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EXPERIMENTAL STUDY OF LOW ASPECT RATIO COMPRESSOR BLADING

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INTRODUCTION

The attainment of improved cycle efficiency for advanced gas turbine engines requires increased pressure ratios for the core compressor. During the past few years NASA-Lewis has been conducting an extensive research program on axial flow compressors with high pressure ratio transonic stages. As a part of this program, four single-stage compressors, that are representative of the inlet stage of a multistage core compressor, were designed and evaluated experimentally.

The stage designs feature two levels of rotor aspect ratio (1.19 and 1.63) and two levels of pressure ratio (1.82...
and 2.05). The aerodynamic designs for the four stages are given in reference 1. This paper presents a more detailed investigation of the flow phenomena for the four stages utilizing selected blade element parameters. Comparisons of blade element parameters are presented for the two different aspect ratio configurations at each of the design pressure ratio levels. Blade loading levels (diffusion factors) are compared for the near-stall conditions at all speeds tested. Comparisons are made of loss and diffusion factors (D-factors) over the operating range of incidence angles at several span locations. The axial distributions of rotor tip static pressure are presented for three flow conditions at design speed for all four stages.

**APPARATUS AND PROCEDURE**

**Test Facility**

The compressor stages were tested in the Lewis Research Center single stage compressor test facility, which is described in detail in reference 2. A schematic diagram of the facility is shown in figure 1. Atmospheric air enters the facility at a point located on the top of the building and flows through the flow-measuring orifice and into the plenum chamber upstream of the test stage. The air then passes through the experimental compressor stage into the collector and is exhausted to the atmospheric exhaust system. The rotor is driven by a variable-speed electric motor through a gearbox.

**Test Compressors**

The detailed aerodynamic and mechanical designs of the compressors used in this investigation are presented in reference 1 and thus only a brief description will be presented herein. The basic designs feature two levels of stage pressure ratio, two levels of rotor aspect ratio, and two levels of stator aspect ratio. The designs are summarized in table 1. Stages 35 and 36, having a design pressure ratio of 1.82 were designed for rotor blade aspect ratios of 1.19 and 1.63, respectively. Similarly, stages 37 and 38, having a design pressure ratio of 2.05, also had rotor blade aspect ratios of 2.05. Stator blade aspect ratios were 1.19 and 1.63, respectively. Stator vane aspect ratios were 1.26 and 1.78. All of the rotor and stator blades have multiple circular arc airfoils. Careful positioning of the blade rows allowed all four stages to be tested with the same flow path geometry (fig. 2). The design specified flow (100.1 kg/sec/cm²) and rotor tip speed (455.0 m/sec) were the same for all four stages. These are relatively high values of mass flow and tip speed for core type stages.

**Test Procedure**

The stage survey data were taken over a range of flows for speeds from 50 to 100 percent of design speed. For each flow, data were recorded at nine radial positions upstream (station 1) and downstream (station 3) of the test stage. At station 3, the instrumentation was also circumferentially traversed to nine positions across the stator gap. The axial locations of the survey stations are shown in figure 2. The survey measurements consisted of total pressure, static pressure, total temperature, and flow angle. Flow was measured with a thin plate orifice. A more complete description of the survey instrumentation and test procedure is given in reference 1.

The estimated errors in the data, based on inherent accuracies of the instrumentation and recording system, are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow, kg/sec</td>
<td>±0.3</td>
</tr>
<tr>
<td>Rotative speed, rpm</td>
<td>±30</td>
</tr>
<tr>
<td>Flow angle, deg</td>
<td>±1.0</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>±0.6</td>
</tr>
<tr>
<td>Rotor-inlet (station 1)</td>
<td>±0.01</td>
</tr>
<tr>
<td>Rotor-outlet (station 3)</td>
<td>±0.17</td>
</tr>
<tr>
<td>Stator-outlet (station 3)</td>
<td>±0.10</td>
</tr>
</tbody>
</table>

**Calculation Procedure**

Because of the close spacing between the rotor and stator, no instrumentation could be used at station 2 (see fig. 2). The values of pressure, temperature, and flow angle at this station were obtained as follows: At each radial survey position, total pressure and total temperature were translated along design streamline from station 3. The circumferentially mass-averaged total temperatures from station 3 were used as the total temperatures at station 2. The arithmetic mean of the three highest total pressure values from the circumferential distributions at station 3 were used as the total pressures at station 2. The radial distributions of static pressure and flow angle were calculated based on continuity of mass flow and radial equilibrium. Measured airflow and rotative speed were inputs. Design values of streamline curvature and blockages were also used in the calculations.

