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**CALCULATED PERFORMANCE MAP OF A
4 $\frac{1}{2}$ -STAGE 15.0-CENTIMETER- (5.9-IN.-)
MEAN-DIAMETER TURBINE DESIGNED
FOR A TURBOFAN SIMULATOR**

by Charles A. Wasserbauer
Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract The overall performance of an existing high-pressure-ratio turbine is calculated analytically over a range of speed and pressure ratio in order to determine its capability for other applications. The analytical performance covers a speed range from 50 to 120 percent of design and a pressure-ratio range from 5.0 to 35.0. The turbine was designed for a 50.8-centimeter- (20.0-in.-) tip-diameter turbofan simulator. Computed results are compared with the experimental turbine data obtained from testing three fan configurations with the turbofan simulator in air. The comparison indicates good agreement over the range of speeds and pressure ratios covered by the experimental data.			
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CALCULATED PERFORMANCE MAP OF A $4\frac{1}{2}$ -STAGE 15.0-CENTIMETER- (5.9-IN. -) MEAN-DIAMETER TURBINE DESIGNED FOR A TURBOFAN SIMULATOR

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Lewis Research Center

SUMMARY

The overall performance of a $4\frac{1}{2}$ -stage 15.0-centimeter- (5.9-in. -) mean-diameter turbine, used in a 50.8-centimeter- (20.0-in. -) tip-diameter turbofan simulator, was computed analytically over a range of speed and pressure ratio. This turbine was designed for an equivalent mass flow rate of 0.26 kilogram per second (0.57 lb/sec) and a static efficiency of 0.594 at a total- to static-pressure ratio of 24.3 and uses air as the driving fluid. The performance map is needed to determine the capabilities of the turbine for other present and future applications.

The computer program of NASA CR-710 was used to compute the overall performance. Efficiency coefficients were selected so that the calculated performance matched the experimental performance at one reference point at design speed and a pressure ratio near design. The performance map was then calculated over a pressure-ratio range from 5.0 to 35.0 and a speed range from 50 to 120 percent of design. At equivalent design speed and pressure ratio the calculated static efficiency is 0.65. This is about 6 points higher than the design value of 0.594.

The computed performance was compared with the turbine experimental data obtained from the testing of three fan configurations in the turbofan simulator. The comparison shows good agreement between the analytical and experimental results over the range of experimental speeds and pressure ratios. It was thus concluded that the computed performance map does represent the overall performance of the $4\frac{1}{2}$ -stage turbine.

INTRODUCTION

The NASA Lewis Research Center uses engine simulators in the study of aircraft propulsion and lift system components. One such simulator is currently being used to study nacelle and fan characteristics associated with an externally blown flap propulsion

system for STOL aircraft. This simulator has a 50.8-centimeter (20.0-in.) tip diameter and a 1.15-pressure-ratio fan and is driven by a $4\frac{1}{2}$ -stage, 15.0-centimeter- (5.9-in.-) mean-diameter turbine using an external air supply. In order to determine the capability of this drive turbine for other present and future applications, there was a need to generate a performance map for this turbine.

A performance map was calculated by using a computer program for multistage axial-flow turbine off-design performance (ref. 1). Experimental turbine data from the simulator tests were used to determine the efficiency coefficients for the computer program so as to match the experimental and analytical work and mass flow at one operating point. The performance map was calculated by using these coefficients. The calculated performance covered a range of speeds from 50 to 120 percent of design and a pressure-ratio range from 5.0 to 35.0. Experimental turbine data, obtained from simulator tests using three fan configurations, were used to verify the calculated map.

This report presents a description of the turbine, the calculated performance map, calculated velocity diagrams at design speed and pressure ratio, and a comparison of calculated performance with experimental performance. The calculated performance map is presented in terms of equivalent specific work or equivalent horsepower plotted against equivalent speed for lines of constant pressure ratio.

