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EFFECT OF SLOTTED CASING TREATMENT WITH CHANGE IN REYNOLDS NUMBER INDEX ON PERFORMANCE OF A JET ENGINE

by John E. Moss, Jr., and Willis M. Braithwaite

Lewis Research Center

SUMMARY

A test program was run on a J85-13 engine in an altitude test facility at Lewis Research Center to determine the effect of tip treatment on compressor performance. This J85 engine compressor case had been modified to allow inserts to be installed over the rotor tips of six of its eight stages. Tests were run with solid and slotted inserts installed over the tips of the first three compressor stages. Data were taken at Reynolds number indices (RNI) of 0. 3 and 0. 7 with clean inlet conditions at 80- and 100-percent corrected engine speeds.

Compressor maps were generated for both the solid inserts compressor case test data and the slotted inserts case data. At 100-percent corrected engine speed, the stall pressure ratio for both the 0. 3 RNI and the 0. 7 RNI was 6 percent lower for the tip-treated compressor than it was for the untreated compressor. Also, at 100-percent corrected engine speed, the stall pressure ratio was 3. 8 percent lower at 0.3 RNI than it was at 0. 7 RNI for both the treated and untreated compressor cases. At 80-percent corrected engine speed, the stall pressure ratio was 2. 8 percent lower at 0.3 RNI than it was at 0. 7 RNI. The location of the stall line on the compressor map was not significantly affected by decreasing RNI. The loss in stall pressure ratio resulted from a shifting of the speed lines.

Data were obtained showing the effect of two RNI values on the boundary layer thickness at stations 2, 2. 2, and 2. 7. Flow coefficients and pressure coefficients were calculated for each stage. Plots of pressure coefficients against flow coefficients show little change with tip treatment or RNI change.

INTRODUCTION

Experimental and analytical studies (refs. 1 to 4) have shown that tip treatment could improve the distortion tolerance and flow range of axial flow compressors. The effectiveness of grooved and slotted tip treatments applied to a J85-13 engine has been reported in references 5 and 6. These studies were conducted at a Reynolds number index (RNI) of 0.5.

Since the character of the inlet boundary layer is a function of RNI, the effectiveness of tip treatment especially on the front stages could be influenced by RNI. Additional data were taken at RNI's of 0.3 and 0.7 to evaluate this influence. The J85-13 was run untreated and with slotted tip treatment over the first three stages. The results of this investigation are presented in this report.

APPARATUS

The compressor of a J85-13 was redesigned to permit changes in the case wall over the rotor tips of the first three and last three of the eight stages. This was effected by providing segmented rings (T-shaped cross section) which slipped into mating grooves in the compressor case. Figure 1(a) shows half of the compressor case with rings in place; figure 1(b) shows the case with the rings removed. The eighth-stage ring and groove are not shown in these photographs; this ring is sandwiched between the compressor case and the main frame.

Figure 2 shows a sketch and dimensions of the slotted rings. The angles of the slots are parallel to the chords of the rotor blades at their respective stages.

For this investigation, tip treatment was limited to the first three compressor stages. Solid inserts were installed in the last three stages. The RNI effect should be felt primarily in the front stages of the compressor.

The engine's inlet guide vanes were linked to the compressor interstage bleed doors so that when the guide vanes were fully closed the bleed doors were fully open. These were operated according to the manufacturer's schedule; bleed doors varied linearly from fully open at a corrected engine speed of 80 percent and below to fully closed at 94 percent and above. The sensitivity of the bleed schedule to inlet temperature was removed; therefore, comparisons of results could be made independent of small variations in inlet temperatures.

A first-stage turbine nozzle with approximately 74 percent nominal area was used. This nozzle allowed compressor stalls without excessive turbine inlet temperatures.

The exhaust nozzle was manually controlled. Closing the exhaust nozzle forced the compressor into stall. Six blockage plates were added to the inner surface of the nozzle. With these in place, the range of nozzle area available was 400 to 1130 square centimeters.

INSTRUMENTATION

Figure 3 shows the layout of instrumentation. Station 2 pressure probes were located 3.7 centimeters upstream of the compressor face. This array consisted of twelve rakes. Eleven of these rakes contained five probes each. The other rake was an outer diameter boundary layer rake with ten probes. Station 2 thermocouples were located 7.9 centimeters upstream of the engine face. Hub and tip boundary layer rakes were installed at interstage stations 2.2 and 2.7. Closely coupled, high-response static pressure transducers were provided at each stator row to locate the compressor stall sites.