All data are corrected to standard day conditions based on the rotor inlet conditions. Overall total pressure ratios and total temperature ratios are based on an energy average of the pressures and temperatures obtained from the calibrated survey instrumentation. Blade element data are translated along design streamlines to the blade leading and trailing edges. Details of the calculation procedure are given in reference 1.

**RESULTS AND DISCUSSION**

An assessment of the effects of blade aspect ratio is made by comparing some of the basic flow phenomenon for the two aspect ratio configurations for each level of design pressure ratio. The overall performance comparisons are presented to show the overall effects of blade aspect ratio on the performance characteristics. Radial distributions of performance parameters are compared for the peak efficiency conditions at design speed to show how the difference
in overall performance manifests itself over the blade span. Rotor tip and stator hub diffusion factors for the four stages are compared for the near-stall conditions over the entire speed range. This comparison is made in an attempt to determine which blade row is controlling the flow range and to assess the effects of blade aspect ratio on blade loading limits. Blade element performance comparisons are made to assess the effects of blade aspect ratio on typical blade element parameters over a range of flow conditions. Axial distribution of rotor tip static pressures are presented at design speed to assess the effect of blade aspect ratio on end wall flow conditions when shocks are present.

Overall Performance Comparisons

The effects of aspect ratio on overall performance are presented in figure 3. For both design pressure ratio levels, the overall rotor and stage performances for the lower aspect ratio configurations are substantially better than those for the higher aspect ratio configurations. The lower aspect ratio configurations achieved a higher peak pressure ratio and efficiency and a larger flow range over the range of speeds tested. The largest increase in flow range occurred at the design speed.

For the higher design pressure ratio configurations the peak rotor efficiency, at design speed, for the lower aspect ratio configuration (stage 37) is about 2.5 points higher than that for the higher aspect ratio configuration (fig. 3(b)).

However, the difference in stage efficiency is about one point.

Similar trends are shown for the lower design pressure ratio configurations (fig. 3(a)). At design speed, the peak efficiency for both rotor and stage is approximately 2 points higher for the lower aspect ratio configuration.

The highest overall rotor and stage efficiencies were obtained with the lower aspect ratio higher-pressure configuration (stage 37) and they occurred at 90 percent design speed. The maximum rotor and stage efficiencies are 91.6 percent and 89.3 percent, respectively. The corresponding pressure ratios are 1.775 and 1.751.

The peak efficiencies at design speed along with the corresponding pressure ratios for rotor and stage for all four configurations are summarized in table II. Also shown are the values of stall margin based on conditions at peak efficiency and stall.

Radial Distributions of Performance Parameters

Comparisons of the radial distributions of rotor performance parameters, for the peak rotor efficiency at design speed, are presented in figure 4. Some general trends common to both aspect ratio configurations, are noted. The radial distributions of total pressure ratio are similar for all four rotors. The highest pressure ratio and efficiency occurred in the hub region. For both levels of design pressure ratio, the lower aspect ratio rotors (35 and 37) achieved higher efficiencies and higher pressure ratio over practically the entire blade span. The radial distribution of rotor inlet relative Mach number is practically identical for all four configurations. The rotor inlet relative Mach numbers are supersonic over the entire span and the exit relative Mach numbers (not shown) are subsonic over the entire blade span. It is apparent that the distributions of efficiency and total loss parameters are strongly influenced by the shock losses.

