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MEMORANDUM

USE OF STAGE-STACKING TECHNIQUE FOR PREDICTING OVER-ALL PERFORMANCE IN MULTISTAGE AXIAL-FLOW COMPRESSOR UTILIZING INTERSTAGE-AIR B

By James G. Lucas

Lewis Research Center
Cleveland, Ohio

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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USE OF STAGE-STACKING TECHNIQUE FOR PREDICTING OVER-ALL PERFORMANCE IN MULTISTAGE AXIAL-FLOW COMPRESSOR UTILIZING INTERSTAGE-AIR BLEED*

By James G. Lucas

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SUMMARY

An experimental investigation was conducted to determine the changes in over-all compressor performance and stage and stage-group characteristics of a 13-stage axial-flow compressor due to interstage-air bleed over the fifth- and tenth-stage rotor blade rows, both separately and together. Bleed tended to alter the contours of the stage performance characteristic curves. Fifth-stage bleed, alone or in combination with tenth-stage bleed, tended to improve the medium and low-speed performance of the four stages preceding it and tended to reduce the performance of the five succeeding stages as a group. Tenth-stage bleed alone had no appreciable effect on the performance of preceding stages, but did tend, along with the combination bleed, to move the characteristic curves of the succeeding stages to lower values of flow coefficient.

The changes in stage characteristics with bleed were accompanied by disturbances of the radial gradients of some of the flow parameters within the compressor. The few gradients obtained, temperature and total-pressure ratios, were unaffected by bleed in the high-speed range, where rotating stall was not present. At low speeds the inlet stages as a group showed poor performance at the blade tip section with the presence of rotating stall. This effect was carried through the compressor by the temperature gradients, but not by the pressure gradients.

An analytical investigation, based on the experimental results, was conducted to determine the feasibility of using a stage-stacking procedure to predict over-all compressor performance and stall-range characteristics under the experimental bleed conditions. The stacking was done using bleed ratios and no-bleed stage-group characteristic curves obtained experimentally. With either bleed separately, the stacking procedure yielded very good over-all performance and rotating-stall-range results. With the combination of the two bleeds, the predicted over-all performance

*Title, Unclassified

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and stalled-operation range are not very accurate, although the indicated rotating-stall limit is at least on the conservatively high speed side of the measured limit.

INTRODUCTION

The axial-flow compressors used on most current turbojet engines have been designed to produce high pressure ratios and high mass flows per unit frontal area at the design point. When the engine is being operated at design speed, efficient and unstalled operation of all the blade elements is possible. However, at lower speeds the rear stages choke because the front stages can still pass high flows (but at a lower pressure ratio) and thereby cause the rear stages to operate at a higher volume flow, for which there is insufficient annulus area. As the rear stages choke, they limit the inlet mass flow to the front stages. As the speed and flow are lowered, the front stages are forced to operate at higher incidence angles, and below a certain speed and flow combination (known as the inlet-stage stall line) they will be operating stalled. Operation in this regime is usually accompanied by one or more regions of low flow spaced around the annulus and rotating in the same direction as the rotor at about half rotor speed. If the frequency of passage of these rotating-stall zones past a row of blades is in resonance with the natural bending frequency of the blades, high vibratory bending stresses can be excited in them, which frequently result in fatigue failure (ref. 1). This effect, coupled with a general and often severe deterioration of compressor performance in the rotating-stall regime, means that it is not wise to operate in this region for a great length of time and that it is difficult to accelerate a turbojet engine through it rapidly. The slow acceleration is a definite disadvantage in itself, and it also means a longer period of operation in this region during engine acceleration, which can be destructive.

A number of methods have been proposed to overcome the difficulty of operation in or through the rotating-stall regime. Most of them are aimed at elimination or alteration of the rotating-stall patterns so they cannot excite dangerous blade vibrations. Annular inlet area blockage has been used to destroy the periodic nature of the stall (ref. 2), and adjustable inlet guide vanes have been used to alter the incidence angle at the first stage (ref. 3). Another method, the one discussed in the present report, is interstage-air bleed. This method attempts to overcome inlet-stage stall, and consequent rotating stall, or to lower its speed range to a safe value by allowing the inlet stages to operate with higher mass flows than the rear stages, which will still be choked. The obvious method for doing this is to remove some of the air after it has been compressed by the inlet stages. The inlet stages then handle the discharge choked flow as before plus the bleed flow and can, as a result, operate at lower and more acceptable incidence angles.

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In order to check the effectiveness of this method of rotating-stall elimination or alteration experimentally, the performance of a suitably modified compressor was obtained from a full-scale engine test on a sea-level static test stand. The compressor used was a commercial 13-stage axial-flow unit altered to provide for roughly 9 to 16 percent bleed after each of the fourth and ninth stages. The effects of interstage bleed on compressor over-all performance, rotating stall, and blade vibrations for this test rig are reported in references 4 and 5. These studies indicated that with a combination of the two bleeds rotating stall was eliminated down to a speed somewhat less than 50 percent of design, and with either bleed alone the rotating-stall maximum-speed limit was reduced appreciably, though less than with the combination bleed.

The purpose of this report is to show whether or not the performance of a given compressor with interstage-air bleed could be accurately determined by the conventional stage-stacking method based upon the stage and stage-group characteristic performance curves obtained without bleed during the investigation of references 4 and 5. The success of this method would be important in a design procedure if bleed tended to alter the stage characteristics, as will be shown to be true for this compressor.

These no-bleed characteristic curves and the experimentally observed bleed ratios were used with a stacking procedure similar to that of reference 6 on an automatic computer to yield over-all compressor performance maps which were then compared with the corresponding maps obtained from the experimental tests in order to evaluate the accuracy of the technique. This report presents the results of this investigation, and shows the experimentally observed results of interstage-air bleed on the individual-stage and stage-group performance characteristics and on radial gradients of total-pressure and temperature rise through the compressor.

EXPERIMENTAL APPARATUS AND INSTRUMENTATION

A commercial axial-flow turbojet engine was modified for use in this investigation. The compressor for this engine was a 13-stage axial-flow unit having a design total-pressure ratio of about 7 with an airflow of approximately 120 pounds per second at a speed of 8300 rpm. The compressor casing was machined over the fifth- and tenth-stage rotor blade rows to allow air to be bled radially outward from the interior. Figure 1 shows sectional views of the casing with the bleed-slot configurations outlined. The bleed slots had been sized to allow the maximum amount of bleed area consistent with the requirements of casing rigidity and space for necessary and immovable engine accessories. Consideration was given to the circumferential spacing of the segments of each slot in order to prevent any possible resonance between the natural bending frequencies of the rotor blades below these slots and the periodic blade force caused by rotation past the slot segments. The slots were rounded slightly at the interior of the casing, the inner edges having a radius of about 1/8 inch. Actual bleed areas at the fifth- and tenth-stage locations were 46.7 and 20.6 square inches, respectively. These bleed areas were such that, with the assumed orifice coefficient of 0.4, about 9 to 16 percent of the inlet flow could be bled from the two areas separately, the variation being over the speed range of 50 to 85 percent of design speed.

Figure 2 shows two views of the modified casing, both with and without the associated collectors. The bleed air leaving the collectors was ducted through separate orifices and control valves to the engine exhaust muffler. The amount of bleed flow at each location could be regulated separately by the valves and was measured with thin-plate orifices.

The engine was equipped with an adjustable exhaust nozzle to permit a range of variation of the compressor operation at any given speed. The nozzle was sized so that at its open position the engine would operate at rated temperature ratio at design speed.

The instrumentation used to measure the over-all performance and stage and stage-group performance of the compressor is diagrammed in figure 3. Additional instrumentation needed to measure the bleed flow rates consisted of a single total-pressure tube, two unshielded thermocouples, and two orifice flange static-pressure taps in each orifice pipeline. Rotating stall was detected and measured by hot-wire anemometer probes, which were traversed radially by probe actuators in each of the first three stator blade rows.

EXPERIMENTAL PROCEDURE

The investigation was conducted on a static sea-level test stand with the engine drawing in atmospheric air from the test cell at ambient conditions and discharging through a muffler to the atmosphere.

The compressor was operated at constant equivalent speeds from 50 to 100 percent of design without bleed, and up to 85 percent with bleed, at increments of 5 percent. The speed range investigated with bleed was extended to somewhat higher speeds than those at which bleed would probably be used in order to determine the performance trends adequately. At each speed and bleed condition where it was possible, the exhaust-nozzle size was varied in order to cover a range of compressor-inlet weight flow. The range of flows obtainable at any given speed was small because of turbine temperature limits.

Data for the present report were taken for each of the bleed conditions with the appropriate control valve, or valves, open fully to simulate an application where the air bled would be dumped to the atmosphere.

STAGE-STACKING PROCEDURE

Compressor over-all performance characteristic maps were obtained for each of the bleed configurations considered (fifth stage, tenth stage, fifth and tenth stages, and no bleed) by use of a stage-stacking technique similar to that of reference 6. This stacking method was set up for use with an automatic computer. The curves used were obtained experimentally without bleed for the first, second, third and fourth, fifth to ninth, and tenth to thirteenth stages. The bleed ratios (ratio of bleed flow to
4776 inlet flow at any speed) used were those obtained experimentally under the actual bleed conditions and are shown in figure 4. Rather than using the designer's approach, wherein the bleed flow must be calculated, it was decided to use the approach to the stacking problem as outlined above in order to determine just how well the stacking procedure will duplicate or predict over-all compressor performance, if the bleed flow can be accurately predicted. Because the axial distance between adjacent stages was very small, the actual slots were machined over the fifth- and tenth-stage rotor blade rows. In the stage-stacking analysis, however, it was necessary to assume that the bleed occurred between stages and also that the performance of the following stage groups was unaffected by the bleed. It was expected that the spacing of the slots around only two-thirds of the circumference would induce asymmetry of flow around the annulus into the following stages. However, it was assumed for the purposes of the analysis that such flow would not affect the performance of the later stages.

RESULTS AND DISCUSSION

Effects of Bleed on Stage and Stage-Group Performance

Compressor stage and stage-group performance was obtained with each of the bleed configurations for the following stages or combinations of stages: first, second, third and fourth, fifth to ninth, and tenth to thirteenth. These stage characteristic performance curves are presented as total-pressure and temperature coefficients plotted against flow coefficients at the inlet to the particular stage groups. Distortion due to circumferential nonuniformity of flow was considered to have no effect on the measurements. The stage curves with no bleed, fifth-stage bleed, tenth-stage bleed, and fifth- and tenth-stage bleed are presented in figures 5 to 8. To facilitate detection of performance changes caused by bleed, the no-bleed curves (fig. 5) were faired and then replotted over the data plots with bleed (figs. 6 to 8). Any aberrations in performance of a given stage or group with one of the bleed configurations can then be noted as a discrepancy between the no-bleed faired line and the general trend of bleed data points. In addition, the no-bleed flow coefficient ranges at various percentages of design speed shown in figure 5 are also replotted in figures 6 to 8 for the purpose of showing the shift of operation point with bleed.

An examination of figure 6(a) indicates that with fifth-stage bleed the first-stage peak pressure coefficient occurs at a lower flow coefficient than without bleed, and the pressure coefficient is higher than without bleed at all flow coefficients lower than that for peak pressure coefficient. Figure 8(a) indicates that the same holds true for the combination of the two bleeds, the peak pressure coefficient being even higher and at a lower flow coefficient than with fifth-stage bleed only. Figure 7(a) indicates that tenth-stage bleed alone had very little effect on the first-stage characteristic pressure coefficient curve, but did shift the operating point on the curve at any given speed. With each of the bleed configurations the temperature coefficient was lower than that without bleed below the flow coefficient corresponding to the condition of peak pressure coefficient. 4776

Comparison of the characteristic curves for the second stage (figs. 6 to 8) reveals virtually identical effects due to bleed as indicated by the first-stage curves.

The stage-group curves for stages 3 and 4 (figs. 6(c), 7(c), and 8(c)) indicate that with tenth-stage bleed performance is almost unaffected, though the operating point at any given speed is shifted, while with fifth-stage or fifth- and tenth-stage bleed the pressure coefficients are higher over the full range of flow coefficient. The maximum measured pressure coefficient (which had possibly not reached the actual peak value) was considerably higher and occurred at a considerably lower flow coefficient. The temperature coefficients varied from somewhat higher at high flow coefficients to about the same at the low-flow-coefficient end of the scale as compared with the no-bleed values.

The data for stages 5 through 9 as a group (figs. 6(d), 7(d), and 8(d)) indicate that with either fifth- or fifth- and tenth-stage bleed the peak pressure coefficient remains about the same as without bleed, but occurs at a higher flow coefficient. With lower flow coefficients the pressure coefficient is much lower and the stage group is operating on a positive-sloped (or stalled) portion of its curve rather than at a peak value as with no bleed. As was the case with the previous stages, tenth-stage bleed had practically no effect on the pressure coefficient. Fifth-stage bleed and fifth- and tenth-stage bleed caused a decrease in temperature coefficient over all but the high-flow-coefficient range, and tenth-stage bleed had no effect on temperature coefficients.

The stage-group performance curves for stages 10 through 13 (figs. 6(e), 7(e), and 8(e)) indicate that fifth-stage bleed causes very little change in performance, while tenth-stage or fifth- and tenth-stage bleed causes the temperature and pressure coefficients to be decreased at any given flow coefficient, or, to put it another way, the characteristic curves move to a somewhat lower flow-coefficient range.

As would be expected, the flow-coefficients for a given speed with bleed are higher than without bleed for stages ahead of the bleed location. This is simply due to the higher mass flow being passed by these stages. After the bleed location, however, the range varies from slightly lower to about the same as without bleed. The stage group between bleeds with the combination bleed follows the same trend as earlier stages, but with a lesser degree of change from the no-bleed case.

From the preceding observations of the stage-group performance curves it appears that fifth-stage bleed either alone or in combination with tenth-stage bleed causes the flow coefficient for peak pressure coefficient to be lowered for the stages preceding the bleed and the peak pressure coefficient to be raised, both effects becoming more pronounced in the stages immediately preceding the fifth-stage bleed. In fact, the stage group just preceding the fifth-stage bleed benefits from increased pressure coefficients over the entire flow-coefficient range. Fifth-stage bleed, again in combination with tenth-stage bleed or alone, causes the temperature coefficients for the first two stages to be generally lower than those without bleed and the temperature coefficients for the stage group immediately preceding the bleed to be generally higher than those without bleed.

The stage group immediately following the fifth-stage bleed, again alone or in combination with tenth-stage bleed, has the flow coefficient for peak pressure coefficient increased considerably, and below this flow coefficient, in the "stalled-operation" region, the pressure coefficient decreases rapidly. The temperature coefficients are decreased over nearly the entire flow range.

The first ten stages are not appreciably affected by tenth-stage bleed alone. However, the stage group following this suffers decreased temperature and pressure coefficients at a given flow coefficient with tenth-stage bleed alone or in combination with fifth-stage bleed, while fifth-stage bleed alone does not affect the performance of this group of stages.

Therefore, it can be said that for the 13-stage compressor under investigation fifth-stage bleed alone or in combination with tenth-stage bleed tended to improve the medium- and low-speed performance of the four stages preceding it and tended to worsen the performance of the five succeeding stages as a group, while tenth-stage bleed alone had no appreciable effect on the performance of preceding stages, but along with the combination bleed did tend to move the characteristic curves of the succeeding stage group to lower flow coefficients.

The only obvious explanation for the alteration of these curves by bleed is that the stage inlet conditions actually were affected. Evidently the bleed sufficiently altered the radial gradients of flow angle, Mach number, and so forth to change the stage performance characteristics. With fifth-stage bleed, either alone or in combination, the radial disturbance effects were evidently transmitted to stages ahead of the bleed as well as after it. The changing of rotating-stall patterns and speed ranges, as shown in reference 5, could also result from these radial flow disturbances.

Effects of Bleed on Radial Gradients of Total Pressure and Temperature

Radial gradients of total pressure and temperature were obtained before the last two stage groups, that is, after the fourth and ninth stages and at the compressor discharge. These values are shown in figures 9 to 11 as ratios to mean-radius measuring-station values taken along the rated-exhaust-nozzle-area operating line for speeds of 80, 60, and 50 percent of design. It should be noted that at 50 percent design speed the compressor suffered rotating stall with all configurations except the combination bleed (ref. 4). At 60 percent design speed rotating stall was present only with no bleed and with tenth-stage bleed, and at 80 percent design speed no rotating stall was present with any of the configurations.

At 80 percent design speed all the curves show about the same gradients or trends under the different bleed conditions (fig. 9). A few discrepancies may be noted, but they are small, and may be due to measurement inaccuracies.

At 60 percent design speed the first four stages as a group show a deterioration of performance (low pressure ratio and high temperature ratio) near the tip section of the passage with no bleed and with tenth-stage bleed, and both conditions were accompanied by rotating stall (fig. 10(a)). The change in temperature gradient was felt through the entire compressor (figs. 10(b) and (c)), while the pressure gradient reverted to that with no bleed as the air passed through the fifth to ninth stages.

At 50 percent design speed practically identical gradients are shown as at 60 percent design speed (fig. 11). Rotating stall was present with fifth-stage bleed as well as with tenth-stage bleed and no bleed, although no indications of it are to be seen in the curves of figure 11. Perhaps this is related to the fact that the rotating-stall zones at this point were very unstable and tended to change rapidly in number and depth of penetration.

The changes in gradient with bleed are probably caused by combinations of several different effects. Changing stall-zone configurations, radial flows due to bleed, and the range of flow coefficient for operation at different speeds, as well as interactions of these effects, could be among the causes.

Use of Stage-Stacking Technique in Predicting

Over-All Compressor Performance with Bleed

By use of the no-bleed stage curves of figure 5 and the measured bleed ratios shown in figure 4, over-all performance maps were determined for the compressor under the various bleed conditions. These maps, plus a map for no bleed determined in the same manner, are shown in figure 12 for no bleed, fifth-stage bleed, tenth-stage bleed, and combination bleed. The maps are presented as lines of total-pressure ratio and adiabatic temperature-rise efficiency against inlet equivalent weight flow at various constant speeds in the range 50 to 85 percent design speed. Also shown on these maps are data taken under the actual bleed conditions to indicate the accuracy with which over-all compressor performance can be determined under conditions of interstage-air bleed. In addition, these figures show the experimentally determined rotating-stall-limit points with rated exhaust-nozzle area and the predicted approximate inlet-stage stall-limit line, which is generally considered to be the high flow limit for rotating stall. This line is actually an approximate locus of predicted over-all performance points at which the inlet-stage flow coefficient is equal to 0.42. This value is the first stage flow coefficient at which rotating stall actually does occur along the rated operating line with no bleed. These lines are termed approximate because they were determined by only one known point (intersection with a constant-speed line) in each case and an assumed approximate slope.

Figure 12(a), which presents compressor performance without bleed, shows very good correlation between the experimental and predicted curves. This indicates that the stacking procedure will, under normal conditions, accurately predict compressor performance. The close correlation also indicates accurate fairing of the experimentally obtained stage curves. The rotating-stall-limit point at rated exhaust-nozzle area should and does fall on the predicted inlet-stage stall line.

With fifth-stage bleed the predicted over-all performance agrees quite well with the measured data, the only significant discrepancy being a slightly too low efficiency at the very lowest speeds (fig. 12(b)). The predicted approximate inlet-stage stall-limit line comes reasonably close to the stall-limit data point shown. The difference along the rated exhaust-nozzle-area operating line is of the order of 4 to 5 pounds per second of flow or about 2 to 3 percent in speed.

With tenth-stage bleed the predicted over-all performance again agrees quite well with the measured data (fig. 12(c)). In this case the only significant discrepancy occurs in weight flow over the 65- to 75-percent design speed range and is not severe. The predicted approximate inlet-stage stall-limit line again comes reasonably close to the stall-limit data point, the difference along the rated operating line being about 3 pounds per second of flow or about 2 percent in speed.

With the combination of fifth- and tenth-stage bleed the predicted over-all performance agrees well with the measured data above about 75 percent speed (fig. 12(d)). However, at lower speeds the predicted pressure ratios are much too high, while the flows and efficiencies are in fair agreement. The predicted approximate inlet-stage stall-limit line would indicate a rated-operating-line rotating-stall limit of about 58 percent speed, whereas it was experimentally determined to be less than 50 percent of design speed. This would seem to be a serious error in prediction, although it should be noted that rotating stall is often difficult to detect at low speeds and is usually sufficiently weak to cause 4776
little trouble. Inasmuch as rotating stall is not just related to first-stage stall, but is affected by stage-matching and stage-interaction phenomena with their resulting stability problems, the prediction error does not seem too severe and is at least on the conservative side.

