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EFFECTS OF TIP CLEARANCE ON OVERALL PERFORMANCE OF TRANSONIC FAN STAGE WITH AND WITHOUT CASING TREATMENT

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EFFECTS OF TIP CLEARANCE ON OVERALL PERFORMANCE OF TRANSONIC FAN STAGE WITH AND WITHOUT CASING TREATMENT

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SUMMARY

The overall performance of a transonic fan stage is presented for various tip clearances, with and without casing treatment. The stage was tested with a solid casing, and with open skewed slots and closed skewed slots in the casing over the rotor blade tips. Four nominal nonrotating rotor blade tip clearances from 0.061 to 0.178 centimeter were used. For all three casings, the pressure ratio and efficiency decreased with increasing tip clearance. The stall margin for a given casing also decreased with increasing clearance. At design speed and a given tip clearance, the highest stall margin was obtained with the open-slot casing, and the lowest stall margin was obtained with the solid casing.

INTRODUCTION

Modern aircraft may be required to operate over a wide range of flight speeds, with conditions of varying inlet flow distortions and time-unsteady flow into the engine. When the fan experiences a stalling condition, the rotor blades may rub the outer casing; thus, the rotor blade tip clearances are usually larger for commercial engines than those for experimental fan stages.

Increased rotor blade tip clearance generally results in lower efficiency and stall margin. It would be desirable to attenuate the decrease in fan performance that results from increased clearance. Casing treatment across the tips of the rotor blades has been an effective method for improving the stall margin of fans (refs. 1 to 5). In the investigation of reference 5, a low-speed axial-flow rotor was tested with various tip clearances for various casing treatments. The results of that investigation indicated that stall margin with skewed-slot casing treatment was unaffected by tip clearance. In the present investigation, conducted at NASA Lewis Research Center, the effect of tip clearance on the overall performance of a transonic fan stage with both a solid casing and a skewed-slot casing treatment was evaluated. The skewed slots extended over the middle portion of the rotor blades and were tested both with the slots open and with them closed by a backing plate. This report presents the overall performance results for uniform inlet flow conditions for the stage with a solid casing and with the two skewed-slot casings. Data were obtained at four nominal nonrotating tip clearances from 0.061 to 0.178 centimeter. The fan was tested over the stable operating range for speeds of 50 to 100 percent of design speed.

APPARATUS AND PROCEDURE

Test Facility

The fan stage was tested in the Lewis single-stage compressor facility, which is described in detail in reference 6. A schematic of the facility is shown in figure 1. Atmospheric air enters the test facility at an inlet located on the roof 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 fan stage, into the collector, and is exhausted to the atmosphere.

Test Stage

The test stage is the same one that was described in detail in reference 7. Thus, only a brief description is included herein for completeness.

The overall design parameters for stage 8-8 are listed in reference 7, and the flowpath geometry is shown in figure 2 herein. This stage was designed for an overall pressure ratio of 1.750 at a flow of 29.5 kilograms per second (200.6 (kg/sec)/m^2 of annulus area). The design tip speed was 423 meters per second. The stage was designed for a tip solidity of 1.5 for the rotor and 1.5 for the stator. This resulted in 49 rotor blades with an aspect ratio of 2.4 and 54 stator blades with an aspect ratio of 2.0.

The rotor and stator are shown in figures 3 and 4, respectively. Each rotor blade had a vibration damper located at about 48 percent span from the outlet rotor tip. The maximum thickness of the damper was 0.214 centimeter. The axial spacing between the rotor-hub trailing edge and the stator-hub leading edge was 3.33 centimeters.

Casing Treatments and Tip Clearances

The casing treatments were fabricated as inserts to fit in a casing recess over the tips of the rotor blades (fig. 2). Two different casing inserts were designed. Each was machined so that the casing treatment was parallel to the rotor tip with a nominal (nonrotating) clearance of 0.061 centimeter.

For the tip clearance studies, a uniform increment of material was removed from the insert (see fig. 5) in the region over the rotor tip. The diameter was then faired to the casing diameter to approximately 1.3 centimeters ahead of the leading edge and downstream of the trailing edge.

The growth of the rotor blades was calculated to be approximately 0.040 centimeter, and thus the true clearances at design speed are approximately 0.040 centimeter less than the values presented.

The skewed-slot insert is shown in figure 6. A similar insert was used in the investigation of reference 1. This insert was tested with and without the backing plate. The slots were designed to be approximately parallel to the axial direction and were skewed in the direction of rotation at a 60° angle relative to the radial direction. There were 260 slots, with the slot width twice the land width. The slots extended over the mid portion of the rotor blades.

Instrumentation

Two Chromel-constantan thermocouples were located in the plenum chamber for sensing inlet total temperature. Inlet total pressure was assumed equal to plenum static pressure and was determined from four manifolded wall static-pressure taps located approximately 90° apart in the plenum chamber. The stage outlet conditions were determined from measurements obtained from four rakes located approximately 90° apart and 4 centimeters downstream of the stator trailing edge. Each rake (fig. 7) had five total-pressure - total-temperature elements, located at 11.0, 30.5, 50.0, 69.5, and 89.0 percent of the passage height from the outer casing. The thermocouple material for the rakes was Chromel-Alumel. The outlet static pressure at the various rake positions was determined by assuming a linear variation between the outer- and inner-wall static pressures. A calibrated orifice was used to determine airflow. Rotor speed was determined by use of a magnetic pickup in conjunction with an electronic counter.

The estimated errors of the data based on inherent accuracies of the instruments and recording systems are as follows:

Airflow, kg/sec	±0.3
Temperature, K	±0.6
Inlet total pressure, N/cm^2	±0.01
Outlet total pressure, N/cm^2	±0.10
Outlet wall static pressure, N/cm^2	±0.10
Rotor speed, rpm	±50

Test Procedure

Data were recorded at 50, 60, 70, 80, 90, and 100 percent of design speed for each configuration. For each speed, the data were taken over a range of flows from maximum flow to stall conditions. The stall points were established by increasing the back pressure until stall occurred. This was indicated by the simultaneous drop in stage outlet pressure and increase in audible noise level.

Calculation Procedure

The overall stage performance is based on average conditions in the plenum chamber and on mass-averaged values of total pressure and total temperature at the stator outlet. The rake temperatures were corrected for Mach number. All performance parameters were corrected to standard-day conditions based on plenum measurements.

The percent stall margin is based on the pressure ratio and flow at stall and those values at a reference point on the speed line corresponding to an assumed operating line.

RESULTS AND DISCUSSION

All the data are presented in tabular form in tables I to III for all the speeds tested. However, for discussion purposes, only the data for 70 and 100 percent of design speed and the stall line are plotted for each configuration.