SYMBOLS

Δh	specific work, J/g; Btu/lb
hp	horsepower
N	turbine speed, rpm
p	pressure, N/cm ² ; psia
T	temperature, K; °R
V	absolute gas velocity, m/sec; ft/sec
W	relative gas velocity, m/sec; ft/sec
w	mass flow rate, kg/sec; lb/sec
δ	ratio of inlet total pressure to U.S. standard sea-level pressure, p'_0/p^*
η_s	static efficiency (based on inlet total- to exit static-pressure ratio)
θ	squared ratio of critical velocity at turbine inlet to critical velocity at U.S. standard sea-level temperature, $(V_{cr}/V_{cr}^*)^2$

Subscripts:

cr	critical
eq	equivalent
0	turbine inlet
1	first-stage stator exit
2	first-stage rotor exit
3	second-stage stator exit
4	second-stage rotor exit
5	third-stage stator exit
6	third-stage rotor exit
7	fourth-stage stator exit
8	fourth-stage rotor exit
9	exit of downstream stator

Superscripts:

'	absolute total state
*	U.S. standard sea-level conditions (temperature equal to 288.15 K (518.67° R), pressure equal to 10.13 N/cm ² (14.70 psia))

TURBINE DESCRIPTION

Figure 1 shows the 50.8-centimeter- (20.0-in.-) tip-diameter turbofan simulator installed in the wind tunnel. The turbine is powered by an external air supply that passes through the strut to an annulus chamber in front of the turbine and then to the turbine nozzle. The air expands through the turbine and is discharged into the wind tunnel. The design turbine inlet temperature is 366.7 K (660.0° R), and the design inlet pressure is 241.3 newtons per square centimeter (350.0 psia). All design point values, with air as the working fluid, and air equivalent values are given in table I.

The turbine used in the turbofan simulator was designed as a $4\frac{1}{2}$ -stage turbine with a constant mean diameter of 15.0 centimeters (5.9 in.). The tip clearance for all rotors is 0.013 centimeter (0.005 in.). A description of the turbine geometry is given in figure 2.

The design static efficiency of 0.594 is lower than one would expect from an optimum design. This value was selected because some of the turbine design features,

selected in some cases for ease of fabrication and low cost, were not conducive to maximum efficiency. All stator and rotor blades were untwisted, thus introducing incidence losses. Velocities leaving all blade rows were in the high subsonic or transonic region, where the profile losses are high and the incidence losses are more severe. Solidities were generally lower than optimum values. From figure 2 it can be seen that all rotor blades overlapped the preceding stators at both hub and tip, thus introducing losses due to churning of stagnant flow.

EXPERIMENTAL RESULTS

Two identical 50.8-centimeter (20.0-in.) turbofan simulators were used. One simulator was used in the 9- by 15-foot subsonic wind tunnel. Fan configurations 1 and 2 were tested in this simulator. Fan configuration 3 was tested in the second simulator, which was installed in the 8- by 6-foot supersonic wind tunnel.

The instrumentation used to obtain the turbine experimental results was as follows. Two static-pressure taps were located 150° apart and two thermocouple probes were located 150° apart in the annulus chamber in front of the turbine, where the velocity was very low. At the turbine exit there were four combination total-temperature and total-pressure rakes equally spaced around the annulus. Both the total-temperature and total-pressure probes on these rakes were set at three radial positions in order to provide a degree of radial averaging. Data from these probes are considered accurate since the flow was turned axially with the downstream stator.

Data from operating lines for the three fan configurations are presented in figures 3 to 5. The performance data presented are equivalent values referenced to standard conditions in air. The total- to static-pressure-ratio range covered in the three figures is from about 3.4 to 25.5. Figure 3 shows the variation of equivalent mass flow with total- to static-pressure ratio. The average equivalent mass flow for configurations 1 and 2 is fairly constant at a value of about 0.28 kilogram per second (0.62 lb/sec). The average equivalent mass flow for configuration 3 is constant at a value of about 0.27 kilogram per second (0.60 lb/sec). The difference in mass flow between the data for configuration 3 and the other two configurations could be attributed to differences in throat areas in the two turbines due to manufacturing tolerances. The figure indicates that the turbine is choked over the entire pressure-ratio range investigated. The value of 0.27 kilogram per second (0.60 lb/sec) for configuration 3 is about 4 percent higher than the design value of 0.26 kilogram per second (0.57 lb/sec). This could be attributed to the measured efficiency being higher than the design efficiency.

