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RESEARCH MEMORANDUM

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for the

Air Research and Development Command, U. S. Air Force

PERFORMANCE OF 15-STAGE EXPERIMENTAL J71 AXIAL-FLOW

COMPRESSOR

II - INDIVIDUAL STAGE PERFORMANCE CHARACTERISTICS

By James G. Lucas and Richard E. Filippi

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SUMMARY

The individual stage performance characteristics of the 15-stage experimental J71 axial-flow compressor were determined by means of fixed radial rakes measuring total pressure and temperature at the discharge of each stage.

From the results of this experimental investigation it was determined that the poor low-speed over-all efficiency was due in part at least to the poor efficiencies of the first four stages. The first and the twelfth to fifteenth stages cause the surge pressure ratio at design speed to be less than the design pressure ratio. The multiple over-all performance curves obtained at 78.5 percent of design speed were directly related to double-branched individual stage pressure ratio characteristic curves for the third and seventh stages. Operation on the lower pressure ratio branches occurred under a condition of four rotating-stall zones. Over the speed range where rotating stall existed, a tip stall condition that was indicated increased in radial extent and number of stages affected with decreasing speed.

INTRODUCTION

The experimental 15-stage axial-flow compressor for the J71 turbojet engine was tested at the NACA Lewis laboratory at the request of the Air Research and Development Command, U. S. Air Force. The over-all performance characteristics (presented in ref. 1) show that the experimental compressor exhibited very low efficiency at low speeds and a marked discontinuity in the surge-limit line. Consequently, in an effort to determine the causes of the poor part-speed performance of the compressor, the stage performance was determined for each of the 15 stages.

The present build-up of the compressor had slight variations in over-all performance from that of reference 1 because of minor differences in blading. However, it is essentially the same compressor with the same performance problems. The over-all performance of the present compressor is included in reference 2.

The individual stage performance characteristics were obtained from fixed radial rake measurements of total temperature and total pressure after each stage for a range of flows from maximum obtainable to surge over a range of speeds from 30 to 100 percent of design speed. The present report discusses these experimentally determined stage operating characteristics.

COMPRESSOR DESIGN

In the design of the compressor, certain compromises were made with the intention of obtaining better performance in the part-speed range. These compromises were concerned with the design incidence settings for the blading, particularly in the front and rear stages. The inlet stages, which operate at higher incidence angles as the speed is decreased below design, were set to have slightly lower than optimum incidence angles at the design point. Similarly, the rear stages, which operate at lower incidence angles below design speed, were set at slightly higher than optimum incidence angles. These compromises, in effect, move the stage-match point from the design point to a speed somewhat below design, as discussed in reference 3.

In addition, certain simplifying assumptions were made in the design procedure that would affect the compressor performance. The inlet guide vanes were designed without consideration of the turning rules for such vanes presented in reference 4, with the result that the vanes will probably not produce the turning for which they were designed. This in turn raises the incidence angles on the first rotor blade row, which counteracts the desired feature of lower incidence angles for the inlet stages at the design point to provide better part-speed performance. The first stage was designed to produce a radial gradient of energy addition, and the design procedure did not account for the effect of this gradient on the axial-velocity distributions entering the succeeding stages. Consequently, the desired incidence distributions would not be obtained. In addition, simple radial equilibrium, as discussed in reference 5, was not considered beyond the first stage, straight-through flow being assumed. This again will affect the axial-velocity distributions. Because of these three simplifying assumptions, it is felt that the design conditions could not be satisfied.

APPARATUS AND INSTRUMENTATION

The apparatus and over-all performance instrumentation for the present tests are the same as outlined in reference 1. In addition, the following instrumentation was used for determining the individual stage performance characteristics: one fixed radial total-pressure rake and one fixed radial spike-type thermocouple rake in each stator blade row with the probe tips placed approximately at centers of equal radial increments of the annulus. Examples of these types of instruments are shown in figure 1. Each of the total-pressure rakes had five measuring tips; while the thermocouple rakes had six tips for the discharge of the first stage, five tips for stages 2 to 8 and at the compressor discharge, and three tips for stages 9 to 14. Total-pressure losses across the inlet and exit guide vanes were charged to the first and fifteenth stages, respectively. The rakes were located circumferentially in positions which would not be in the wakes of stator blades and probes immediately upstream under predictable conditions. Although the accuracy of these fixed rakes decreases quite rapidly when the flow angle deviation exceeds about ±15°, the data obtained are considered accurate, since the flow angles through the stators will remain reasonably constant for unstalled flow. Data obtained under conditions of stalled or unsteady flow are considered to be at least qualitatively correct.

PROCEDURE

The compressor was operated at equivalent speeds from 30 to 100 percent of design and over a range of weight flow at each speed from the maximum obtainable to the minimum flow, at which point surge occurred. The inlet pressure was adjusted with speed to maintain a Reynolds number relative to the tip of the first rotor within the range of 240,000 to 400,000, as shown in reference 1.

The over-all compressor performance was calculated from the method of reference 6. This method, which uses the average of the measured discharge static pressures plus the velocity pressure computed from the inlet mass flow and discharge conditions to obtain the discharge total pressure, does not credit the compressor with either nonaxial or nonuniform velocity.

The individual stage performance was determined by the method of reference 7, using arithmetic radial averages of the total temperature and total pressure at the discharge of each stage. The stage performance is presented as curves of equivalent adiabatic temperature-rise efficiency and equivalent total-pressure ratio plotted against stage-inlet flow coefficient. The equivalent values are those which would be obtained if the entire flow-coefficient range of each stage could

be obtained at design speed. The flow coefficient, which is a ratio
of the average axial velocity to the mean wheel speed at any axial
measuring station, is an inverse indication of the average angle of
attack on a particular stage. That is, as the flow coefficient de-
creases, the average angle of attack at the entrance to the particular
stage increases.

Several assumptions were made that could slightly alter the abso-
lute magnitudes of the various stage performance parameters. Among these
assumptions are the following: (1) no Mach number correction to the den-
sity term in the flow coefficient, (2) no variation in annulus blockage
due to boundary layer for the various conditions of flow, (3) an arith-
metic radial average of temperature and pressure being truly representa-
tive, and (4) no effect of upstream wakes on the instrumentation. While
these assumptions can all affect the numerical values of the stage per-
formance parameters, they will not affect the general shapes of the re-
sulting curves.

In addition to the stage characteristic curves obtained from radi-
ally averaged values of pressure and temperature, curves are presented
to show the radial gradients of pressure and temperature at various com-
pressor operating points.

RESULTS AND DISCUSSION

Over-All Compressor Performance

The compressor over-all performance characteristics are presented
in figure 2, which is reproduced from reference 2. These performance
characteristics differ slightly from those presented in reference 1,
which is part I of this series, because of minor manufacturing differ-
ences in blading in the present compressor build-up. The data points
shown on this figure are those at which the present interstage data were
obtained. Additional data are shown on the individual stage curves at
77 and 78.5 percent of design speed, for which the over-all performance
points are not shown on this figure. The compressor performance is pre-
sented as over-all total-pressure ratio and adiabatic temperature-rise
efficiency plotted against equivalent weight flow over a range of equiv-
alent speeds from 30 to 100 percent of design. A maximum flow of 161
pounds per second was obtained at design speed, compared with the design
flow of 174 pounds per second. The peak efficiency rises from about
0.76 at design speed to a maximum of about 0.81 at 85 percent of design
speed. The peak efficiency at any speed in the range from 30 to 65 per-
cent of design speed never rises above approximately 0.53. The design
over-all total-pressure ratio of 9.44 was not attained at design speed,
the pressure ratio at the surge point being about 8.8.

The indicated inlet-stage stall line is an approximate locus of points at which the first stage reaches its stall point as determined from the first-stage performance characteristics. At any lower over-all compressor mass flow at a given speed in this range, the inlet stage is operating in a stalled condition. The line is about coincident with the severe drop in over-all performance indicated in the intermediate-speed range. The corresponding stall lines for succeeding stages would have lesser slopes with the high-speed ends of the lines terminating at about the same point on the surge line as does the first-stage line. This indicates that the inlet stage is the one which determines the high-speed limit of over-all compressor stall conditions on any given throttle line.

As was stated in reference 2, the surge-limit line exhibits a very severe knee or discontinuity in the speed range from 70 to 80 percent of design speed. The combination of this surge-line discontinuity with the very poor efficiency in the low-speed range would result in very poor acceleration characteristics in an engine. In fact, equilibrium engine operation could probably not be reached for this compressor over a range of speeds near the discontinuity without the occurrence of surge.

Individual Stage Performance

The multiplicity of performance curves found at 78.5-percent speed was reported in reference 8, and the over-all performance curves for which interstage data were obtained are repeated from that reference in figure 3. In figures 4 to 6, all points taken at 78.5 percent of design speed are solid. Different solid symbols are used to indicate the numbers of rotating-stall zones present at each point for this speed.

Stages 1 to 6. - The performance characteristics of stages 1 to 6 are presented in figure 4 as plots of adiabatic temperature-rise efficiency and equivalent total-pressure ratio against stage-inlet flow coefficient. The first stage operates at a stalled angle of attack over at least part of its span at all flow coefficients below about 0.62. Stall is denoted by a transition from a negative to a positive slope at about this point on the equivalent pressure ratio curve. Stall of the inlet stage along the surge line occurs below about 80-percent speed, as shown in figure 4(a), which is coincident with the rapid decrease in both over-all compressor pressure ratio and efficiency shown in figure 2. At low speeds the efficiency of the inlet stage is very poor, varying from 0.10 to 0.33 at 50-percent speed, which is approximately the engine starter cut-off speed. The inlet-stage stall line in figure 2 is an approximate plot of over-all performance points at which the inlet stage operates at a flow coefficient of 0.62. At design speed, the inlet-stage pressure ratio at surge is only about 1.05, compared with a design value of 1.10, which shows that this is one of the stages contributing to the failure to attain design over-all pressure ratio at design speed.

The various points at 78.5 percent speed, shown as solid points in
figure 4(a), fall along the general first-stage curves, which would in-
dicate that the first stage probably has little, if any, direct effect
on which of the multiple over-all performance curves is reached for a
given means of approach to this speed. However, it may have an indirect
effect, in that its stall characteristics may influence the performance
of succeeding stages.

Stages 2 to 6 operate over a fairly wide range of flow coefficient
and reach the peaks of their equivalent pressure ratio curves at some
flow coefficient in the range from 0.60 to 0.67. Since the flow coef-
ficient at the 80-percent-speed surge point is at or below the flow co-
efficient for peak pressure ratio for each of these stages, as was the
case for the inlet stage, it would be expected that the first six stages
would probably stall as a group and thus tend to accentuate the severity
of the stall effects. In addition, this condition makes it rather diffi-
cult to determine exactly which stage instigates the discontinuity in the
compressor performance in the intermediate-speed range.