Performance with Solid Casing

The overall performance for the solid casing is presented in figure 8 for nominal tip clearances of 0.061, 0.102, 0.140, and 0.178 centimeter. For the reference case of 0.061 centimeter, the stall point at design speed was at an airflow of 26.66 kilograms per second and at a pressure ratio of 1.757. As the tip clearance was increased, both the operating flow range and the stall pressure ratio decreased. At design speed, peak efficiency of 0.803 for the reference case occurred at an airflow of 29.23 kilograms per second. As the clearance increased, not only did the peak efficiency decrease, but the flow at which it occurred moved closer toward the stall point. The stall margin progressively decreased with increasing tip clearances, as indicated by the stall lines moving to the right (higher flows). The first increment of change in tip clearance (from 0.061 to 0.102 centimeter) had the most significant effect on the performance. This increase in clearance caused a drop in peak efficiency from 0.803 to 0.769, and a corresponding decrease in pressure ratio from 1.711 to 1.660. Further increases in the tip clearance resulted in progressively smaller effects.

Performance with Closed-Skewed-Slot Casing

The overall performance for the closed-skewed-slot configuration is presented in figure 9 for nominal tip clearances of 0.061, 0.102, 0.140, and 0.178 centimeter. The general trend is similar to that for the solid casing; that is, stall pressure ratio and flow range decrease with increasing clearances. Peak efficiency also decreased, and the flow at which peak efficiency occurred moved closer to the stall line as clearance increased.

Increasing the clearance from 0.102 to 0.140 centimeter had approximately the same effect on the stall line as did increasing the clearance from 0.061 to 0.102 centimeter. This is in contrast to the corresponding changes produced by the same increases in tip clearance with the solid casing.

Performance with Open-Skewed-Slot Casing

The overall performance for stage 8-8 with the open-skewed-slot configuration is presented in figure 10 for nominal tip clearances of 0.061, 0.140 and 0.178 centimeter. This configuration was not tested with a tip clearance of 0.102 centimeter. The basic trends produced by increasing tip clearances with the two previous configurations are also evident with this configuration.

Effects of Tip Clearance and Casing Treatment

The effects of tip clearance and casing treatment on the overall performance and stall margin for stage 8-8 at design speed are summarized in figures 11 and 12. Pressure ratio and efficiency are presented as functions of tip clearance for the three configurations in figure 11. Stall margin is presented as a function of the same parameter in figure 12. The data presented are based on an assumed operating line which passes through the stall point with the solid casing with 0.178-centimeter tip clearance. This operating line corresponds very closely to the peak efficiency point for all configurations.

Performance was most affected by tip clearance with the solid casing. As the tip clearance was increased from 0.061 to 0.178 centimeter, the pressure ratio decreased from 1.69 to 1.61, and the efficiency decreased from 0.80 to 0.74. Whereas with both the closed-skewed-slot casing and the open-skewed-slot casing, the same increase in tip clearance reduced the efficiency from 0.775 to 0.75. Although the efficiency with both skewed-slot casings is lower than that for the solid casing when the clearance is minimal, the decrease in efficiency with increasing clearance is not as rapid. Therefore, at the larger clearances, the efficiencies are equal to, or greater than, those with the solid casing. The effect of increasing tip clearance on pressure ratio is similar. Although the open-skewed-slot casing had the lowest pressure ratio at a clearance of 0.061 centimeter, it had the highest pressure ratio at clearances of 0.140 and 0.178 centimeter.

For the solid casing, the stall margin decreased from 15 percent to 3 percent as the tip clearance was increased from 0.061 to 0.102 centimeter (fig. 12). As the tip clearance was further increased to 0.178 centimeter, the stall margin decreased to zero. For all clearances, the stall margin was at least 7 percent greater for the closed-skewed-slot casing than for the solid casing. Opening the slots resulted in a further increase in stall margin.

As indicated previously, the nominal tip clearances were obtained statically, and the blade growth was calculated to be about 0.040 centimeter at design operating conditions. At the stall condition, the temperature ratio is higher for the skewed-slot configurations than for the solid casing. And it is highest in the configuration with open slots. Therefore, the operating tip clearance is probably smallest for the open configuration for a given nominal clearance. The resulting actual reduced tip clearance may account, at least in part, for the increased stall margin for the open-skewed-slot configuration.

SUMMARY OF RESULTS

The overall performance of a transonic fan stage with various casing treatments and blade tip clearances was investigated. The stage was tested with a solid casing, and with closed skewed slots and open skewed slots in the casing over the rotor blade tips. Four nominal nonrotating rotor blade tip clearances from 0.061 to 0.178 centimeter were used. Data were obtained over the stable operating flow range of the stage at rotative speeds from 50 to 100 percent of the design speed. The following were the principal results of the investigation:

1. Increasing tip clearance had an adverse effect on the performance of all three configurations tested. The effect was the greatest for the solid casing.

2. Stall margin for the solid casing decreased from 15 percent to 3 percent for an increase in tip clearance from 0.061 to 0.102 centimeter. As clearance was further increased to 0.178 centimeter, the stall margin decreased to zero. Stall margin for the closed-skewed-slot configuration was at least 7 percent greater than that for the solid casing over the range of tip clearances tested. The open-skewed-slot configuration resulted in further increases in stall margin.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 5, 1976,
505-04.

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TABLE I. - OVERALL PERFORMANCE OF FAN STAGE WITH SOLID CASING

(a) Rotor blade tip clearance, 0. 061 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0527	90.3	27.42	1.449	1.149	0.752
0528	90.2	26.85	1.517	1.158	0.799
0529	90.3	25.97	1.558	1.167	0.808
0530	90.2	24.81	1.578	1.175	0.797
0531	90.2	23.85	1.585	1.181	0.778
0532	100.2	29.58	1.588	1.189	0.749
0533	100.1	29.23	1.711	1.207	0.803
0534	100.0	28.30	1.748	1.217	0.798
0535	100.1	27.47	1.761	1.223	0.787
0536	100.0	26.66	1.757	1.227	0.769
0537	80.1	25.19	1.289	1.107	0.705
0538	80.2	24.24	1.364	1.117	0.794
0539	80.0	23.11	1.403	1.126	0.810
0540	80.1	21.53	1.421	1.134	0.788
0541	80.0	19.97	1.417	1.141	0.743
0542	70.0	22.88	1.174	1.073	0.641
0543	70.1	21.74	1.244	1.082	0.783
0544	70.1	20.36	1.280	1.091	0.800
0545	70.1	18.87	1.299	1.099	0.783
0546	70.0	17.37	1.303	1.105	0.749
0547	60.3	20.51	1.115	1.050	0.628
0548	60.2	19.21	1.161	1.057	0.762
0549	60.3	17.75	1.194	1.065	0.797
0550	60.2	16.16	1.213	1.072	0.785
0551	60.3	14.75	1.219	1.078	0.747
0552	50.0	17.63	1.070	1.033	0.601
0553	50.1	16.34	1.103	1.038	0.741
0554	50.1	15.15	1.123	1.043	0.782
0555	50.0	13.52	1.141	1.049	0.784
0556	50.0	12.08	1.148	1.054	0.743

