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PERFORMANCE DATA FOR A SMALL LOW-SPECIFIC-SPEED TEN STAGE TURBINE TESTED IN ARGON

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ABSTRACT

A turbine with low flow rate and high expansion ratio requirements, such as would be applicable to a SNAP-8 space power system, was designed and tested. The design incorporated the features necessary to provide high efficiency for this type of application. Performance data in argon are presented over a range of turbine pressure ratios from 6 to 28 and speeds ranging from 60 to 110 percent of equivalent design speed.

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SUMMARY

A turbine with low flow rate and high expansion ratio requirements, such as would be applicable to a SNAP-8 space power system, was designed, built, and tested. The design incorporated features necessary to provide high efficiency for this type of application. This turbine had ten stages with a tip diameter increasing from 3.008 inches at the inlet to 5.572 inches at the exit. Performance data using argon as the working fluid was experimentally determined and are presented over a range of turbine pressure ratios from 6 to 28 and speeds ranging from 60 to 110 percent of equivalent design speed.

An equivalent weight flow of 0.2147 pounds per second and an overall static efficiency of 0.891 were obtained at equivalent design speed and pressure ratio. The flow and efficiency were 16.7 and 12.6 percent, respectively, higher than the design values of 0.1839 pounds per second and 0.791. The higher values obtained experimentally are attributed to the conservative design approach used and the associated overestimation of performance degradation due to small size.

INTRODUCTION

Turbines for space applications such as SNAP-8, which is a turboelectric nuclear space power system using a Mercury Rankine cycle, are characterized by low flow rates and high expansion ratios. High expansion ratio implies high specific work and this in conjunction with the low flow results in low values for the overall specific speed parameter. The high expansion ratio also results in a large increase in volume flow as the fluid passes through the turbine.

The turbine (ref. 1) designed to meet the SNAP-8 requirements was a cantilevered constant-diameter four-stage impulse turbine with partial admission in the first two stages and full admission in the last two stages. This turbine had a design efficiency of 60 percent, but operated with a somewhat lower efficiency. Reference 2 shows that many stages (about 15 for the assumptions of that study) along with an increase in diameter (about double for that study) from inlet to exit are required in order to obtain high efficiency for SNAP-8 type requirements.

As a result, a turbine of this type was designed and tested in order to verify its performance potential. In order to provide high efficiency, the turbine has 10 stages with conservative symmetrical diagrams, increasing diameter from inlet to exit, and full admission throughout. The turbine was designed aerodynamically for flow, rotative speed, and pressure ratio corresponding approximately to SNAP-8 equivalent conditions with argon as the fluid. The turbine was run from 60 to 110 percent speed with pressure ratios between 6 and 28. This report presents a description of the turbine and the experimental performance data.

SYMBOLS

A	flow area, in.^{2}
g	dimensional constant, 32.174 ft/sec^2
H_{id}	stage ideal work based on total-to-total pressure ratio, ft-lb/lb
N	rotative speed, rpm
p	pressure, psia
Q_{ex}	stage exit volume flow, ft^3/sec
R	gas constant, (ft-lb)/(lb-$^{\circ}$R)
T	temperature, $^{\circ}$R
U	blade speed, ft/sec
w	weight flow, lb/sec
α	absolute flow angle measured from axial direction, deg
γ	ratio of specific heats
δ	ratios of inlet total pressure to standard pressure (14.7 psia), p'/p^*

$\bar{\eta}_s$ overall static efficiency (based on overall inlet-total- to exit-static-pressure ratio)

η_t total efficiency (based on inlet-total to exit-total pressure ratio)

θ_{cr} ratio of temperature at turbine inlet to standard temperature $T_1/518.67$

Γ torque, in.-lb

Subscripts:

1 station at turbine inlet (fig. 1)

3 station at turbine exit (fig. 1)

Superscripts:

' absolute total state

TURBINE DESIGN

The design values of the turbine performance parameters are:

Equivalent torque, Γ/δ, in.-lb 40.11

Equivalent rotative speed, $N/\sqrt{\theta_{cr}}$, rpm 14,892

Equivalent weight flow, $w\sqrt{\theta_{cr}}/\delta$, lb/sec 0.1839

Overall total-to-static pressure ratio, p_1'/p_3 . . . . 23.3

Overall static efficiency, $\bar{\eta}_s$ 0.791

All equivalent values presented in this report are referenced to argon at standard temperature and pressure and not air.