The foregoing observations indicate that, for the compressor being considered, compressor over-all performance and rotating-stall limits can be quite accurately predicted when using interstage-air bleed at any one axial location, and that such performance cannot be satisfactorily predicted when using a combination of two bleeds at different axial locations. The degree of accuracy in prediction can be considered fortunate inasmuch as the stage characteristics were considerably altered by bleed. The explanation for this probably lies mostly in the compensation of stage-curve changes by opposite changes in other stages for bleed at a single axial location. Evidently with the multiple bleed locations such compensating effects were not sufficient. It is possible that stacking, with bleed, a set of stage curves from another compressor having different characteristics could produce somewhat different results. It should also be emphasized that predicting the bleed flows with sufficient accuracy could be something of a problem, though not insurmountable.

SUMMARY OF RESULTS

The following results were obtained from an experimental investigation of the effects of interstage bleed on compressor stage performance curves and radial temperature and total-pressure gradients within the compressor and from a subsequent analytical investigation of the feasibility of using the stage-stacking procedure for predicting over-all performance with interstage bleed:

1. Fifth-stage bleed alone or in combination with tenth-stage bleed improved the medium- and low-speed performance of the four stages preceding it and worsened the performance of the five succeeding stages as a group, while tenth-stage bleed alone had no appreciable effect on the performance of preceding stages, but along with the combination bleed did move the characteristic curves of the succeeding stage group to lower values of flow coefficient.

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2. At high speeds, out of the rotating-stall range, radial distributions of temperature and total-pressure gradients within and through the compressor were not changed by bleed. At low speeds the inlet stages as a group showed poor performance at the tip section when rotating stall was present, this effect being carried through the compressor by the temperatures, but not by the pressures.

3. With interstage bleed from a single axial location within the compressor the stage-stacking procedure gave very satisfactory over-all performance results, while with a combination of bleeds in two locations the predicted over-all total-pressure ratios below about 75 percent of design speed were much too high. The predicted inlet-stage stall-limit line (rotating-stall limit) was at a conservatively high speed range in each case but was quite close to the measured values with bleed at only a single location.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 30, 1958

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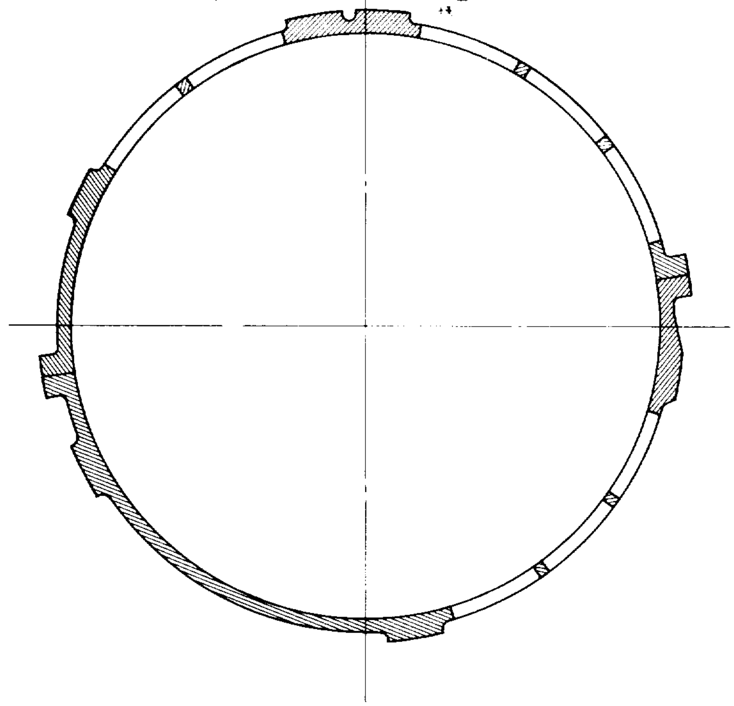
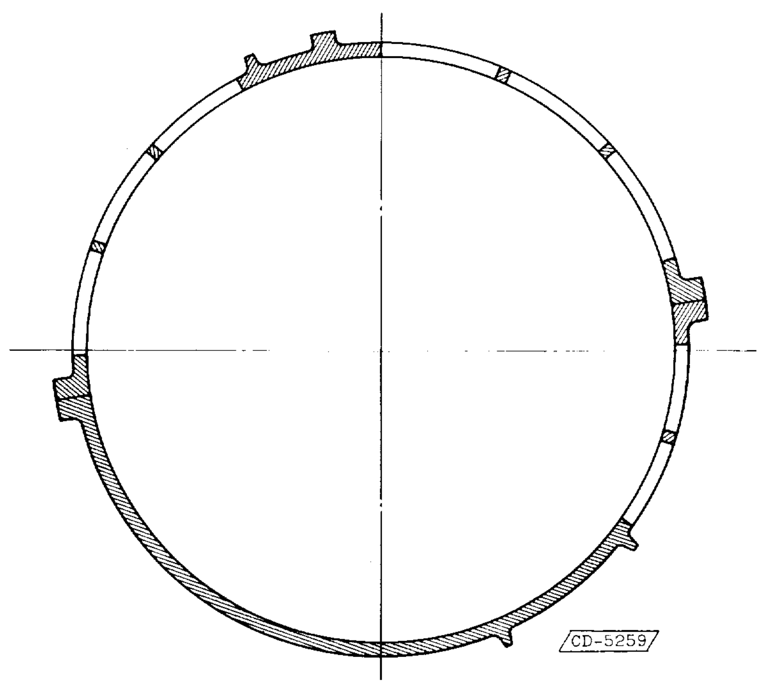


(a) Fifth stage.



(b) Tenth stage.

Figure 1. - Sectional views (looking downstream) of compressor casing showing bleed slots.

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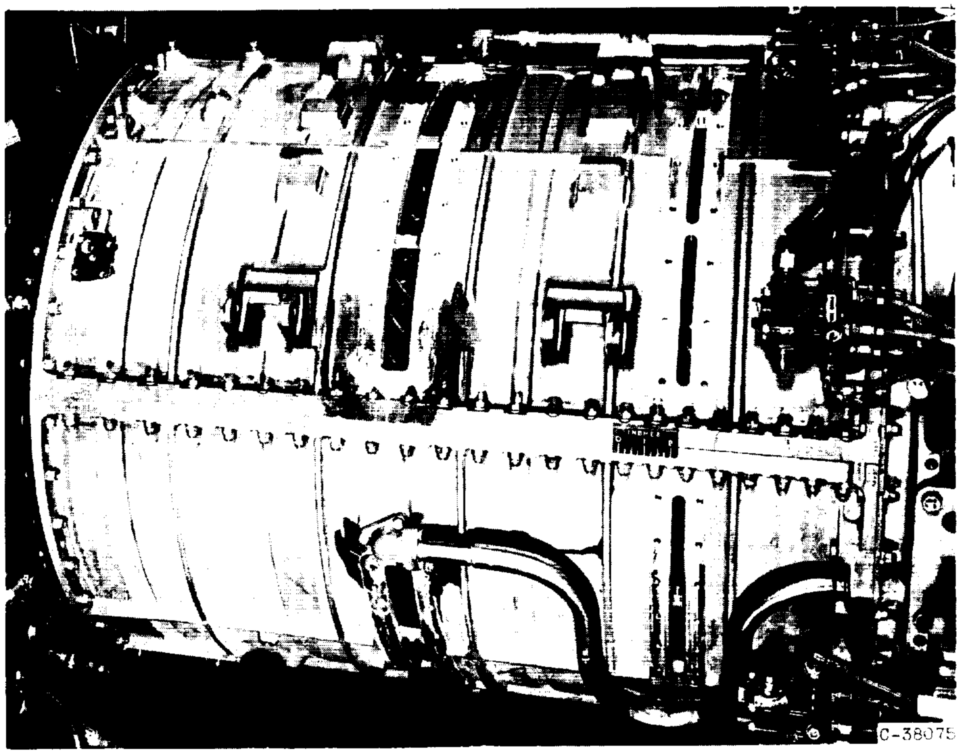
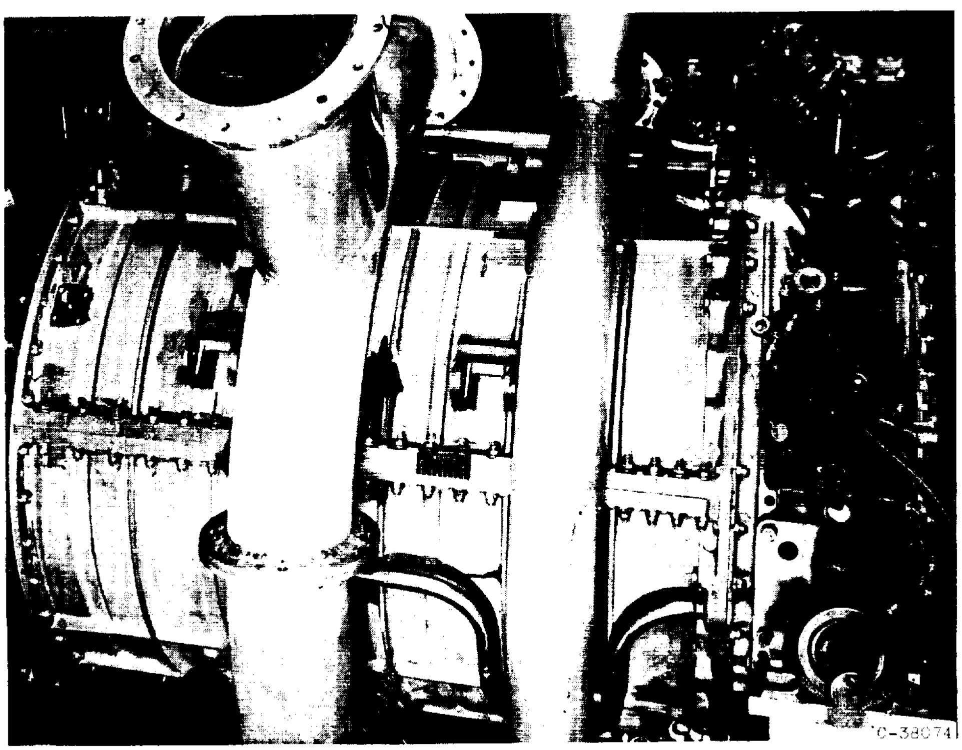


(a) Without bleed manifolds.



(b) With bleed manifolds.

Figure 2. - Modified compressor casing.

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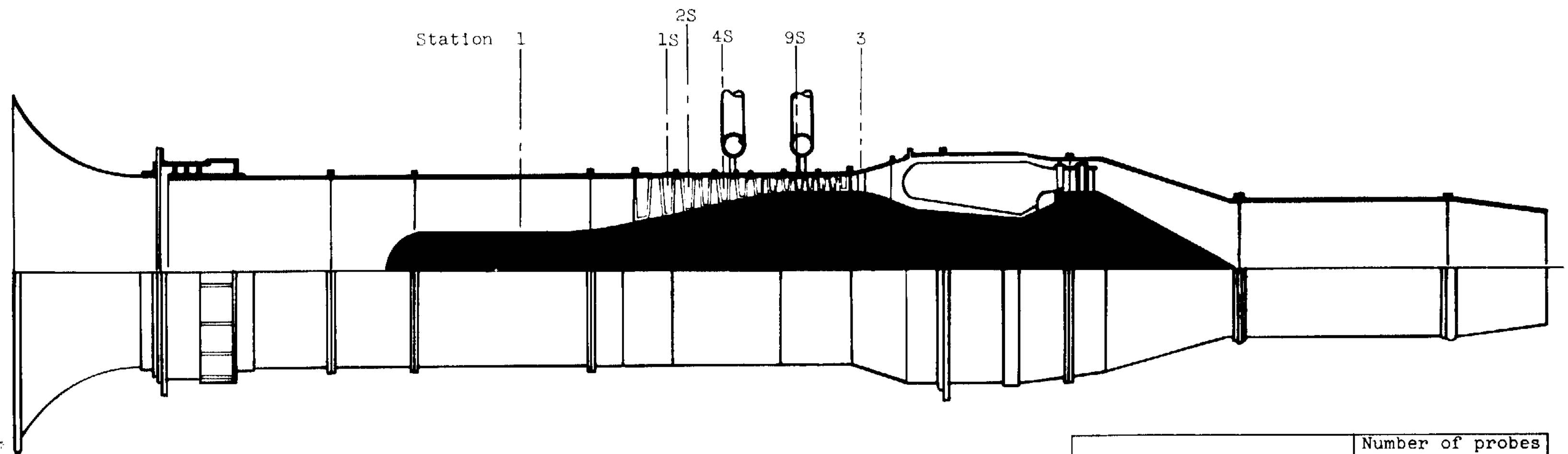

Type of probe	Number of probes per station at station-					
	1	1S	2S	4S	9S	3
○ Total pressure	15	5	5	5	3	12
□ Temperature	12	5	5	5	3	6
◇ Stream static pressure	4	-	-	-	-	-
△ Wall static pressure	4	1	1	1	1	3

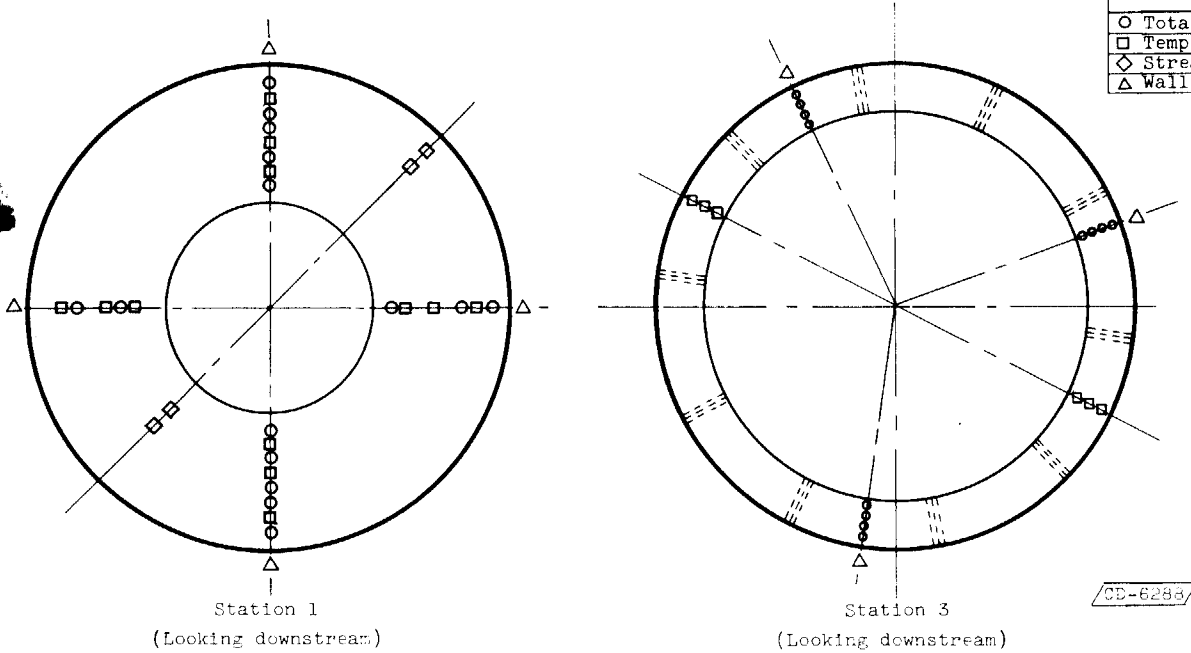

Figure 3. - Schematic diagram of compressor instrumentation.

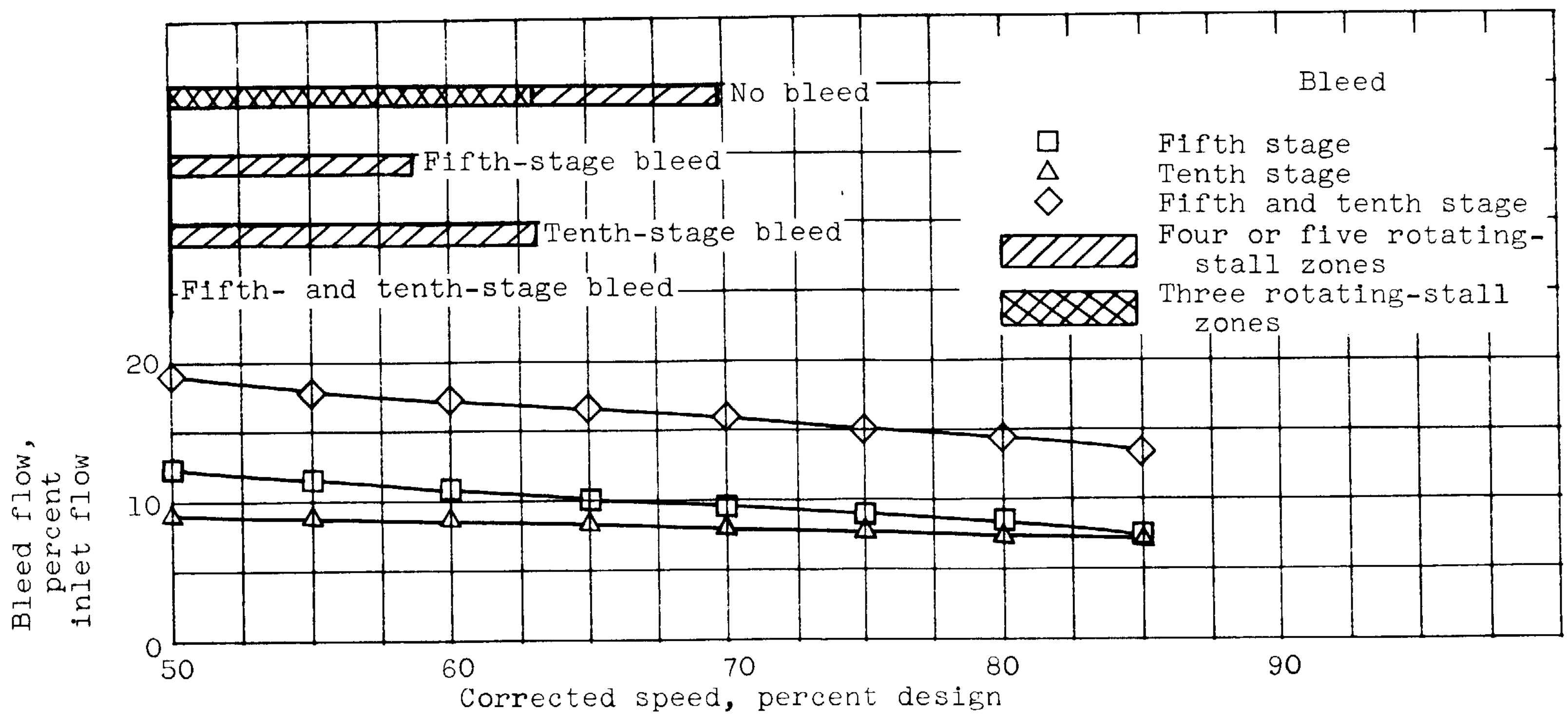

Figure 4. - Bleed flow and rotating-stall range with each bleed configuration.