TABLE I. - Continued

(b) Rotor blade tip clearance, 0.102 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0642	49.8	12.43	1.136	1.051	0.723
0643	49.8	13.89	1.135	1.048	0.766
0645	49.9	15.17	1.120	1.043	0.760
0646	49.9	16.28	1.102	1.039	0.726
0647	50.0	17.58	1.075	1.034	0.616
0648	59.9	15.49	1.210	1.074	0.760
0649	60.0	16.74	1.201	1.069	0.781
0650	60.0	18.15	1.180	1.062	0.777
0651	60.1	19.21	1.157	1.057	0.748
0652	60.1	20.32	1.119	1.051	0.642
0653	70.0	18.39	1.297	1.101	0.767
0654	69.8	19.53	1.286	1.095	0.784
0655	69.9	20.78	1.267	1.089	0.787
0656	70.0	21.89	1.233	1.081	0.761
0657	69.9	22.77	1.177	1.074	0.648
0658	80.2	21.95	1.407	1.131	0.782
0659	80.1	22.74	1.397	1.127	0.789
0660	80.1	23.67	1.373	1.120	0.789
0661	80.0	24.45	1.338	1.113	0.769
0662	80.1	24.98	1.282	1.106	0.690
0663	90.0	25.17	1.529	1.165	0.780
0664	90.0	25.63	1.522	1.163	0.783
0665	90.0	26.32	1.499	1.157	0.781
0666	90.0	26.76	1.474	1.152	0.771
0667	89.8	27.05	1.430	1.145	0.740
0668	100.0	28.23	1.671	1.206	0.767
0669	99.9	28.53	1.660	1.203	0.769
0670	100.0	28.90	1.645	1.199	0.769
0671	99.9	29.33	1.605	1.191	0.758
0672	100.1	29.42	1.540	1.186	0.705

TABLE I. - Continued

(c) Rotor blade tip clearance, 0.140 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0703	90.2	27.07	1.414	1.146	0.713
0704	90.3	26.66	1.468	1.152	0.761
0705	90.2	26.19	1.486	1.155	0.773
0706	90.2	25.69	1.496	1.159	0.769
0707	90.2	25.25	1.501	1.160	0.769
0708	100.1	29.33	1.527	1.185	0.693
0709	100.0	28.99	1.589	1.190	0.743
0710	100.1	28.50	1.620	1.197	0.751
0711	100.2	28.06	1.631	1.200	0.750
0712	80.0	24.97	1.289	1.106	0.709
0713	79.8	24.24	1.337	1.113	0.768
0714	79.9	23.51	1.363	1.118	0.783
0715	79.9	22.84	1.380	1.123	0.783
0716	79.8	21.80	1.378	1.125	0.767
0717	70.0	22.81	1.171	1.073	0.630
0718	70.0	21.85	1.228	1.080	0.754
0719	70.1	20.87	1.260	1.087	0.786
0720	69.9	19.87	1.279	1.093	0.785
0721	69.9	18.74	1.283	1.097	0.764
0722	59.9	20.29	1.112	1.050	0.619
0723	59.9	19.26	1.150	1.056	0.733
0724	59.8	17.92	1.182	1.063	0.779
0725	59.9	16.58	1.199	1.068	0.779
0726	59.9	15.94	1.202	1.071	0.764
0727	59.7	15.13	1.190	1.070	0.731
0728	50.0	17.53	1.073	1.033	0.608
0729	50.1	16.47	1.100	1.038	0.729
0730	50.1	15.36	1.119	1.042	0.775
0731	50.2	13.98	1.136	1.048	0.777
0732	50.2	12.80	1.137	1.050	0.743

TABLE I. - Concluded

(d) Rotor blade tip clearance, 0.178 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0764	90.0	24.99	1.479	1.157	0.751
0765	90.0	25.45	1.479	1.156	0.759
0766	90.0	26.16	1.464	1.152	0.754
0767	90.0	26.69	1.444	1.149	0.745
0768	90.0	26.97	1.374	1.144	0.660
0769	100.1	28.04	1.604	1.196	0.739
0770	99.9	28.36	1.594	1.193	0.737
0771	100.0	28.68	1.587	1.191	0.738
0772	100.1	29.00	1.567	1.188	0.727
0773	100.0	29.12	1.517	1.185	0.682
0774	80.0	21.91	1.367	1.123	0.757
0775	79.9	22.71	1.368	1.122	0.770
0776	80.0	23.56	1.355	1.117	0.773
0777	80.0	24.32	1.329	1.111	0.760
0778	79.8	24.83	1.253	1.104	0.638
0779	70.2	18.80	1.274	1.095	0.756
0780	70.0	19.99	1.273	1.092	0.778
0781	70.0	20.91	1.256	1.086	0.778
0782	70.0	21.99	1.222	1.079	0.746
0783	70.1	22.87	1.156	1.072	0.585
0784	59.8	15.62	1.193	1.069	0.754
0785	59.7	16.89	1.192	1.066	0.776
0786	59.7	18.13	1.174	1.060	0.775
0787	59.9	19.37	1.144	1.054	0.727
0788	59.8	20.41	1.109	1.049	0.616
0789	49.9	12.77	1.131	1.049	0.736
0790	50.0	14.29	1.130	1.046	0.773
0791	50.1	15.67	1.113	1.041	0.762
0792	50.1	16.78	1.093	1.036	0.706
0793	50.0	17.71	1.069	1.032	0.597