Stages 2 to 4 show the same characteristic of poor low-speed effi-
ciency as was shown by stage 1, with the value of efficiency being not
over about 60 percent up to 75 percent of design speed along the surge
line.

It is apparent from figure 4(c) that the third stage is operating
at pressure ratios lower than those of its general characteristic curve
at 78.5-percent speed under a condition of four rotating-stall zones.
The measurements appear to be accurate, since any error in pressure meas-
urement across this stage would be reflected as an increased pressure
ratio for one of the two adjacent stages, which is not the case. There-
fore, it seems that this stage has a multiple-branched characteristic at
this speed. Such a stage characteristic was postulated in reference 9
in order to determine the causes of multiple-branched over-all compressor
performance characteristics.

It should be noted that, for stage 6 and all succeeding stages, the
adiabatic temperature-rise efficiency is not shown. The temperature
data for these stages were not sufficiently accurate to give consistent
efficiency results.

Stages 7 to 10. - The performance characteristics of stages 7 to 10
are presented in figure 5. These stages operate over a relatively narrow
range of flow coefficient near their respective peak pressure ratios.
Each of these stages produces about its design pressure ratio at design
speed. Stage 7 indicates the same effect as stage 3 at 78.5-percent
speed under a condition of four rotating-stall zones, the stage operation
apparently being on a lower pressure ratio branch of the general charac-
teristic curve.

Stages 11 to 15. - The performance characteristics of stages 11 to
15 are presented in figure 6. These stages, like the inlet group, op-
erate over a fairly wide range of flow coefficient; but, unlike the in-
let group, they are always operating on the negative-slope portion of
their respective characteristic curves. Of these stages, only stage
11 produces the design pressure ratio at design speed, the others being
below design. None of these stages shows a double-branched effect at
78.5-percent speed, as would be expected, since the double branches
could occur only on the positive-slope portion of their respective stage
curves. Stages 14 and 15 seem to produce little usable pressure rise at
any speed and actually give a considerable loss in pressure at any speed -
below design. Stage 15 produces a pressure rise only at or near the
surge point at design speed. However, if the pressure drop through the
exit guide vanes had not been charged to the last stage, it would have
appeared somewhat better. It is unlikely, however, that the character-
istic would have been any better than that of stage 14.

Radial Gradients of Total Pressure and Temperature

The measured pressure and temperature-rise ratios at design speed
for the first seven stages are shown in figures 7(a) and 8(a). As was
stated in the COMPRESSOR DESIGN section, the first stage of the present
compressor was designed to produce a radial gradient in energy addition.
This gradient is shown in figure 8(a) as a dashed line. Comparison of
the first-stage lines shows that a gradient in temperature-rise ratio
was achieved after the first stage, but not to the extent predicted by
the design. A comparison of figures 7(a) and 8(a) indicates that poor
efficiencies would be obtained at the hub and tip radius sections, as
evidenced by the increase in the temperature-rise ratio and decrease in
pressure ratio, with the possible exception of the third stage.

The curves of 75-percent design speed shown in figures 7(b) and
8(b) indicate that in this intermediate-speed region a severe tip stall
occurs which results in high temperature-rise ratios and low pressure
ratios over approximately the outer half of the annulus. As the speed
is decreased, this tip stall becomes more severe both in radial extent
and stagewise, as shown by the 50-percent-speed curves of figures 7(c)
and 8(c).

SUMMARY OF RESULTS

An experimental investigation was conducted to obtain individual
stage performance characteristics of the 15-stage J71 axial-flow com-
pressor. The following results were obtained from this investigation:

1. The poor low-speed efficiency of this compressor is due, in part
at least, to the poor efficiencies of the first four stages.

2. The failure to attain design over-all pressure ratio at design speed is the result of lower than design stage pressure ratio obtained in the first and the twelfth to fifteenth stages.

3. The multiple over-all performance curves found at 78.5 percent of design speed seem to be at least partly the result of third- and seventh-stage characteristic curves that were double-branched during stall. The lower branches of these two curves were those on which the stages operated under a condition of four rotating-stall zones.

4. The interstage pressure and temperature measurements indicated a tip stall condition that increased in radial extent and number of stages affected with decreasing speed in the compressor operating region where rotating stall existed.

Lewis Flight Propulsion Laboratory.
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, October 19, 1954