Compressor discharge instrumentation was installed through the four bleed ports at the rear of the compressor. At each port, three total-pressure, one static-pressure, and three total-temperature probes were used. A sketch of the pressure probe is presented in reference 5. At the compressor discharge, the following weightings were used in averaging the data: 20 percent for the inner probe, 60 percent for the middle probe, and 20 percent for the outer probe.

More detailed information on the instrumentation is given in reference 7.

Engine airflow was calculated from pressures and temperatures measured in a plenum upstream of the inlet by using a previously determined inlet bellmouth calibration and station 1 static pressure as presented in appendix A. (The symbols are defined in appendix B.)

PROCEDURE

Tests were conducted with ambient inlet temperatures and a nominal inlet pressure of 6.6 newtons per square centimeter. These inlet conditions yielded an RNI of 0.70 at the compressor face. Tests were also conducted with ambient inlet pressure of 2.82 newtons per square centimeter. These inlet conditions yielded an RNI of 0.3 at the compressor face. The altitude chamber was maintained at a pressure sufficiently low to ensure a choked exhaust nozzle.

The compressor was mapped with and without tip treatment with clean inlet conditions. Each mapping consisted of three constant corrected speed lines (80, 90, and 100 percent of rated). Several steady-state data points were taken along each speed line from wide open exhaust nozzle to stall. The exhaust nozzle area was reduced manually in increments until compressor stall occurred.

As data were taken along the constant corrected speed lines, turbine-discharge total temperature was observed on a control room gage and recorded. This gage was monitored carefully to obtain the turbine-discharge temperature at stall. Data obtained in this way were used to draw curves of compressor pressure ratio and corrected airflow as functions of turbine-discharge temperature. These curves were extrapolated to the turbine-discharge temperature at stall, thus determining the compressor pressure and corrected airflow at the stall point.

RESULTS AND DISCUSSION

The effect of tip treatment with decreasing RNI was investigated using a J85-13 turbojet engine. Data were obtained with and without tip treatment in the first three compressor stages for RNI's of 0.7 and 0.3. The effects will be discussed in terms of boundary layer thickness, compressor performance, and stage characteristics.

Boundary Layer Thickness

The boundary layer was measured at stations 2, 2.2, and 2.7. The station 2.7 boundary layer rakes contained three probes each. Two of these probes were in the boundary layer flow and the other probe was in the free stream. Two probes were not sufficient to determine the thickness directly; therefore, in order to obtain comparative values of thickness, these pressure measurements were used with the boundary layer equation for viscous boundary layer to calculate the boundary layer thickness (see appendix A).

The boundary layer profile obtained at station 2, where there were ten probes, indicated that the value 7 for the exponent in the boundary layer equation provided the best fit of the data. Therefore, 7 was also used for stations 2.2 and 2.7 calculations.

Compressor face. - The boundary layer thickness at the compressor face is a function of the distance from the bellmouth as well as the pressure and temperature levels. Therefore, the exact thickness is pertinent only to the test setup. However, the change in thickness is indicative of the effects of the temperature and pressure variations.

As shown in figure 4, for both the tip-treated and untreated cases, reducing the RNI from 0.7 to 0.3 increases the boundary layer for 80- and 100-percent corrected engine speeds. Tip treatment also increased the boundary layer thickness for both 0.7 and 0.3 RNI's at 100-percent corrected engine speed, and for 0.7 RNI at 80-percent corrected engine speed.

Interstage effects. - The boundary layer thicknesses calculated in the second- and seventh-stage stators are also shown in figure 4. The boundary layer thickness has decreased significantly from that at station 2, even in the second-stage stator.

With tip treatment, reducing the RNI from 0.7 to 0.3 decreased the tip boundary layer thickness for 80- and 100-percent corrected engine speeds. Without tip treatment decreasing the RNI from 0. 7 to 0. 3 increased the tip boundary layer thickness for 100-percent corrected engine speed and decreased the boundary layer thickness for 80-percent corrected engine speed. Tip treatment had little effect on the hub boundary layer thickness for 80- and 100-percent corrected engine speeds.

Tip treatment had little effect on the seventh-stage stator boundary layer thickness. Decreasing the RNI from 0. 7 to 0. 3 decreased the hub boundary layer thickness for 80-percent corrected engine speeds.

