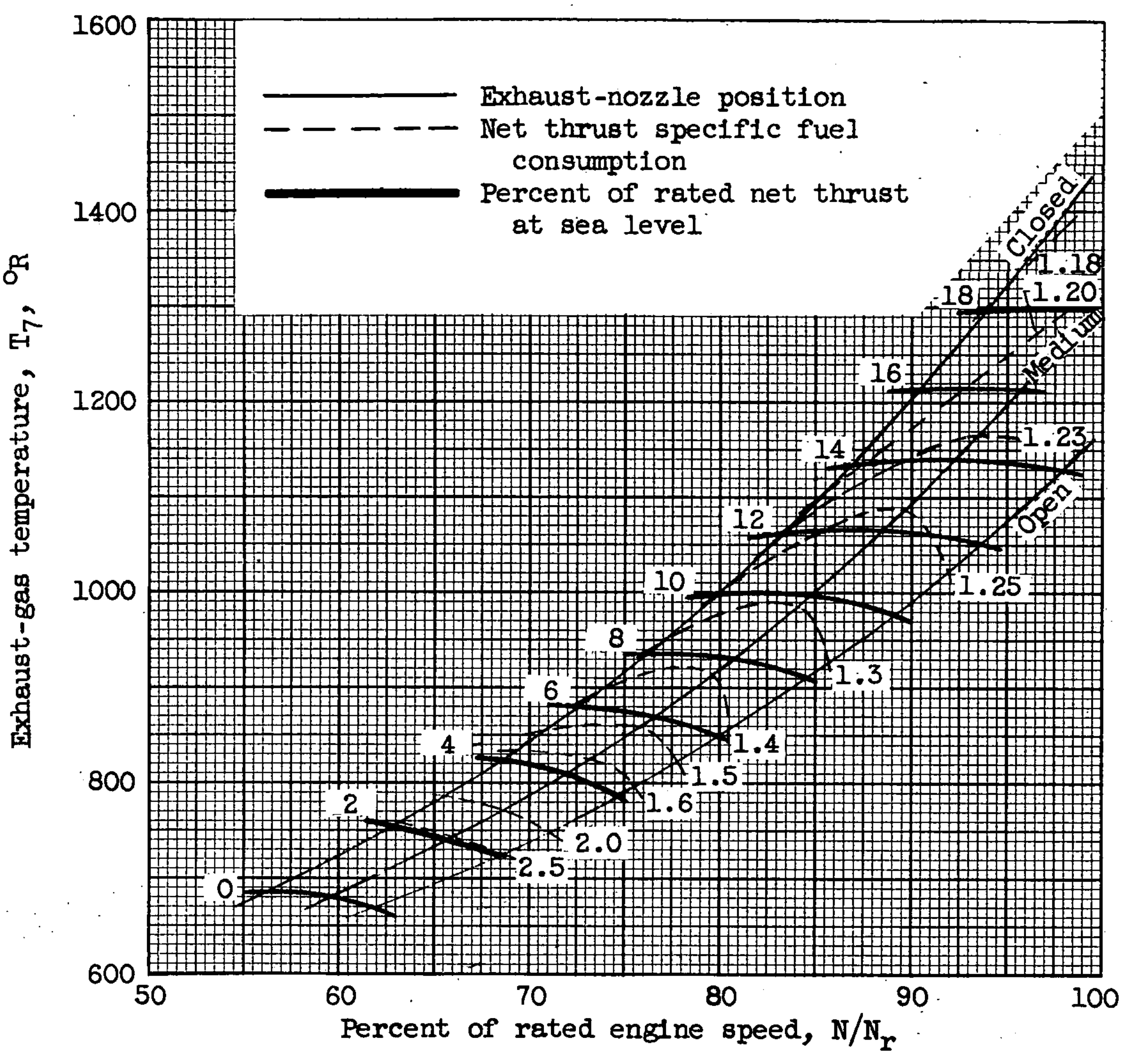
(b) Inlet-guide-vane setting, 20°.

Figure 15. - Continued. Engine performance maps at altitude of 35,000 feet and flight Mach number of 0.8.



(c) Inlet-guide-vane setting, 30°.

Figure 15. - Continued. Engine performance maps at altitude of 35,000 feet and flight Mach number of 0.8.