Figure 4 presents the variation of equivalent speed with total- to static-pressure ratio. Equivalent speeds vary from 5000 to 10 700 rpm. Figure 5 shows the variation

of equivalent specific work with total- to static-pressure ratio. Work was calculated from total temperatures obtained from probes at the inlet and exit of the turbine. The experimental data from figures 4 and 5 will be compared with the results of the analytical investigation in the section COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS.

ANALYTICAL RESULTS

The multistage-axial-flow-turbine computer program of reference 1 was used for this analysis. Radial variation of flow conditions was included in the analysis. The specific-heat ratio was kept constant at 1.40. The geometric values needed for the input are listed in figure 2. Inlet total temperature and pressure at design conditions are taken from table I.

To determine a performance map analytically with the reference computer program, the first step is the selection of an efficiency coefficient for each blade row. The blade-row efficiency coefficient is defined as the ratio of absolute or relative exit kinetic energy to the theoretical exit kinetic energy. Selection of the proper efficiency coefficients is made on the basis of matching the calculated performance to some reference performance at one operating point. The reference point selected was the experimental performance at equivalent design speed and the pressure ratio closest to design. This reference point, which is on the configuration 3 curve, is shown in figures 4 and 5. From figure 4, at the equivalent design speed of 9015.6 rpm, the pressure ratio is 17.1. When this pressure ratio is used in figure 5, an equivalent specific work of 107.7 joules per gram (46.3 Btu/lb) is obtained. The equivalent mass flow for the reference point is the value of 0.27 kilogram per second (0.60 lb/sec) obtained from configuration 3 of figure 3.

The program cannot be used to compute the performance of half stages. Therefore, the analysis was made for a 4-stage turbine with the efficiency coefficients chosen to give the overall performance for the $4\frac{1}{2}$ -stage turbine. With the efficiency coefficients so selected to match the reference work and flow, the map was calculated.

Performance Map

The overall performance map for the turbine is presented in figure 6. Equivalent specific work and equivalent horsepower are plotted against equivalent speed with total-to static-pressure ratio, percent equivalent design speed, and static efficiency as parameters. Mass flow was not included as a variable in the abscissa since it remained

constant over the entire map. Equivalent horsepower can be plotted parallel with equivalent specific work as a consequence of constant mass flow. The performance map covers a pressure-ratio range from 5.0 to 35.0 and a percent-design-speed range from 50 to 120.

At equivalent design pressure ratio and speed the static efficiency is 0.65. This is about 6 points higher than the design value of 0.594. The difference between the design mass flow and the experimental mass flow could be attributed to this higher efficiency. The equivalent specific work at design speed and pressure ratio is 112.3 joules per gram (48.3 Btu/lb). At design speed and a pressure ratio of 35.0, which is very near limiting loading (choked exit annulus), the work is 114.4 joules per gram (49.2 Btu/lb) and the static efficiency is about 0.62.

Velocity Diagrams

Figure 7 shows the calculated velocity diagrams for 4 stages of the $4\frac{1}{2}$ -stage turbine. These velocity diagrams were calculated at equivalent design speed and design pressure ratio by using the computer program of this analysis. The first value listed is the velocity in meters per second. The value in parenthesis is the Mach number. The figure shows a high level of velocity at all stations. A number of stator and rotor blade rows are choked at this turbine condition.

COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

A comparison between the experimental turbine performance obtained from simulator tests using three fan configurations and the results of the computed performance is presented in figure 8. For each speed - pressure-ratio operating curve shown in figure 4, the experimental work is shown in figure 5, and the analytically calculated work can be obtained from figure 6. These experimental and analytical values of work are compared in figure 8 for each operating curve over the range of experimental pressure ratios and speeds. The figure shows that the maximum deviation between the calculated and experimental results is no more than 2 percent. The analytical results are seen to be in good agreement with the experimental data over the range of the data. This close agreement provides confidence in the accuracy of the calculated map.

CONCLUDING REMARKS

The overall performance of a $4\frac{1}{2}$ -stage 15.0-centimeter- (5.9-in.-) mean-diameter turbine was calculated analytically over a range of speed and pressure ratio. This turbine is used in a 50.8-centimeter- (20.0-in.-) tip-diameter turbofan simulator. The overall performance is needed to determine the capability of this turbine for other present and future applications.

Comparison of the analytical and experimental performance showed good agreement over a pressure-ratio range from 3.4 to 25.5 and an equivalent-speed range from 5000 to 10 700 rpm. The comparison indicates that the analytically determined performance map does represent the overall performance of the $4\frac{1}{2}$ -stage turbine.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 23, 1973,
501-24.

REFERENCE

1. Flagg, E. E.: Analytical Procedure and Computer Program for Determining the Off-Design Performance of Axial Flow Turbines. NASA CR-710, 1967.

TABLE I. - TURBINE DESIGN VALUES

(a) Design point

Mass flow rate, w , kg/sec (lb/sec)	5.44 (12.00)
Specific work, Δh , J/g (Btu/lb)	130.7 (56.2)
Turbine speed, N , rpm	10 170.0
Total- to static-pressure ratio, p'_0/p_g	24.3
Inlet total pressure, p'_0 , N/cm ² (psia)	241.3 (350.0)
Inlet total temperature, T'_0 , K (^o R)	366.7 (660.0)
Static efficiency, η_s	0.594
Horsepower, hp	954.0

(b) Air equivalent (U.S. standard sea level)

Mass flow rate, $w\sqrt{\theta/\delta}$, kg/sec (lb/sec)	0.26 (0.57)
Specific work, $\Delta h/\theta$, J/g (Btu/lb)	102.8 (44.2)
Rotative speed, $N/\sqrt{\theta}$, rpm	9015.6
Horsepower, $hg/\delta\sqrt{\theta}$	35.5

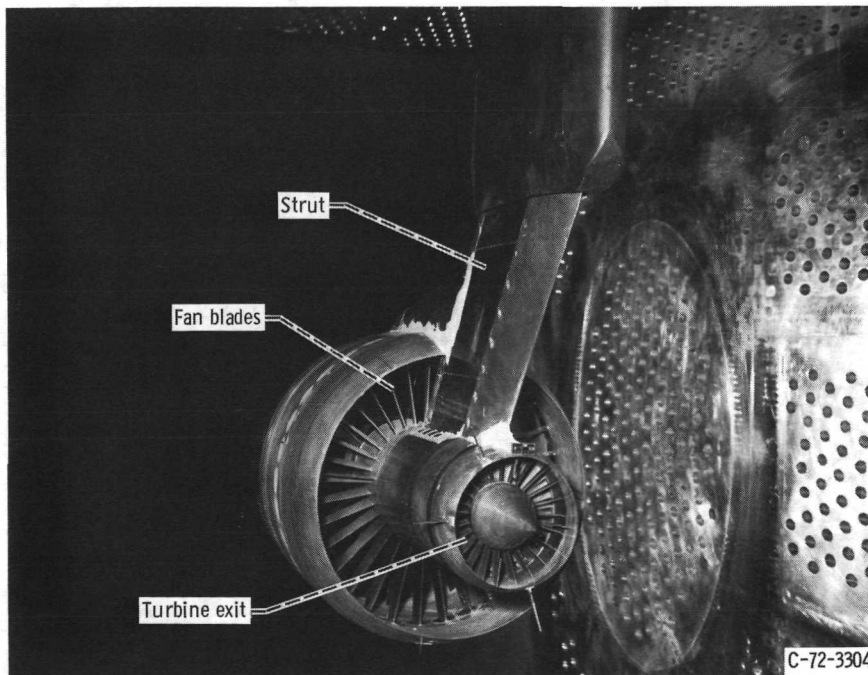


Figure 1. - Installation of 50.8-centimeter- (20.0-in.-) tip-diameter turbofan simulator in 8- by 6-foot supersonic wind tunnel.