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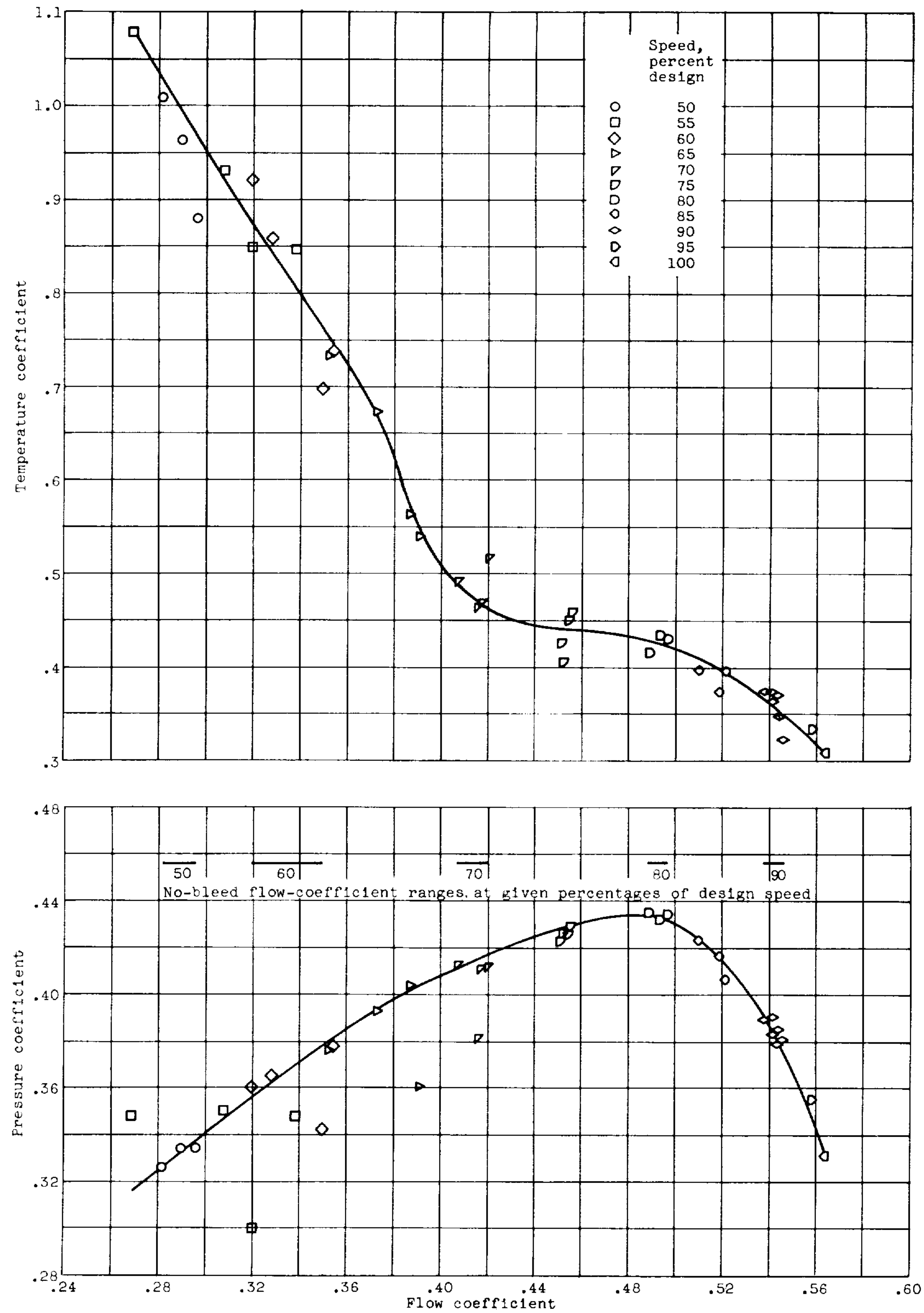

(a) First stage.

Figure 5. - Performance characteristics without bleed.

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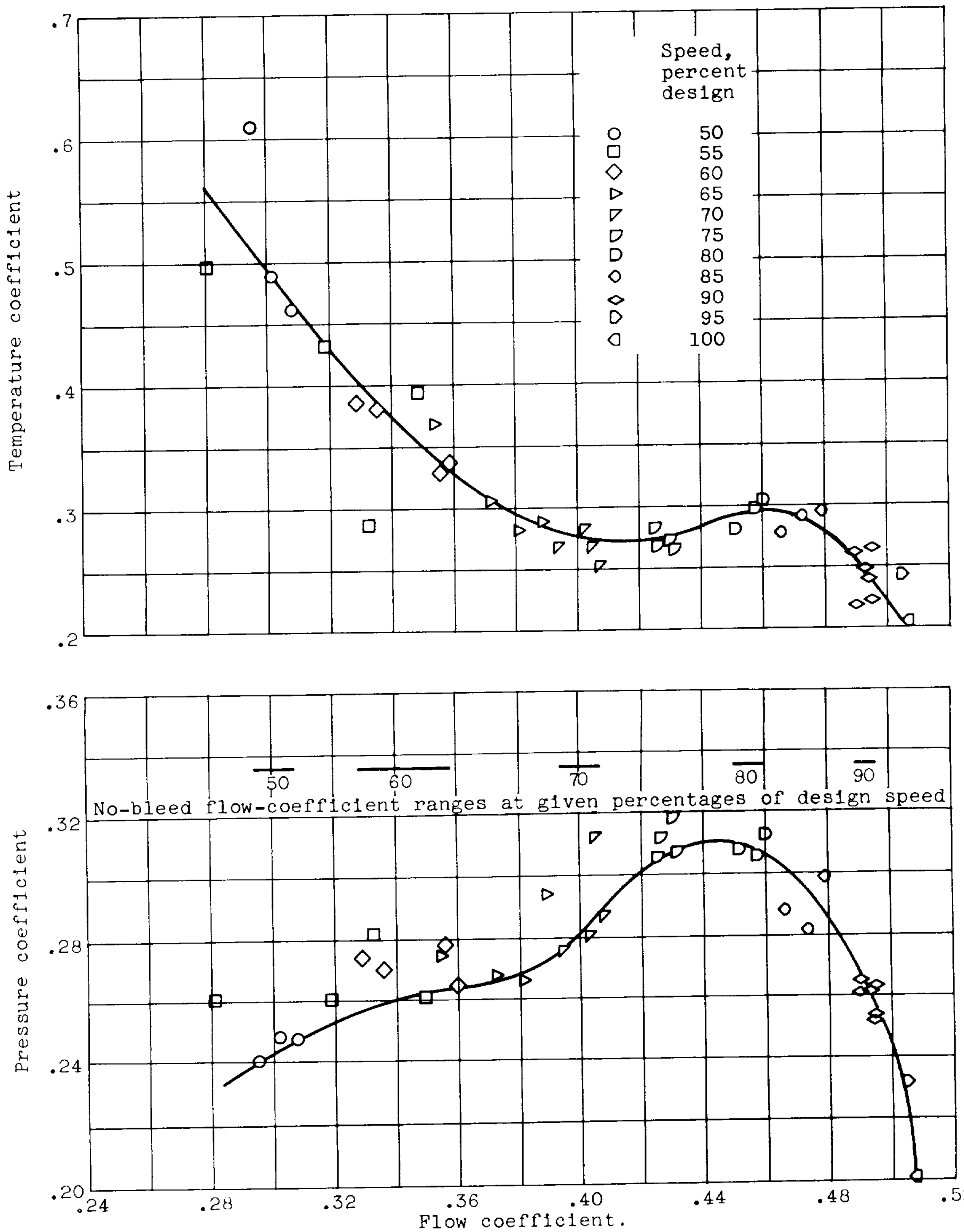

(b) Second stage.

Figure 5. - Continued. Performance characteristics without bleed.

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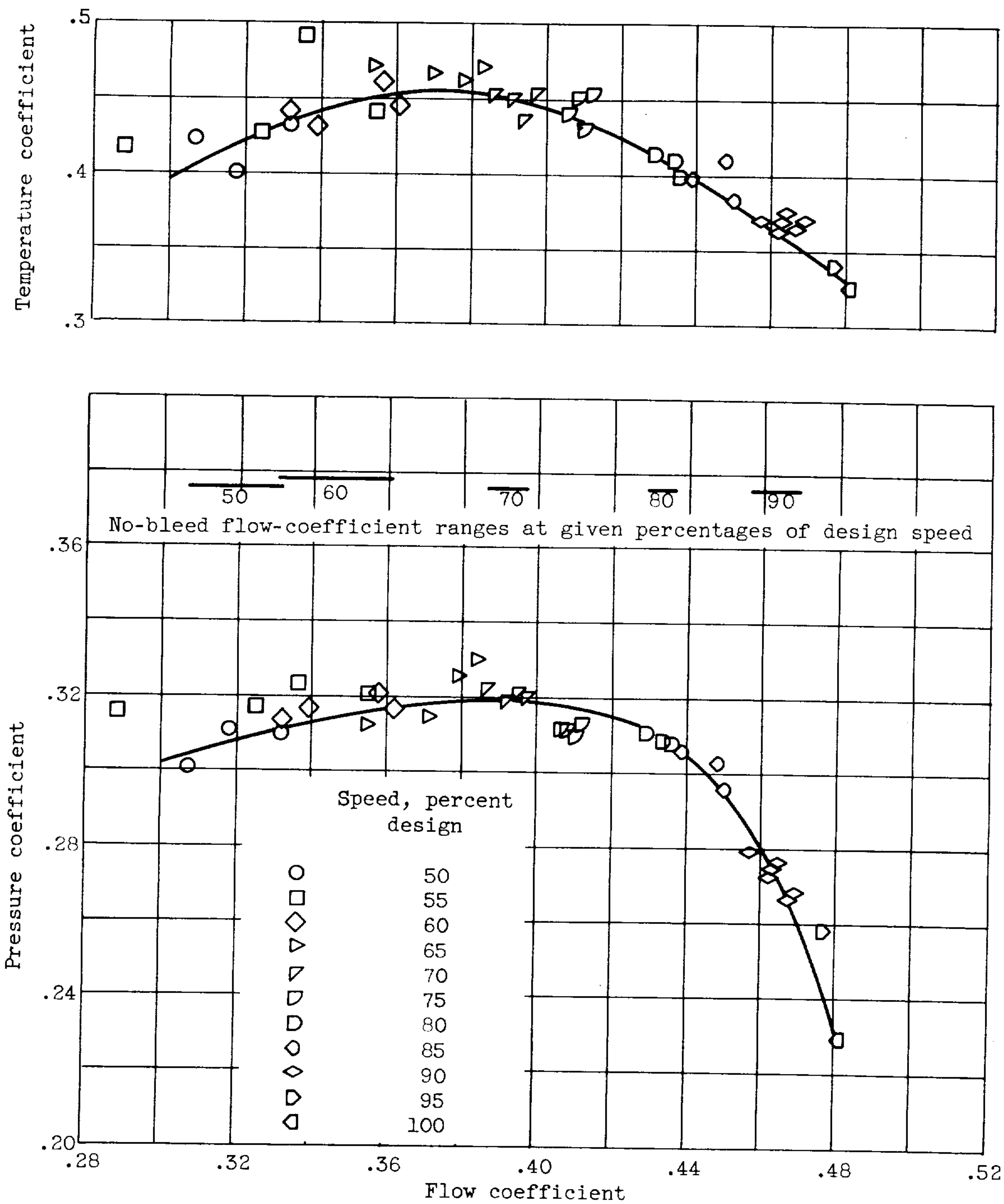

(c) Stages 3 and 4.

Figure 5. - Continued. Performance characteristics without bleed.

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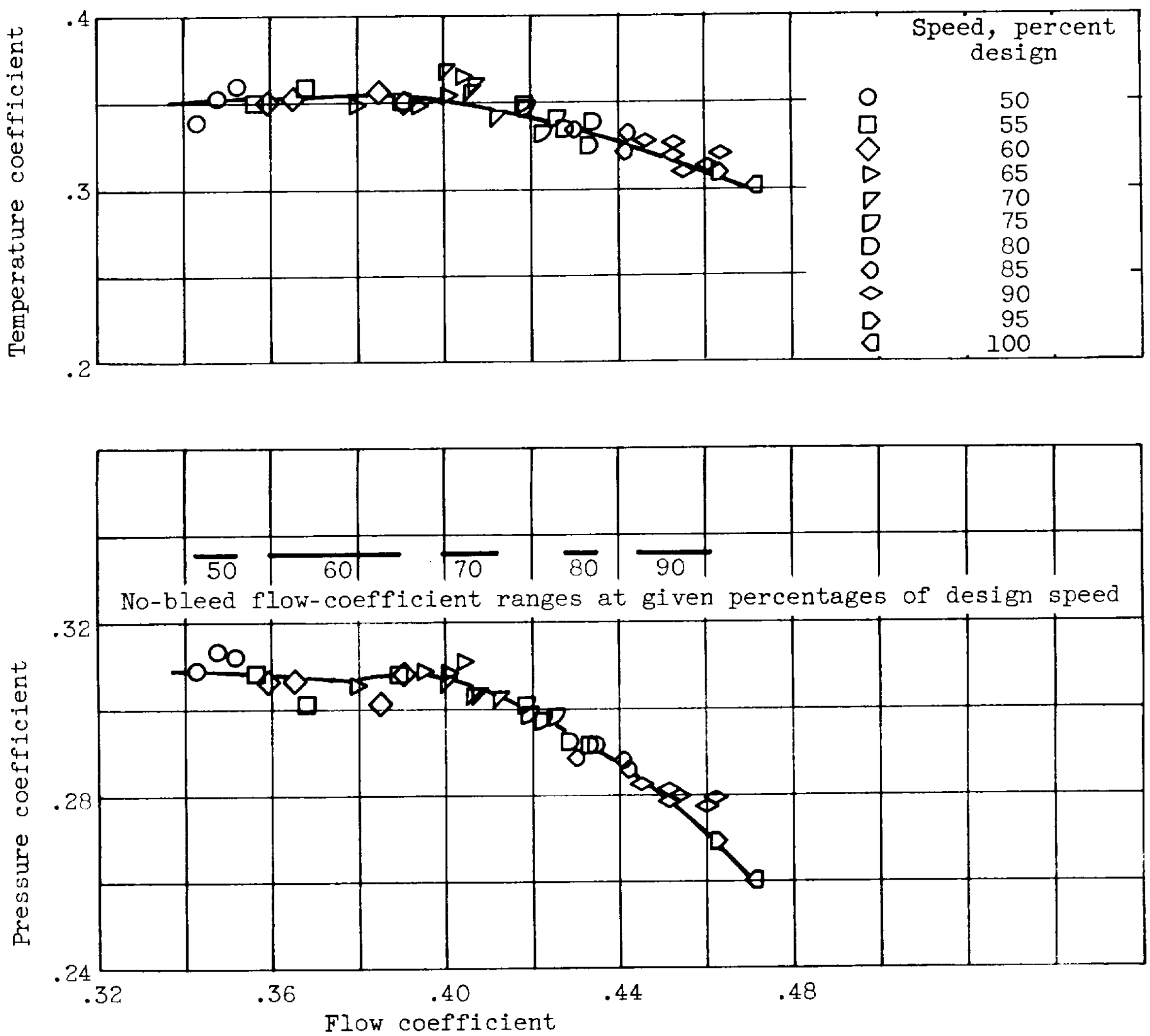

(d) Stages 5 to 9.

Figure 5. - Continued. Performance characteristics without bleed.

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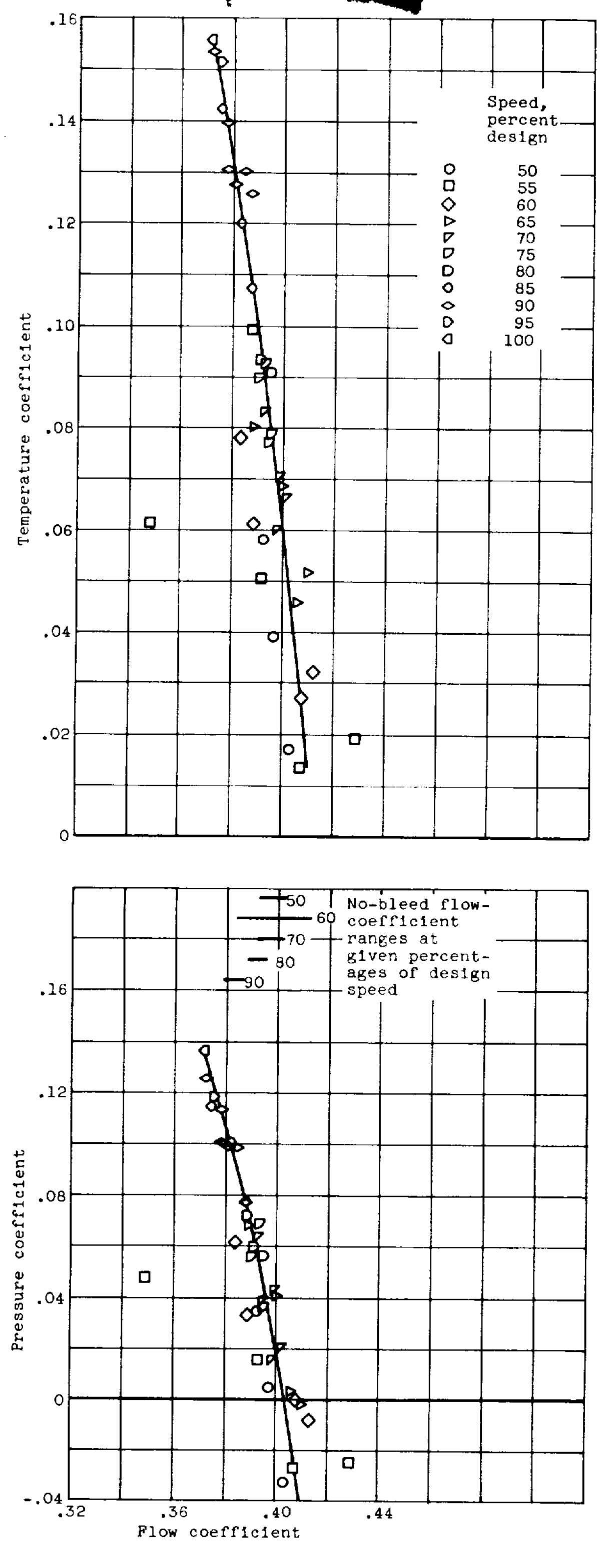

(e) Stages 10 to 13.

Figure 5. - Concluded. Performance characteristics without bleed.

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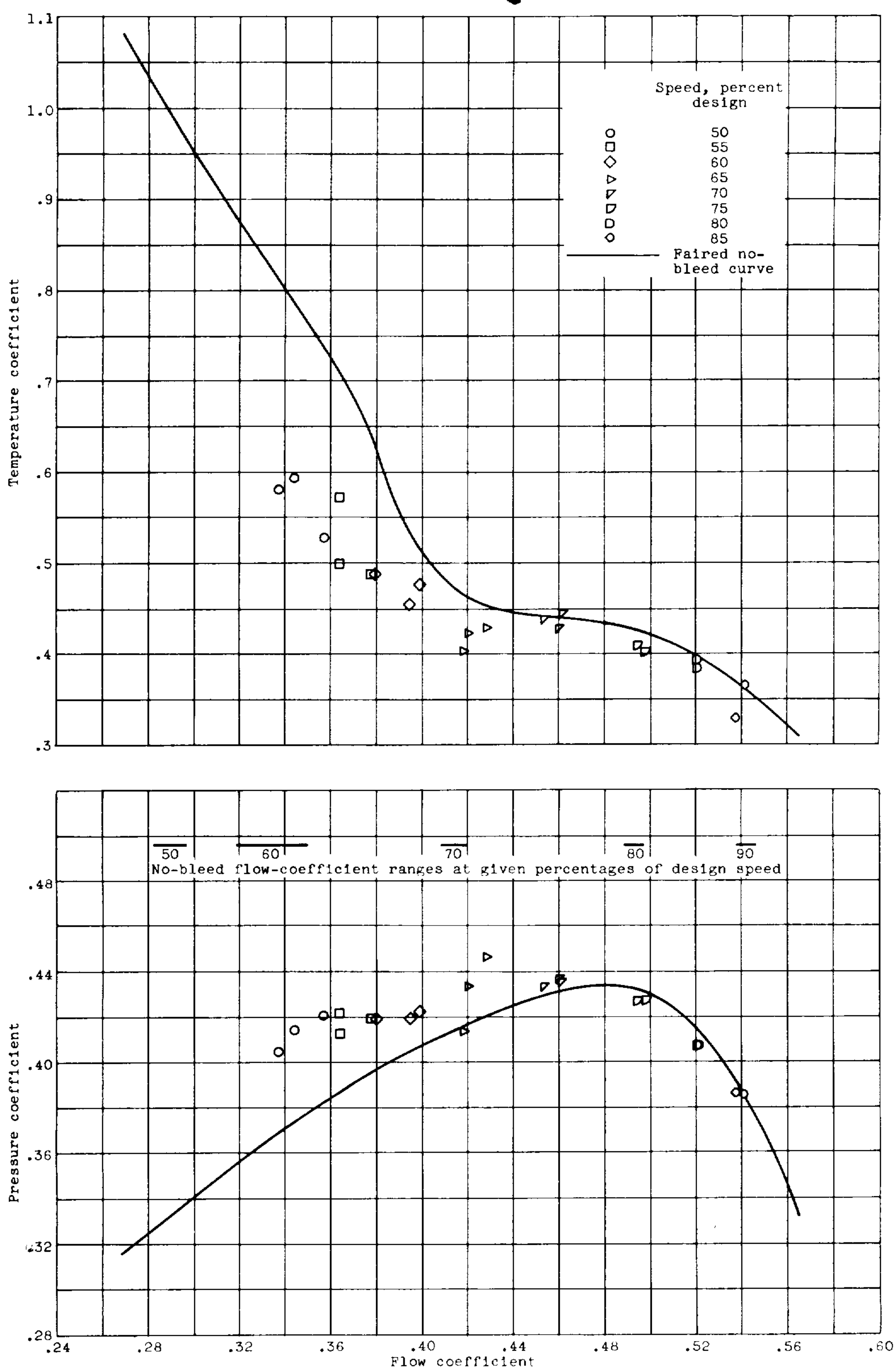