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9. Benser, William A.: Analysis of Part-Speed Operation for High-Pressure-Ratio Multistage Axial-Flow Compressors. NACA RM E53I15, 1953.
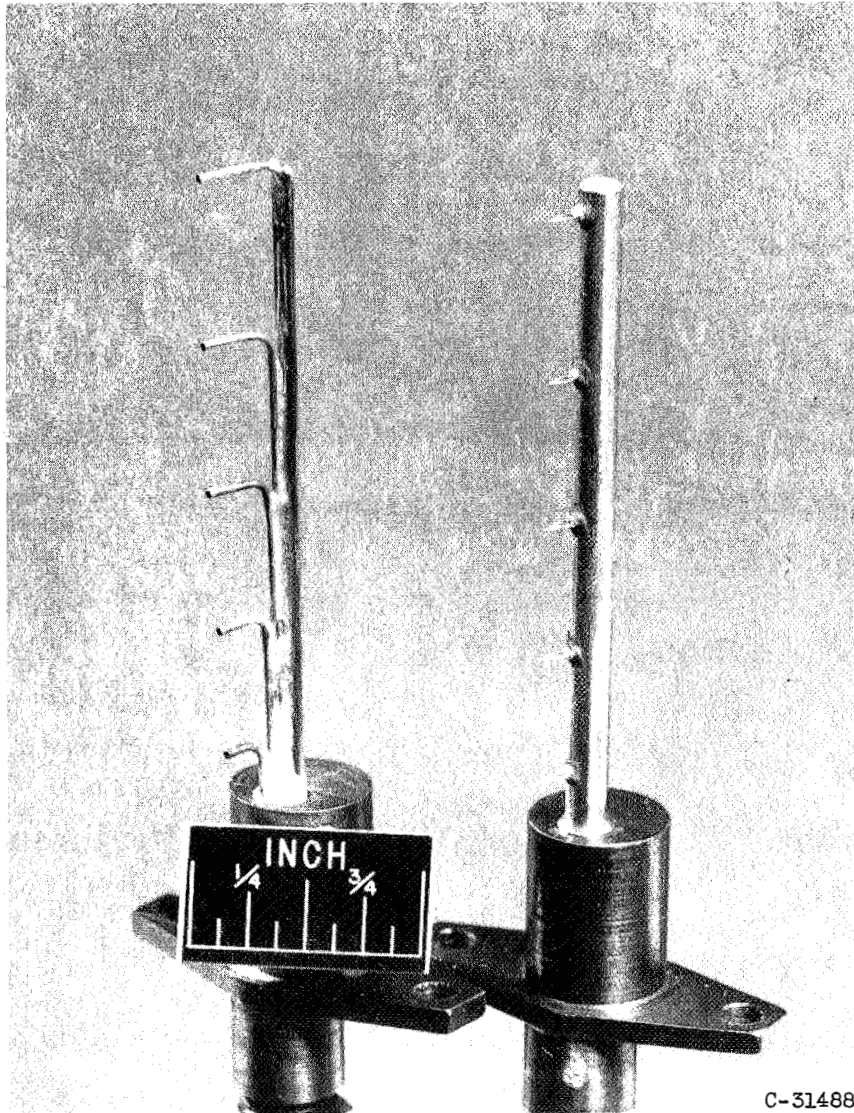
Figure 1. - Interstage total-pressure and temperature rakes.
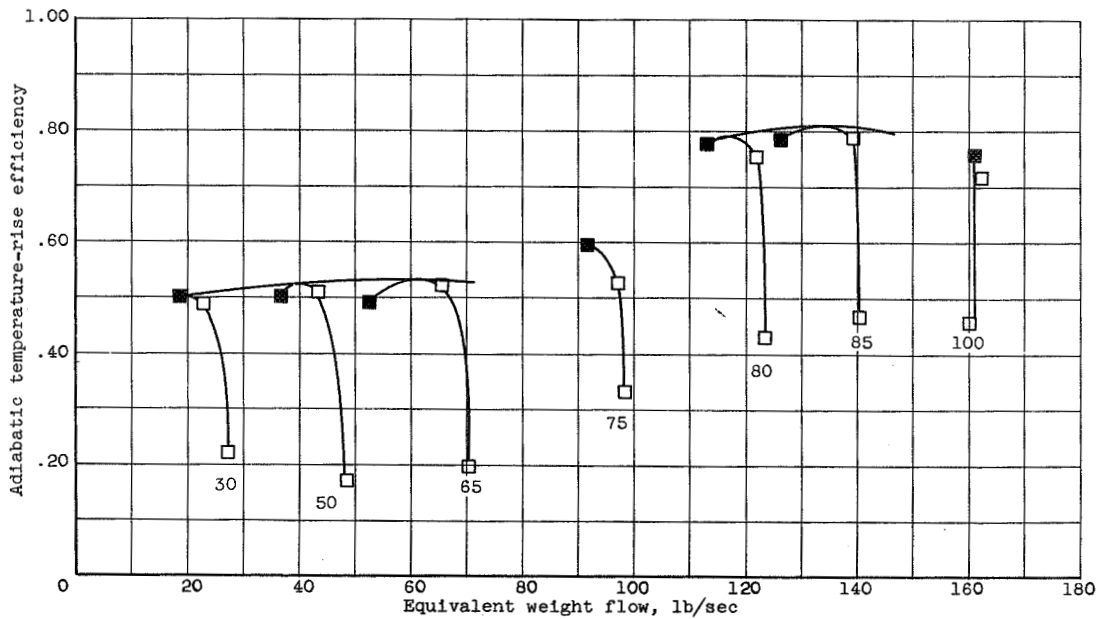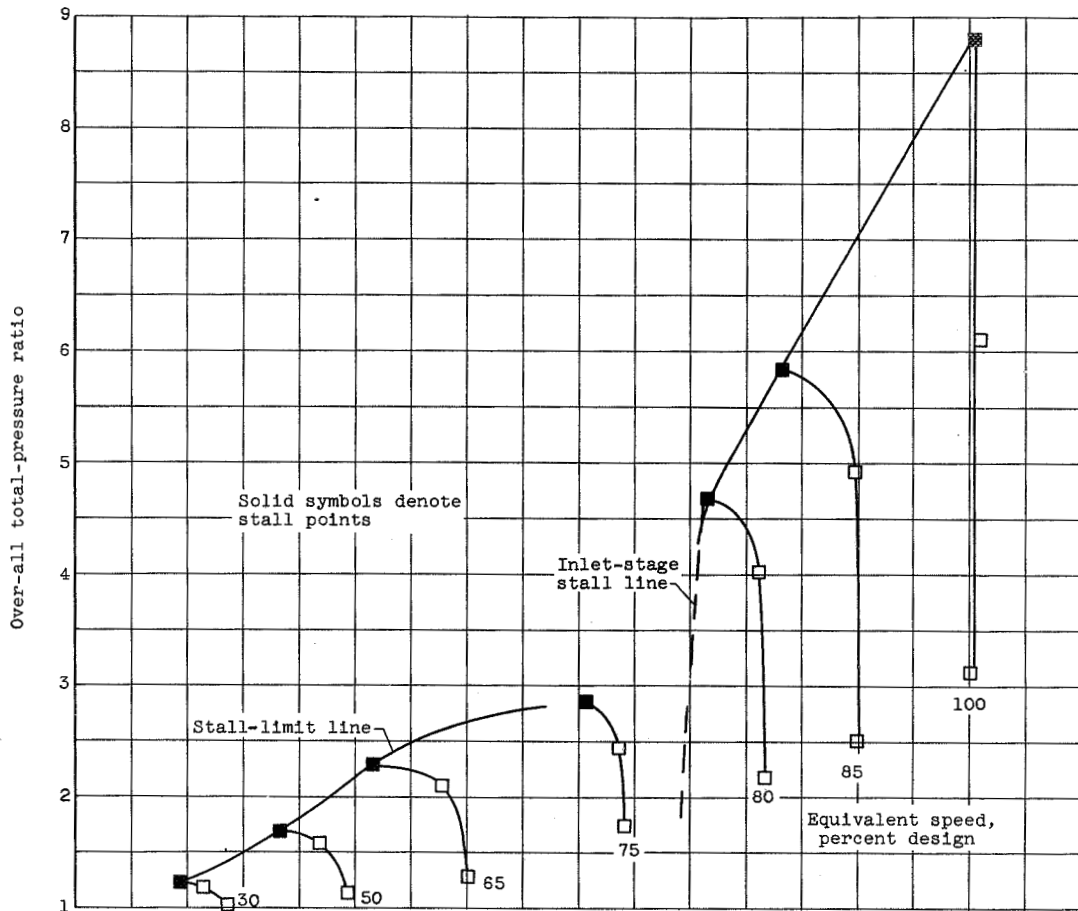
Figure 2. - Over-all compressor performance.
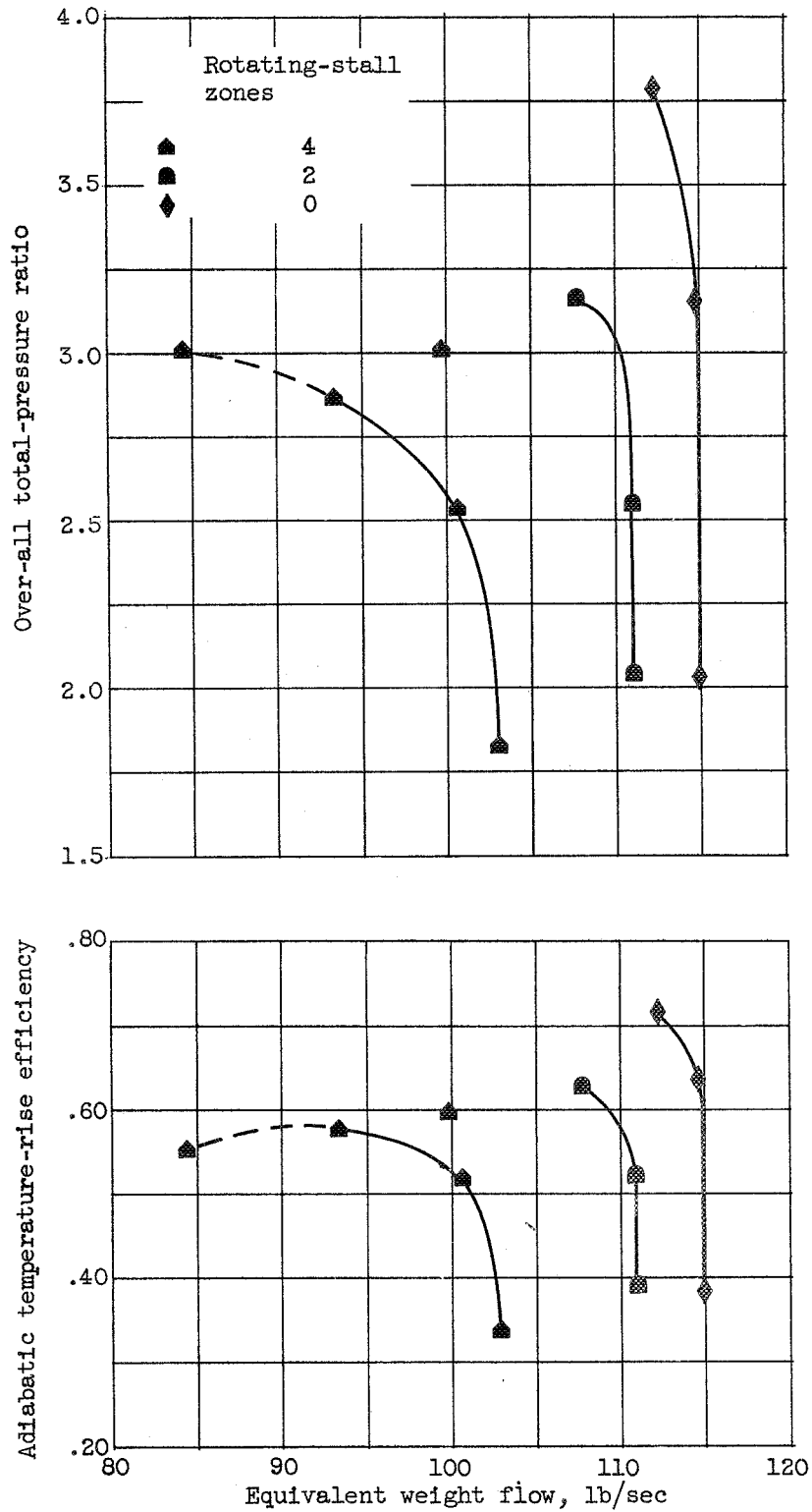
Figure 3. - Over-all compressor performance at 78.5-
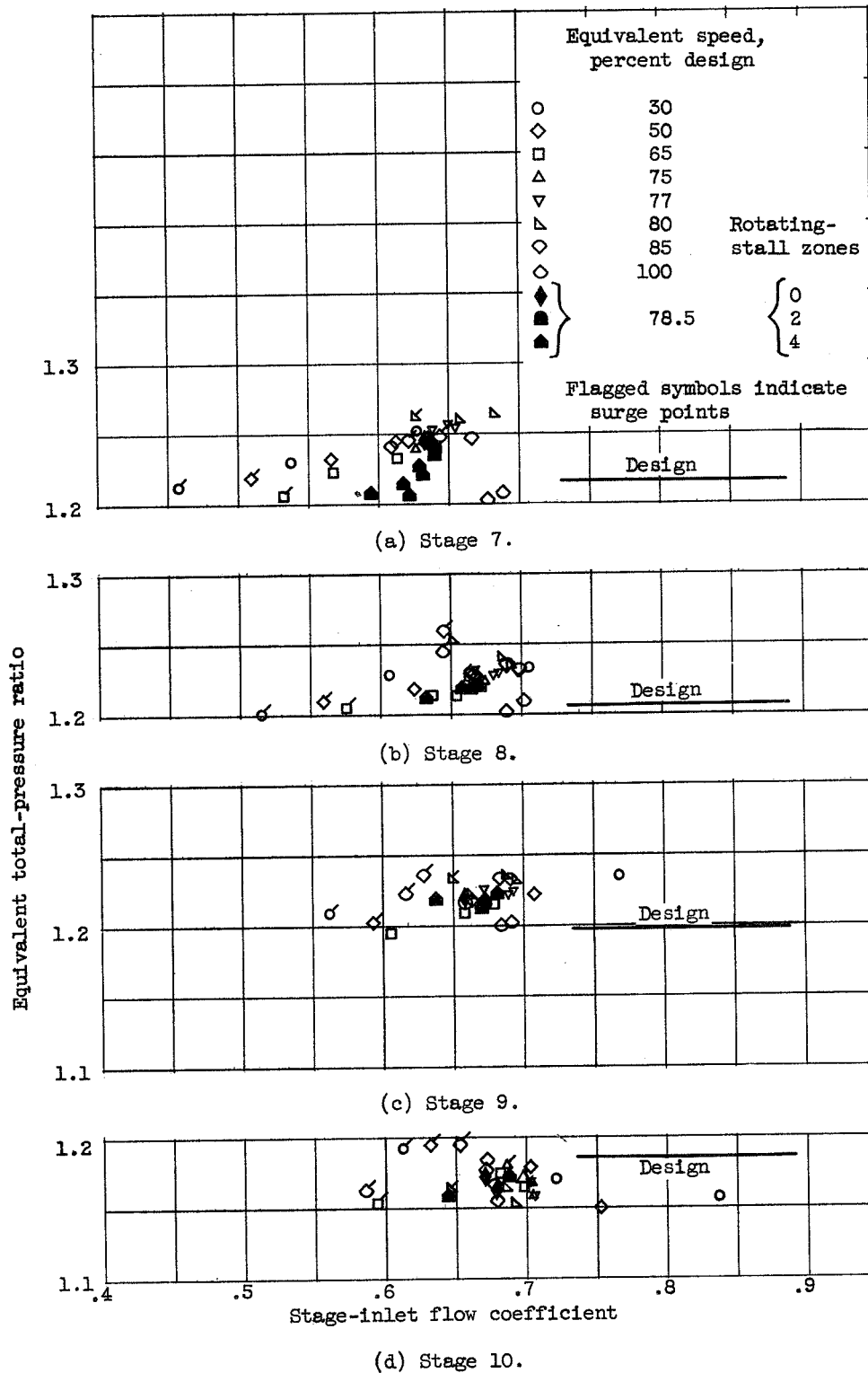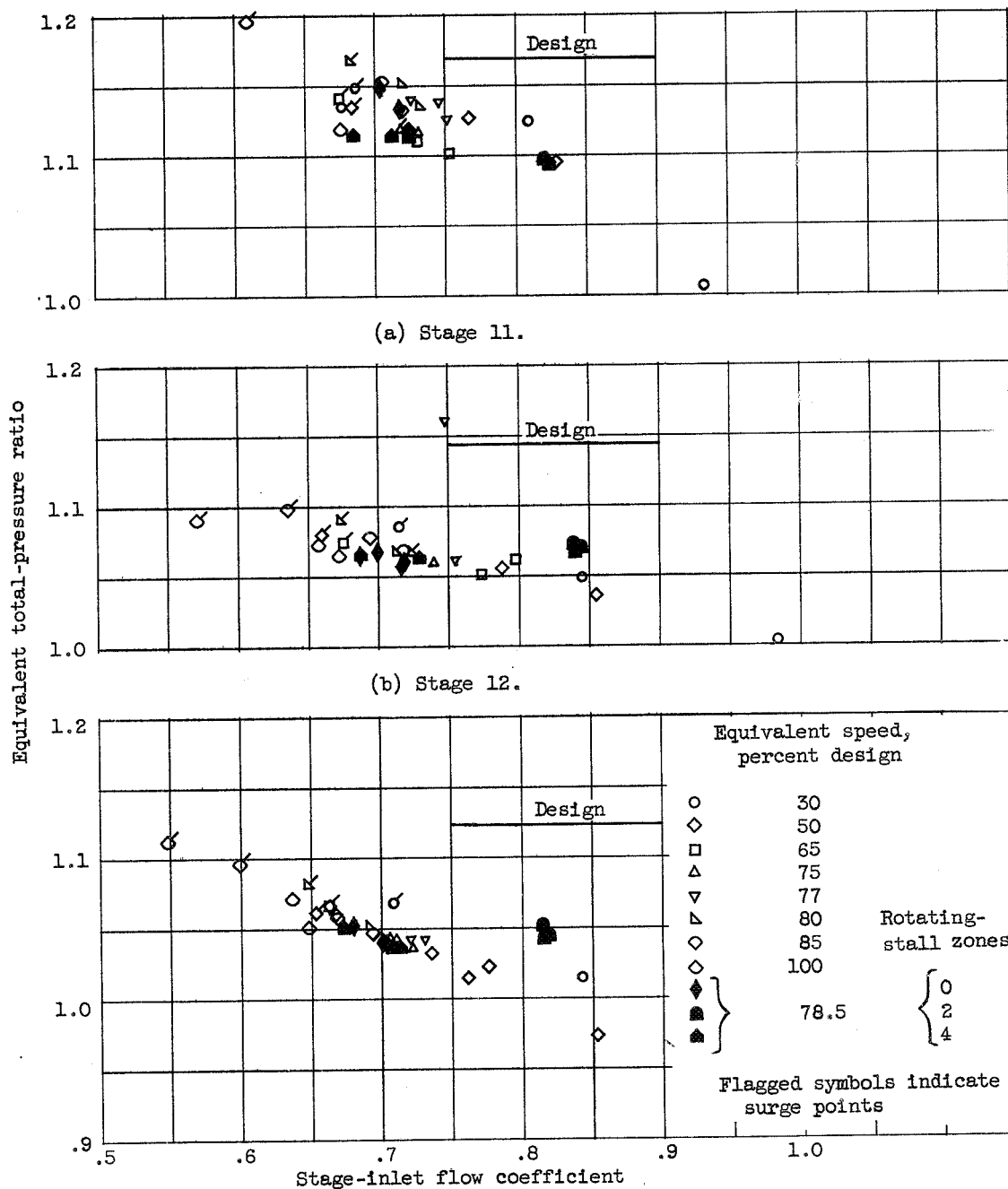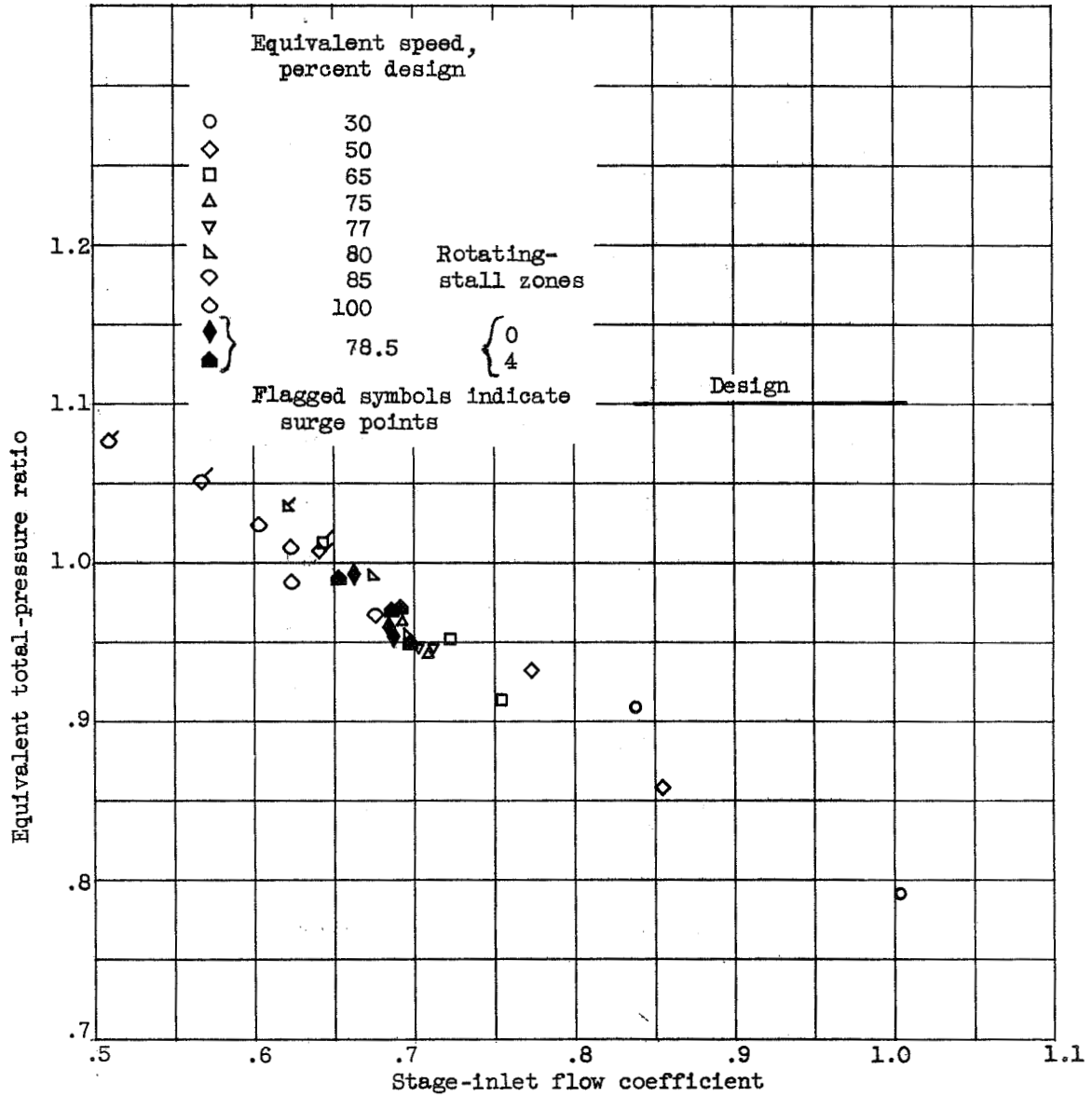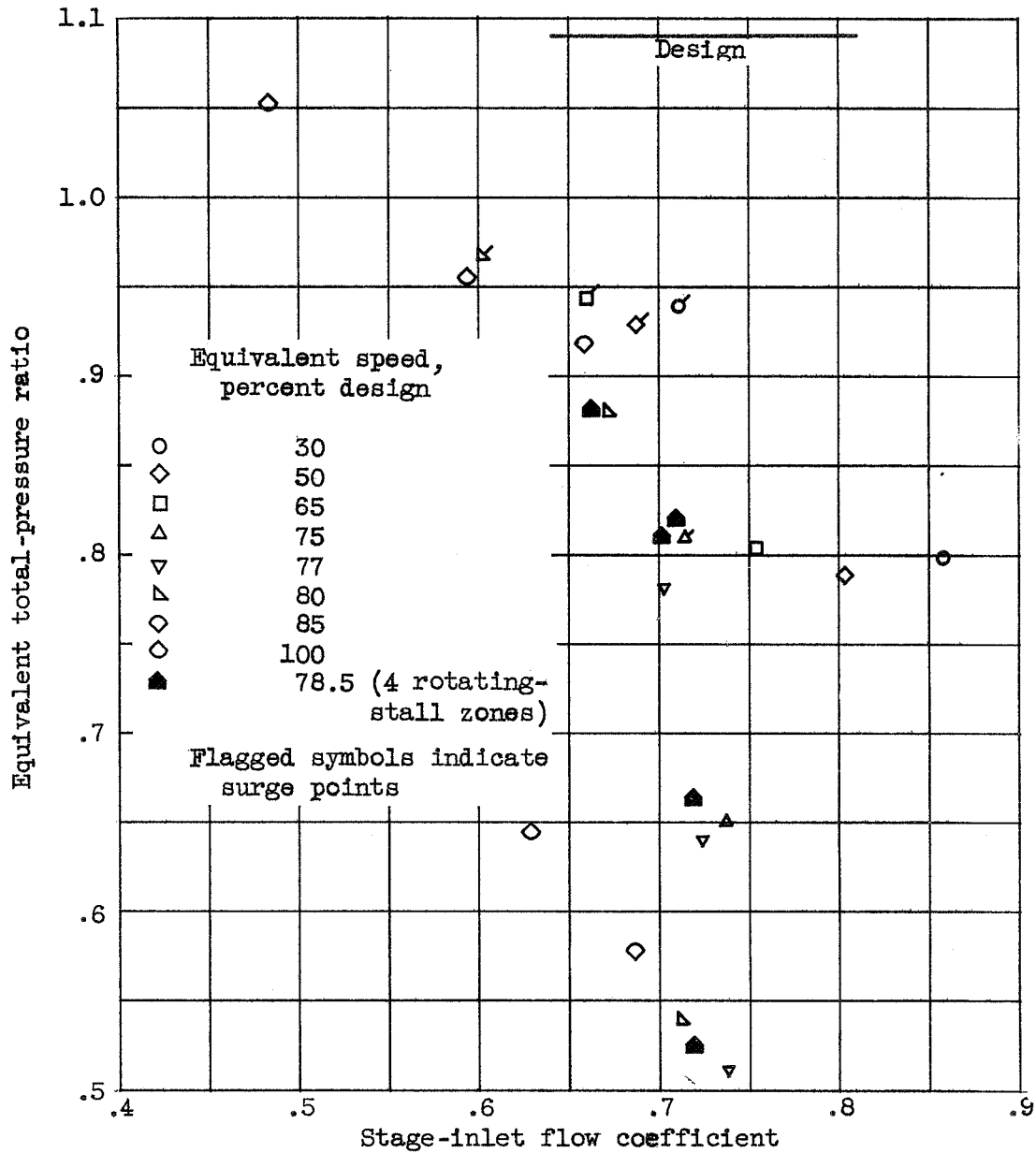   percent equivalent design speed.
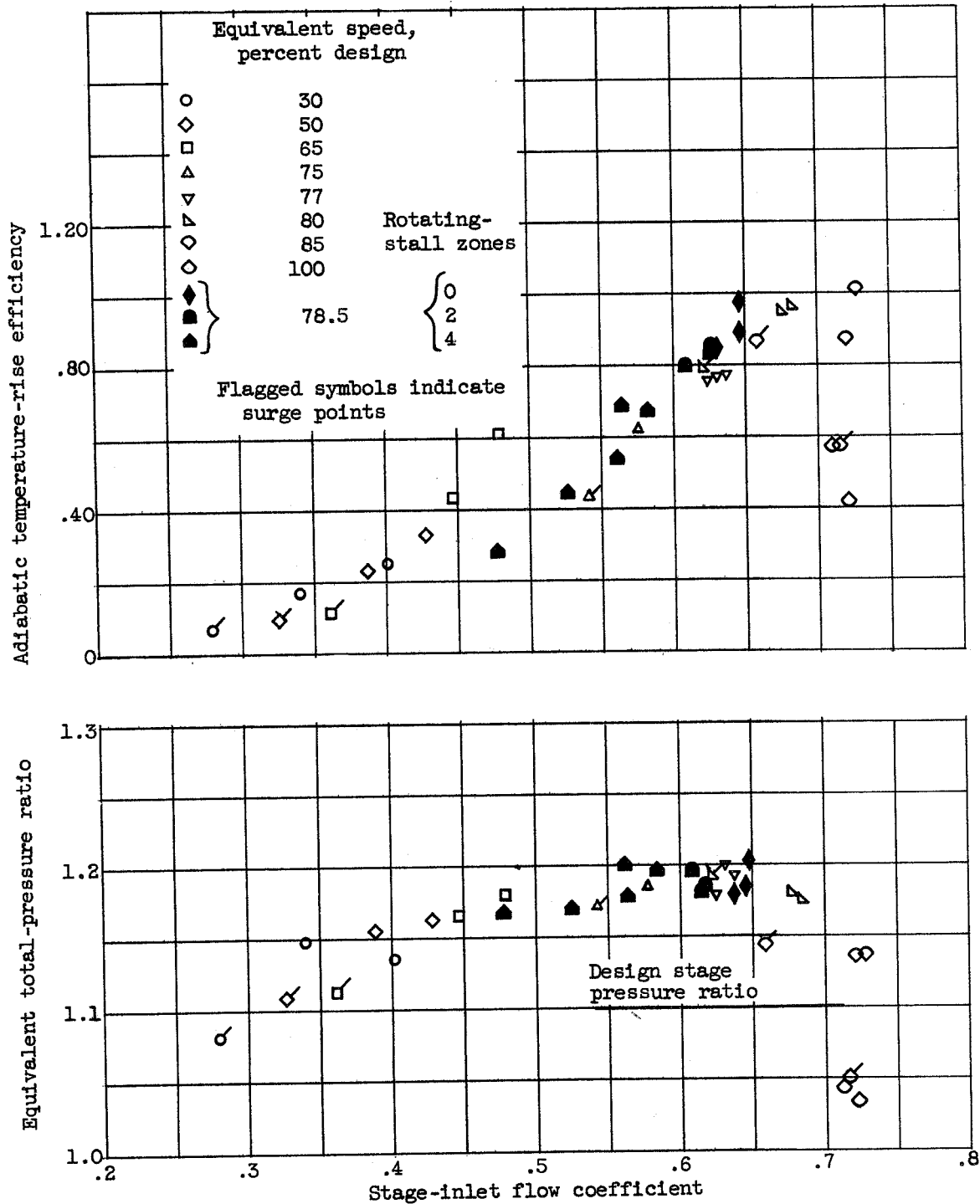
(a) Stage 1.