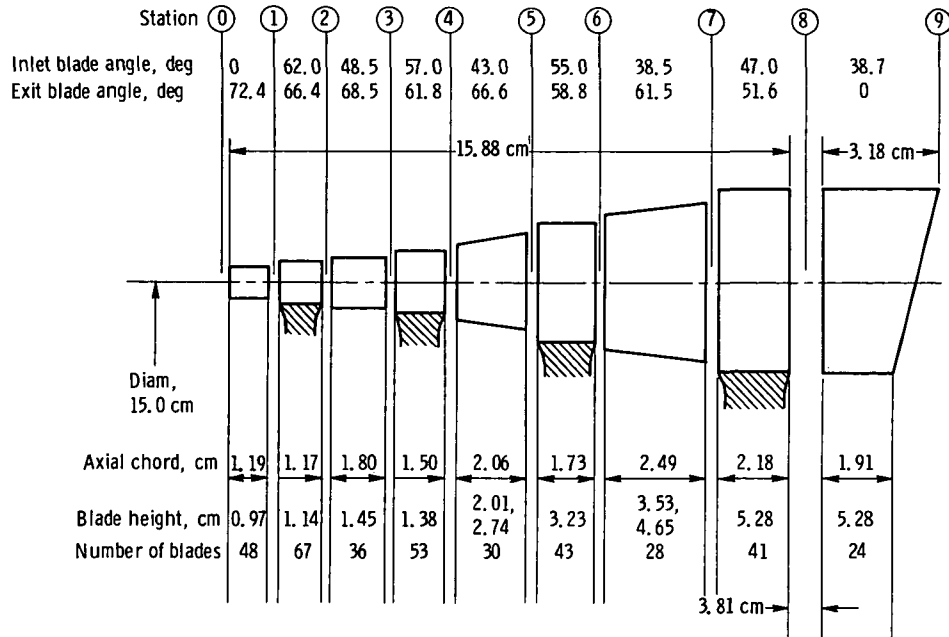


Figure 2. - Turbine stage geometries. Axial spacing for all stages, 0.25 centimeter.

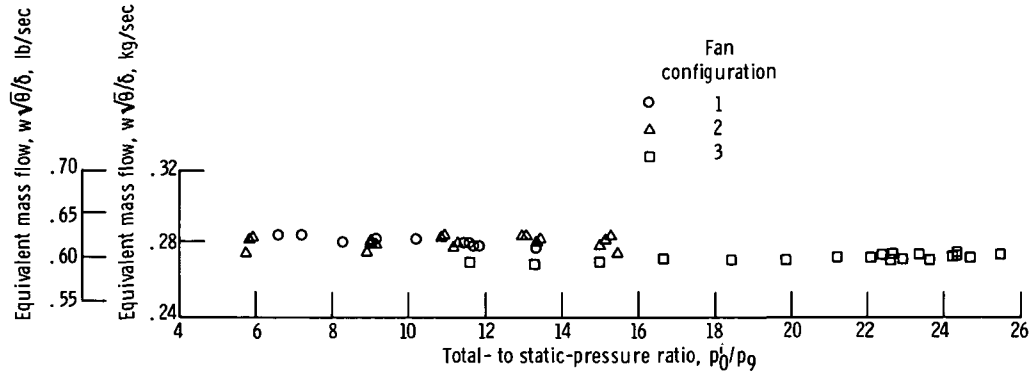


Figure 3. - Variation of turbine mass flow with pressure ratio.