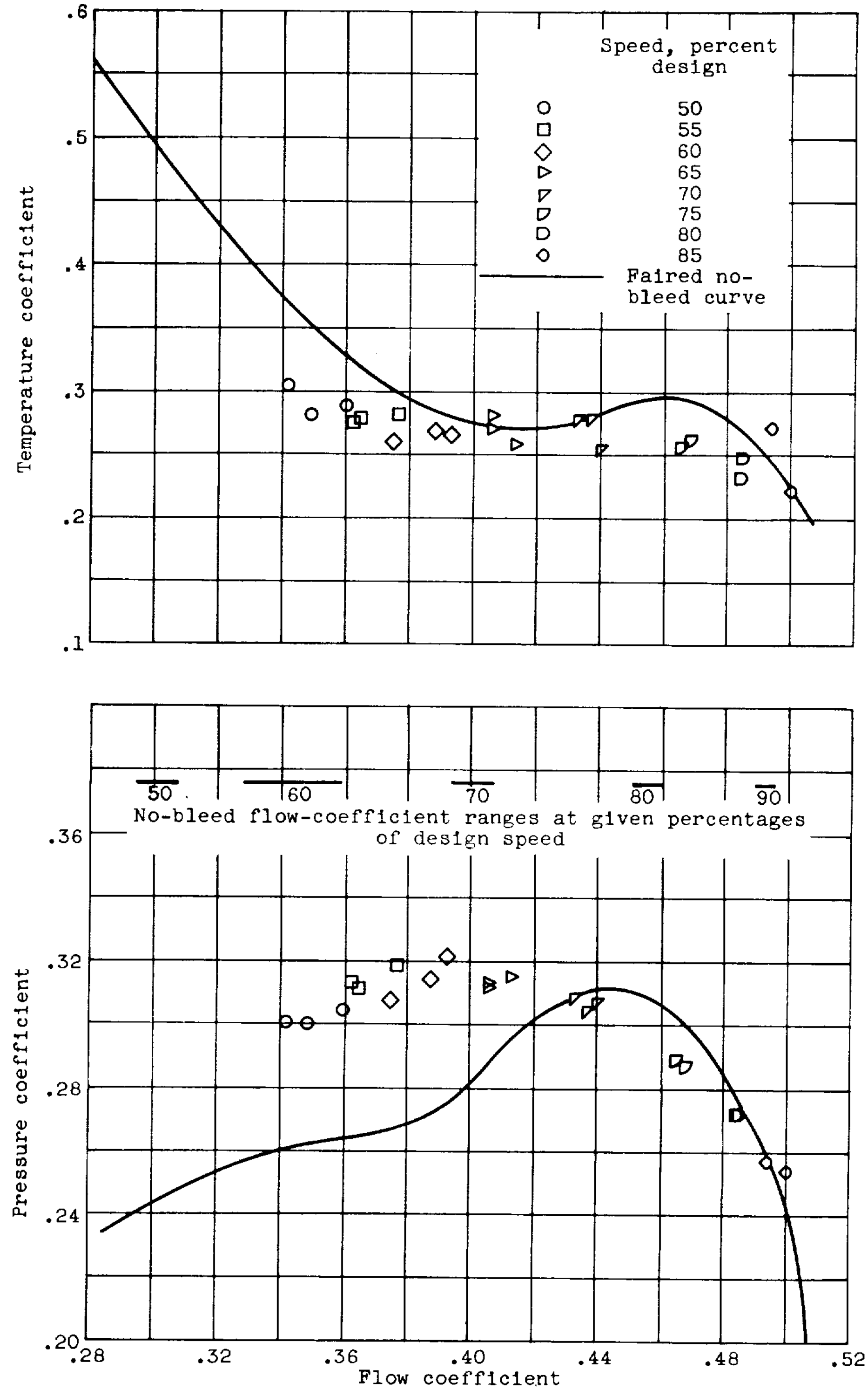
(a) First stage.

Figure 6. - Performance characteristics with fifth-stage bleed.

[redacted]

[redacted]

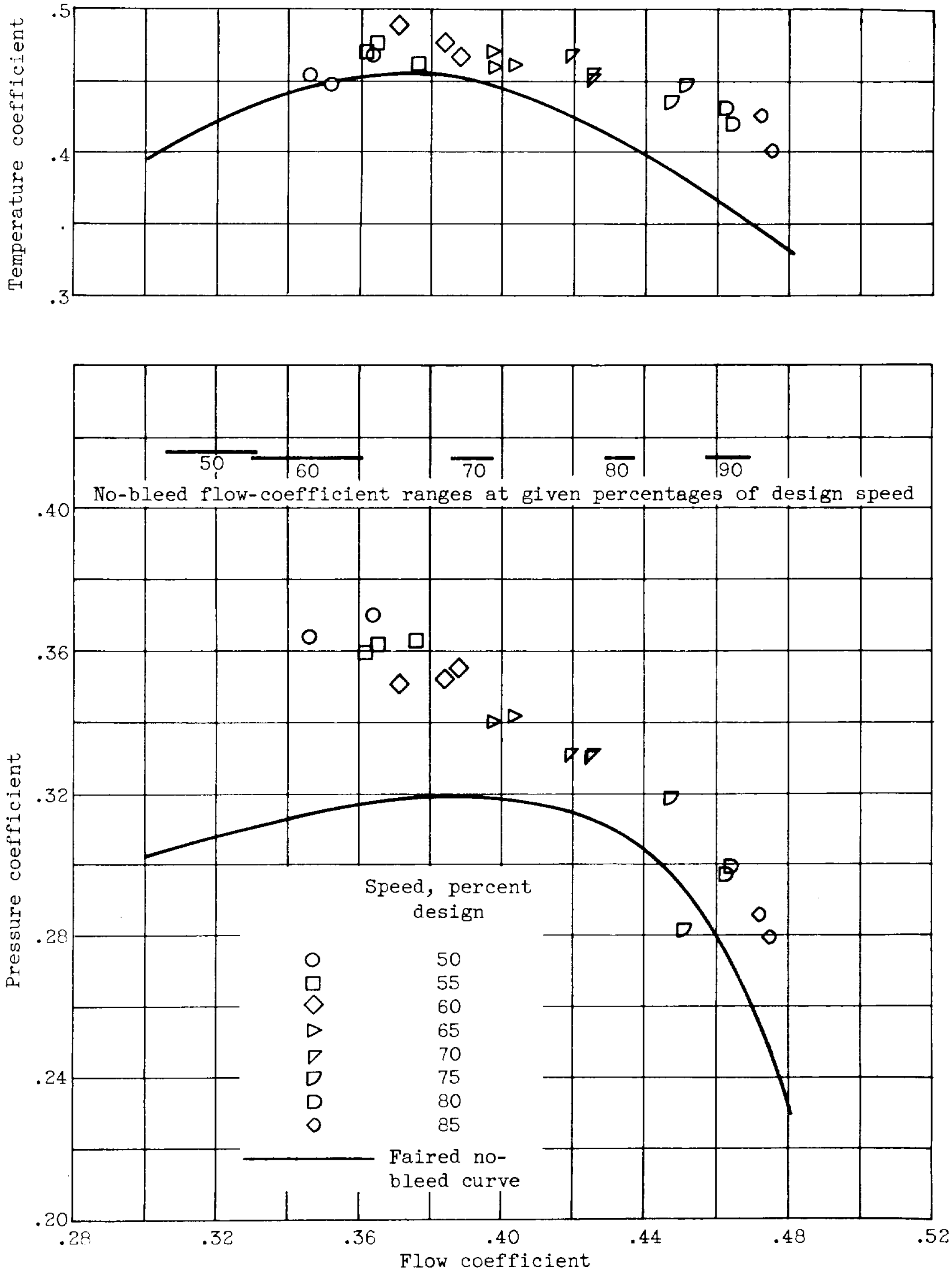
4776



(b) Second stage.

Figure 6. - Continued. Performance characteristics with fifth-stage bleed.

[redacted]



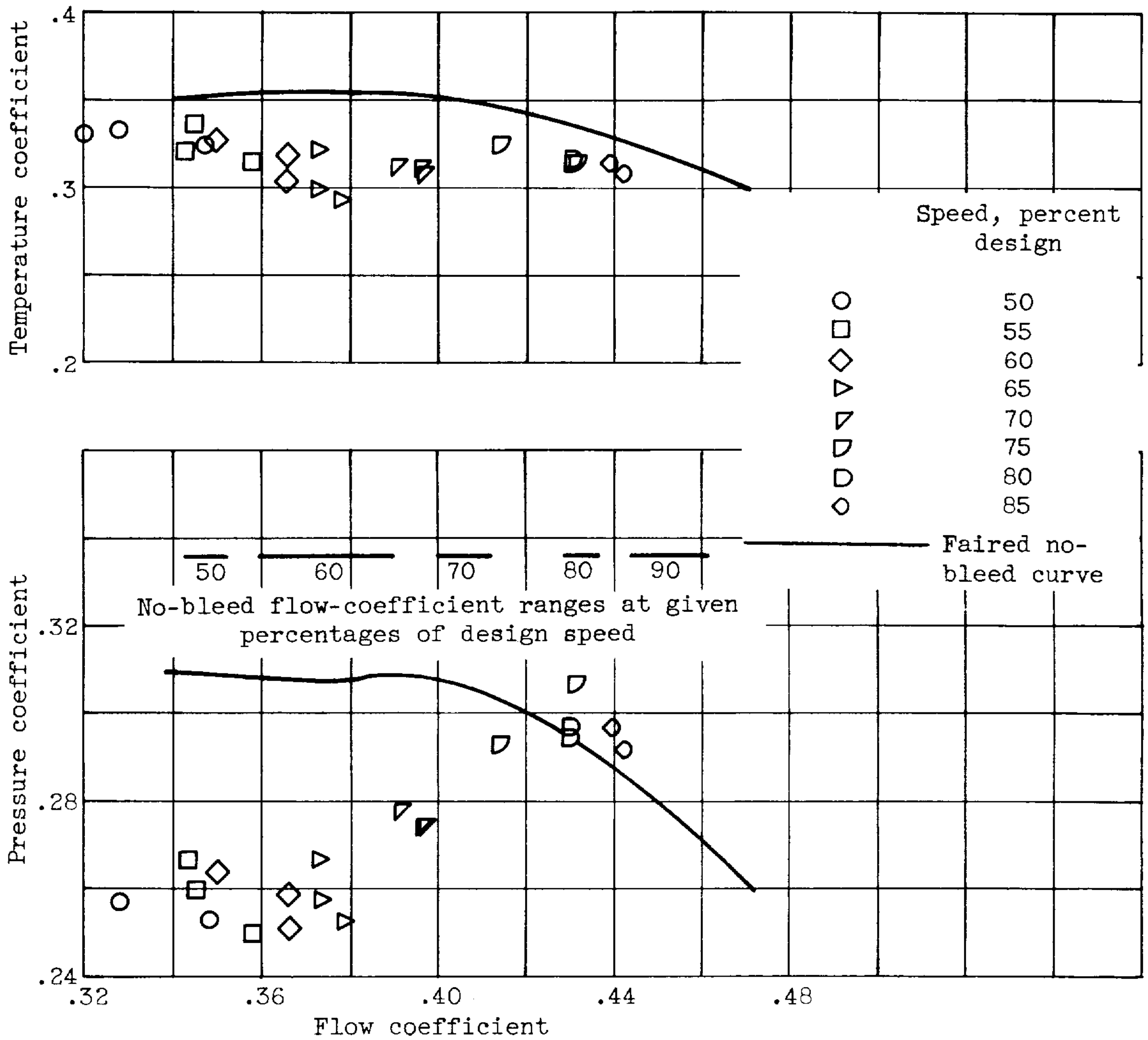
(c) Stages 3 and 4.

Figure 6. - Continued. Performance characteristics with fifth-stage bleed.

[redacted]

[redacted]

4776



(d) Stages 5 to 9.

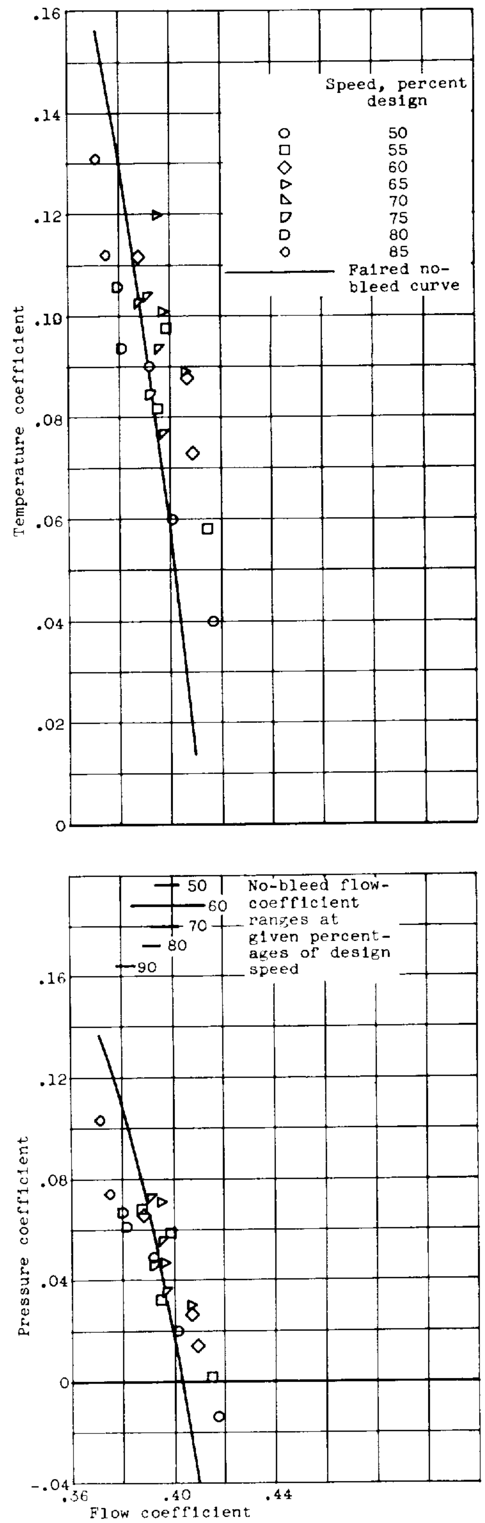
Figure 6. - Continued. Performance characteristics with fifth-stage bleed.

[redacted]

[redacted]

4776

CW-4



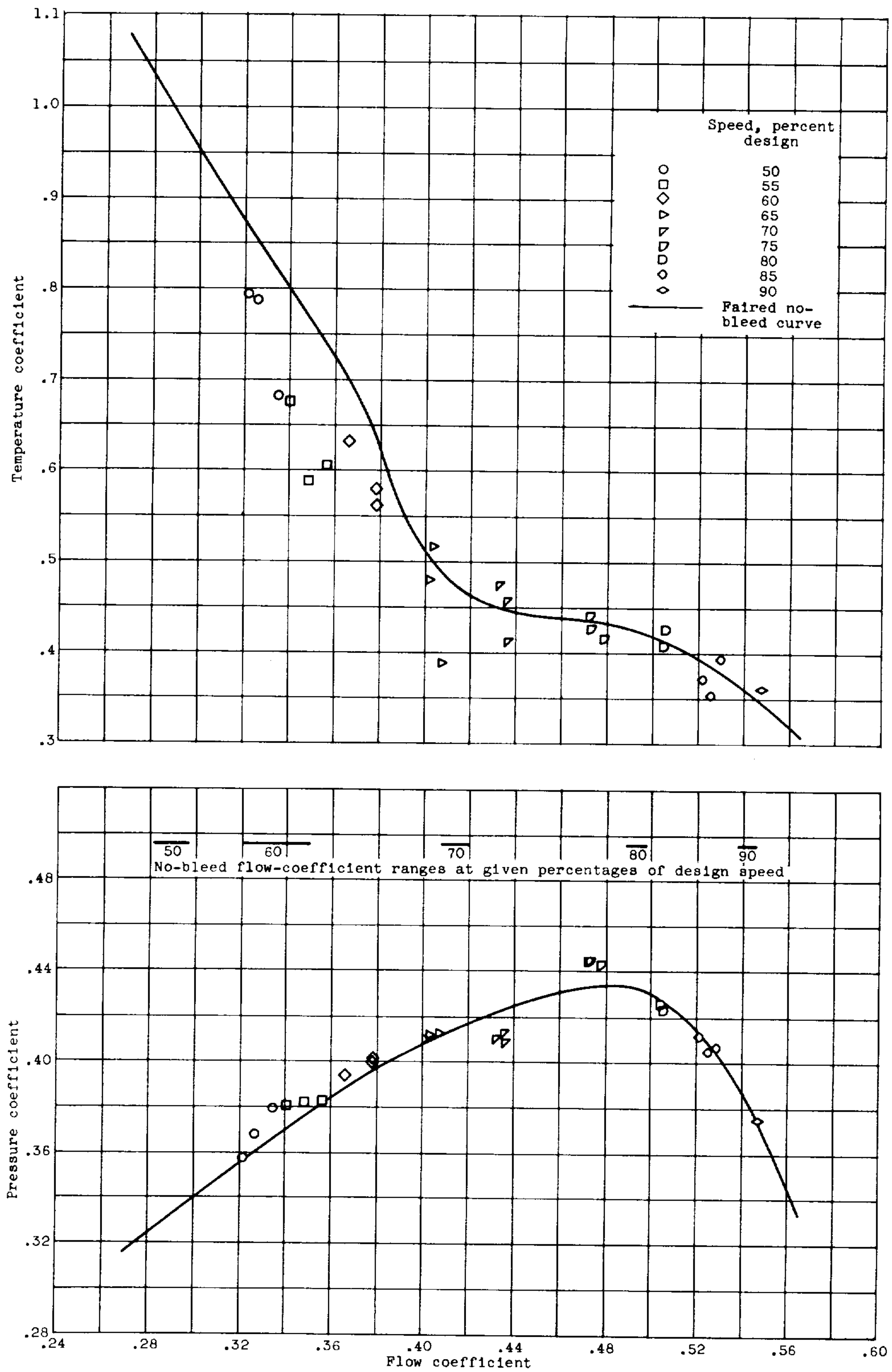
(e) Stages 10 to 13.

Figure 6. - Concluded. Performance characteristics with fifth-stage bleed.

[redacted]

[redacted]

4776



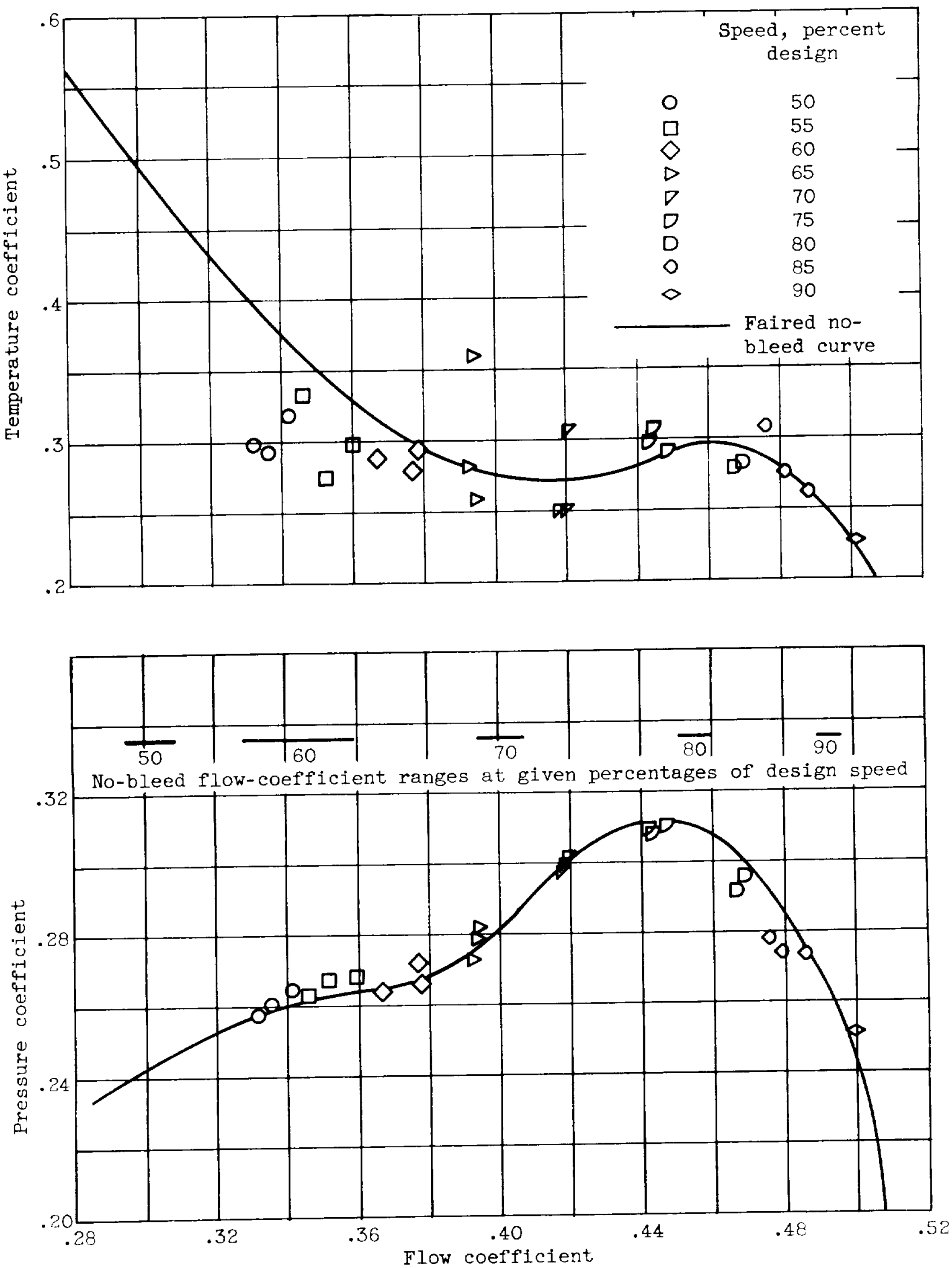
(a) First stage.