TABLE II. - OVERALL PERFORMANCE OF FAN STAGE WITH CLOSED SKEWED SLOTS IN CASING OVER THE ROTOR BLADE TIPS

(a) Rotor blade tip clearance, 0.061 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0466	70.3	22.77	1.191	1.076	0.675
0467	70.4	21.78	1.251	1.085	0.780
0468	70.4	19.81	1.293	1.097	0.786
0469	70.4	17.53	1.311	1.109	0.736
0470	70.5	15.81	1.310	1.120	0.672
0471	100.1	24.96	1.761	1.248	0.707
0472	100.1	27.11	1.777	1.234	0.763
0473	100.0	28.72	1.728	1.216	0.785
0474	100.1	29.45	1.625	1.194	0.765
0475	100.2	29.55	1.538	1.188	0.698
0476	90.0	21.75	1.552	1.192	0.695
0477	90.1	23.57	1.590	1.188	0.756
0478	90.1	25.49	1.568	1.173	0.790
0479	89.9	26.79	1.498	1.156	0.782
0480	90.0	27.31	1.429	1.147	0.730
0481	79.8	24.99	1.303	1.107	0.732
0482	79.8	24.22	1.361	1.116	0.790
0483	79.8	22.66	1.408	1.129	0.795
0484	80.2	20.61	1.421	1.142	0.745
0485	80.1	18.12	1.408	1.154	0.669
0486	60.0	20.03	1.132	1.052	0.689
0487	60.1	18.73	1.172	1.060	0.775
0488	60.1	17.37	1.198	1.067	0.790
0489	60.0	15.25	1.219	1.077	0.752
0490	60.1	13.00	1.222	1.089	0.661
0491	50.0	17.35	1.079	1.034	0.641
0492	50.0	15.92	1.112	1.041	0.761
0493	49.9	14.29	1.134	1.047	0.781
0494	49.9	12.37	1.148	1.055	0.739
0495	49.9	10.55	1.151	1.062	0.657

TABLE II. - Continued

(b) Rotor blade tip clearance, 0.102 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0612	100.0	29.36	1.470	1.186	0.624
0613	100.1	29.25	1.584	1.190	0.741
0614	100.0	28.61	1.673	1.206	0.770
0615	99.8	27.71	1.723	1.218	0.772
0616	99.8	26.48	1.751	1.230	0.754
0617	89.8	27.08	1.349	1.145	0.618
0618	89.9	26.68	1.476	1.154	0.765
0619	89.8	25.66	1.535	1.166	0.784
0620	89.8	24.70	1.570	1.176	0.782
0621	89.8	23.65	1.578	1.182	0.764
0622	80.1	25.01	1.277	1.107	0.678
0623	79.8	24.07	1.353	1.116	0.777
0624	80.0	22.79	1.400	1.128	0.788
0625	80.0	21.00	1.419	1.138	0.761
0626	80.0	18.81	1.407	1.148	0.694
0627	69.8	22.78	1.163	1.073	0.602
0628	69.8	21.79	1.236	1.082	0.762
0629	69.8	20.40	1.273	1.091	0.782
0630	69.8	18.53	1.298	1.101	0.762
0631	69.8	16.63	1.303	1.109	0.717
0632	59.9	20.34	1.113	1.050	0.618
0633	59.8	18.96	1.158	1.057	0.748
0634	59.8	17.53	1.190	1.065	0.780
0635	59.8	15.71	1.211	1.073	0.766
0636	59.6	13.65	1.216	1.082	0.702
0637	49.9	17.58	1.069	1.033	0.587
0638	50.0	16.38	1.101	1.038	0.728
0639	49.9	15.07	1.123	1.044	0.774
0640	50.0	13.32	1.142	1.051	0.763
0641	49.9	11.25	1.150	1.058	0.701

TABLE II. - Continued

(c) Rotor blade tip clearance, 0.140 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0673	90.0	24.47	1.543	1.172	0.769
0674	90.1	25.20	1.536	1.168	0.774
0675	90.0	25.72	1.510	1.162	0.773
0676	90.1	26.48	1.473	1.154	0.760
0677	90.0	27.01	1.395	1.145	0.690
0678	99.8	27.43	1.707	1.215	0.768
0679	99.9	27.94	1.689	1.210	0.768
0680	100.1	28.42	1.655	1.203	0.764
0681	100.0	28.90	1.598	1.193	0.743
0682	100.1	29.10	1.498	1.186	0.660
0683	80.0	20.02	1.397	1.136	0.736
0684	80.0	21.21	1.402	1.133	0.765
0685	79.9	22.80	1.395	1.127	0.787
0686	80.0	23.86	1.357	1.118	0.774
0687	80.0	24.94	1.268	1.106	0.664
0688	69.9	16.94	1.296	1.106	0.727
0689	70.1	18.65	1.297	1.100	0.768
0690	70.0	20.11	1.279	1.093	0.783
0691	70.0	21.52	1.243	1.084	0.766
0692	69.9	22.79	1.172	1.073	0.637
0693	59.7	14.27	1.214	1.078	0.731
0694	59.9	15.91	1.207	1.072	0.771
0695	59.9	17.65	1.187	1.065	0.777
0696	59.8	19.06	1.156	1.056	0.748
0697	59.8	20.28	1.113	1.049	0.627
0698	50.0	11.64	1.147	1.055	0.724
0699	50.0	13.30	1.140	1.050	0.763
0700	49.9	15.04	1.121	1.043	0.771
0701	49.8	16.34	1.099	1.037	0.730
0702	49.9	17.63	1.070	1.032	0.603

TABLE II. - Concluded

(d) Rotor blade tip clearance, 0.178 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0794	90.2	26.93	1.420	1.146	0.720
0795	90.1	26.41	1.468	1.153	0.759
0796	90.0	25.80	1.501	1.160	0.769
0797	89.8	25.35	1.521	1.165	0.773
0798	89.9	24.61	1.525	1.167	0.766
0799	100.0	29.08	1.514	1.186	0.677
0800	99.9	28.81	1.595	1.193	0.740
0801	99.8	28.40	1.638	1.200	0.756
0802	99.9	28.11	1.664	1.206	0.760
0803	99.7	27.66	1.679	1.209	0.762
0804	80.2	24.85	1.275	1.107	0.674
0805	80.1	24.04	1.346	1.116	0.765
0806	80.1	22.95	1.383	1.124	0.781
0807	80.1	21.66	1.394	1.130	0.769
0808	80.2	20.49	1.392	1.134	0.742
0809	69.9	17.26	1.290	1.103	0.733
0810	69.7	18.86	1.283	1.097	0.763
0811	69.9	20.21	1.270	1.091	0.774
0812	69.9	21.52	1.234	1.082	0.753
0813	69.9	22.74	1.169	1.073	0.627
0814	60.0	14.33	1.210	1.077	0.727
0815	59.8	15.92	1.202	1.071	0.763
0816	60.0	17.46	1.187	1.065	0.772
0817	59.9	18.86	1.158	1.057	0.744
0818	60.0	20.25	1.114	1.050	0.630
0819	50.1	11.96	1.145	1.054	0.726
0820	49.8	11.85	1.143	1.054	0.722
0821	50.0	13.53	1.136	1.049	0.758
0822	50.0	14.96	1.120	1.043	0.763
0823	50.0	17.55	1.070	1.033	0.592
0824	49.9	16.27	1.098	1.038	0.722