Figure 4. - Individual stage performance characteristics of stages 1 to 6.
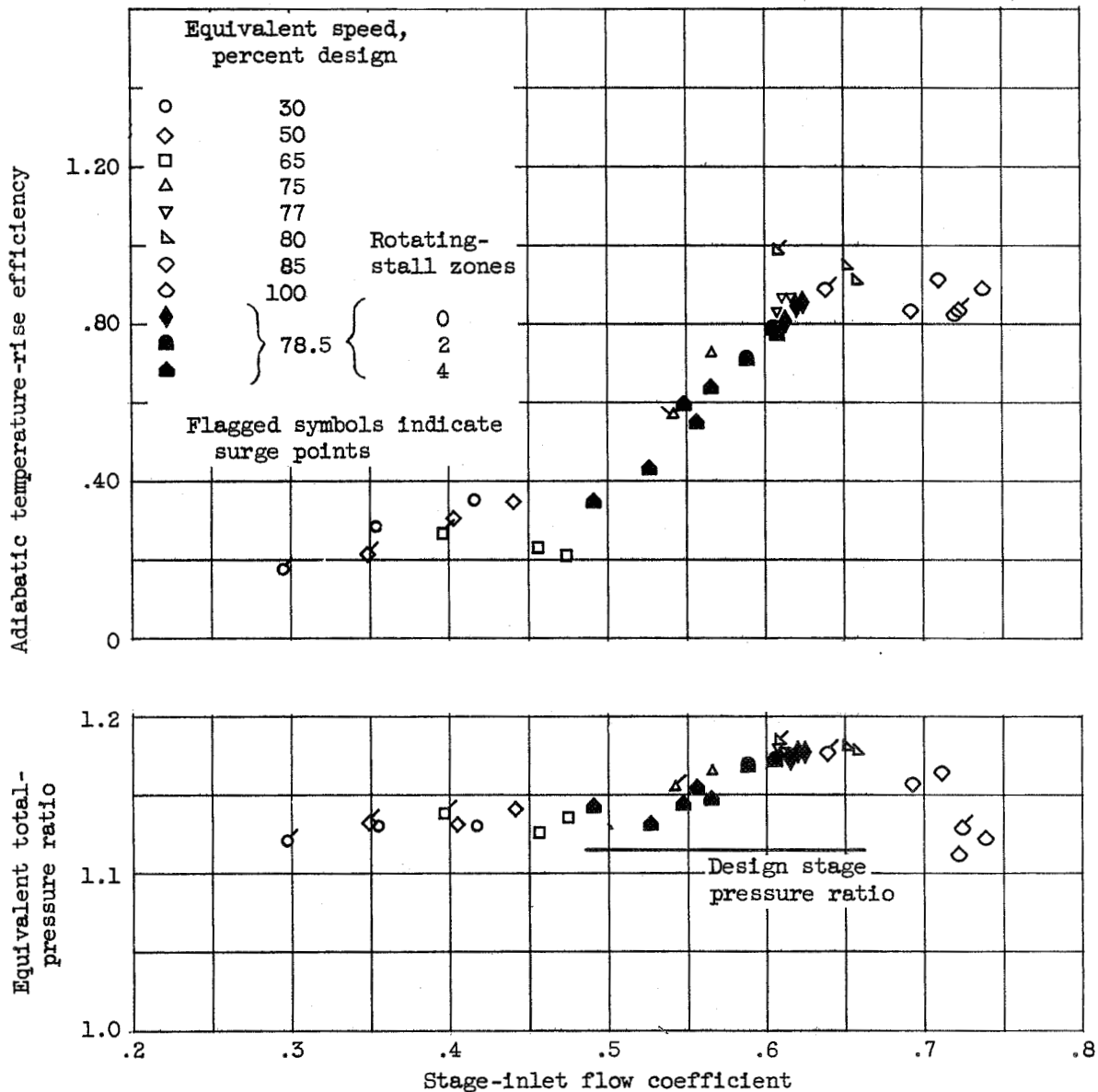
(b) Stage 2.