Figure 7. - Performance characteristics with tenth-stage bleed.

[redacted]

[redacted]

CW-4 back 4776

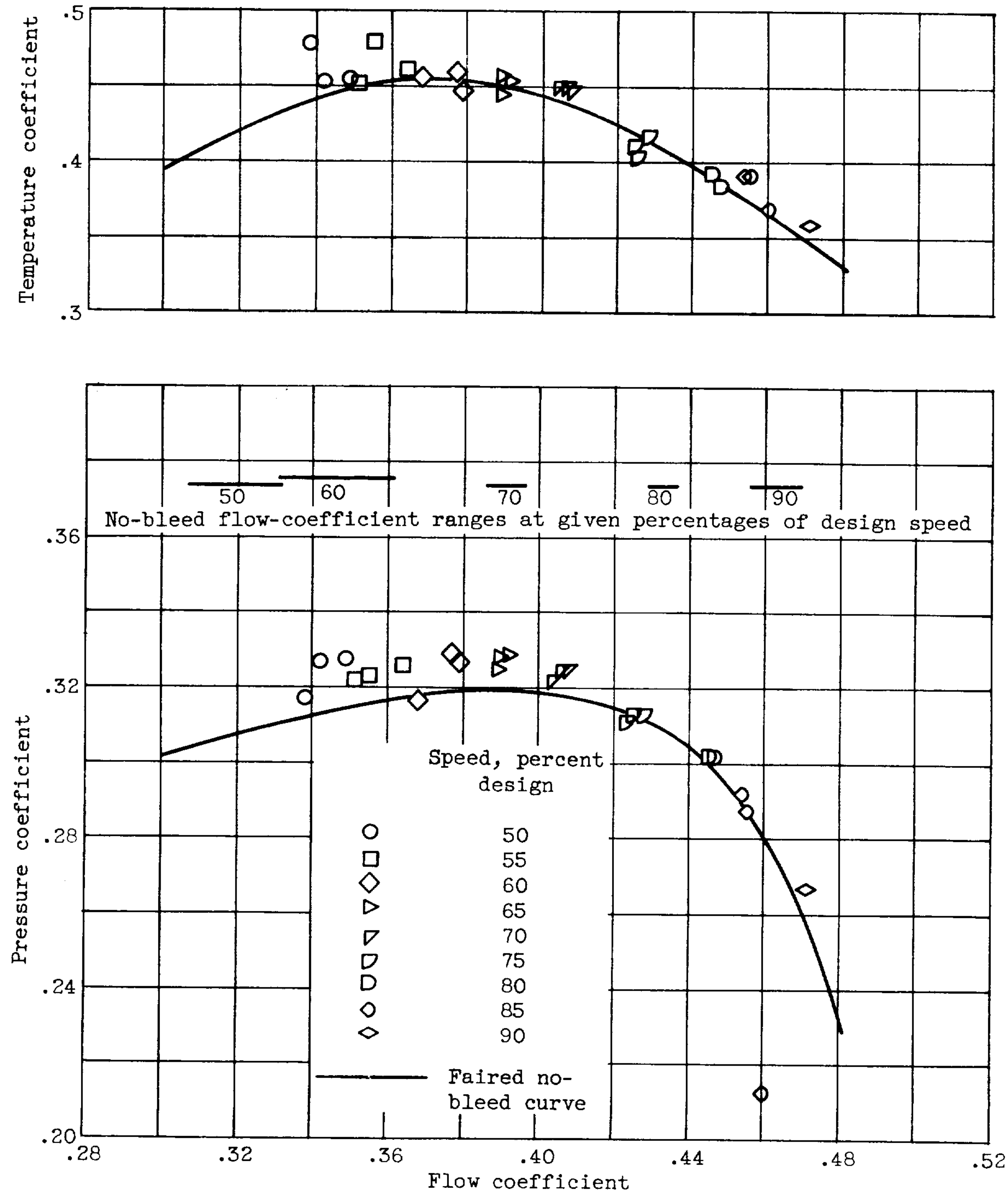


(b) Second stage.

Figure 7. - Continued. Performance characteristics with tenth-stage bleed.

[redacted]

[redacted]



(c) Stages 3 and 4.

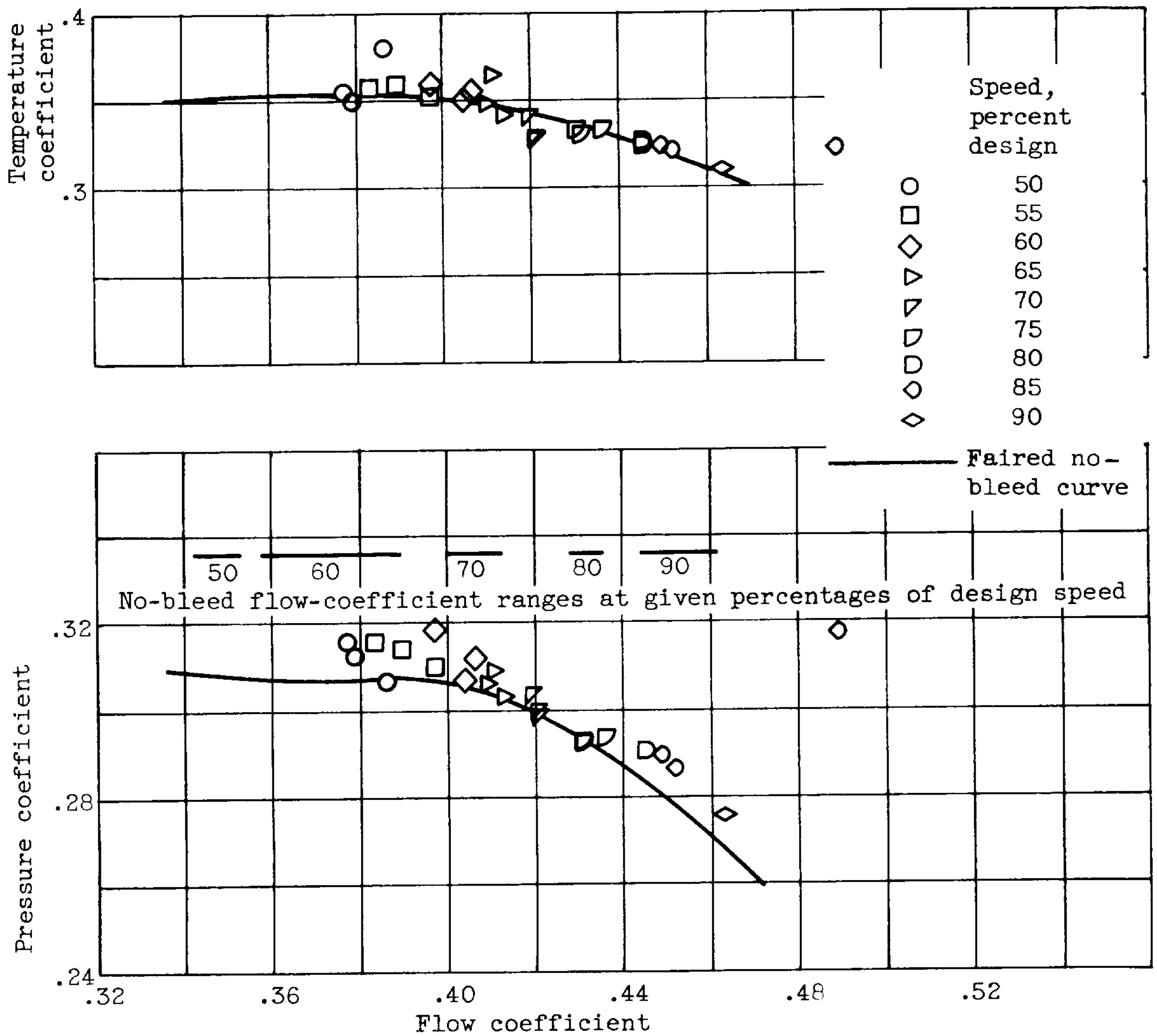
Figure 7. - Continued. Performance characteristics with tenth-stage bleed.

4776

[redacted]

[redacted]

4776

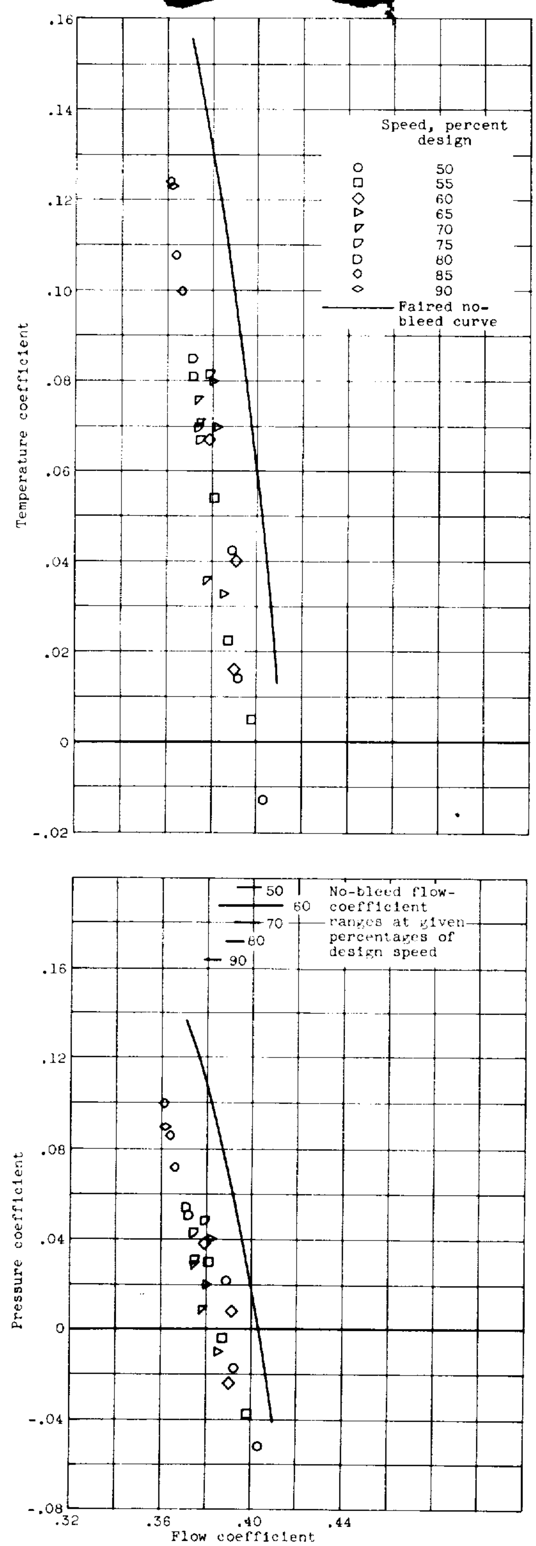


(d) Stages 5 to 9.

Figure 7. - Continued. Performance characteristics with tenth-stage bleed.

[redacted]

[redacted]



(e) Stages 10 to 13.

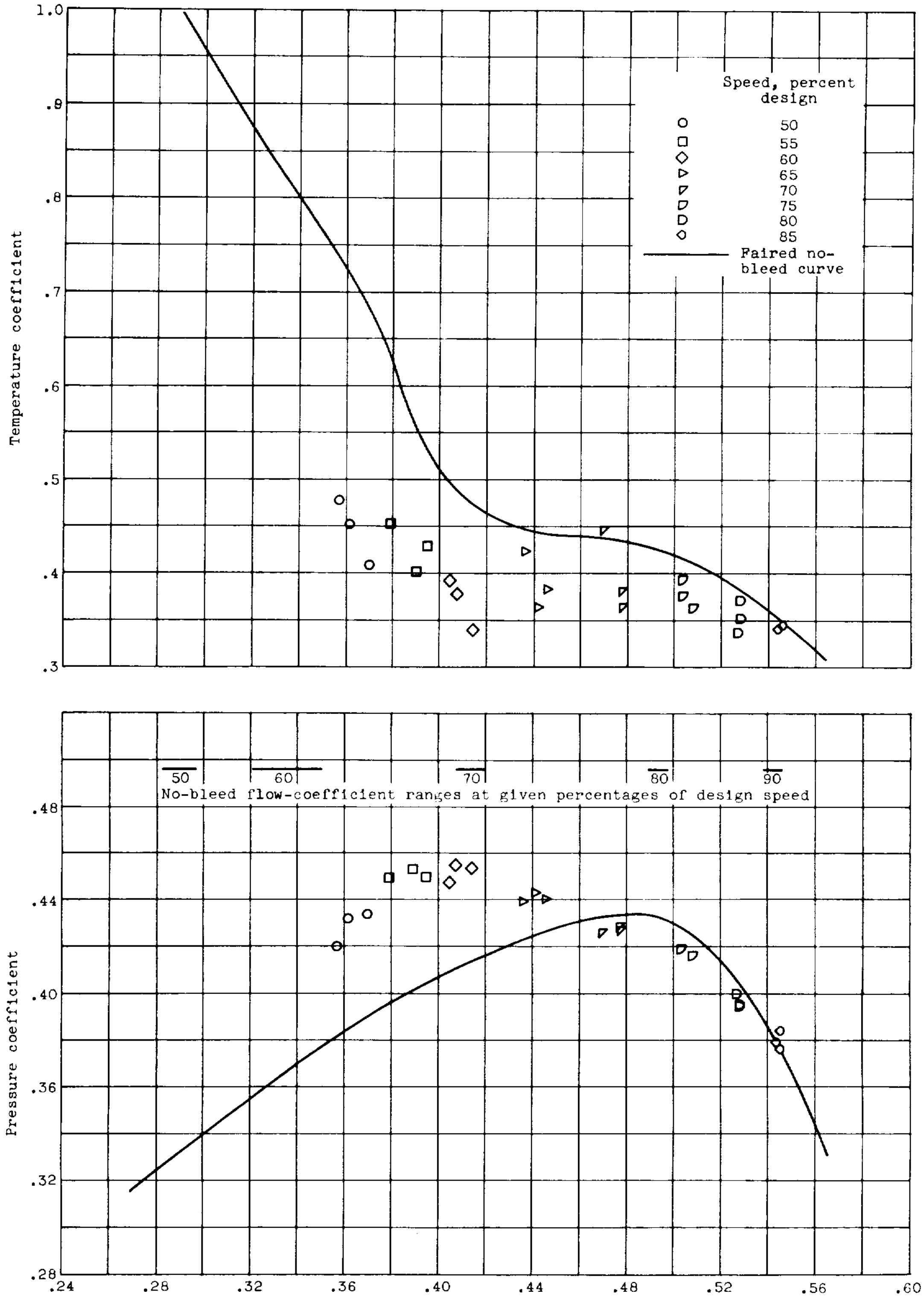
Figure 7. - Concluded. Performance characteristics with tenth-stage bleed.

[redacted]

4776

[redacted]

4776



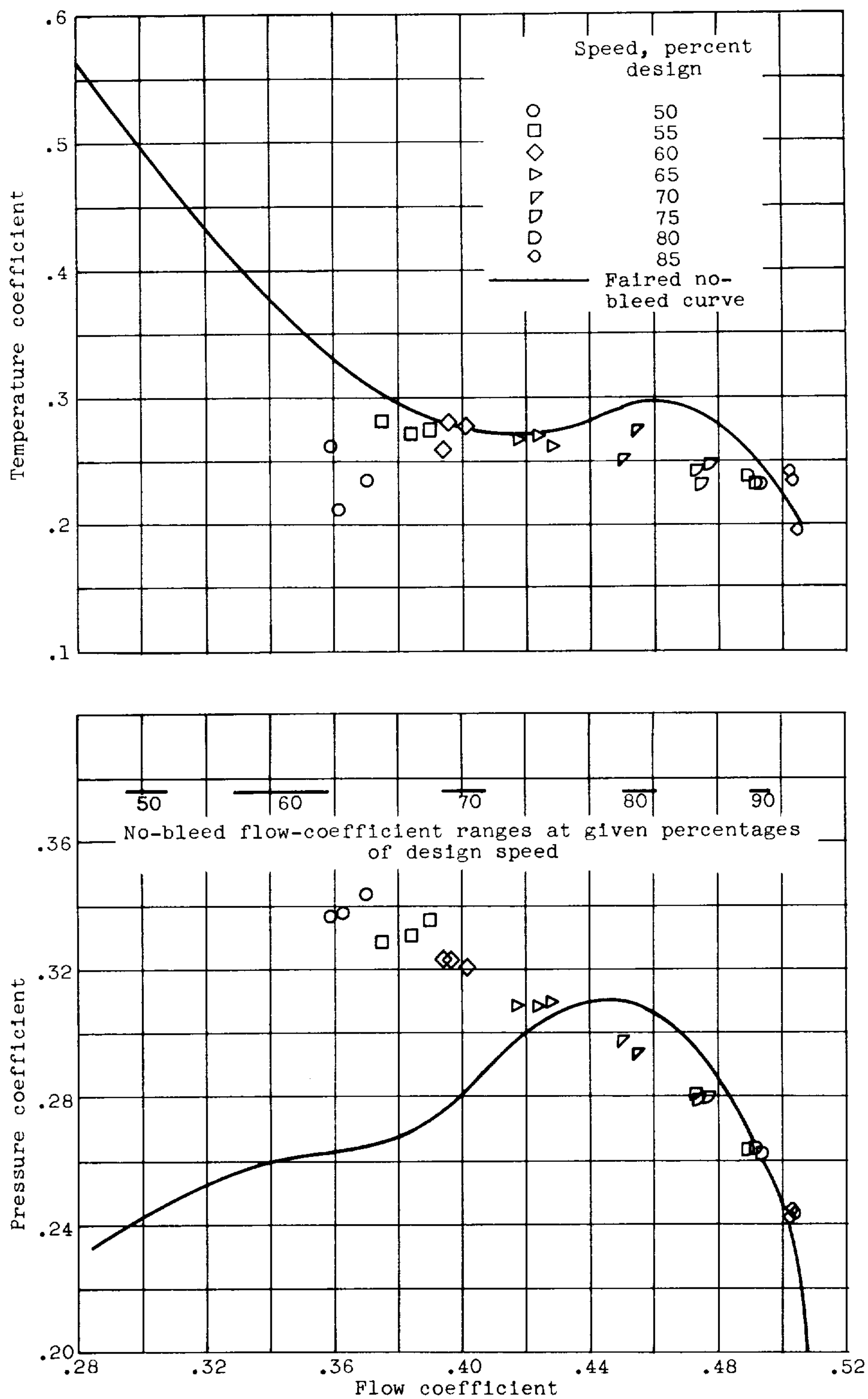
(a) First stage.

Figure 8. - Performance characteristics with fifth- and tenth-stage bleed.