Compressor Performance

Figures 5 and 6 present the compressor performance maps for uniform inlet flow. Figure 5(a) shows a 6-percent loss in the stall margin at 100-percent corrected engine speed at 0. 7 RNI with tip treatment. For greater accuracy in plotting the stall line, baseline data were obtained for 90 percent corrected engine speed with and without tip treatment for 0. 7 RNI. Figure 5(b) also shows a 6-percent loss in stall margin at 100-percent corrected engine speed at 0. 3 RNI.

Figure 6 shows that decreasing the RNI from 0. 7 to 0. 3 reduced the corrected airflow, thus shifting the constant speed lines to the left. A change in RNI also reduced the stall pressure ratio 3. 8 percent at 100-percent corrected engine speed and 2. 8 percent at 80-percent corrected engine speed. The location of the stall line on the compressor map was not significantly affected by decreasing RNI. The loss in stall pressure ratio resulted from a shifting of the speed lines.

A detailed discussion of the effect of tip treatment on the compressor performance of a J85-13 compressor is given in references 5 and 6. Tip treatment did not improve the performance of the J85-13 compressor in its normal operating range for this engine is hub critical (refs. 5 and 6).

Pressure Coefficient as Function of Flow Coefficient

Pressure characteristics curves for the individual stages at 80- and 100-percent of corrected engine speeds at 0. 3 and 0. 7 RNI are shown in figures 7 and 8. Individual stage pressure coefficients were not appreciably affected by tip treatment or change in RNI.

SUMMARY OF RESULTS

Data were obtained to determine the effect of tip treatment with Reynolds number index (RNI) change on the compressor performance of a J85-13. The following results were obtained:

1. There was a 6-percent loss in stall pressure ratio with tip treatment at 100-percent corrected engine speed for both 0.3 and 0.7 RNI's.

2. Decreasing the RNI from 0.7 to 0.3 decreased the stall pressure ratio 3.8 percent for 100-percent corrected engine speed and 2.8 percent for 80-percent corrected engine speed.

3. The location of the stall line on the compressor map was not significantly affected by decreasing the RNI. The loss in stall pressure ratio resulted from a shifting of the speed line.

4. Decreasing the RNI increased the inlet boundary layer thickness at station 2 but had little effect on the internal stages.

5. Individual stage pressure coefficients were not appreciably affected by tip treatment and/or change in the RNI.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 6, 1977,
505-05.

APPENDIX A

CALCULATION METHODS

Airflow:

$$W_1 = C_D A \left(\frac{P_{tot,p}}{RT_p}\right)\left(\frac{P_{s1}}{P_{tot,p}}\right)^{1/\gamma} \sqrt{2gRT_p \frac{\gamma}{\gamma - 1}\left(1 - \frac{P_{s1}}{P_{tot,p}}\right)^{(\gamma-1)/\gamma}}$$

Corrected airflow:

$$WA1C2 = \frac{W_1\sqrt{\theta}}{\delta}$$

Flow coefficient:

$$\varphi_i = \frac{V_{z,i}}{U_i}$$

Pressure coefficient:

$$\psi_{P,i} = \frac{\gamma_{i-1}}{\gamma_{i-1} - 1} gRT_{i-1} \frac{\left(\frac{P_i}{P_{i-1}}\right)^{(\gamma_i-1)/\gamma_i} - 1}{U_i^2}$$

Reynolds number index (RNI):

$$RNI = \frac{\delta}{\frac{\mu}{\mu_{SL}}\sqrt{\theta}}$$

Boundary layer thickness:

$$\xi = \frac{y}{\left(\frac{u}{u_s}\right)^7}$$

$$\frac{u}{u_s} = \sqrt{\frac{\left(\frac{P_{tot, i_{BL}}}{P_{s, i}}\right)^{(\gamma-1)/\gamma} - 1}{\frac{P_{tot, i_{BL}}}{P_{s, i}}}}$$

where $P_{s, i}$ is measured and assumed constant, $P_{tot, i_{BL}}$ is measured in the boundary layer stream, $P_{tot, i}$ is measured in the free stream, and y is the known distance from the wall.