To get the desired efficiency, it was specified that the turbine have full admission, shrouded rotors, a stage specific speed $(NQ_{ex}^{1/2}/H_{id}^{3/4})$ of 60, a stage velocity ratio $(U/\sqrt{2gH_{id}})$ of 0.45, symmetrical diagrams (50 percent reaction), and rotor hub to tip radius ratios of 0.8. Because of the small size of the turbine, a conservative value of 0.7 was assumed for the total efficiency of each stage. The specified requirements resulted in excessive diameter increase in the latter stages, and some tailoring was done to correct this. The final design had ten stages having the above specifications except for the specific speed and rotor radius ratios of the last three stages. The specific speed and radius ratio varied from the specified 60 and 0.8, respectively, in stage 7 to 80.7 and 0.665, respectively, in stage 10.

A sectional view of the turbine is shown in figure 1, and the diameters and number of blades for each stage are given in table I. The turbine tip diameter varies from 3.008 inches at the inlet to 5.572 inches at the exit. Since the rotors were to be shrouded, it was desirable to have constant-diameter rotors with all the diameter change occurring in the stators. This was done for the first eight stages, but the large diameter change in the last two stages dictated splitting this diameter change between stator and rotor. A photograph of the stator and rotor assemblies is shown in figure 2.

Since the stages were designed using symmetrical velocity diagrams, the stator and rotor diagram angles are the same, except for the first stage stator which has axial inlet flow. Stator exit angle adjustments to allow for cylindrical end walls on the rotors were small enough so that the proper stator throat areas could be obtained by small stagger angle adjustments rather than by separately tailoring each stator row. To simplify fabrication, it was specified that all blades have constant sections radially. The velocity levels were low enough so that the resulting incidence losses would be small.

To accommodate the diameter changes, the stator chords were specified to be 1.5 times the rotor chords. The stator and rotor axial chords were 3/8 and 1/4 inch, respectively. Thus, only three blade sections had to be designed: first stage stator, interstage (and last stage) stator, and rotor. The blade and passage profiles for the interstage stators and rotors are shown in figure 3.

APPARATUS, INSTRUMENTATION, AND PROCEDURE

Apparatus

The apparatus consisted of the ten stage turbine described in the preceding section, an airbrake dynamometer to absorb and measure the power output of the turbine and an inlet and exhaust piping system with flow controls. Pressurized argon was used as the working fluid. The argon was piped to the turbine through an electric heater, filter, a remotely controlled pressure valve and choked flow nozzle (weight flow measuring station). After leaving the turbine, the argon was exhausted through a system of piping and a remotely operated valve into the laboratory low-pressure exhaust system. With a fixed inlet pressure, the remotely operated valve in the exhaust line was used to obtain the desired pressure ratio across the turbine.

The airbrake dynamometer, which was cradle mounted on air bearings for torque measurement, absorbed the power output, and at the same time, controlled the speed. A commercial strain-gage load cell was used to measure the force on the torque arm. The rotational speed was measured with an electronic counter in conjunction with a magnetic pickup and a shaft mounted gear. The turbine test facility is shown in figure 4.

Instrumentation

The turbine was instrumented at two stations as shown in figure 1. At the turbine inlet, station 1, there were three static-pressure taps, two total temperature rakes with three probes on each located 120° apart circumferentially, and a total pressure-temperature probe used for setting the inlet conditions. At station 3, the turbine exit, there were three static-pressure taps at the hub, four static pressure taps at the tip, a total temperature rake with two probes, and a self-aligning probe for flow angle, total-temperature and total-pressure measurements.

All pressures were measured by electronic transducers. The data were recorded on integrating digital equipment.

The turbine weight flow was measured with a choked flow nozzle using the upstream temperature and pressure. The throat of the flow nozzle was instrumented with static-pressure taps to assure choking.

Procedure

Performance data were taken at nominal inlet total conditions of 600° R and 42 psia. The overall turbine pressure ratio was obtained by setting the exit static pressure. The data were taken over a range of total- to static-pressure ratios from 6 to 28 and equivalent speed range from 60 to 110 percent of design. At equivalent speeds of 60 and 70 percent of design, the maximum pressure ratio was determined by the torque the airbrake could absorb and still maintain speed control.

The friction torque of the bearings and seals was measured over the range of speeds considered. In measuring the friction torque, the air was evacuated from the turbine to a pressure of approximately 100 micrometer of mercury to minimize the windage loss. The friction torque at design equivalent speed was 0.95 in.-lb. This value corresponds to about 0.63 percent of the turbine torque at design speed and pressure ratio. Friction torque was added to shaft torque when determining turbine efficiency.

The total pressures used in this report were calculated from average static pressures, total temperature, annulus area, flow angle and weight flow from the following equation:

$$p' = p\left\{\frac{1}{2} + \frac{1}{2}\left[1 + \frac{2(\gamma - 1)}{\gamma}\,\frac{R}{g}\left(\frac{w\sqrt{T'}}{pA\cos\alpha}\right)^2\right]^{1/2}\right\}^{\gamma/(\gamma-1)}$$

In calculation of inlet total pressure, flow angle is assumed to be zero.