TABLE III. - OVERALL PERFORMANCE OF FAN STAGE WITH OPEN SKEWED SLOTS IN CASING OVER THE ROTOR BLADE TIPS

(a) Rotor blade tip clearance, 0.061 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0496	89.9	27.16	1.389	1.146	0.674
0497	89.9	26.51	1.516	1.159	0.793
0498	90.0	25.30	1.576	1.174	0.797
0499	90.1	23.48	1.589	1.186	0.759
0500	90.1	21.92	1.556	1.191	0.705
0501	100.1	29.46	1.541	1.188	0.699
0502	100.0	29.19	1.644	1.199	0.768
0503	99.8	28.34	1.735	1.216	0.788
0504	99.8	26.68	1.772	1.234	0.758
0506	99.6	24.70	1.748	1.245	0.706
0507	70.0	14.89	1.307	1.121	0.656
0508	70.2	17.58	1.311	1.108	0.748
0509	70.0	19.65	1.291	1.096	0.790
0510	70.1	21.50	1.251	1.085	0.777
0511	70.1	22.74	1.177	1.074	0.640
0512	80.1	17.68	1.406	1.154	0.663
0513	80.0	20.39	1.421	1.142	0.746
0514	80.3	22.61	1.420	1.132	0.797
0515	80.3	23.96	1.378	1.121	0.794
0516	80.4	25.07	1.289	1.108	0.694
0517	60.2	20.19	1.118	1.051	0.633
0518	60.0	18.53	1.172	1.061	0.767
0519	60.0	16.64	1.207	1.070	0.787
0520	59.8	14.43	1.222	1.080	0.736
0521	59.9	12.07	1.218	1.091	0.633
0522	50.0	17.45	1.073	1.034	0.597
0523	50.1	15.92	1.109	1.040	0.746
0524	50.0	14.16	1.135	1.047	0.782
0525	50.0	12.14	1.151	1.055	0.744
0526	50.1	9.80	1.150	1.065	0.627

TABLE III. - Continued

(b) Rotor blade tip clearance, 0. 140 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0733	89.9	26.87	1.385	1.145	0.670
0734	89.9	26.15	1.498	1.158	0.773
0735	90.0	25.13	1.552	1.171	0.781
0736	90.0	24.19	1.573	1.178	0.777
0737	90.1	23.27	1.575	1.181	0.765
0738	99.9	29.16	1.494	1.188	0.645
0739	99.9	28.45	1.664	1.204	0.766
0740	100.0	27.72	1.715	1.217	0.767
0741	99.9	26.91	1.737	1.225	0.761
0743	99.9	26.36	1.738	1.227	0.755
0744	80.0	24.72	1.236	1.106	0.589
0745	79.9	23.33	1.376	1.121	0.788
0746	80.1	22.01	1.410	1.132	0.784
0747	80.1	20.35	1.416	1.139	0.754
0748	79.9	18.58	1.405	1.145	0.704
0749	69.8	22.59	1.173	1.073	0.634
0750	69.9	21.23	1.247	1.085	0.768
0751	70.1	19.64	1.287	1.095	0.784
0752	70.0	17.96	1.302	1.104	0.755
0753	70.0	16.25	1.304	1.110	0.717
0754	60.1	20.14	1.115	1.051	0.618
0755	60.0	18.80	1.162	1.059	0.749
0756	60.1	17.12	1.198	1.068	0.785
0757	59.9	15.25	1.215	1.075	0.761
0758	59.8	13.33	1.218	1.082	0.709
0759	50.0	17.50	1.070	1.033	0.586
0760	49.9	16.18	1.099	1.038	0.725
0761	49.8	14.56	1.127	1.045	0.773
0762	50.0	12.69	1.145	1.052	0.756
0763	49.8	10.78	1.149	1.058	0.701

TABLE III. - Concluded

(c) Rotor blade tip clearance, 0.178 centimeter

Reading	Rotative speed, percent of design speed	Airflow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0825	89.8	26.87	1.395	1.146	0.685
0826	90.1	26.41	1.477	1.155	0.759
0827	90.1	25.90	1.517	1.163	0.774
0828	90.0	25.16	1.545	1.170	0.779
0829	89.9	24.36	1.552	1.173	0.774
0830	80.0	24.81	1.280	1.107	0.682
0831	80.0	23.65	1.360	1.119	0.773
0832	80.1	22.51	1.400	1.128	0.787
0833	79.8	20.76	1.407	1.134	0.763
0834	79.9	19.44	1.397	1.138	0.725
0835	69.9	22.71	1.164	1.073	0.605
0836	69.9	21.32	1.245	1.084	0.764
0837	69.9	19.80	1.282	1.094	0.783
0838	69.8	18.14	1.297	1.101	0.763
0839	69.9	16.43	1.301	1.108	0.724
0840	59.9	20.18	1.116	1.051	0.625
0841	59.9	18.83	1.158	1.057	0.747
0842	59.8	17.18	1.193	1.065	0.790
0843	60.0	15.53	1.213	1.074	0.767
0844	59.9	13.66	1.218	1.080	0.721
0845	50.0	17.45	1.070	1.033	0.589
0846	49.9	16.16	1.102	1.038	0.730
0847	50.1	14.62	1.128	1.045	0.774
0848	50.0	13.00	1.143	1.051	0.766
0849	50.0	11.14	1.150	1.057	0.710
0850	100.1	29.15	1.498	1.189	0.647
0851	100.0	28.90	1.601	1.195	0.737
0852	100.1	28.35	1.670	1.207	0.763
0853	99.9	27.80	1.691	1.211	0.765
0854	100.1	27.54	1.707	1.215	0.769