APPENDIX B

SYMBOLS

A	flow area, m^2
BL	boundary layer
C_D	flow coefficient
g	acceleration due to gravity, 9.8066 m/sec^2
i	stage number
P_R	pressure ratio, $P_{tot,3}/P_{tot,2}$
P_s	static pressure, N/cm^2
P_{tot}	total pressure, N/cm^2
$P_{tot,p}$	plenum total pressure, N/cm^2
R	gas constant, J/(kg)(K)
SL	sea level
T	total temperature, ^oC
T_P	plenum temperature, ^oC
U	rotor tip velocity, cm/sec
u	velocity
u_s	freestream velocity, cm/sec
V_Z	axial flow velocity, cm/sec
W	airflow rate, kg/sec
y	thickness or distance from wall
γ	ratio of specific heats
δ	ratio of total pressure to standard sea level pressure
θ	ratio of total temperature to standard sea level static temperature
μ	absolute viscosity, kg/(m)(sec)
ξ	boundary layer thickness, cm
φ	flow coefficient
ψ_p	pressure coefficient

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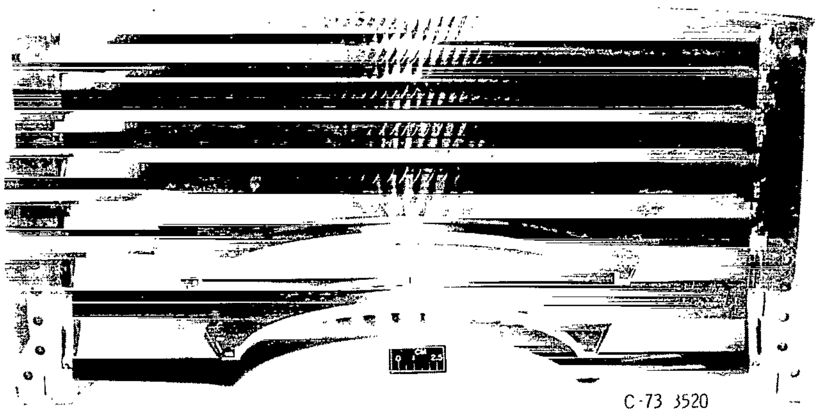
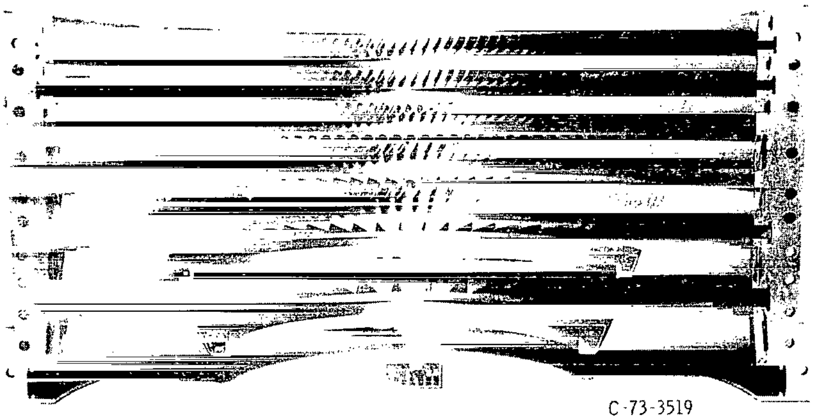
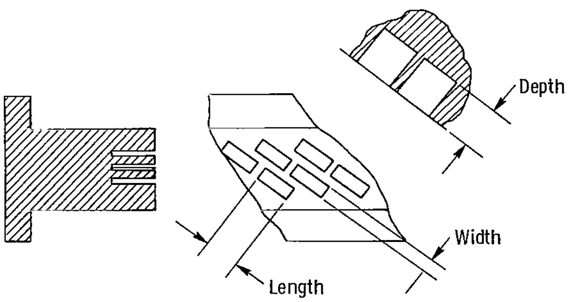


(a) With inserts for case wall treatment in place.



(b) Case wall treatment removed.

Figure 1. - Compressor case.



Stage	Number of pairs of slots	Width, cm	Length, cm	Depth, cm
1	240	0.208	0.932	0.610
2	364	.152	.536	.457
3	388	.137	.297	.406

Figure 2. - Sketch and dimensions of rings.