[redacted]

[redacted]

4776



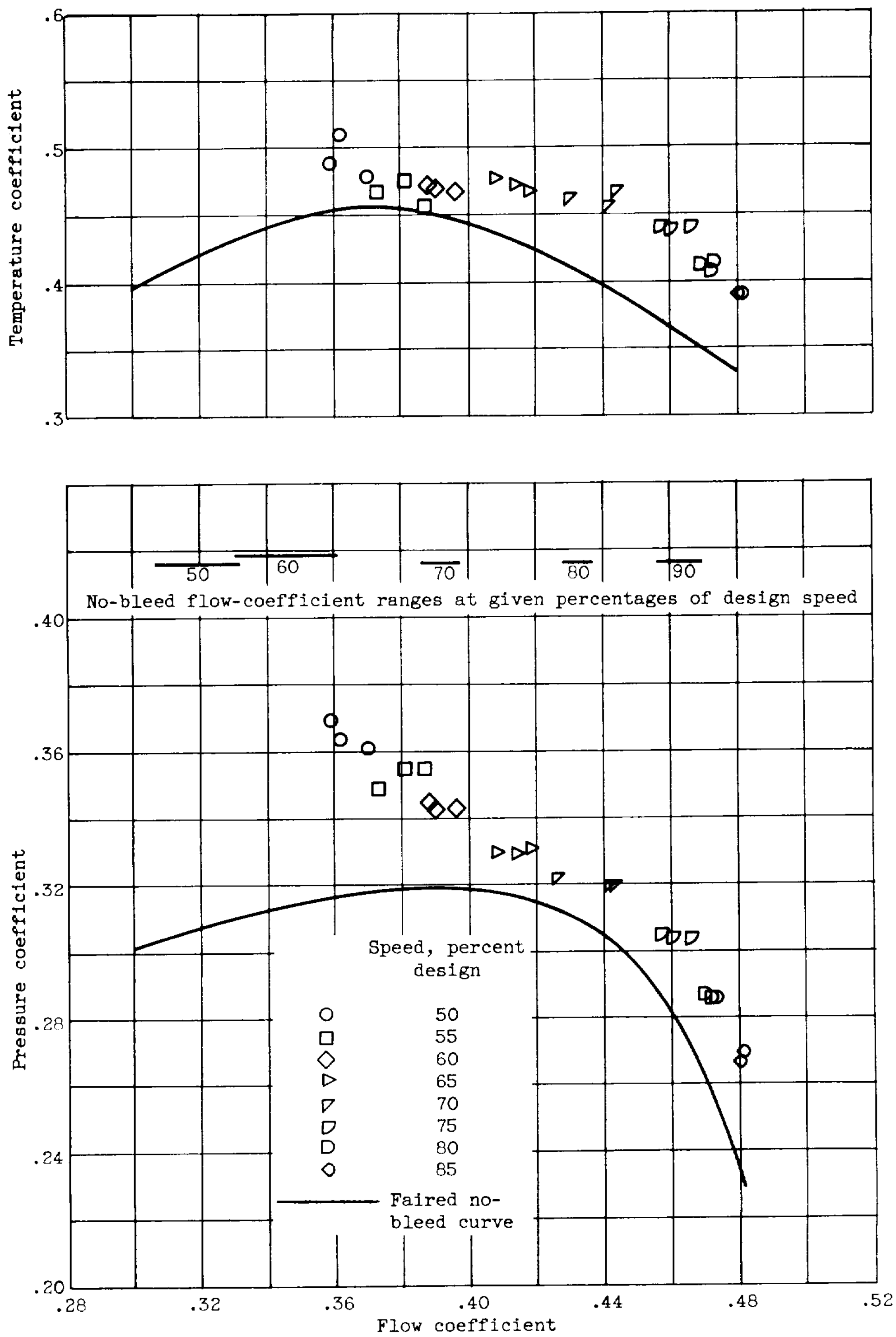
(b) Second stage.

Figure 8. - Continued. Performance characteristics with fifth- and tenth-stage bleed.

[redacted]

4776

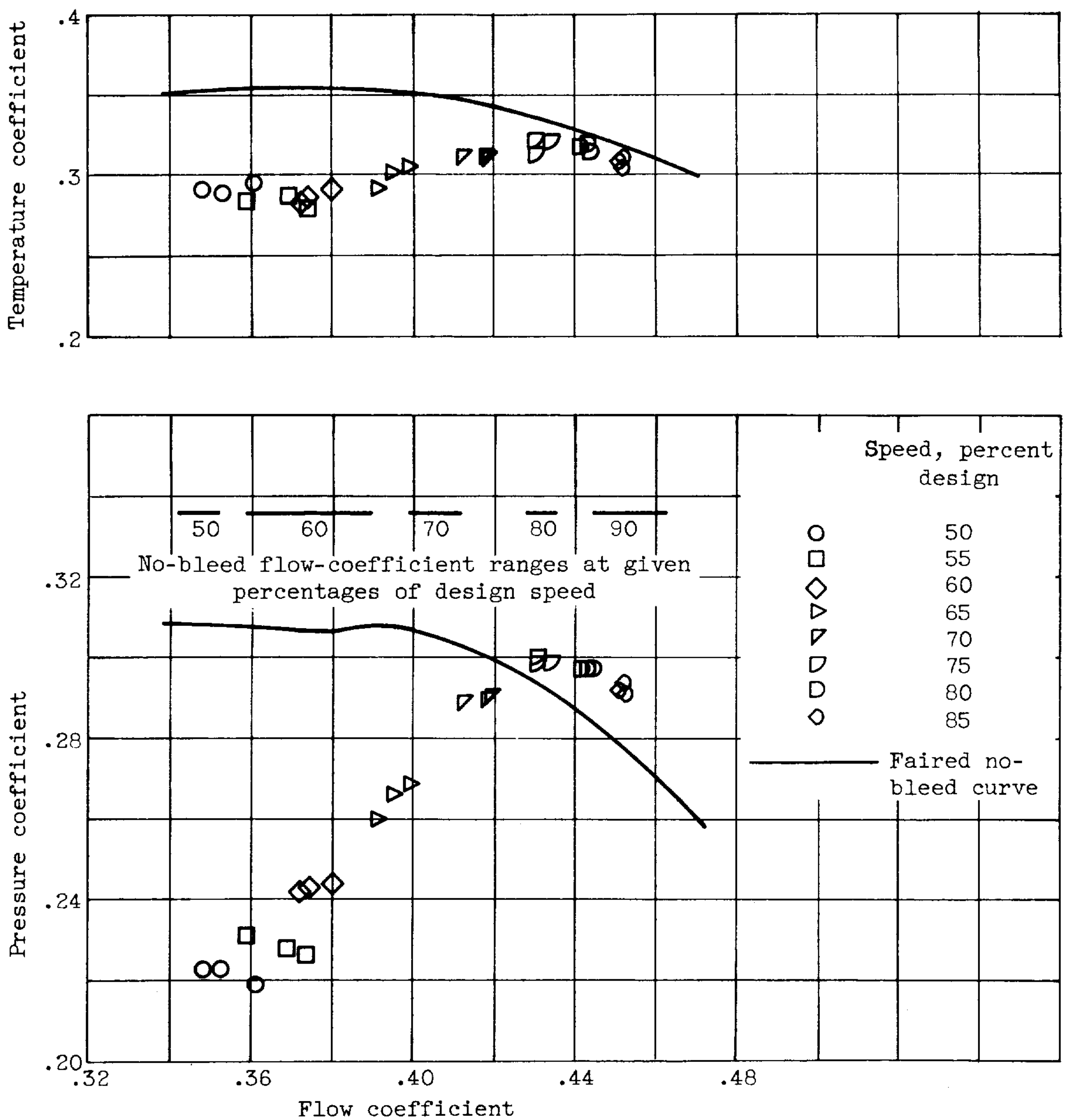
CW-5



(c) Stages 3 and 4.

Figure 8. - Continued. Performance characteristics with fifth- and tenth-stage bleed.

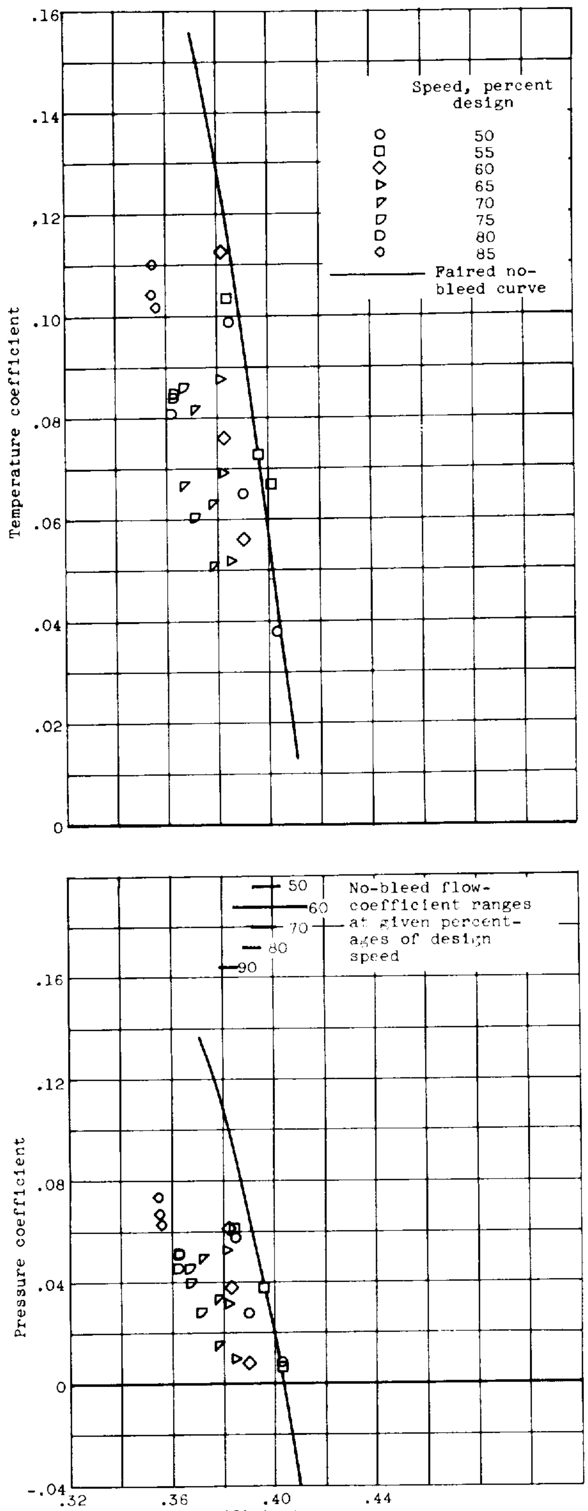
4776



(d) Stages 5 to 9.

Figure 8. - Continued. Performance characteristics with fifth- and tenth-stage bleed.

[redacted]



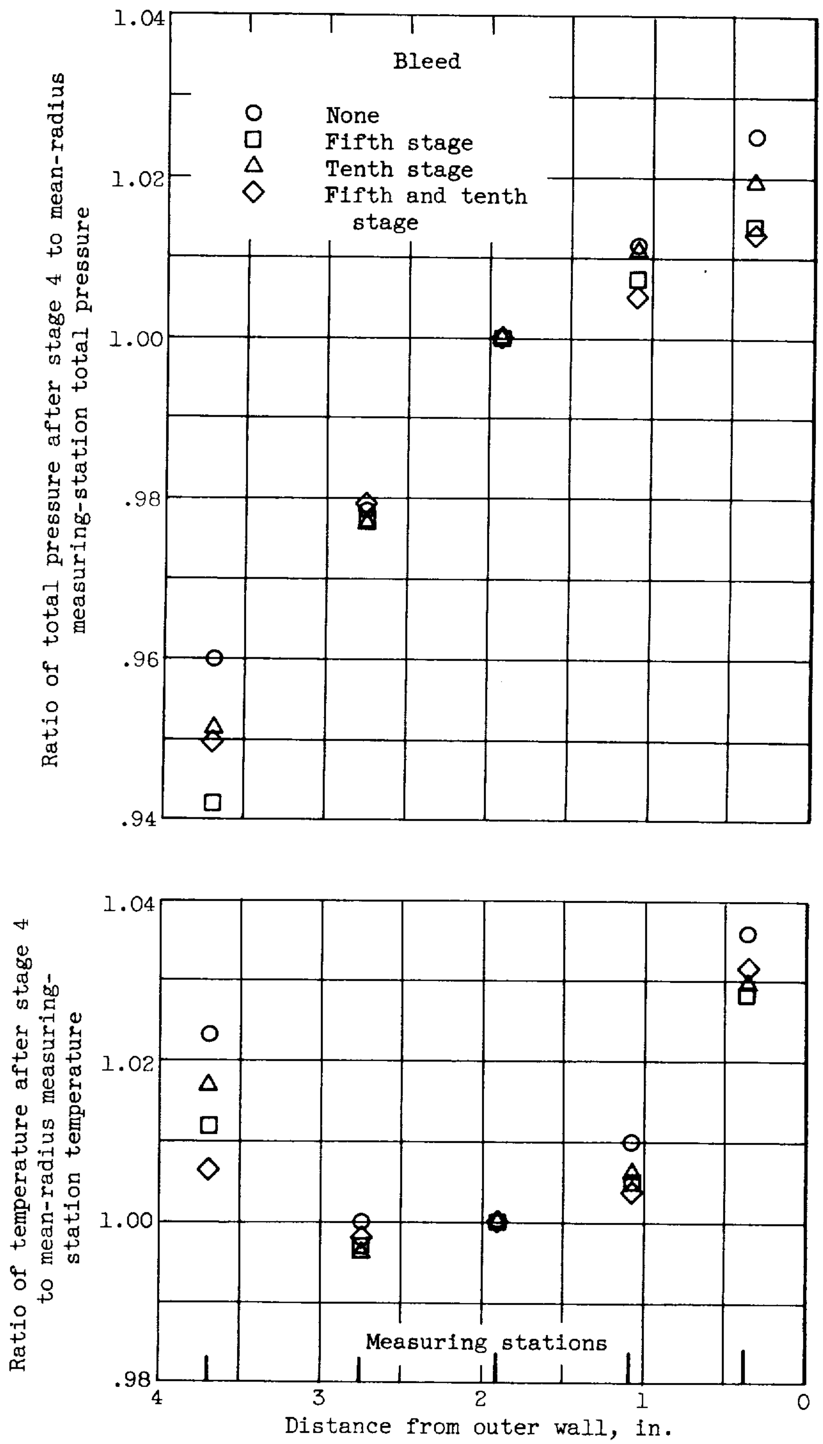
(e) Stages 10 to 13.

Figure 8. - Concluded. Performance characteristics with fifth- and tenth-stage bleed.

[redacted]

[redacted]

4776

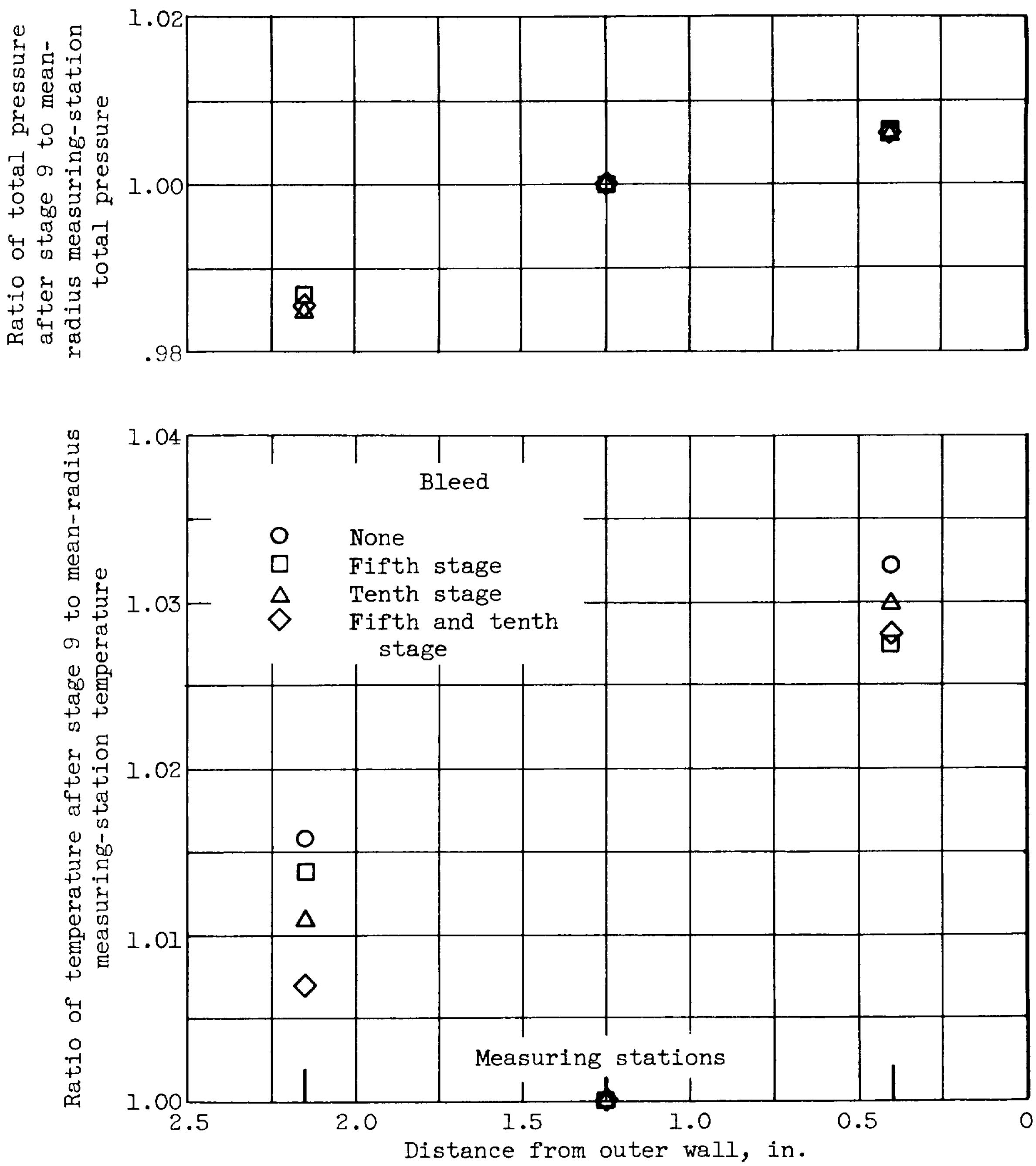


(a) After stage 4.

Figure 9. - Radial gradients of temperature and total pressure with rated nozzle area at 80 percent design speed.

[redacted]

4776

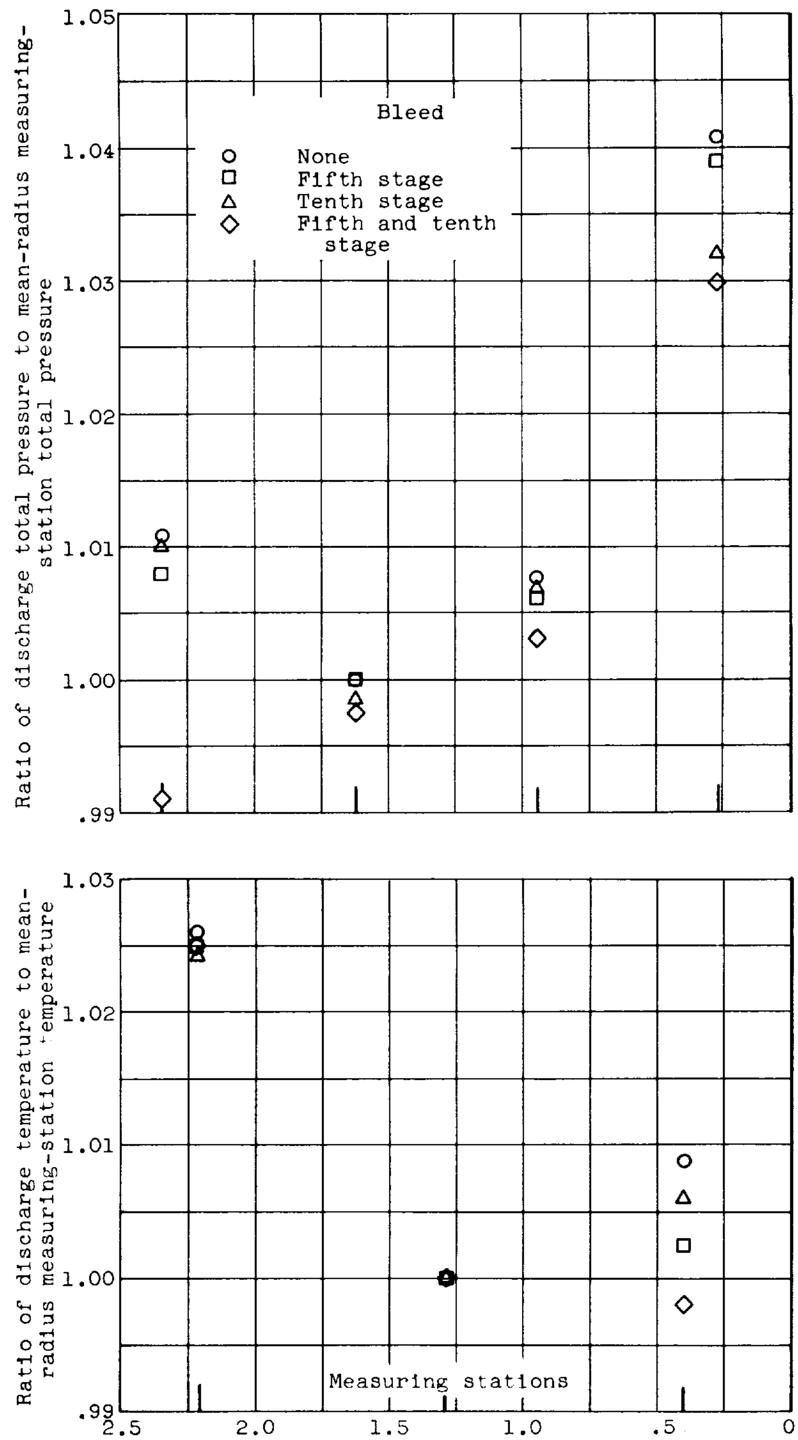


(b) After stage 9.