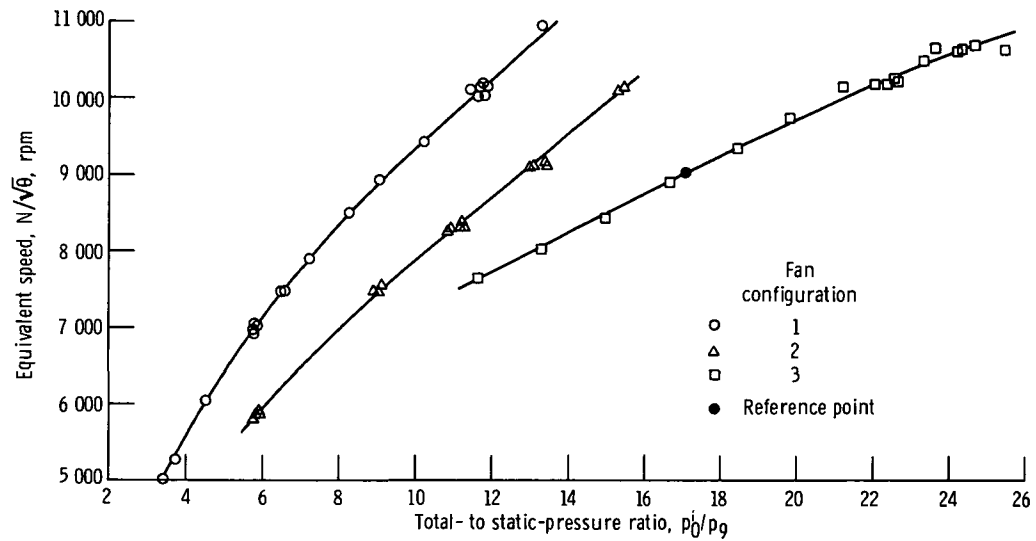


Figure 4. - Variation of turbine speed with pressure ratio for various fan configurations.

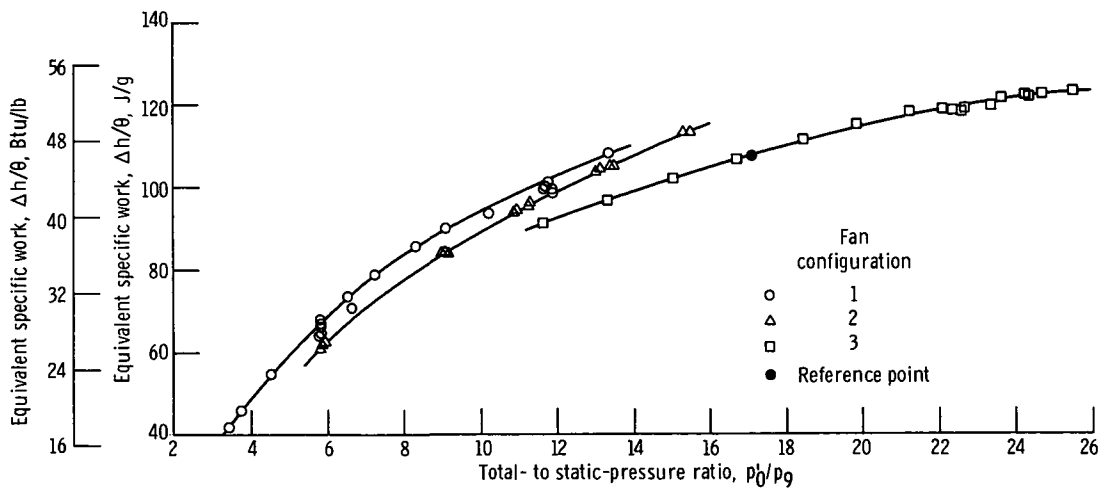


Figure 5. - Variation of turbine work with pressure ratio for various fan configurations.