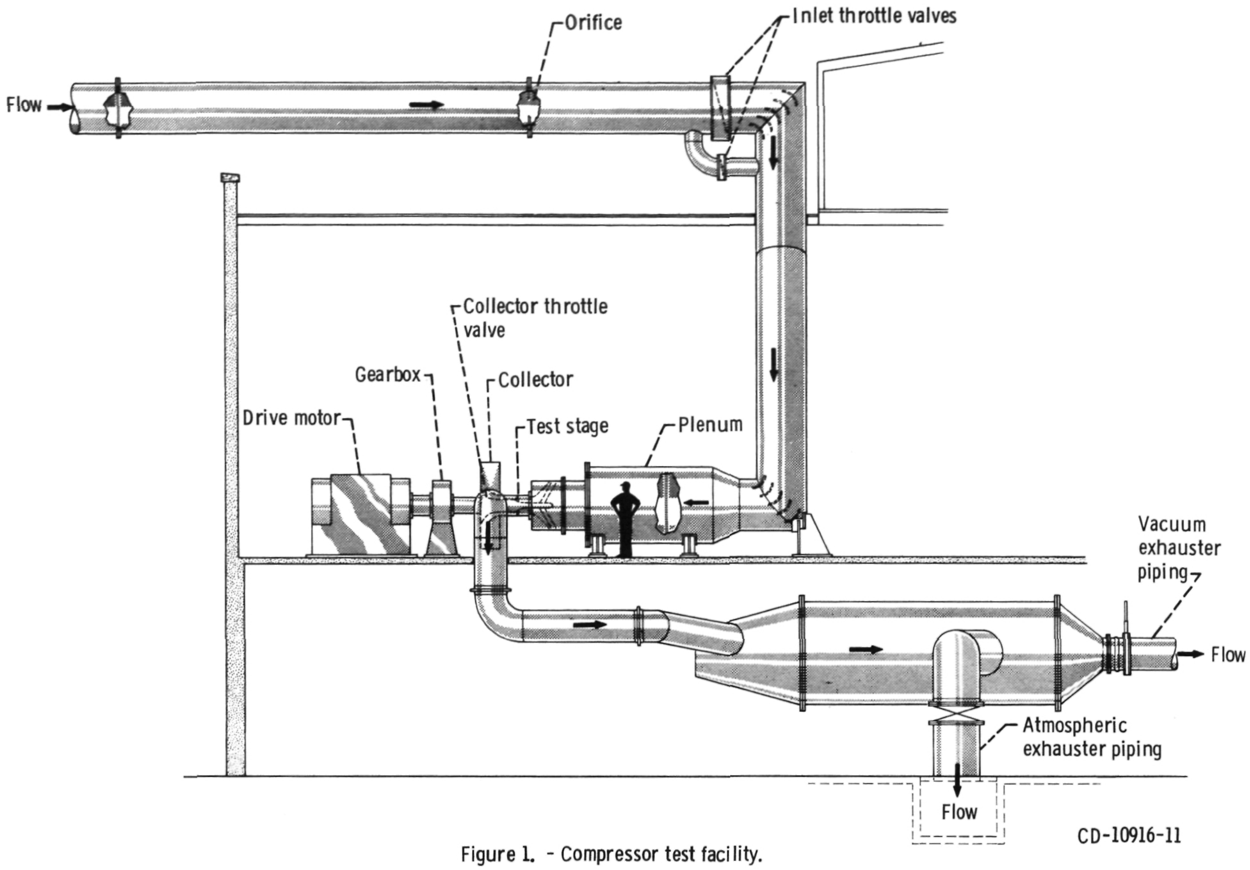

Figure 1. - Compressor test facility.

Flow path coordinates		
Axial distance, cm	Radius, cm	
	Inner	Outer
-30.480	7.303	25.400
-25.400	7.493	
-22.860	7.874	
-20.320	8.255	
-15.240	9.144	
-10.160	10.097	
-5.080	10.922	
-2.540	11.659	
0	12.668	25.273
4.572	14.605	24.511
6.096	15.240	24.397
7.620	15.748	24.384
11.176	16.510	
13.462		
15.240		
20.320		

Figure 2. - Flow path geometry for stage 8-8.

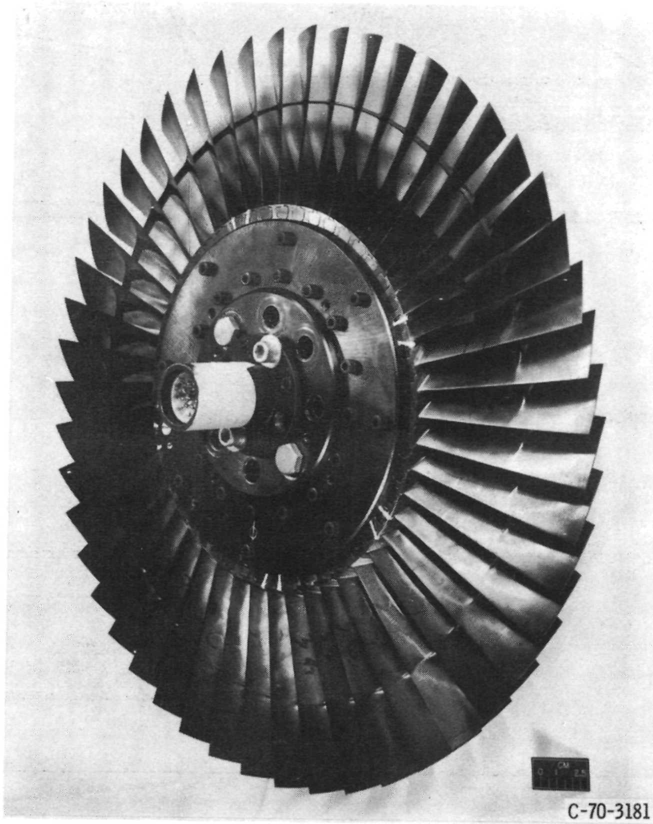

Figure 3. - Rotor 8.

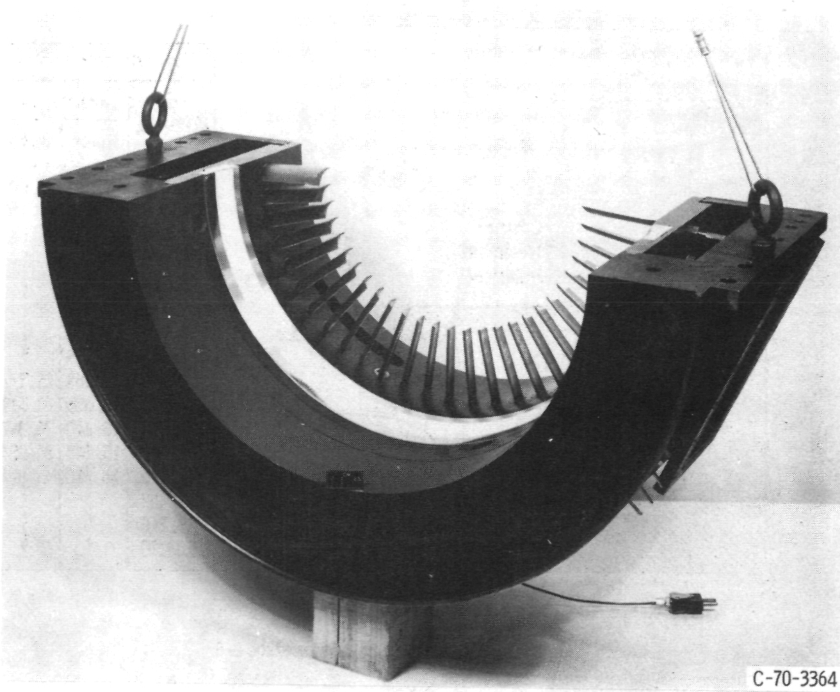

Figure 4. - Stator 8.