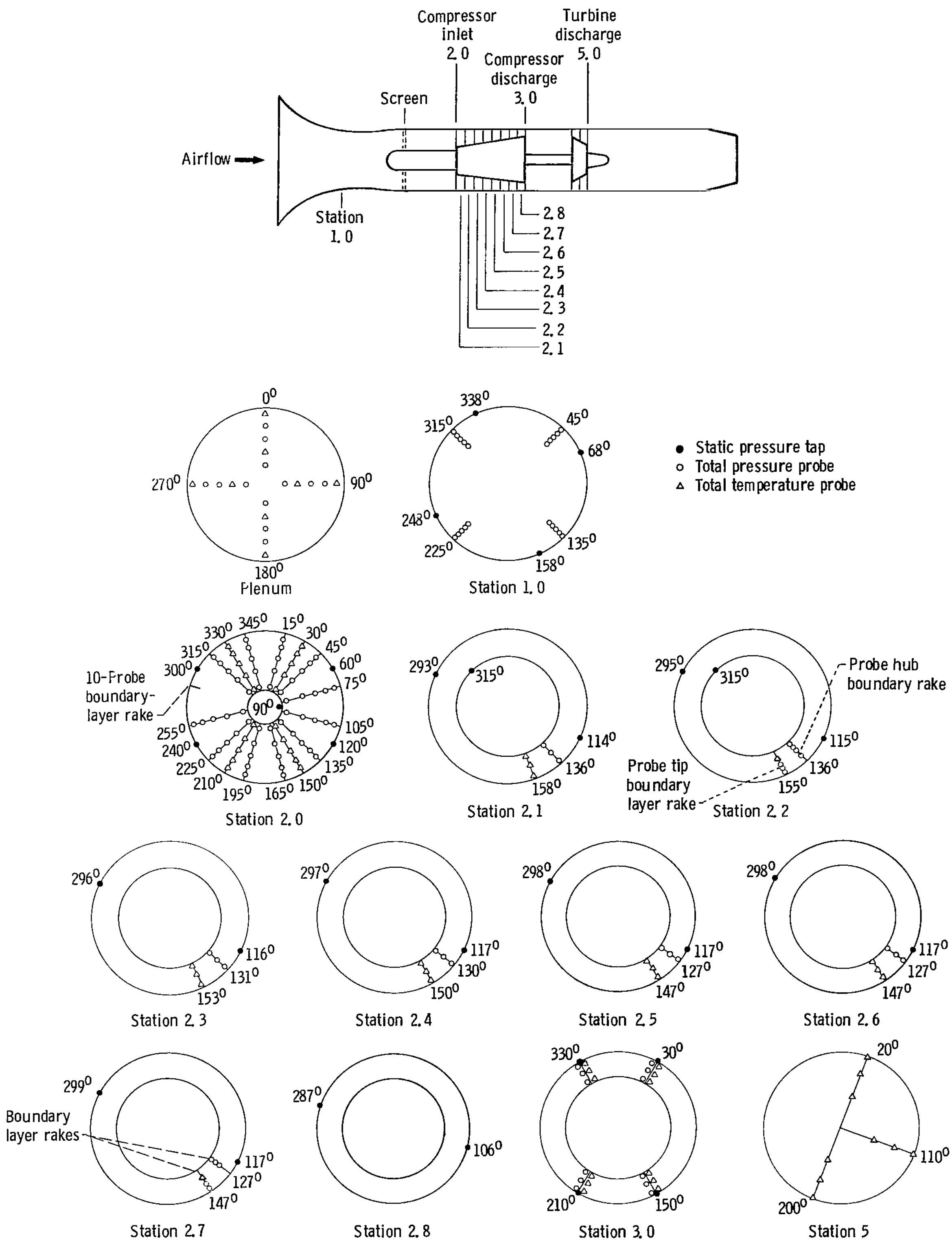
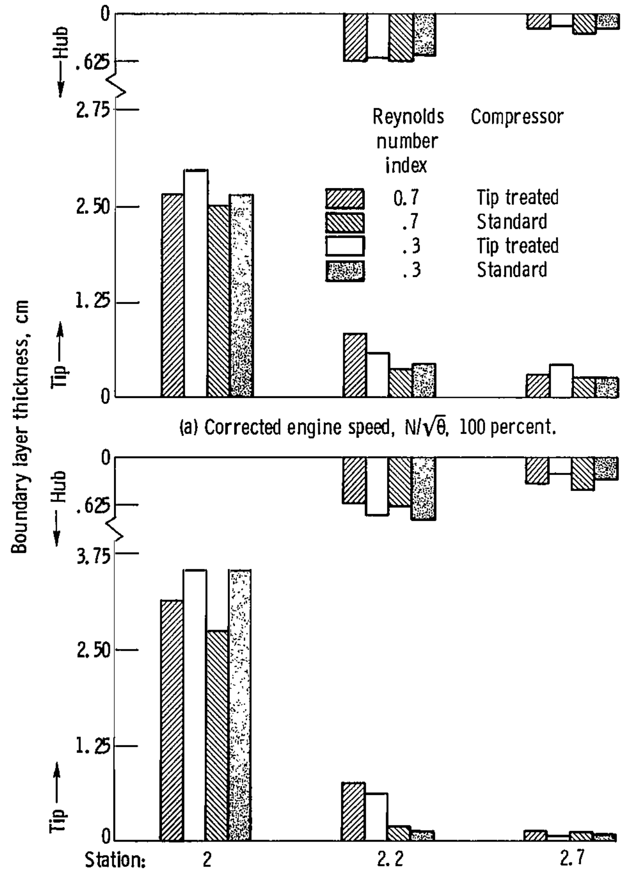