Figure 9. - Continued. Radial gradients of temperature and total pressure with rated nozzle area at 80 percent design speed.

[redacted]

4776



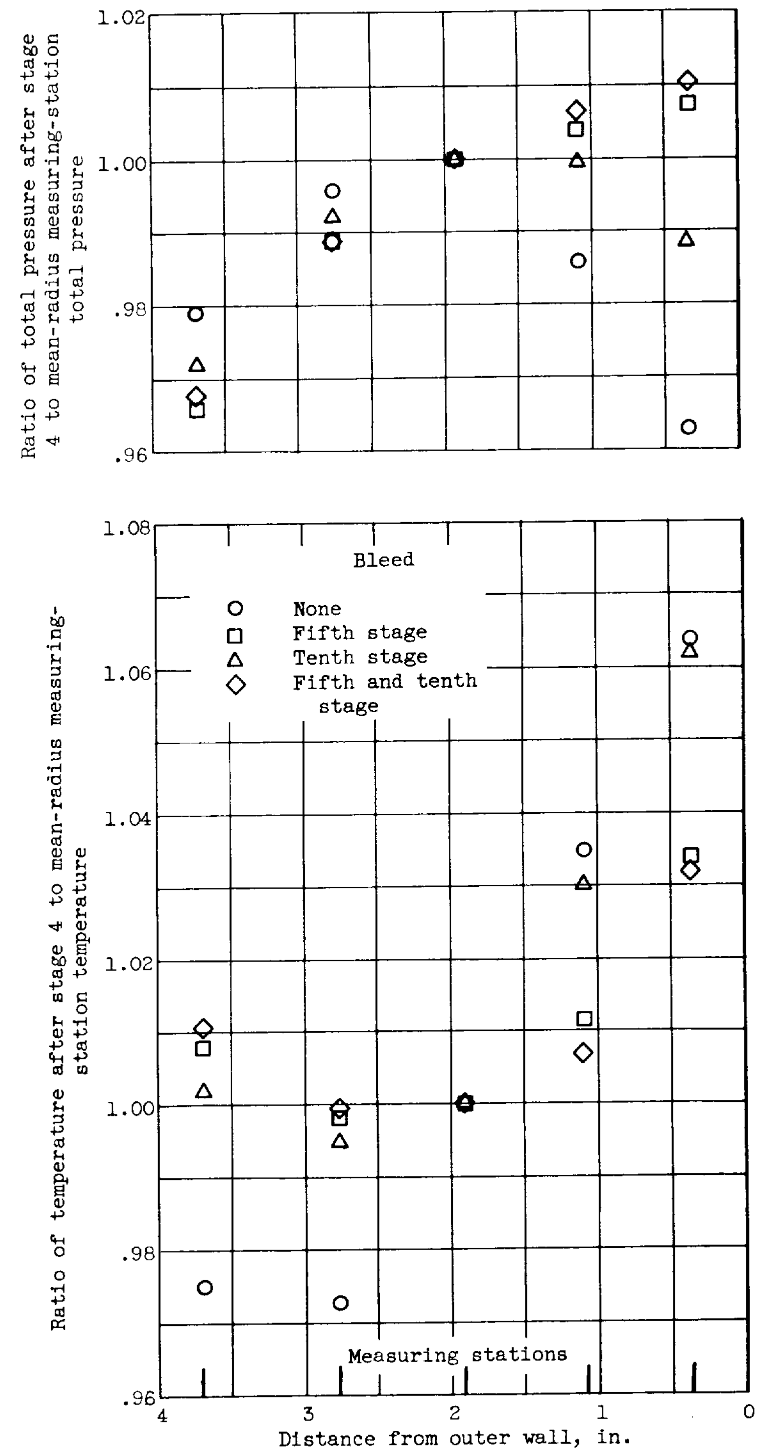
(c) After compressor discharge.

Figure 9. - Concluded. Radial gradients of temperature and total pressure with rated nozzle area at 80 percent design speed.

[redacted]

[redacted]

4776



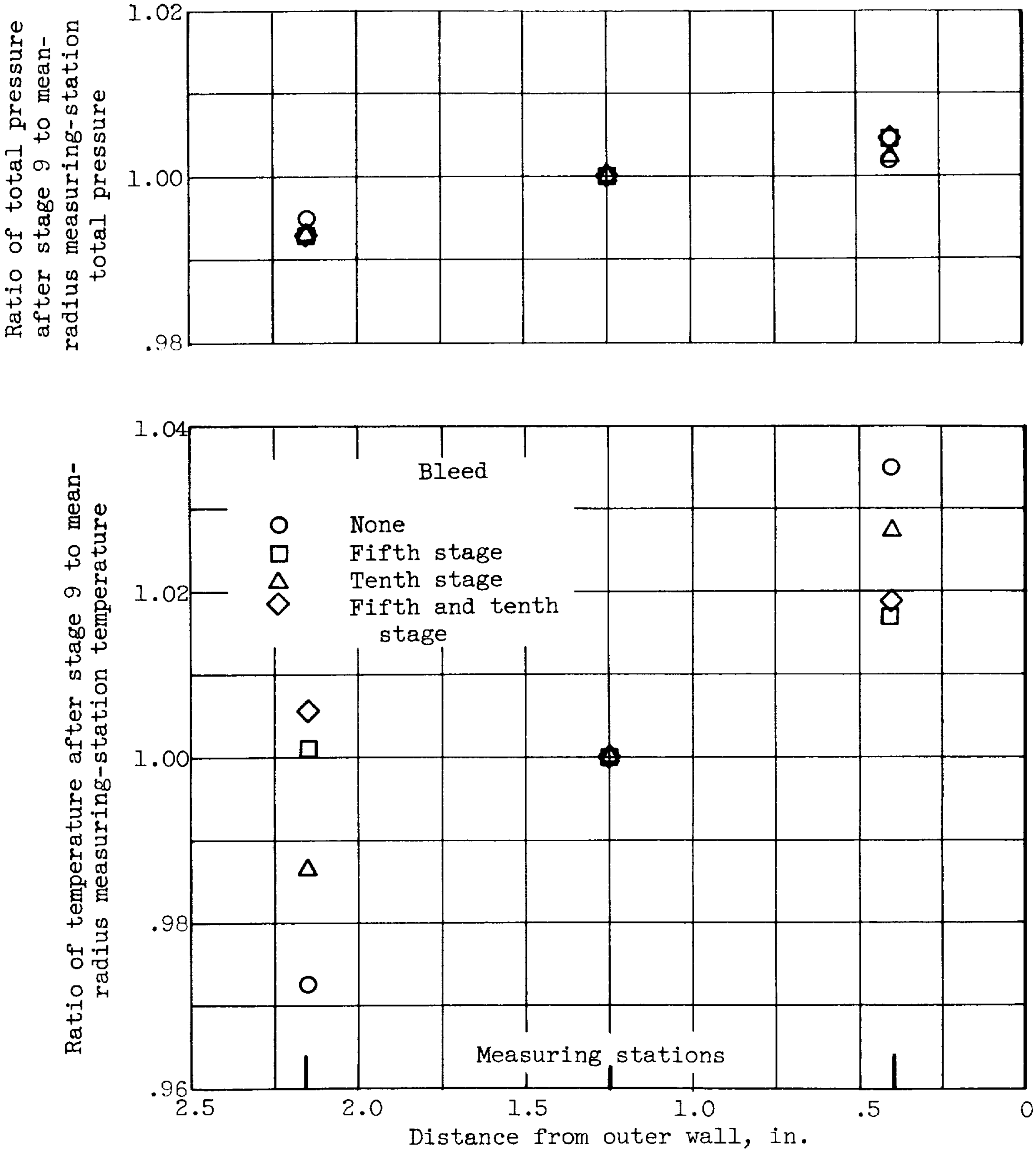
(a) After stage 4.

Figure 10. - Radial gradients of temperature and total pressure with rated nozzle area at 60 percent design speed.

[redacted]

[redacted]

4776



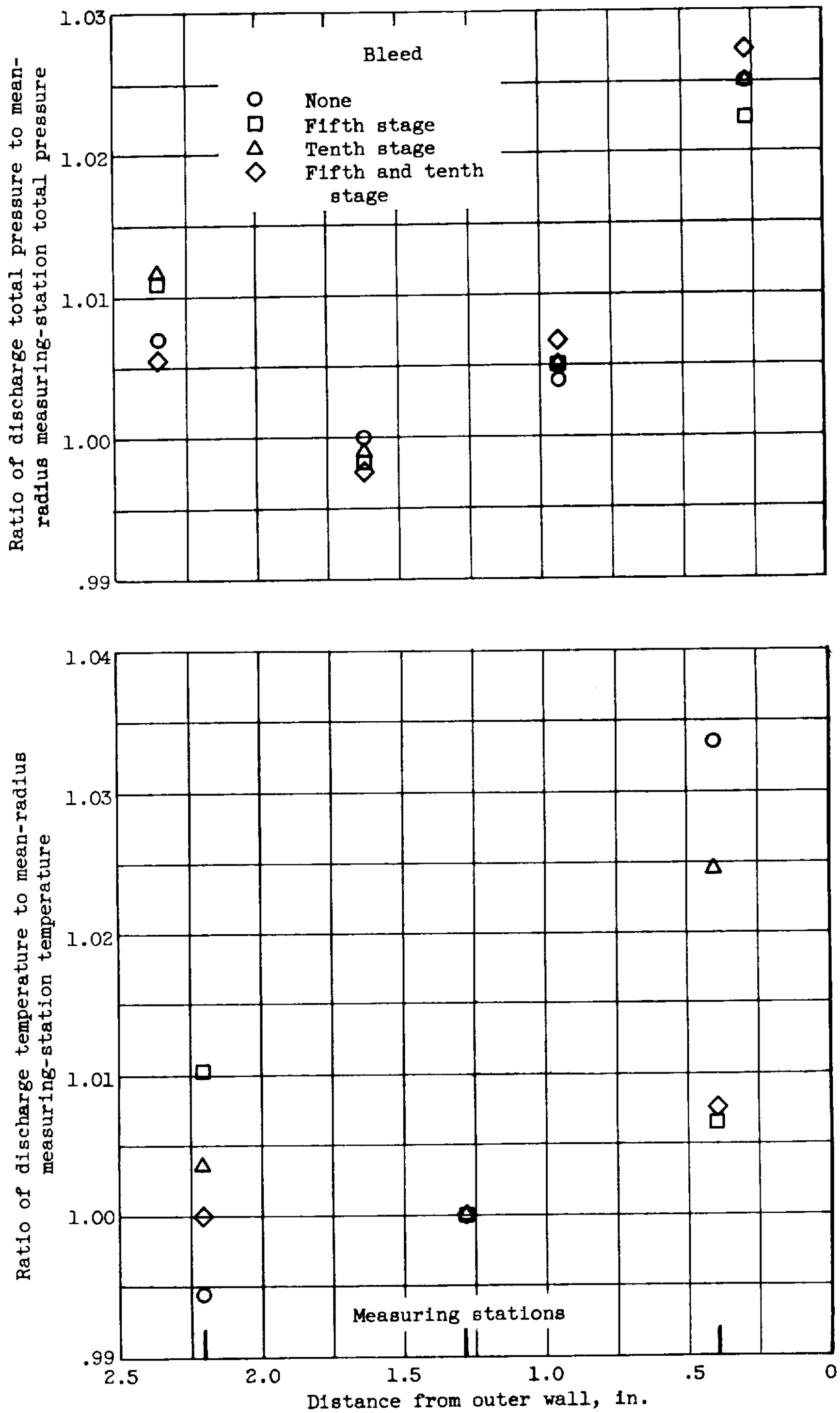
(b) After stage 9.

Figure 10. - Continued. Radial gradients of temperature and total pressure with rated nozzle area at 60 percent design speed.

[redacted]

4776

CW-6



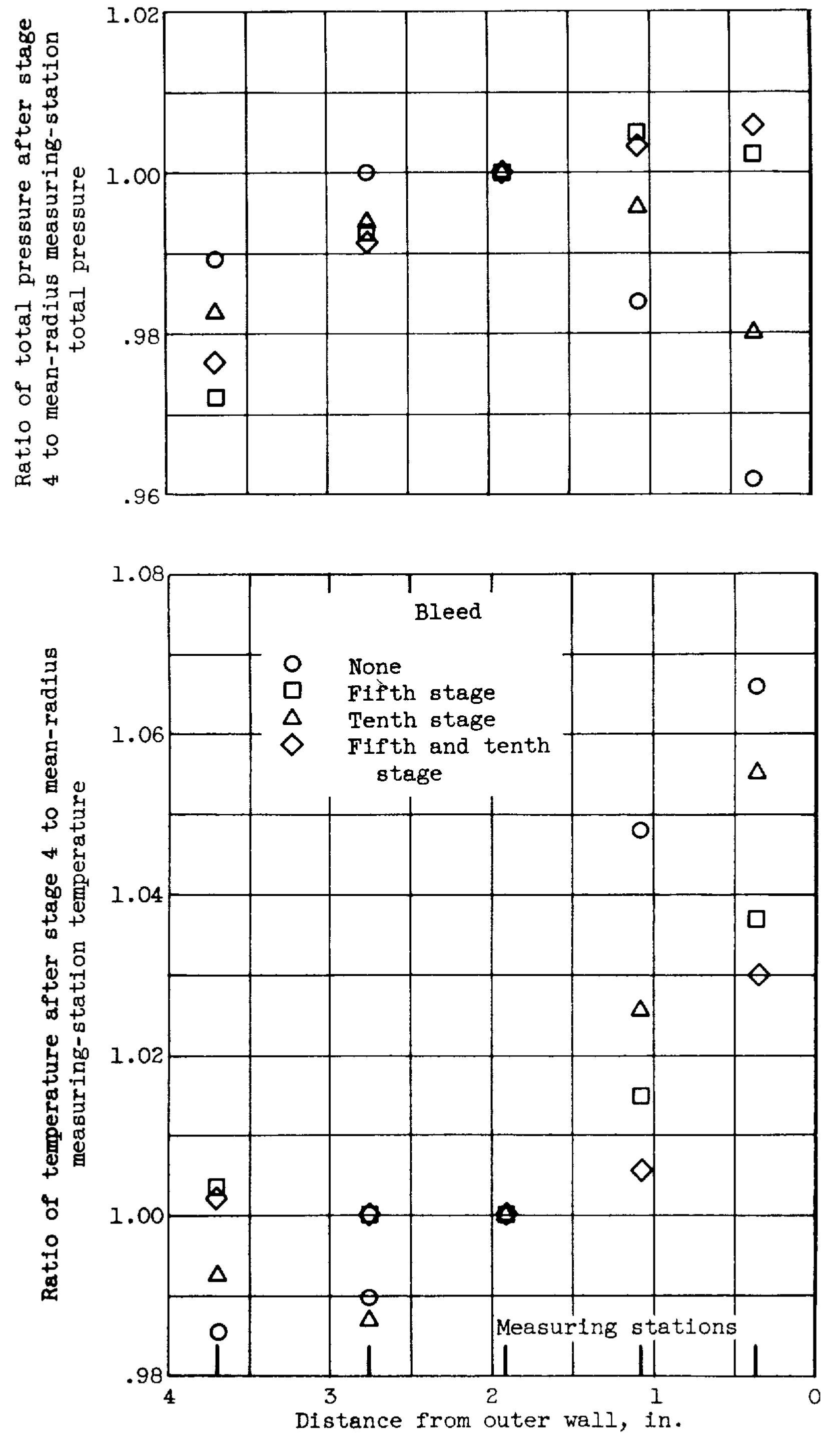
(c) After compressor discharge.

Figure 10. - Concluded. Radial gradients of temperature and total pressure with rated nozzle area at 60 percent design speed.

[redacted]

[redacted]

4776



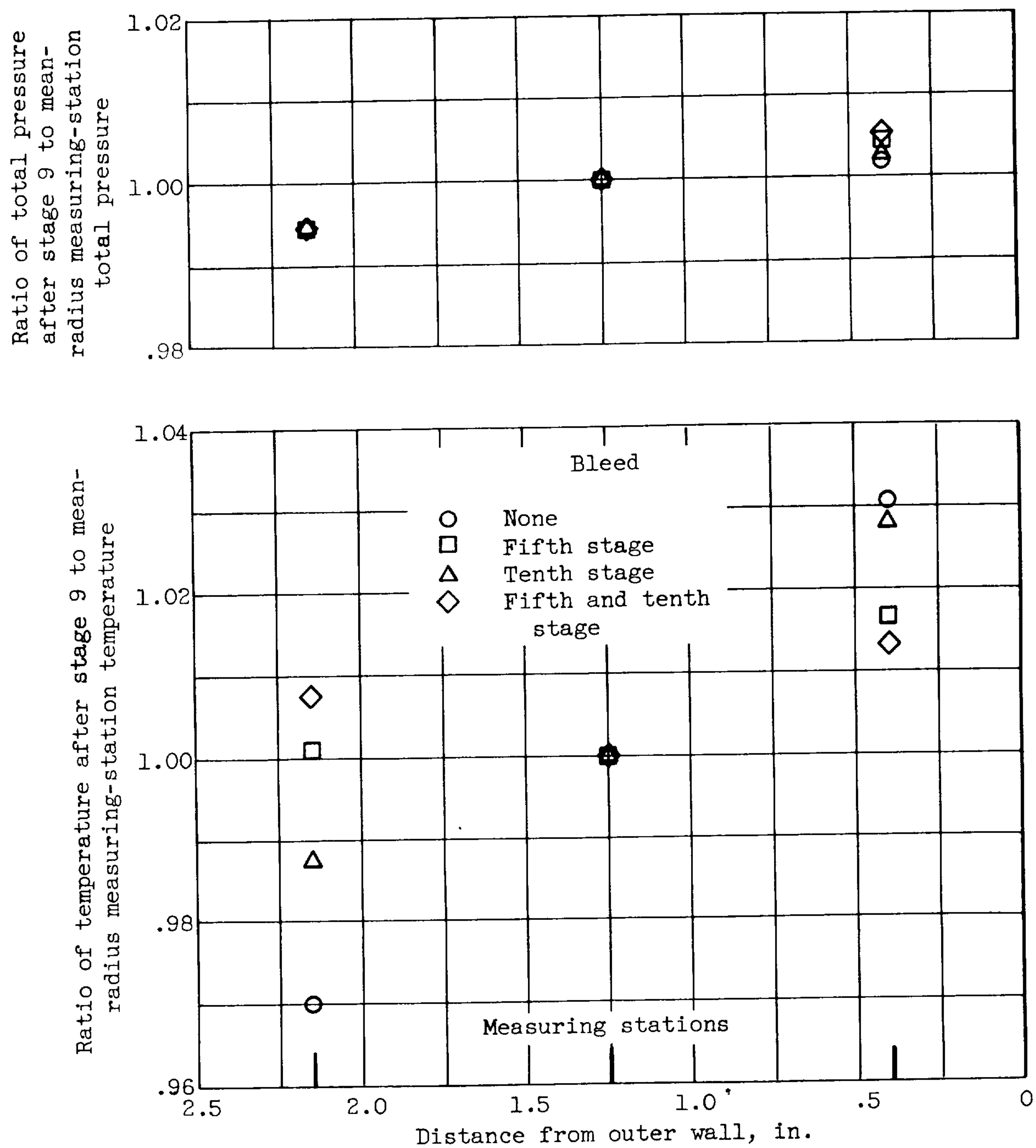
(a) After stage 4.

Figure 11. - Radial gradients of temperature and total pressure with rated nozzle area at 50 percent design speed.