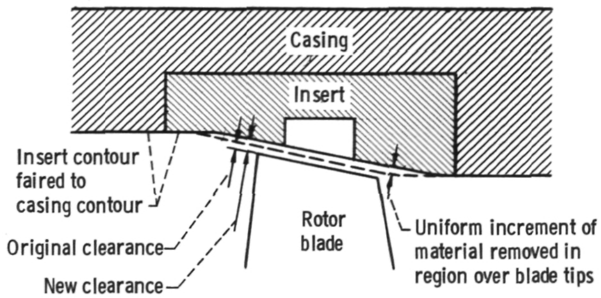

Figure 5. - Method used to change (increase) the rotor-blade tip clearance.

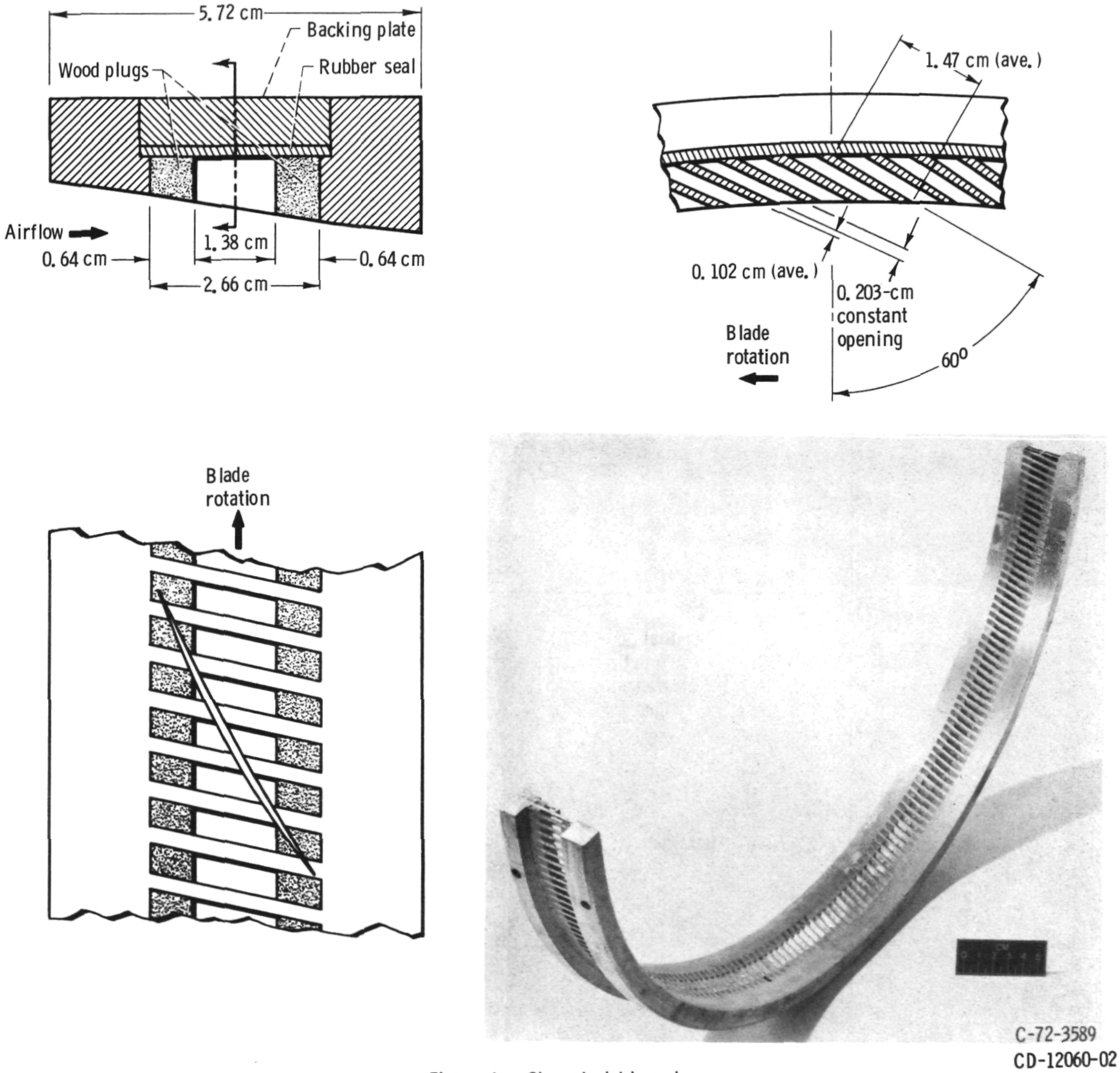

Figure 6. - Skewed-slot insert.

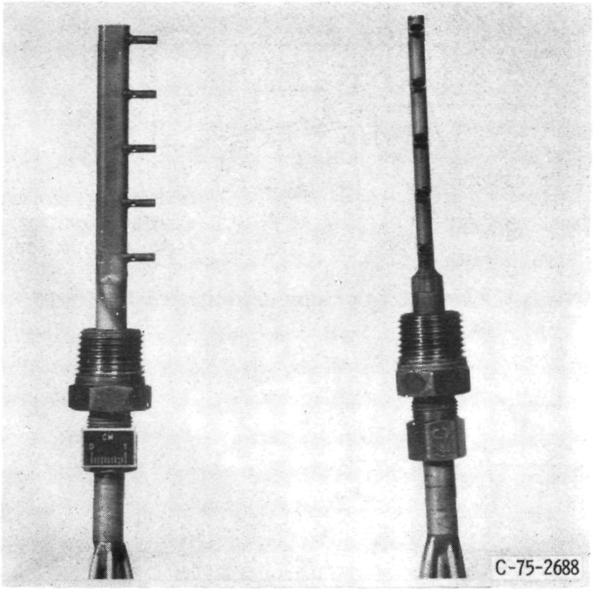

Figure 7. - Total-pressure - total-temperature rake.