In comparing the lower design pressure ratio configurations (fig. 4(a)), the efficiency difference is most pronounced in the region from 30 to 85 percent span. There is a noticeable inflection in the efficiency distributions at the 50-percent span location for both rotors. This could be a result of large shock losses associated with the high inlet relative Mach (1.4) and high blade loading for this span-wise location. For the lower aspect ratio rotor (rotor 35), the efficiency varies from about 0.80 in the tip region to 0.927 at the 85-percent span location. For the higher aspect ratio rotor (rotor 36), the efficiency varies from about 0.79 in the tip region to 0.902 at the 85-percent span location.

In comparing the higher design pressure ratio rotors (rotors 37 and 38), the efficiency for the lower aspect ratio rotor (rotor 37) varies from about 0.77 in the tip region to 0.938 at the 85-percent span location. For the higher aspect ratio rotor, the efficiency varies from 0.76 in the tip region to 0.904 at the 85-percent span location.

Effects of Aspect Ratio on Stall D-Factor

Although the diffusion factor (D-factor) was developed to represent blade loading in a flow field that is totally subsonic, it is commonly used to correlate data from blade rows that operate in a transonic flow field. For flows with shocks, it is recognized that the diffusion factor is questionable for expressing local diffusion (blade loading) on the blade surfaces. However, D-factor has been used with some success in correlating losses and stall margin for transonic blade rows. This indicates that comparative results utilizing D-factor correlations for transonic blade rows can be useful when applied in a consistent manner.

This section shows, on a relative basis, how the D-factors for the near-stall conditions vary with blade aspect ratio.

The diffusion factor and inlet relative Mach number are plotted in figure 5 as a function of percent design speed at the near-stall condition for all four stages. Data are shown for the rotor tip (40% span) and stator hub (90% span). Considering that the rotor tip diffusion factors are substantially higher than the corresponding stator hub diffusion factors and that the maximum stator hub Mach number is about 0.83, it is reasonable to assume that the flow range is limited by the flow conditions in the rotor tip region for all four stages. For the rotor tip (fig. 5(a)), the inlet relative Mach numbers at the near-stall conditions are practically the same for all four rotors. However, the rotor diffusion factors at the near-stall conditions show that the stalling D-factors are substantially larger for the lower aspect ratio
rotors (rotors 35 and 37) than those for the higher aspect ratio configurations at all speeds with a possible exception of the 50-percent speed. For all rotors, the largest value of diffusion factor at near-stall conditions occurred at design speed. The highest design pressure ratio low aspect ratio rotor (rotor 37) had the highest stall diffusion factor of 0.645. This value of diffusion factor is higher than that for other inhouse higher aspect ratio rotors with comparable inlet relative Mach numbers.

The diffusion factor and inlet Mach number at the stator hub 60% span from tip) are plotted as a function of design speed in figure 5(b). The trends of Mach number and D-factor variations with percent design speed are similar to those for the rotor. However, the diffusion factor values are not considered to be stall values for these stators. It is of interest to note, however, that at an inlet Mach number of approximately 0.88 stator 37 (lower aspect ratio) operated at a diffusion factor of approximately 0.575. Based on NASA experience, this is an unusually high value of stator hub diffusion factor for this level of inlet Mach number.

Blade Element Performance Comparisons

Comparisons of rotor blade element performance parameters for the high and low aspect ratio configurations and for each level of design pressure ratio are presented in figure 6. Data are presented for the 10-, 50-, and 90-percent span locations at design speed. Total loss parameter and diffusion factor are plotted as a function of suction surface incidence angles. The lower aspect ratio rotors operated over a wide range of incidence angles than the higher aspect ratio rotors for all three blade elements. For the lower aspect ratio rotors, the 10- and 50-percent elements operated to higher diffusion factors levels than the higher aspect ratio rotors. For the 10- and 50-percent span, the blade elements for the low and high aspect ratio rotors operated along the same incidence angle loss characteristics.