Figure 4. - Continued.   Individual stage performance characteristics of
stages 1 to 6.
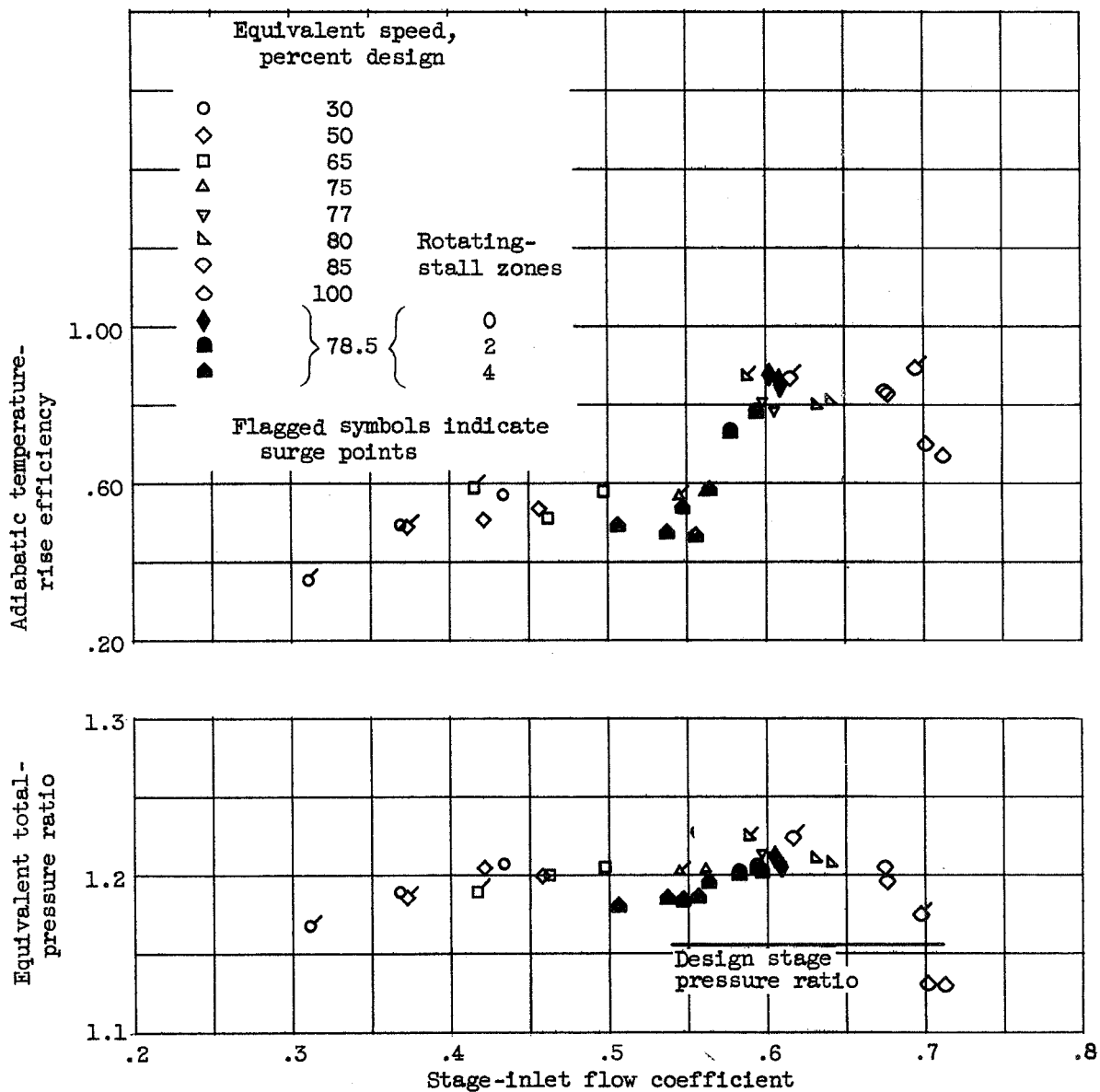
(c) Stage 3.