PERFORMANCE DATA

The performance data presented are equivalent values referenced to standard argon, that is argon at a temperature of 518.67° R and a pressure of 14.7 psia.

The equivalent torque Γ/δ is presented in figure 5 as a function of overall inlet total-to exit-static pressure ratio for lines of constant speed. As can be seen from figure 5, the torque increases as pressure ratio increases and speed decreases. Therefore, it is shown that the turbine has not reached limiting loading at the highest pressure ratios investigated. At equivalent design speed and pressure ratio, the equivalent torque is 52.9 in.-lb. This value is 31.9 percent greater than the design value of 40.11 in.-lb.

The variation of equivalent weight flow $w\sqrt{\theta_{cr}}/\delta$ with overall total to static pressure ratio and speed is presented in figure 6. As can be seen from figure 6, choking weight flow was obtained for all speeds at pressure ratios above about 13 to 15. At 60 percent speed, pressure ratios higher than 12 could not be obtained because the airbrake could not absorb the torque. The weight flow decreased with increasing speed, thus indicating that the choking occurred at some blade row downstream of the first stator. The weight flow at design speed and pressure ratio is 0.2147 lb/sec, which is 16.7 percent greater than the design value of 0.1839 lb/sec.

The overall static efficiency is shown in figure 7 as a function of overall total to static pressure ratio and speed. The peak static efficiency is 0.902 at 110 percent of design equivalent speed and a pressure ratio of 22. The static efficiency at design speed and pressure ratio is 0.891, which is 0.10 (12.6 percent) higher than the design value of 0.791.

As indicated by figures 5, 6, and 7, the turbine performed considerably better than it was designed for. The design was based on an assumed total efficiency of 0.70 for each stage. Associated with the use of symmetrical velocity diagrams and shrouded rotors, this value was too low; however, a performance degradation due to the small size was anticipated. This performance degradation apparently did not occur. Based upon the measured overall efficiency, the average stage efficiency is about 0.83. The higher efficiency, in turn, caused an increase in weight flow.

SUMMARY OF RESULTS

A turbine with low flow rate and high expansion ratio requirements, such as would be applicable to a SNAP-8 space power system, was designed, built, and tested. The design incorporated features necessary to provide high efficiency for this type of application. This turbine had ten stages with a tip diameter increasing from 3.008 inches at the inlet to 5.572 inches at the exit. Performance data with argon as the working fluid was experimentally determined and are presented over a range of turbine pressure ratios from 6 to 28 and speeds ranging from 60 to 110 percent of equivalent design speed. The experimental performance results of this investigation are summarized as follows:

1. The overall static efficiency at equivalent design speed and pressure ratios was 0.891, which was 0.10 (12.6 percent) greater than the design value of 0.791. The peak static efficiency was 0.902 at 110 percent of design speed and about design pressure ratio.

The better performance obtained experimentally was attributed to the too-low value of 0.70 that was assumed for stage total efficiency during the design. The anticipated performance degradation due to small size apparently did not occur and the average stage efficiency turned out to be about 0.83.

2. The equivalent weight flow at equivalent design speed and pressure ratio was 0.2147 lb/sec, which is 16.7 percent greater than the design value of 0.1839 lb/sec. The turbine was choked at the design point. The increased weight flow was caused by the higher efficiency.

3. An equivalent torque of 52.9 in.-lb was obtained at equivalent design speed and pressure ratio. This value is 31.9 percent greater than the design value of 40.11 in.-lb.

REFERENCES

1. Slone, Henry O.: SNAP-8 Development Status. Proceedings of the Space Power Systems Advanced Technology Conference. NASA SP-131, 1966, pp. 147-168.
2. Glassman, Arthur J.; and Stewart, Warner L.: Use of Similarity Parameters for Examination of Geometry Characteristics of High-Expansion-Ratio Axial-Flow Turbines. NASA TN D-4248, 1967.