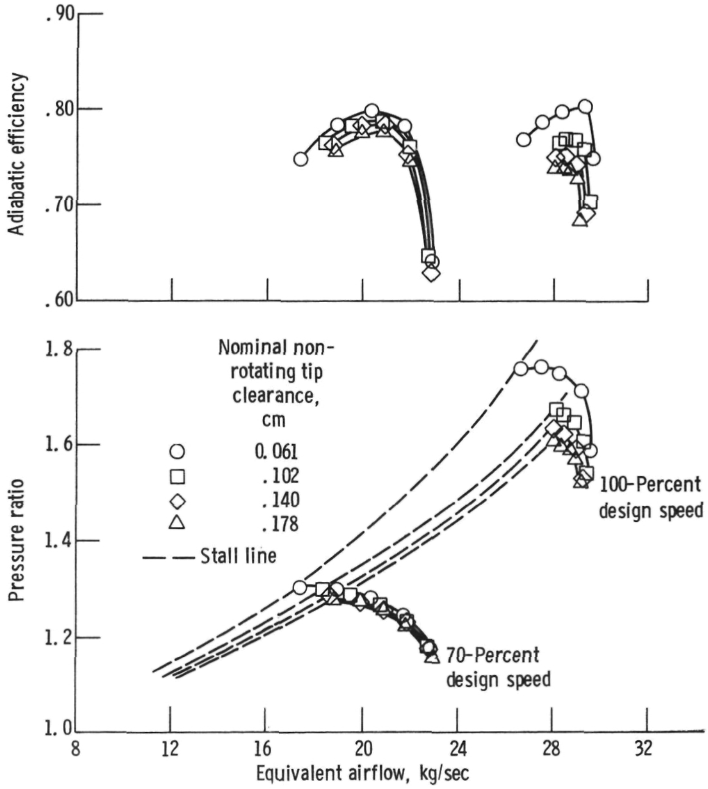

Figure 8. - Effect of rotor-blade tip clearance on overall performance of stage 8-8 with solid casing.

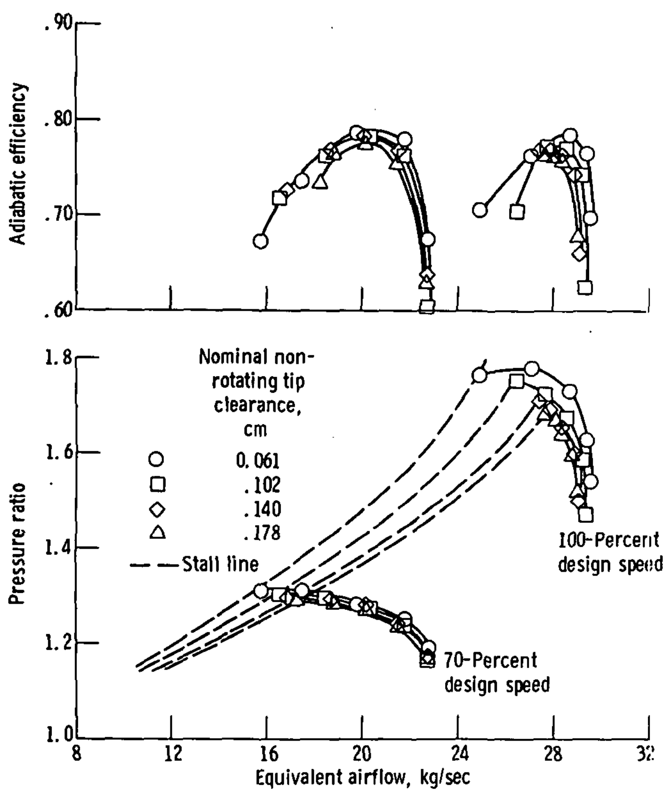

Figure 9. - Effect of rotor-blade tip clearance on overall performance of stage 8-8 with closed skewed slot casing.

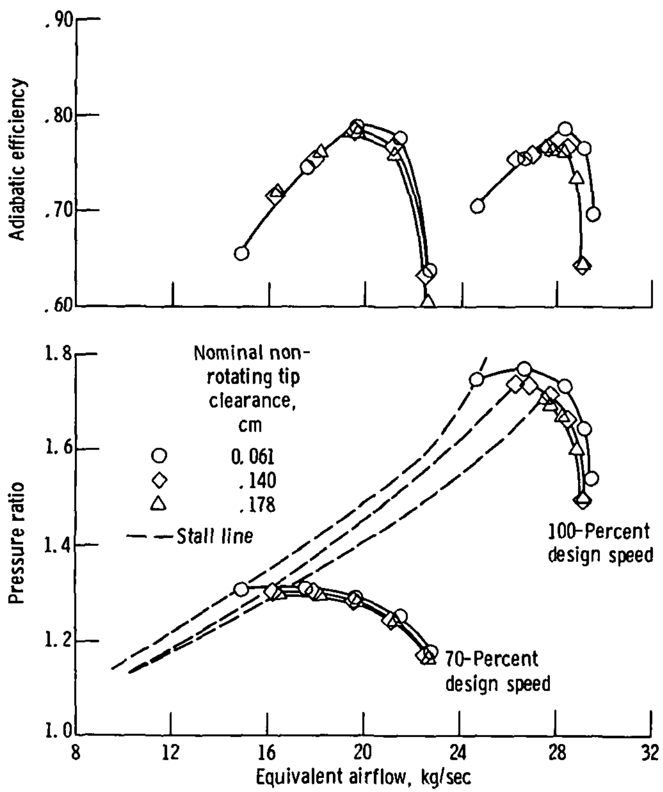

Figure 10. - Effect of rotor-blade tip clearance on overall performance of stage 8-8 with open skewed slot casing.

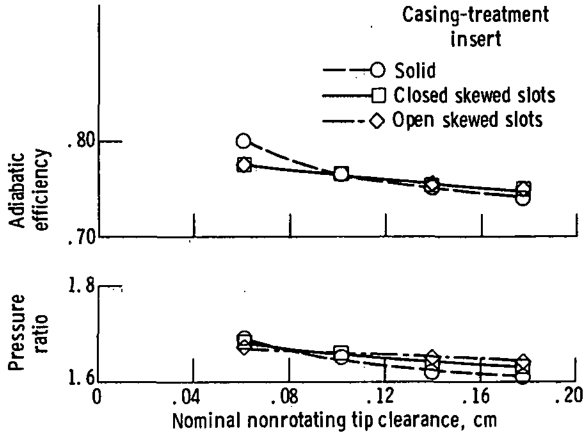

Figure 11. - Effects of rotor-blade tip clearance and casing treatment on overall performance of stage 8-8 at design speed. (Data based on assumed operating line.)

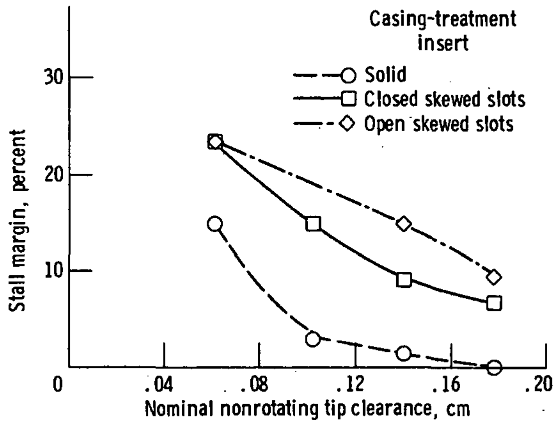

Figure 12. - Effects of rotor-blade tip clearance and casing treatment on stall margin of stage 8-8 at design speed. (Data based on assumed operating line.)

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