Figure 4. - Continued. Individual stage performance characteristics of stages 1 to 6.
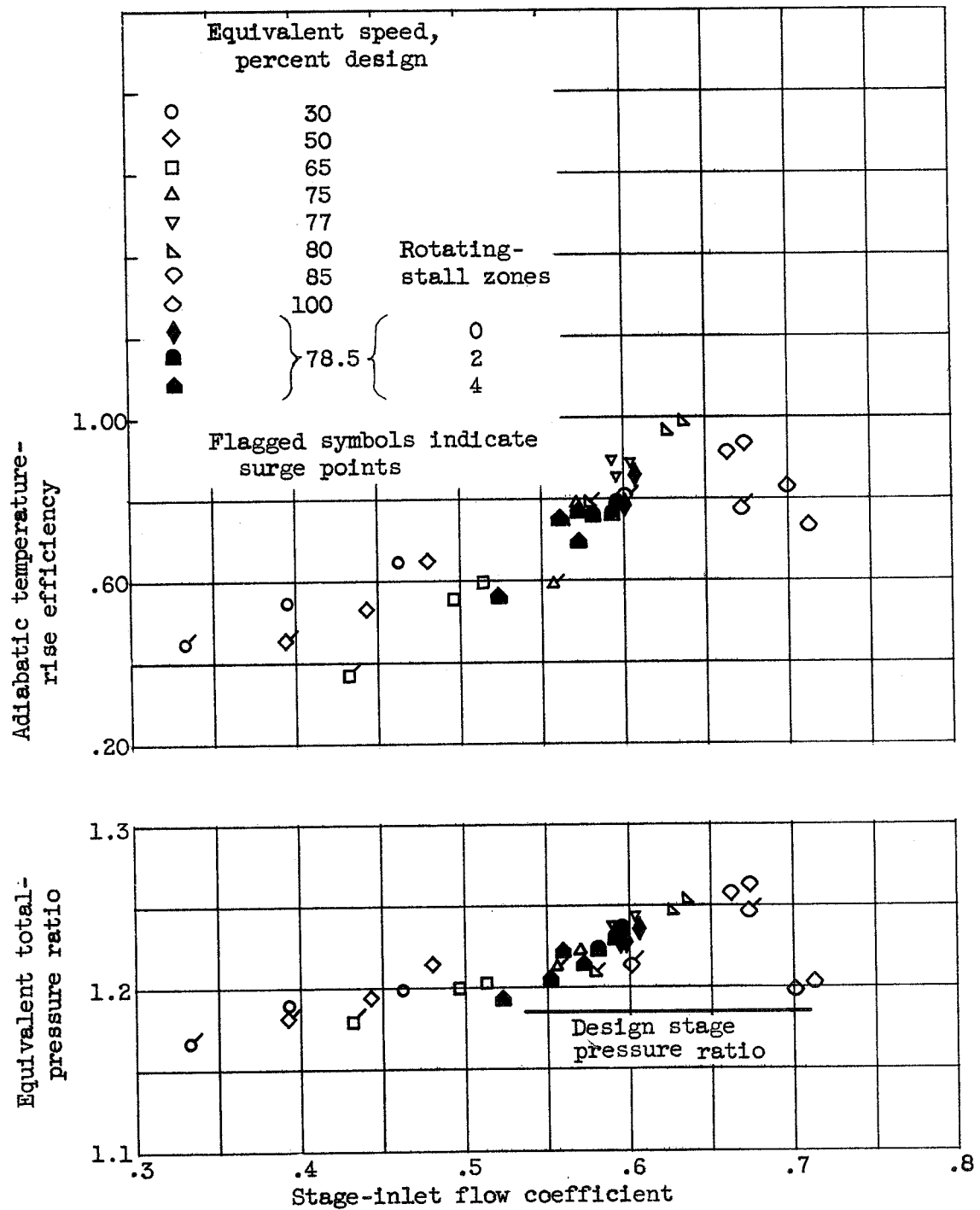
(d) Stage 4.

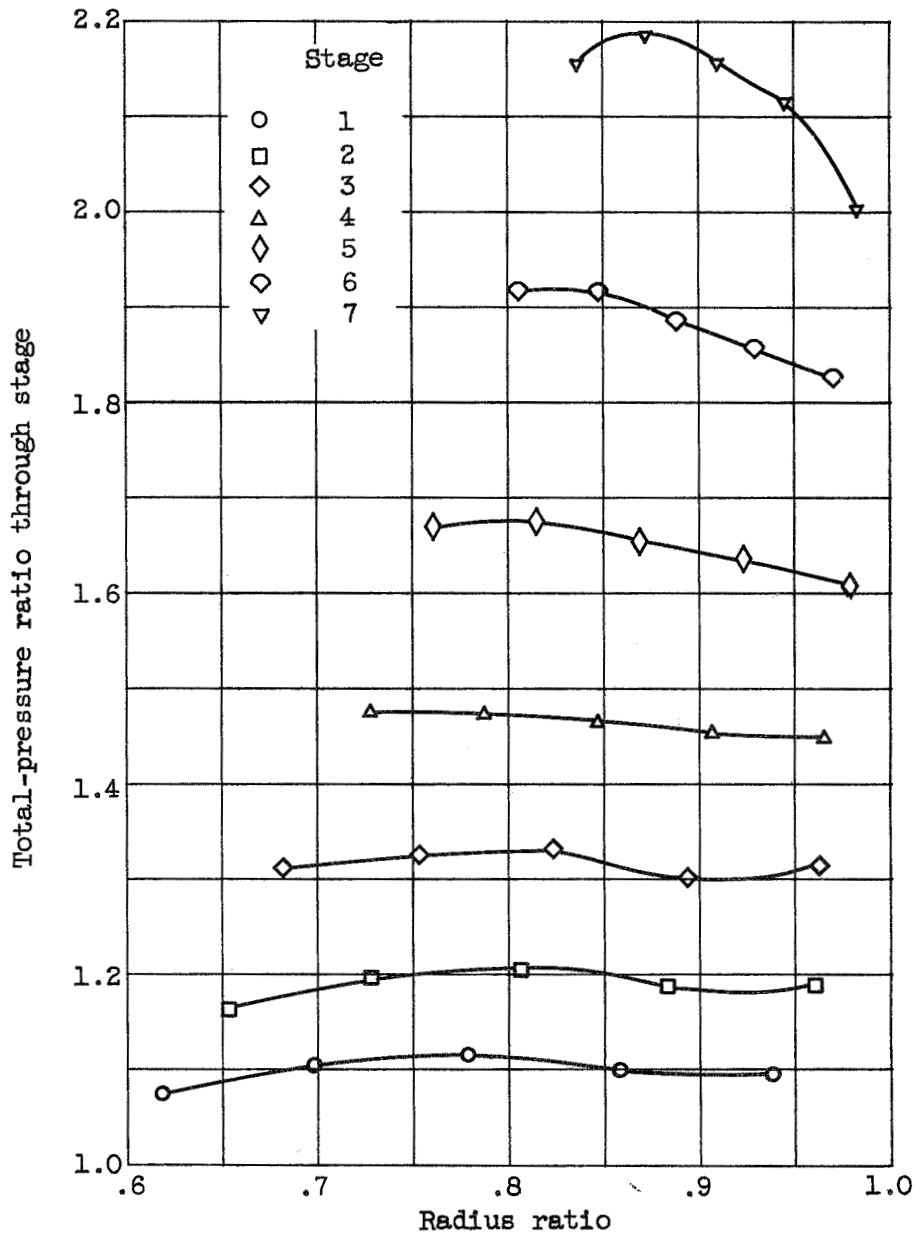Figure 4. - Continued. Individual stage performance charac-
teristics of stages 1 to 6.