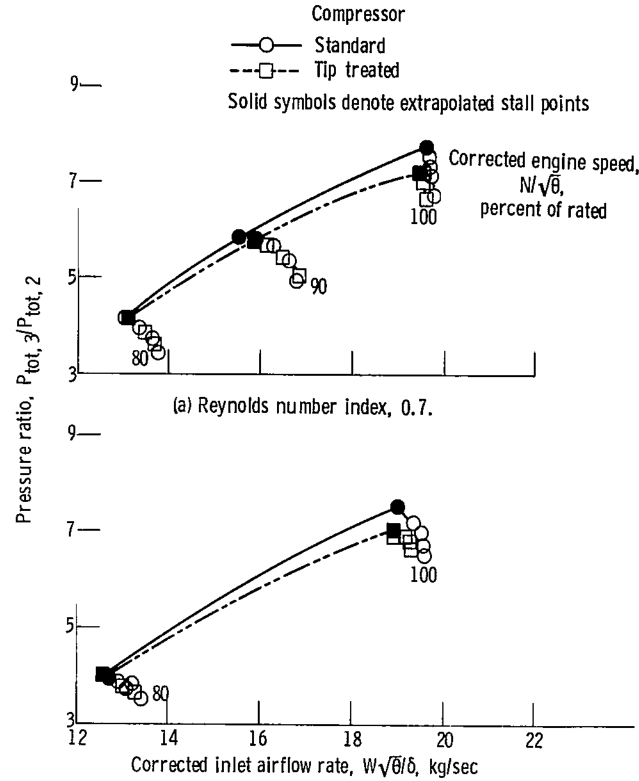
Figure 3. - Station schematic engine layout.



(a) Corrected engine speed, $N/\sqrt{\theta}$, 100 percent.

(b) Corrected engine speed, $N/\sqrt{\theta}$, 80 percent.

Figure 4. - Boundary layer thickness.



(a) Reynolds number index, 0.7.

(b) Reynolds number index, 0.3.

Figure 5. - Compressor performance with uniform inlet flow.