Axial Distributions of Rotor Tip Static Pressure

For rotor blade rows operating in a transonic flow environment, the axial distribution of the time-averaged static pressures over the rotor tips is strongly influenced by the shock patterns within the blade passage. In an attempt to qualitatively relate these axial distributions of static pressure to the shock patterns within the blade, data from another transonic rotor are presented (ref. 3). These data include both the axial distributions of rotor tip static pressures and shock patterns within the blade passage. The shock patterns were obtained from intrablade flow field measurements made with a Laser Anemometer (LA) system. The blade passage shock patterns along with the axial distributions of rotor tip static pressure are presented in figure 7 for the maximum flow and near-stall conditions. The shock patterns derived from the LA system measurements are for the 15-percent span (from the tip) location.

The axial distributions of static pressures measured on the casing over the rotor tips are ratioed to rotor inlet total pressure and plotted as a function of percent of rotor projected chord. At the maximum flow condition (fig. 7(a)), there is a weak shock at the blade entrance region and a strong shock at the exit of the blade passage. The static pressure gradients in the front and rear portions of the blades are indicative of these passage shock strengths. For the near-stall condition (fig. 7(b)) there is a strong passage shock at the blade entrance region. The strength of the shock is represented by the steep static pressure gradient in the front portion of the blade. However, just downstream of the shock the gradient decreases. These data provide a qualitative assessment of how the axial distribution of time-averaged rotor tip static pressure is influenced by the shock patterns within the blade passage. Based on this assessment the shock strengths will be inferred from the axial distributions of rotor tip static pressure for the rotors evaluated in the low aspect ratio study.

The axial distributions of rotor tip static pressure are presented in figure 8 for all four rotor configurations. Data are presented at design speed for three flow rates: maximum flow, peak efficiency, and near-stall conditions. These curves (fig. 8) show quite similar static pressure gradients for rotors with the same aspect ratio even though the blade rows are designed for different total pressure ratios. These imply that the shock patterns for the low aspect ratio rotors (rotors 35 and 37) are similar and the shock patterns for the higher aspect ratio rotors (rotors 36 and 38) are similar.

For the lower aspect ratio rotors, the back pressure is increased (lower flow), there is a substantial increase in the static pressure gradient over the front portion of the blade. This indicates that the strength of the shock is increasing and the shock is moving forward in the blade passage. The smooth and continuous static pressure rise on the rear portion of the blade indicates good subsonic diffusion even behind a strong shock.

For the higher aspect ratio rotors, as the back pressure is increased (lower flow), the increase in static pressure gradient over the front portion of the blade is small. However, the static pressure gradients in the 50- to 60-percent chord region increases very rapidly, and then 'drops off substantially just downstream of the 60-percent chord location. This indicates a strong shock and poor diffusion caused by flow separation and recirculation just downstream of the shock.

A comparison of the axial distribution of rotor tip static pressures for the near-stall conditions is presented in figure 9 for the low and high aspect ratio configurations. The comparison shows that the higher aspect ratio rotors have steeper static pressure gradients than the lower aspect ratio configurations. This indicates that it is the
This paper presents a study of low aspect blading for inlet stages of a high pressure ratio, high-speed core compressor. The basic overall design variables were stage pressure ratio and blade aspect ratio. These four stages represent two levels of total pressure ratio (1.82 and 2.95), two levels of rotor blade aspect ratio (1.19 and 1.63) and two levels of stator vane aspect ratios (1.28 and 1.78). Comparisons of overall performance, radial distributions of performance parameters, diffusion factors at the near-stall condition, blade element data, and axial distribution of rotor tip static pressures has yielded the following results:

1. Higher peak pressure ratio, high stage and rotor efficiencies and greater stall margin were obtained with the lower aspect ratio blading.
2. The lower aspect ratio blading showed improved performance over the entire blade span.
3. The lower aspect ratio rotors operated at higher diffusion factors and higher incidence angles over the entire blade span.
4. Better subsonic diffusion downstream of the passage shock was obtained in the lower aspect ratio rotors.