(e) Stage 5.
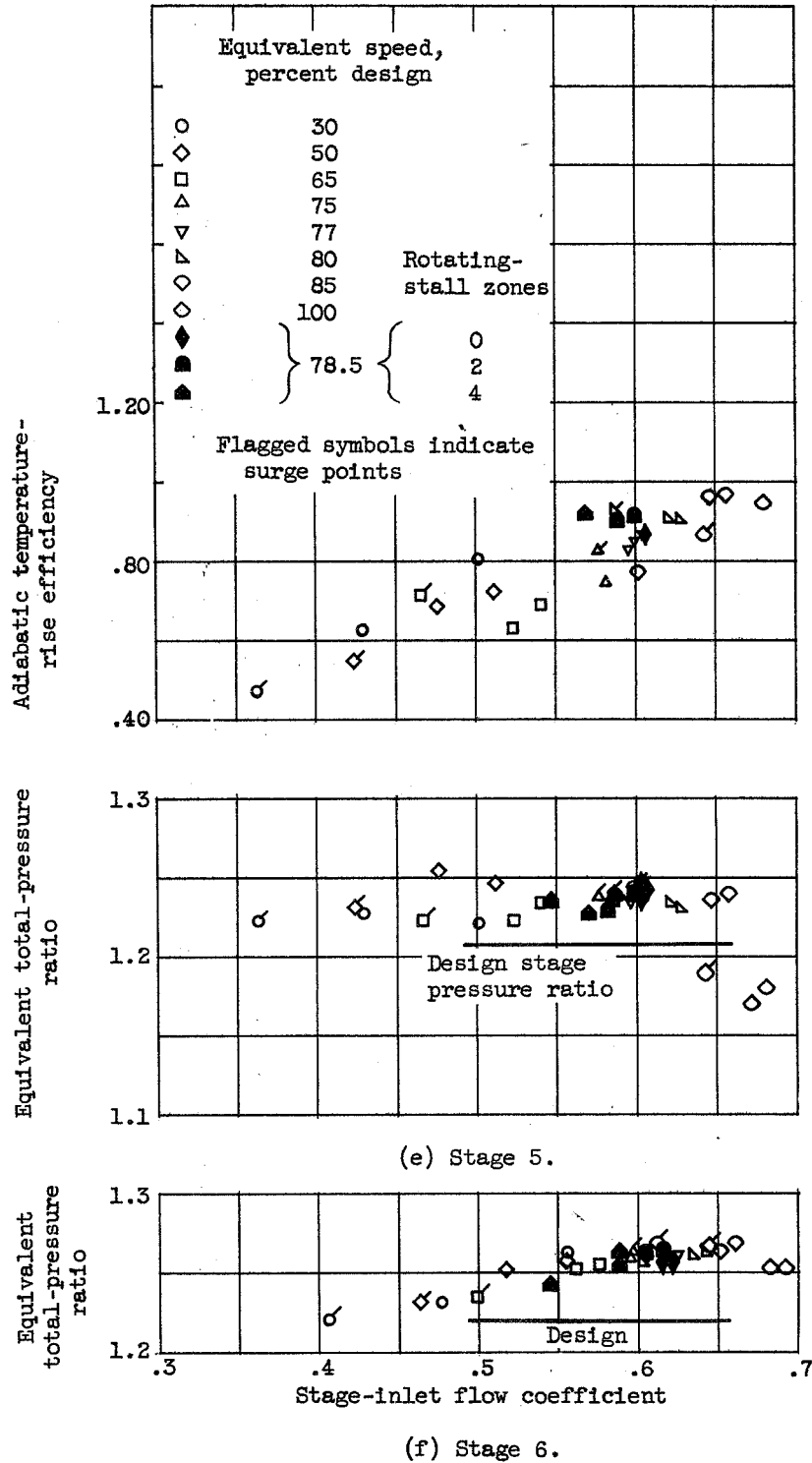
(f) Stage 6.

Figure 4. - Concluded. Individual stage
performance characteristics of stages
1 to 6.

(a) Stage 7.

(b) Stage 8.

(c) Stage 9.

(d) Stage 10.

Figure 5. - Individual stage performance characteristics of
stages 7 to 10.

(a) Stage 11.

(b) Stage 12.

(c) Stage 13.

Figure 6. - Individual stage performance characteristics of stages 11 to 15.

(d) Stage 14.

Figure 6. - Continued. Individual stage performance characteristics of stages 11 to 15.

(e) Stage 15.

Figure 6. - Concluded. Individual stage performance
characteristics of stages 11 to 15.
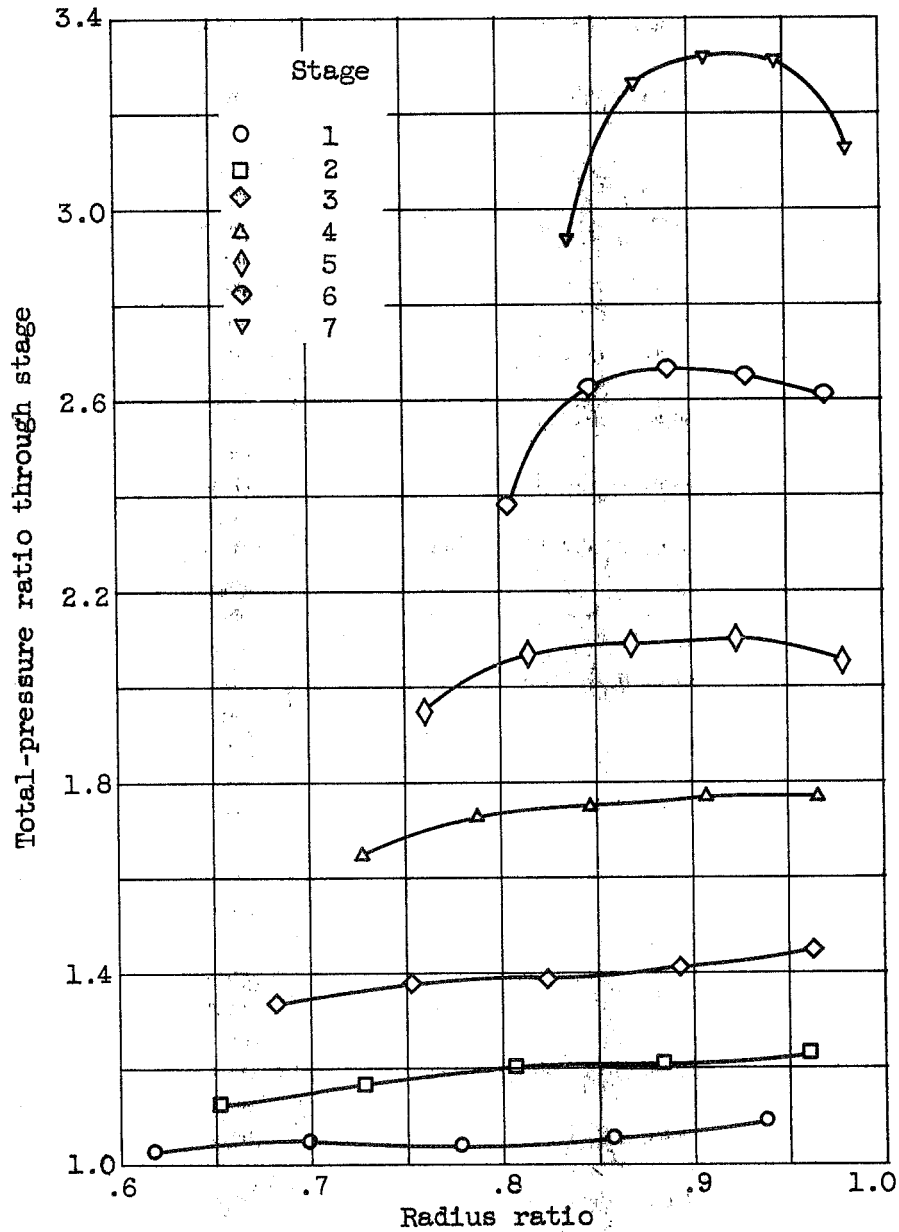
(a) Stages 1 to 7.   Design speed.

Figure 7. - Over-all surge total-pressure ratios.
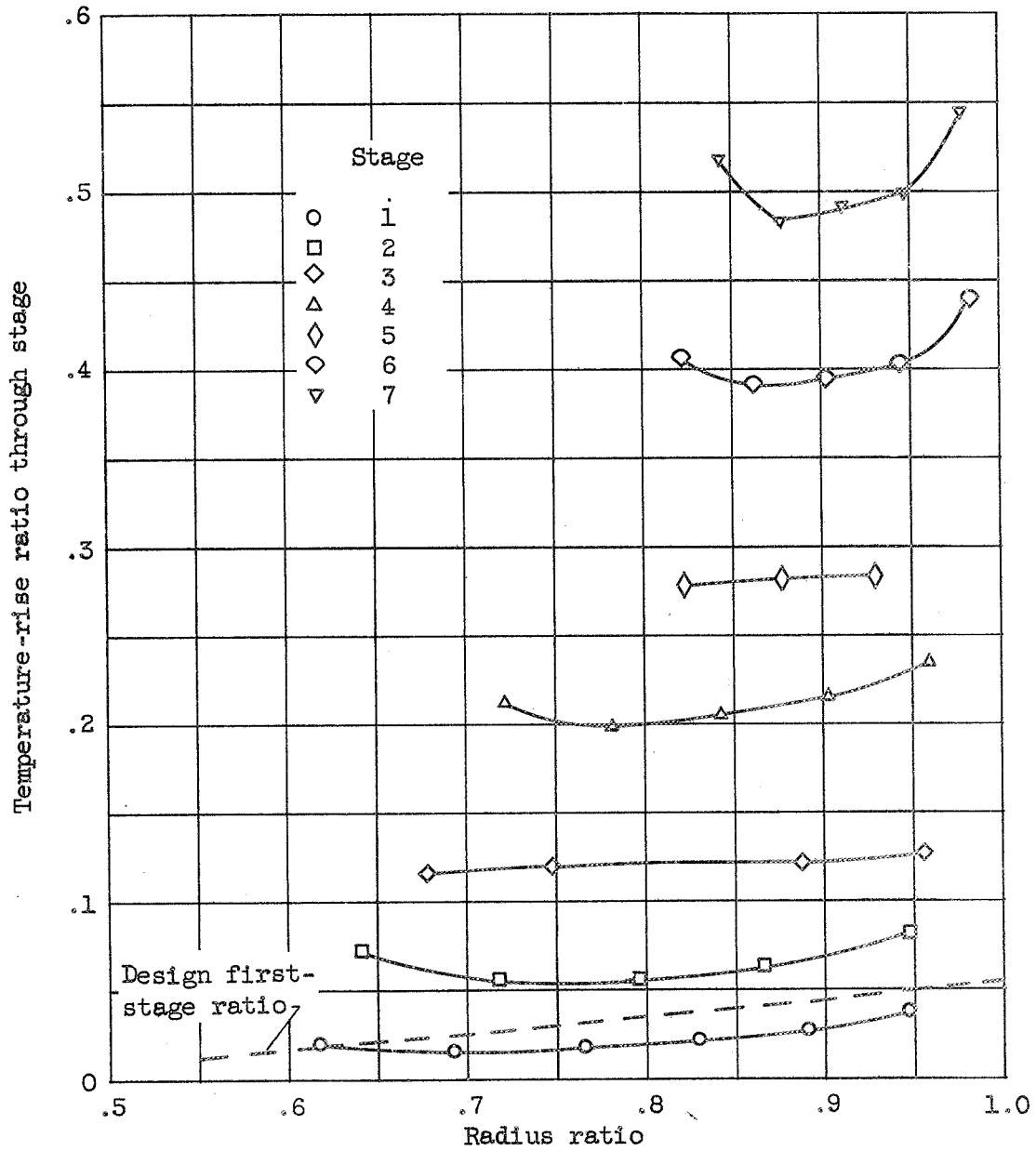
(b) Stages 1 to 7. Speed, 75-percent design.