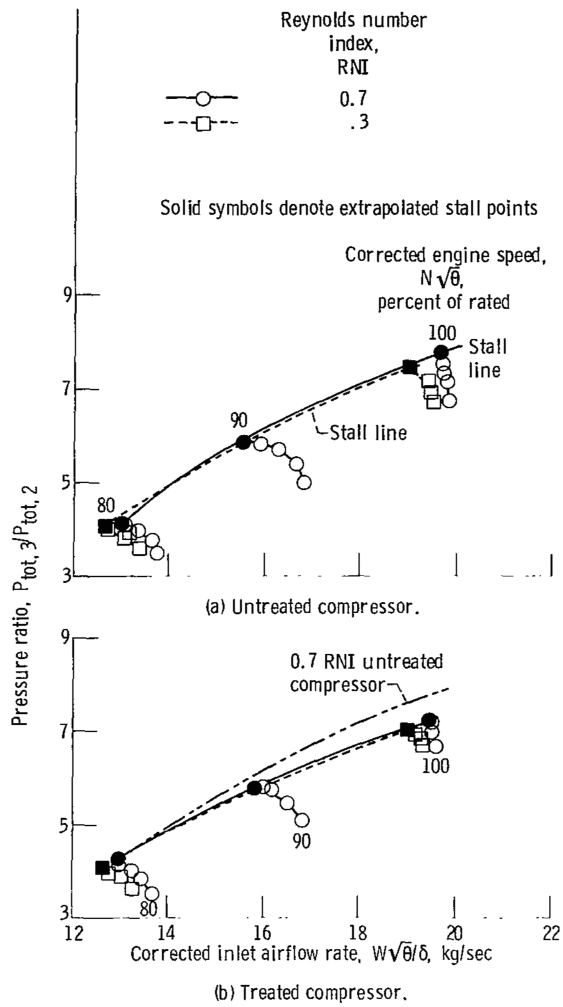
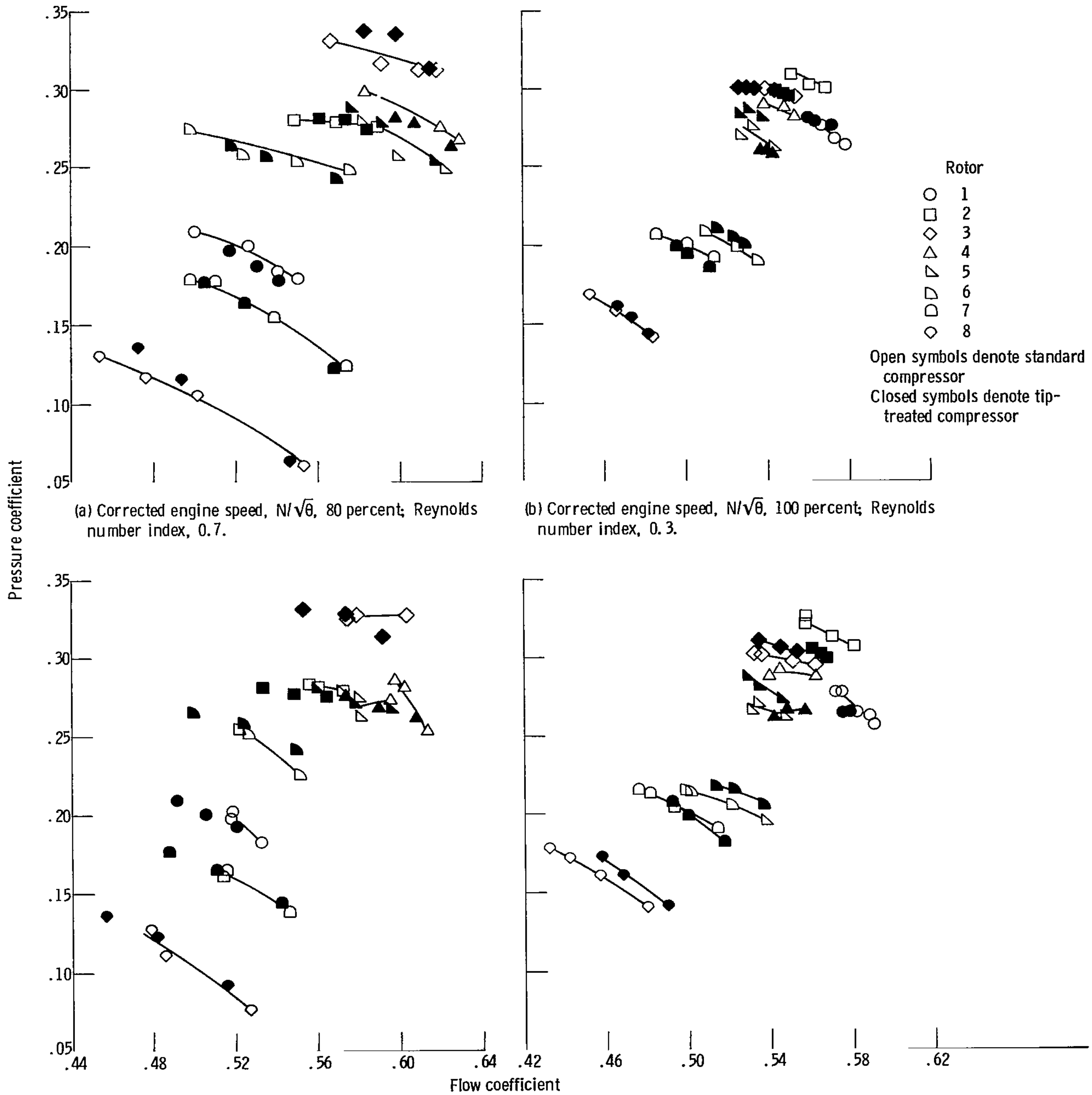


Figure 6. - Compressor performance with treated and untreated rings with uniform inlet flow.



(a) Corrected engine speed, N/√θ, 80 percent; Reynolds number index, 0.7.

(b) Corrected engine speed, N/√θ, 100 percent; Reynolds number index, 0.3.

(c) Corrected engine speed, N/√θ, 80 percent; Reynolds number index, 0.3.

(d) Corrected engine speed, N/√θ, 100 percent; Reynolds number index, 0.7.

Figure 7. - Pressure characteristics for individual stages with and without tip treatment.