APPENDIX - EQUATIONS

Suction surface incidence angle:

\[ \theta_{ss} = \left( \frac{p_t}{p_0} \right)_{le} - \left( K_{ss} \right)_{le} \]

Diffusion factor:

\[ D = 1 + \frac{V_{le}^2}{V_{te}^2} \left( \frac{(rV_0)_{le} - (rV_0)_{te}}{(r_{te} + r_{le})(V_1)_{le}} \right) \]

Total loss coefficient:

\[ \omega = \frac{\left( \frac{p_t}{p_{le}} \right) - \left( \frac{p_t}{p_{te}} \right)}{(p_1)_{le} - (p_1)_{te}} \]

Total loss parameter:

\[ \omega_p = \frac{\omega \cos (\beta)_{te}}{2} \]

Adiabatic efficiency:

\[ \eta_{ad} = \frac{(T)_{le}}{(T)_{le}} - 1 \]

Equivalent mass flow:

\[ \frac{W \sqrt{\theta}}{\delta} \]

Stall margin:

\[ SM = \left[ \frac{\left( \frac{p_3}{p_1} \right)_{stall}}{\left( \frac{p_3}{p_1} \right)_{ref}} - 1 \right] \times 100 \]

REFERENCES

### TABLE I. - DESIGN OVERALL PERFORMANCE PARAMETERS FOR STAGES 35, 36, 37, AND 38

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Stage 35</th>
<th>Stage 36</th>
<th>Stage 37</th>
<th>Stage 38</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor total pressure ratio</td>
<td>1.865</td>
<td>1.863</td>
<td>2.106</td>
<td>2.105</td>
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<td>Stage total pressure ratio</td>
<td>1.830</td>
<td>1.829</td>
<td>2.039</td>
<td>2.030</td>
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<td>Rotor total temperature ratio</td>
<td>1.225</td>
<td>1.227</td>
<td>1.270</td>
<td>1.269</td>
</tr>
<tr>
<td>Stage total temperature ratio</td>
<td>1.225</td>
<td>1.227</td>
<td>1.270</td>
<td>1.269</td>
</tr>
<tr>
<td>Rotor adiabatic efficiency</td>
<td>0.877</td>
<td>0.876</td>
<td>0.877</td>
<td>0.878</td>
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<tr>
<td>Stage adiabatic efficiency</td>
<td>0.832</td>
<td>0.822</td>
<td>0.842</td>
<td>0.844</td>
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<tr>
<td>Rotor polytropic efficiency</td>
<td>0.877</td>
<td>0.870</td>
<td>0.889</td>
<td>0.890</td>
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<td>Stage polytropic efficiency</td>
<td>0.842</td>
<td>0.837</td>
<td>0.857</td>
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<td>Rotor head rise coefficient</td>
<td>0.342</td>
<td>0.325</td>
<td>0.333</td>
<td>0.331</td>
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<td>0.261</td>
<td>0.319</td>
<td>0.318</td>
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<td>Flow coefficient</td>
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<td>0.447</td>
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<td>Weight flow per unit frontal area</td>
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<td>100.464</td>
<td>100.950</td>
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<tr>
<td>Weight flow per unit annulus area</td>
<td>198.969</td>
<td>198.640</td>
<td>200.549</td>
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<tr>
<td>Weight flow</td>
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<td>20.188</td>
<td>20.188</td>
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<td>RPW</td>
<td>17188.700</td>
<td>17188.700</td>
<td>17185.700</td>
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<td>Tip speed</td>
<td>454.456</td>
<td>455.233</td>
<td>454.136</td>
<td>455.096</td>
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<tr>
<td>Hub-tip radius ratio</td>
<td>0.780</td>
<td>0.700</td>
<td>0.700</td>
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<tr>
<td>Rotor aspect ratio</td>
<td>1.109</td>
<td>1.601</td>
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<tr>
<td>Stator aspect ratio</td>
<td>1.861</td>
<td>1.787</td>
<td>1.267</td>
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<tr>
<td>Number of rotor blades</td>
<td>36.0</td>
<td>48.0</td>
<td>36.0</td>
<td>48.0</td>
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<tr>
<td>Number of stator blades</td>
<td>46.0</td>
<td>62.0</td>
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### TABLE II. - SUMMARY OF OVERALL PERFORMANCE