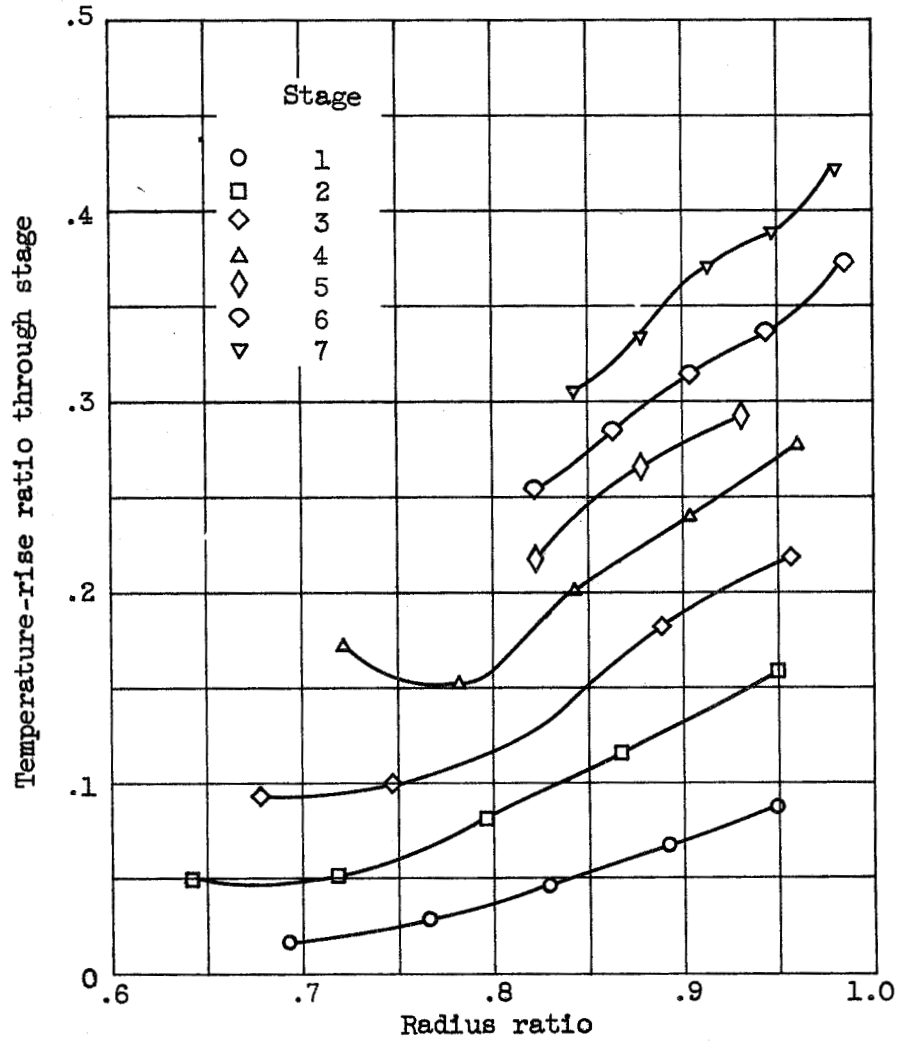Figure 7. - Continued. Over-all surge total-
pressure ratios.
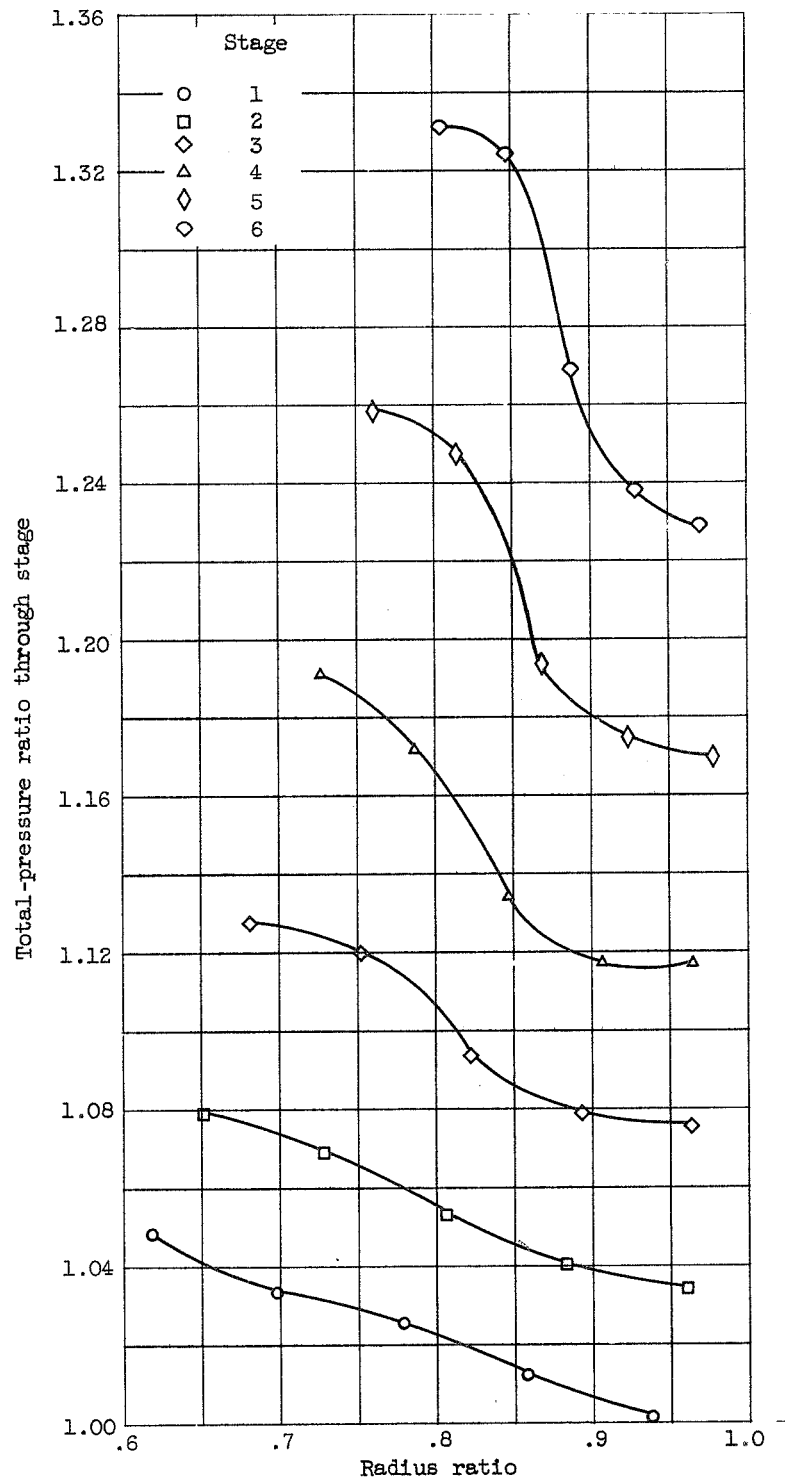
(c) Stages 1 to 6. Speed, 50-percent design.

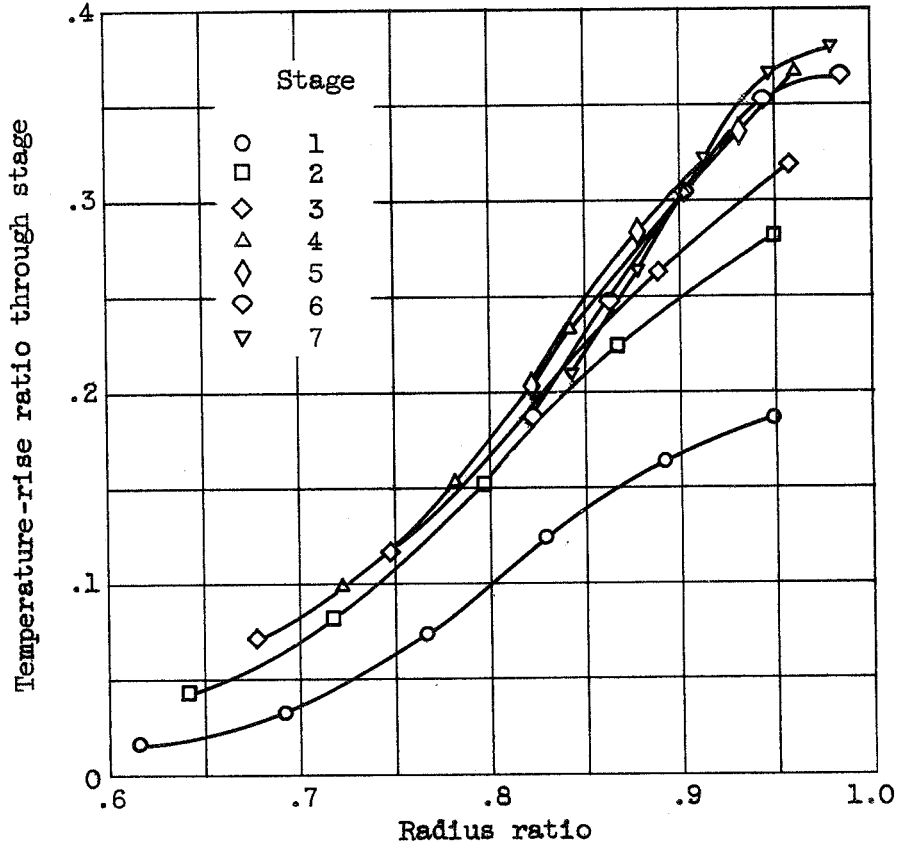Figure 7. - Concluded. Over-all surge total-
    pressure ratios.

(a) Design speed.

Figure 8. - Surge temperature-rise ratios through stages 1
to 7.

(b) Speed, 75-percent design.

Figure 8. - Continued. Surge temperature-rise
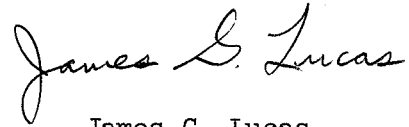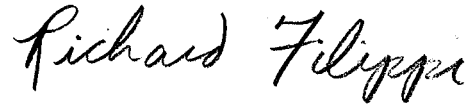ratios through stages 1 to 7.

(c) Speed, 50-percent design.

Figure 8. - Concluded. Surge temperature-rise
ratios through stages 1 to 7.

PERFORMANCE OF 15-STAGE EXPERIMENTAL J71 AXIAL-FLOW COMPRESSOR

II - INDIVIDUAL STAGE PERFORMANCE CHARACTERISTICS

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Compressors - Axial Flow   3.6.1.1

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PERFORMANCE OF 15-STAGE EXPERIMENTAL J71 AXIAL-FLOW COMPRESSOR
II - INDIVIDUAL STAGE PERFORMANCE CHARACTERISTICS

Abstract

The first four stages were found to cause a major part of the poor
low-speed efficiency of this compressor. The low design-speed over-all
pressure ratio at surge was caused by the first and the twelfth to fif-
teenth stages. The multiple over-all performance curves in the
intermediate-speed range were at least partly the result of double-
branched characteristic curves for the third and seventh stages.

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