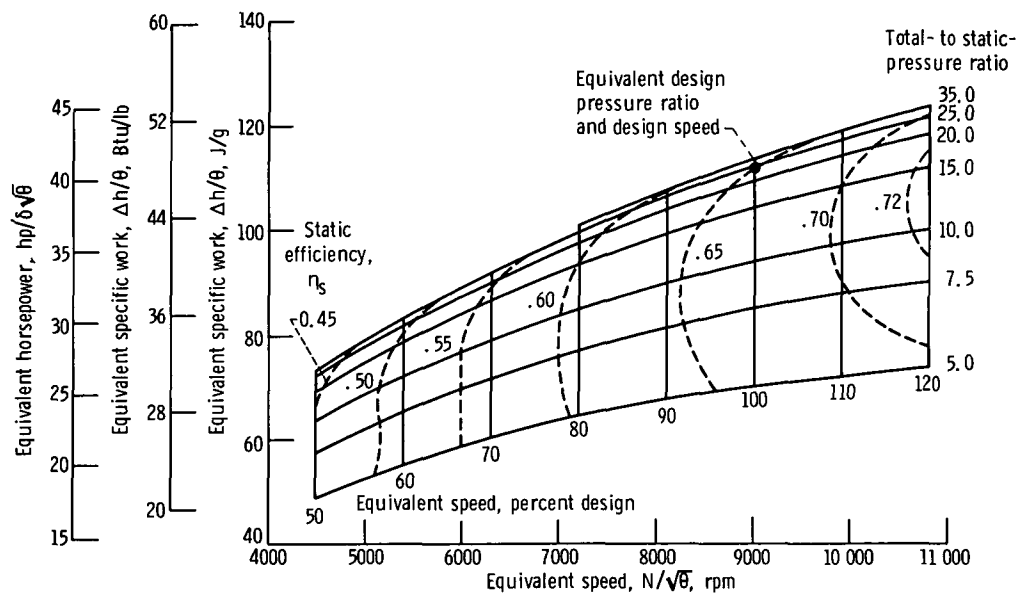


Figure 6. - Analytically obtained turbine performance map. Equivalent mass flow, 0.27 kilogram per second (0.60 lb/sec).