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<thead>
<tr>
<th>Stage number</th>
<th>Rotor aspect ratio</th>
<th>Rotor peak efficiency</th>
<th>Stage peak efficiency</th>
<th>Rotor pressure ratio</th>
<th>Stage pressure ratio</th>
<th>Stall margin</th>
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</thead>
<tbody>
<tr>
<td>37</td>
<td>1.19</td>
<td>0.876</td>
<td>0.840</td>
<td>2.056</td>
<td>2.000</td>
<td>10</td>
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<tr>
<td>35</td>
<td>1.19</td>
<td>0.872</td>
<td>0.845</td>
<td>1.875</td>
<td>1.842</td>
<td>21</td>
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<tr>
<td>36</td>
<td>1.63</td>
<td>0.852</td>
<td>0.821</td>
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<td>1.730</td>
<td>11</td>
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<tr>
<td>38</td>
<td>1.63</td>
<td>0.849</td>
<td>0.831</td>
<td>1.969</td>
<td>1.944</td>
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(a) STAGES 35 AND 37.

STATION: 1 2 3

AIRFLOW

Flow path coordinates

<table>
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<tr>
<th>Axial distance, cm</th>
<th>Inner Radius, cm</th>
<th>Axial distance, cm</th>
<th>Outer Radius, cm</th>
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<td>-22.860</td>
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<td>-15.400</td>
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<td>-7.620</td>
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<td>-2.568</td>
<td>17.539</td>
<td>-2.568</td>
<td>25.643</td>
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<tr>
<td>0.00</td>
<td>17.780</td>
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<tr>
<td>1.854</td>
<td>18.255</td>
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<td>4.137</td>
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<td>12.700</td>
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<td>15.400</td>
<td>19.431</td>
<td>15.400</td>
<td>23.749</td>
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</table>

(b) STAGES 36 AND 38.

Figure 2. - Flow path geometry.
PERCENT OF DESIGN SPEED

50
60
70
80
90
100

SOLID SYMBOLS - DESIGN
PLAIN SYMBOLS - ROTOR OR STAGE 35
TAILED SYMBOLS - ROTOR OR STAGE 36

ROTORS 37 AND 38.

(a) DESIGN STAGE PRESSURE RATIO OF 2.05.

Figure 3. - Effects of blade aspect ratio on overall performance.
PERCENT OF DESIGN SPEED

\[ \begin{align*}
\n50 & \quad \nabla \\
60 & \quad \triangle \\
70 & \quad \square \\
80 & \quad \diamond \\
90 & \quad \circ \\
100 & \quad \bigcirc \\
\end{align*} \]

SOLID SYMBOLS - DESIGN

PLAIN SYMBOLS - ROTOR OR STAGE 37

TAILED SYMBOLS - ROTOR OR STAGE 38

\[ \begin{align*}
\text{ADABATIC EFFICIENCY} \\
\text{TOTAL PRESSURE RATIO} \\
\end{align*} \]

\[ \begin{align*}
\text{EQUIVALENT MASS FLOW, kg/sec} \\
\text{ROTORS 35 AND 36.} \\
\text{STAGES 35 AND 36.} \\
\end{align*} \]

\[ \text{DESIGN STAGE PRESSURE RATIO OF 1.82.} \]

Figure 3. - Concluded.
Figure 4. - Radial distribution of performance parameters.
Figure 5. - Diffusion factor and inlet Mach numbers at near-stall conditions.
Figure 6. - Effects of blade aspect ratio on rotor blade element performance parameters.
Figure 6. Concluded.
Figure 7. - Axial distributions of rotor tip static pressures and rotor shock patterns; rotor 33, design speed.
Figure 8. - Axial distribution of rotor tip static pressures, design speed.
Figure 9. Axial distribution of rotor tip static pressure, near stall condition design speed.