[redacted]

[redacted]

CW-6 back 4776



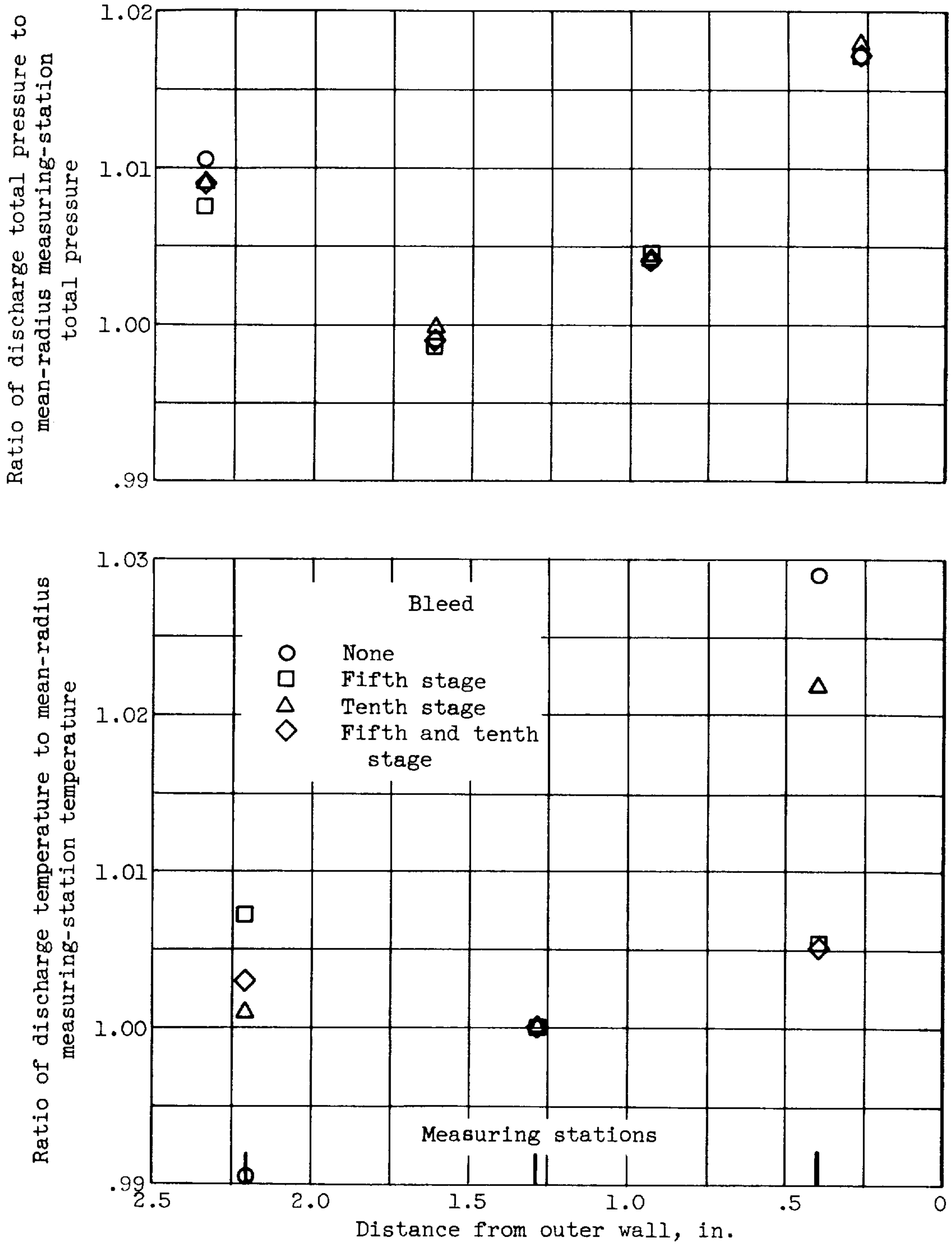
(b) After stage 9.

Figure 11. - Continued. Radial gradients of temperature and total pressure with rated nozzle area at 50 percent design speed.

[redacted]

[redacted]

4776



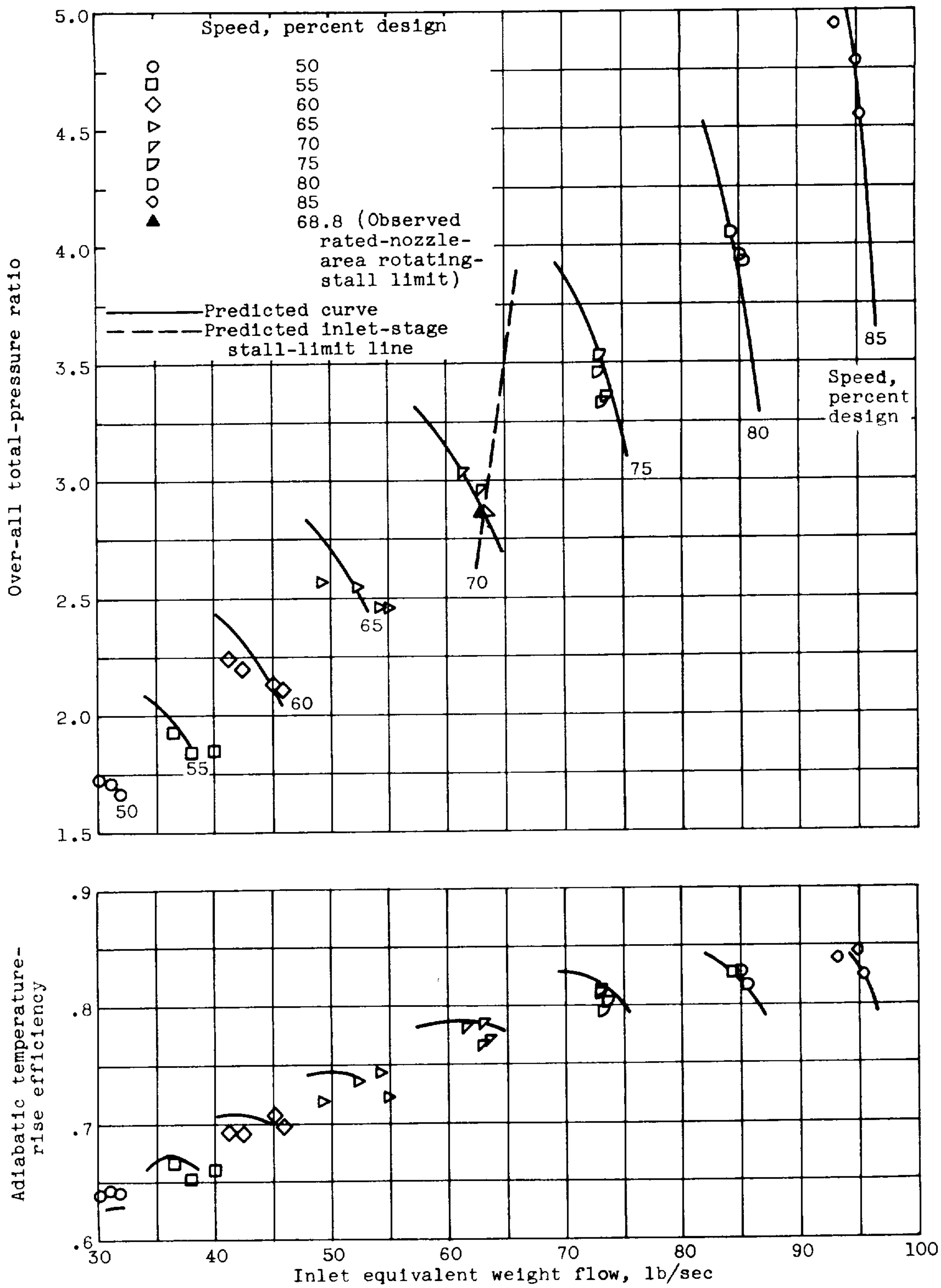
(c) After compressor discharge.

Figure 11. - Concluded. Radial gradients of temperature and total pressure with rated nozzle area at 50 percent design speed.

[redacted]

[redacted]

4776



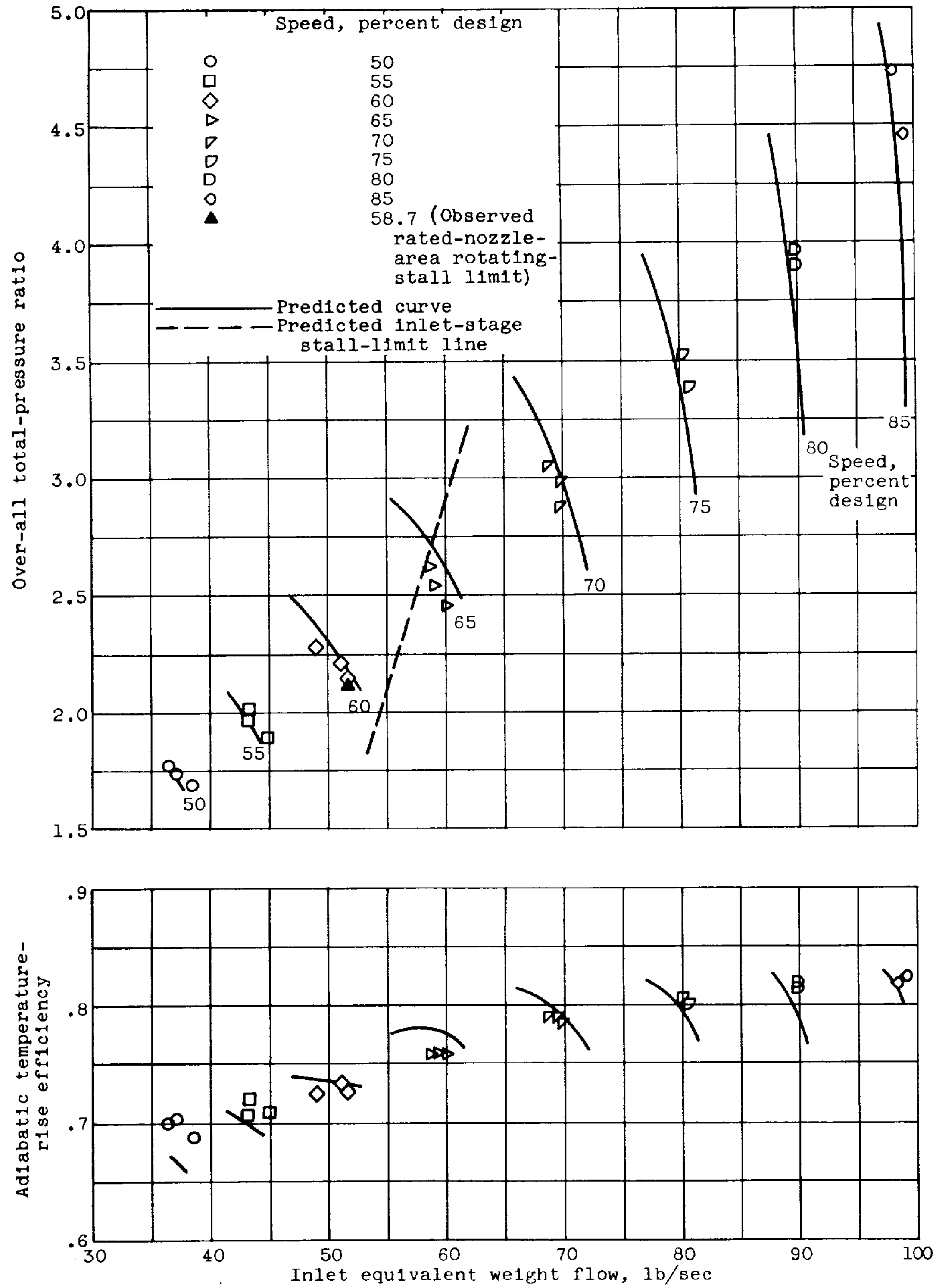
(a) No bleed.

Figure 12. - Comparison of predicted and measured over-all performance.

[redacted]

[redacted]

4776



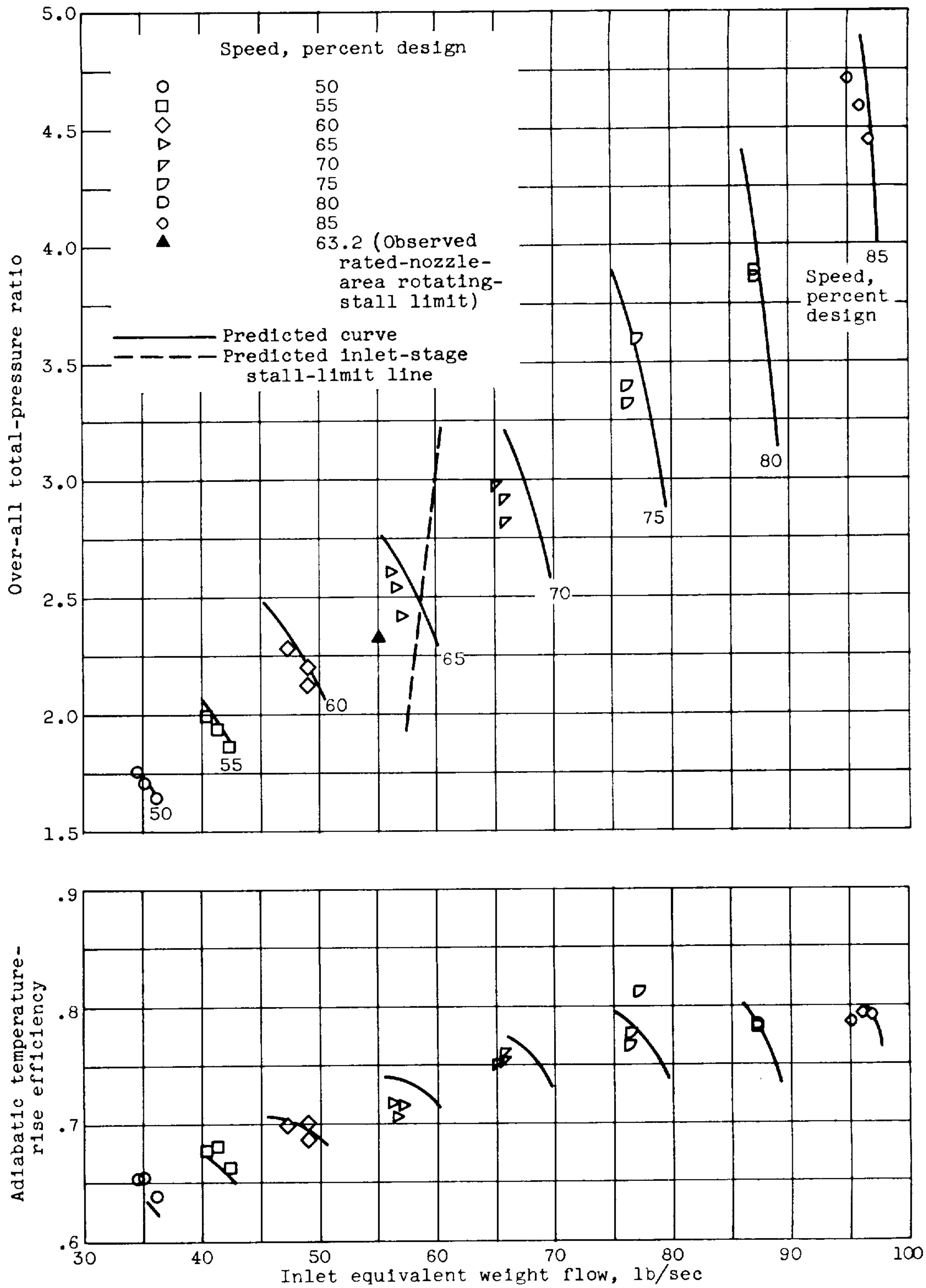
(b) Fifth-stage bleed.

Figure 12. - Continued. Comparison of predicted and measured over-all performance.

[redacted]

[redacted]

4776



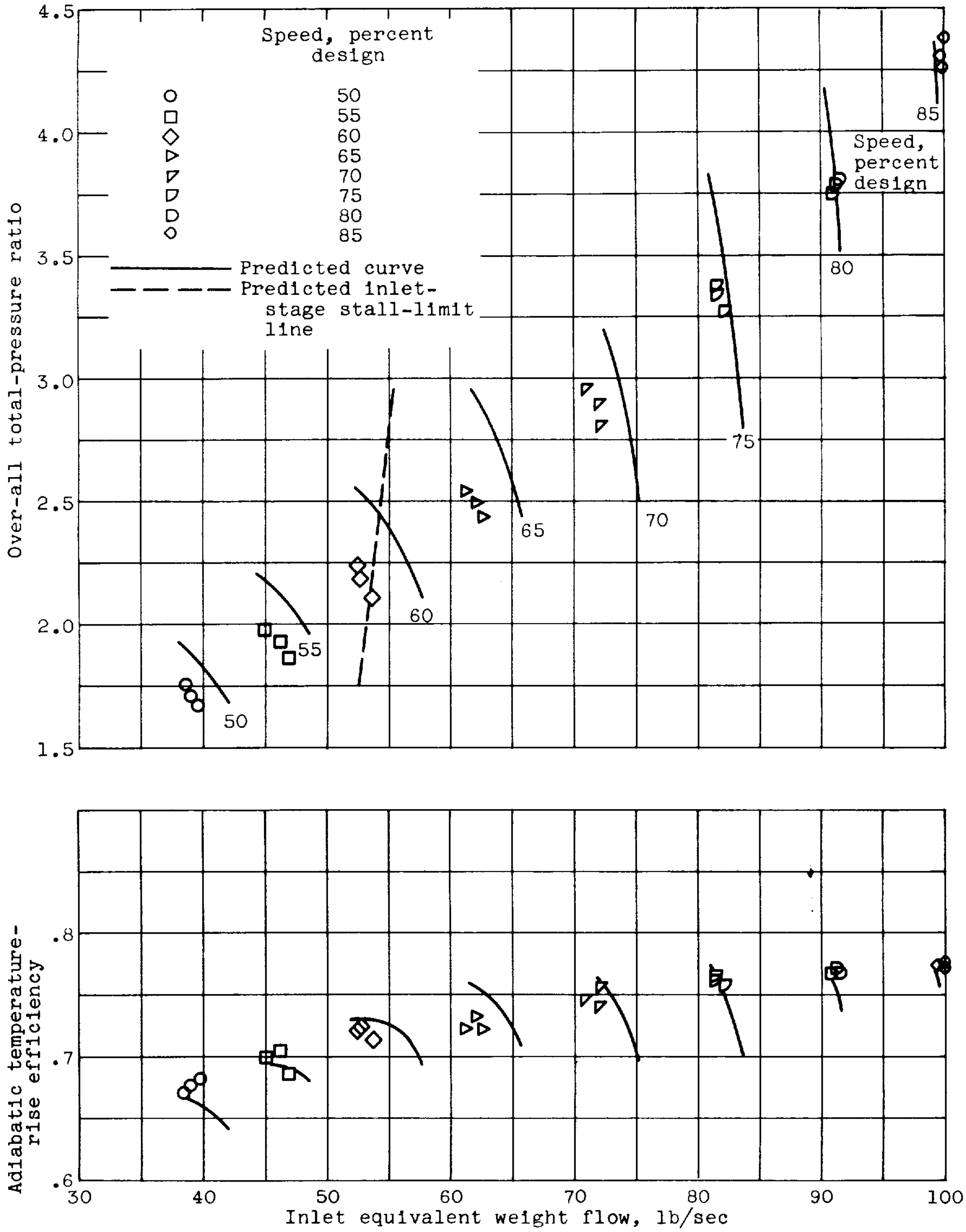
(c) Tenth-stage bleed.

Figure 12. - Continued. Comparison of predicted and measured over-all performance.

[redacted]

[redacted]

4776



(d) Fifth- and tenth-stage bleed. (No rated-nozzle rotating-stall limit was observed.)

Figure 12. - Concluded. Comparison of predicted and measured over-all performance.

[redacted]

NASA MEMO 10-4-58E
National Aeronautics and Space Administration.
USE OF STAGE-STACKING TECHNIQUE FOR PREDICTING OVER-ALL PERFORMANCE IN MULTISTAGE AXIAL-FLOW COMPRESSOR UTILIZING INTERSTAGE-AIR BLEED. James G. Lucas. October 1958. 48p. diagrs., photos. (NASA MEMO 10-4-58E) CONFIDENTIAL
(Title, Unclassified)

Bleed at one or two axial locations caused shifts and alterations in experimental stage-group characteristic curves with accompanying distortions of radial gradients of temperature and total pressure through the compressor. With single-location bleed, a stage-stacking procedure using experimental bleed ratios and no-bleed stage data yielded accurate predictions of overall performance and rotating-stall limits. With dual bleed the predicted performance was less accurate but the predicted rotating-stall limit was at least conservative.

Copies obtainable from NASA, Washington

[redacted]

1. Engines, Turbojet (3.1.3)
2. Compressors - Axial-Flow (3.6.1.1)
3. Compressors, Stress and Vibration (3.6.2)
I. Lucas, James G.
II. NASA MEMO 10-4-58E

NASA

[redacted]

NASA MEMO 10-4-58E
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