(d) Inlet-guide-vane setting, 43° (closed).

Figure 15. - Concluded. Engine performance maps at altitude of 35,000 feet and flight Mach number of 0.8.

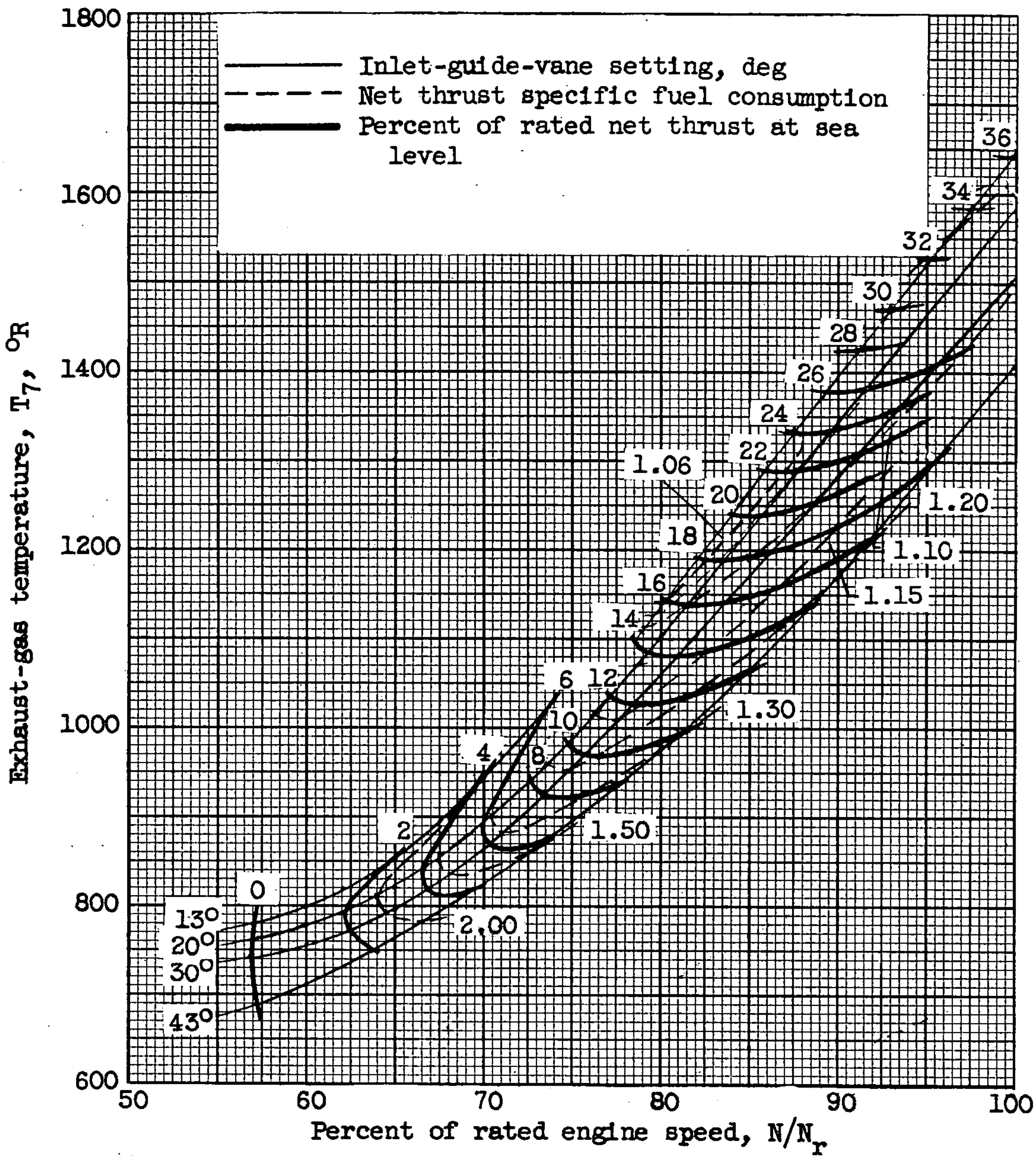


Figure 16. - Engine performance map at rated exhaust-nozzle area, altitude of 35,000 feet, and flight Mach number of 0.8.

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