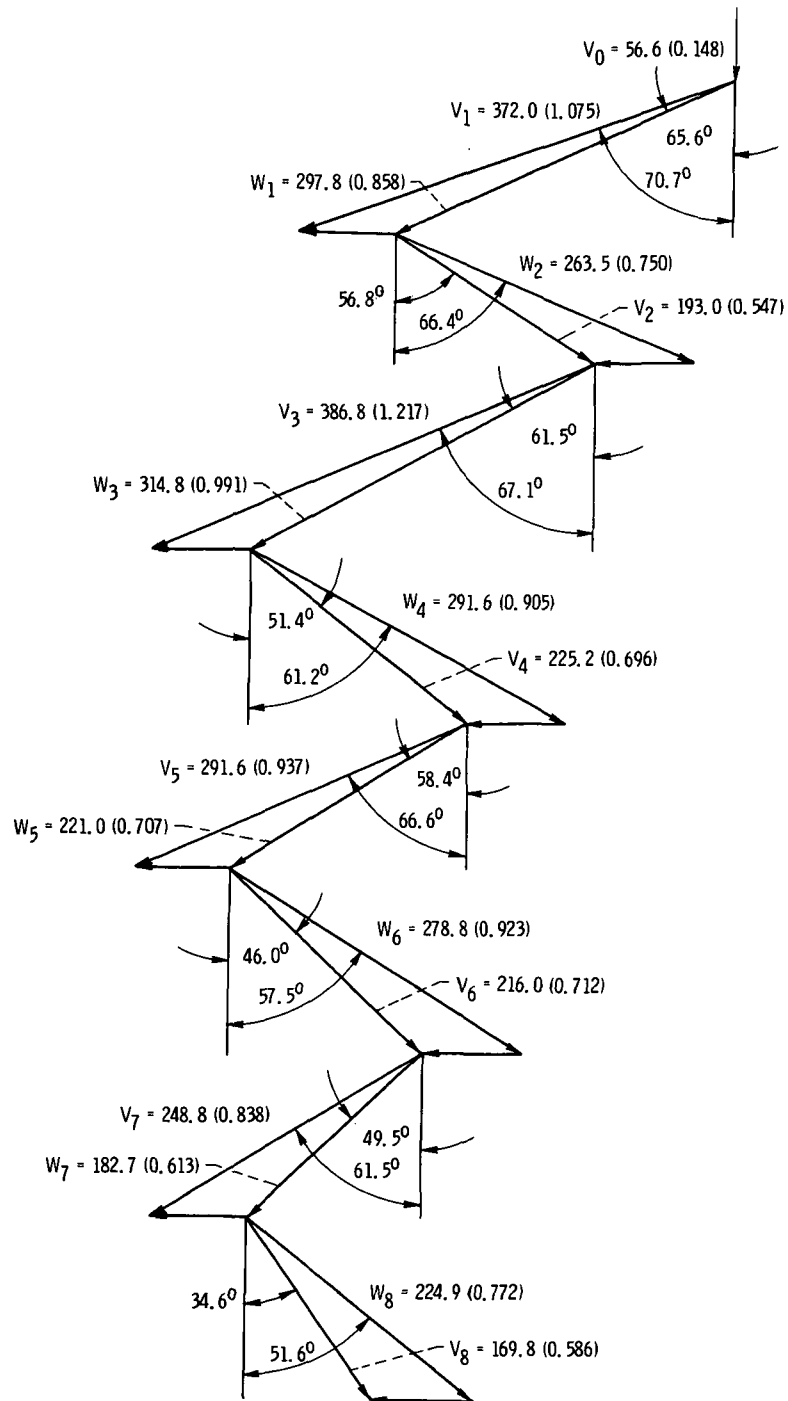


Figure 7. - Analytically obtained velocity diagrams at design speed and pressure ratio. (Velocities given in meters per second (Mach number).)

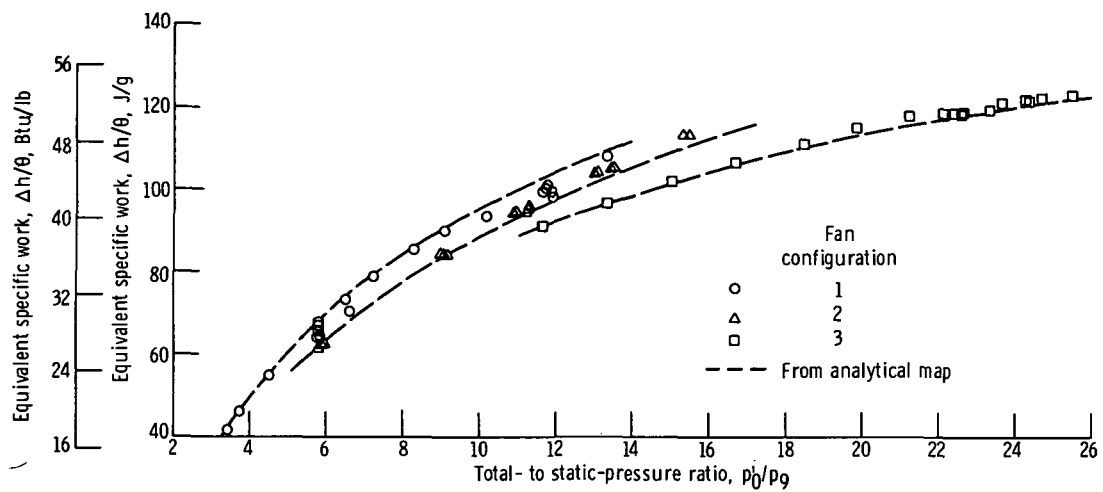


Figure 8. - Comparison of analytical and experimental turbine work for various fan configurations.



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