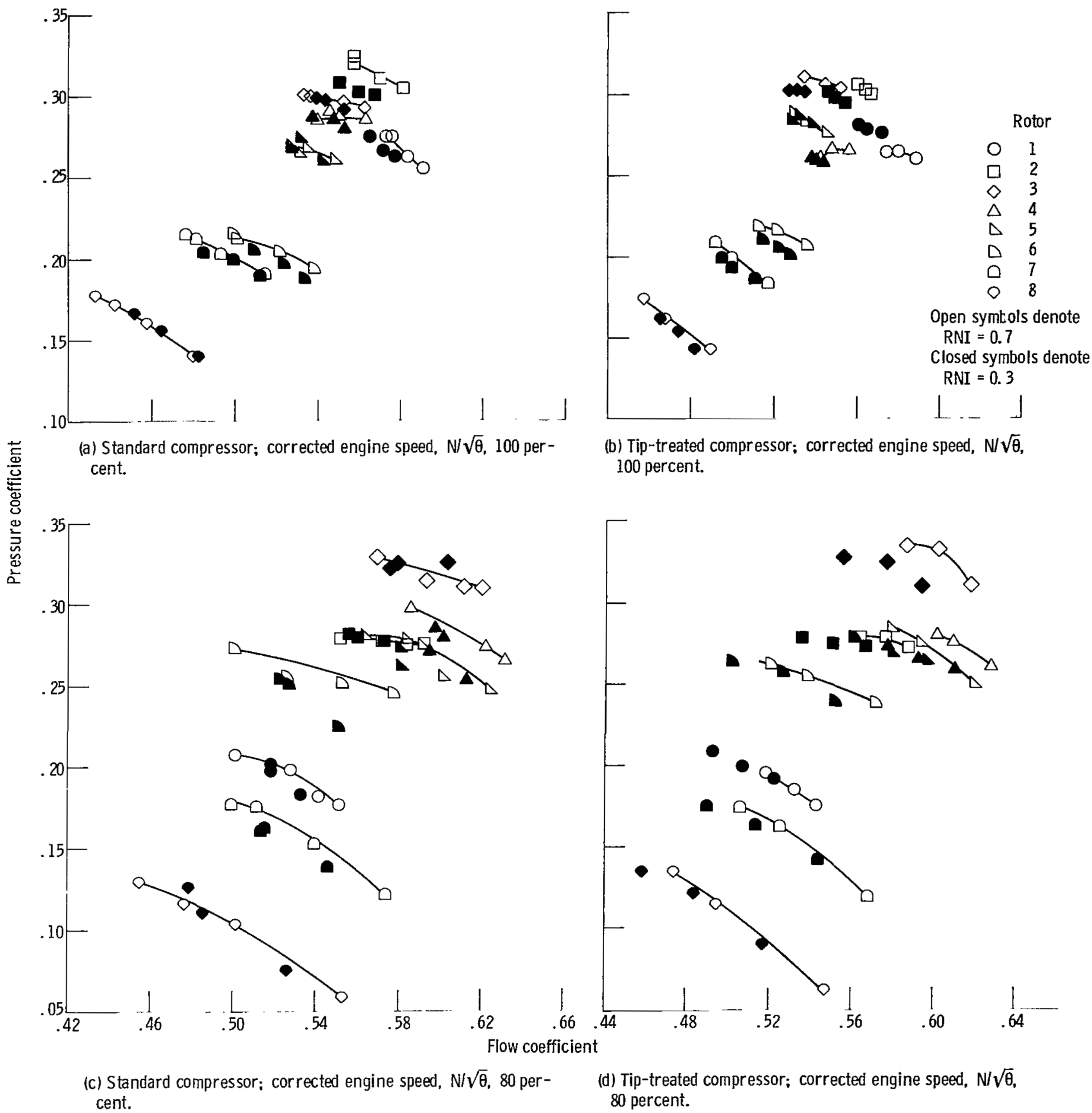


Figure 8. - Pressure characteristics for individual stages with no tip treatment.

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15. Supplementary Notes

16. Abstract

A tip-treated J85-13 engine was tested at Reynolds number indices (RNI) of 0.3 and 0.7 with a clean inlet for 80- and 100-percent corrected engine speeds. This engine was equipped with a compressor case which allowed changes to the case wall over the rotor tips of six of its eight stages. For all tests, the principal effects were (1) with tip treatment, a stall pressure ratio loss of 6 percent at 100 percent corrected engine speeds for both the 0.3 and 0.7 RNI, and (2) with and without tip treatment, decreasing the RNI from 0.7 to 0.3 decreased the stall pressure ratio 3.8 percent for 100 percent corrected engine speed and 2.8 percent for 80-percent corrected engine speed.

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