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TABLE I - TURBINE STAGE GEOMETRIES

Stage No.	Stator			Rotor		
	Number of Blades	Diameter		Number of Blades	Diameter	
		Inlet	Exit		Inlet	Exit
1	23	3.008 2.422	3.008 2.422	40	3.028 2.422	3.028 2.422
2	27	3.048 2.422	3.114 2.508	41	3.134 2.508	3.134 2.508
3	29	3.154 2.508	3.244 2.612	43	3.264 2.612	3.264 2.612
4	30	3.284 2.612	3.384 2.724	45	3.404 2.724	3.404 2.724
5	31	3.424 2.724	3.560 2.864	47	3.580 2.864	3.580 2.864
6	33	3.600 2.864	3.784 3.044	50	3.804 3.044	3.804 3.044
7	36	3.824 3.044	4.088 3.286	54	4.108 3.286	4.108 3.286
8	39	4.128 3.286	4.440 3.510	58	4.460 3.510	4.460 3.510
9	41	4.480 3.510	4.700 3.686	62	4.720 3.686	4.908 3.686
10	44	4.928 3.686	5.260 3.704	66	5.280 3.704	5.572 3.704

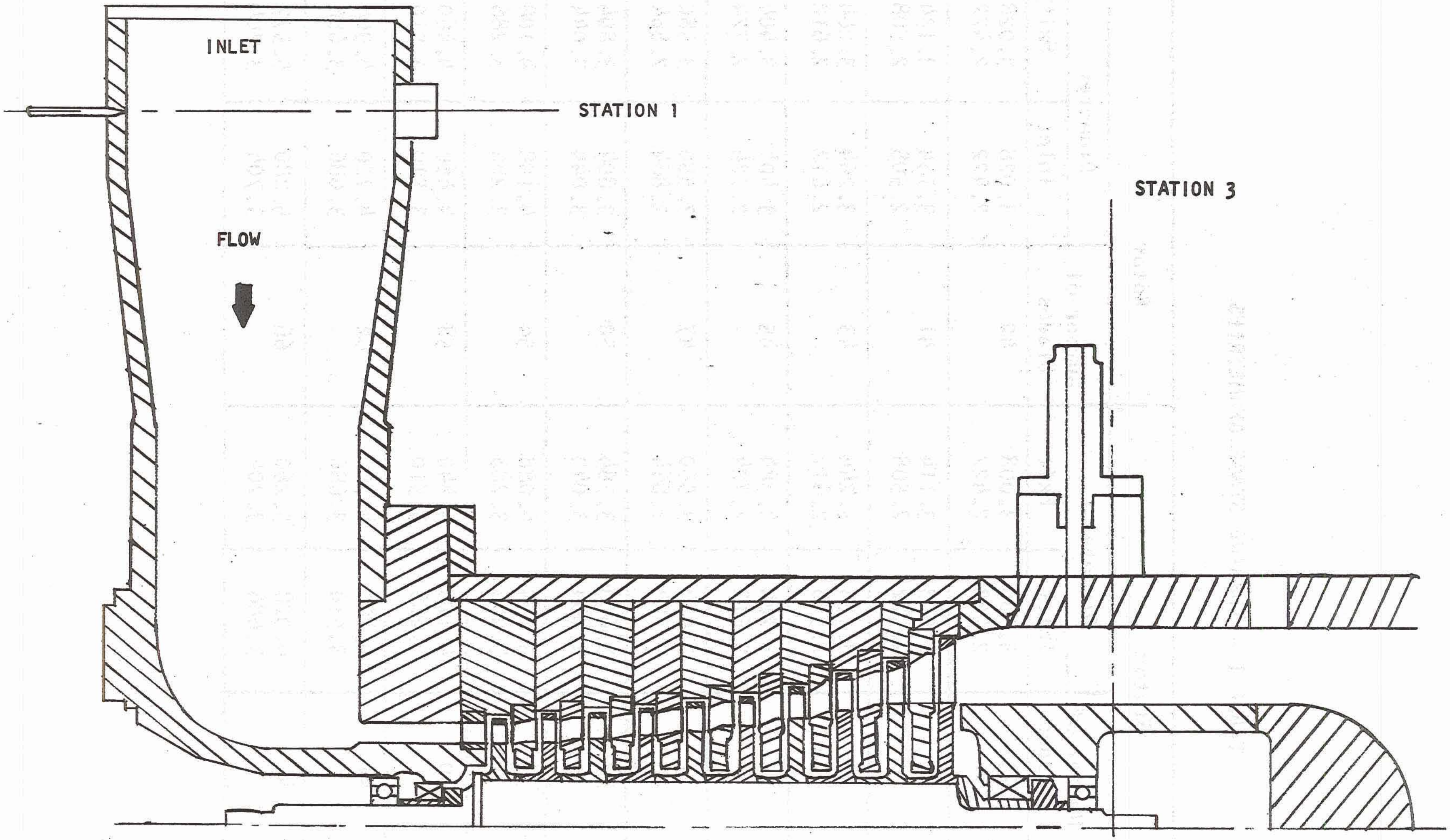

Figure 1 - CROSSECTIONAL VIEW OF TEN-STAGE TURBINE WITH INSTRUMENTATION STATIONS.

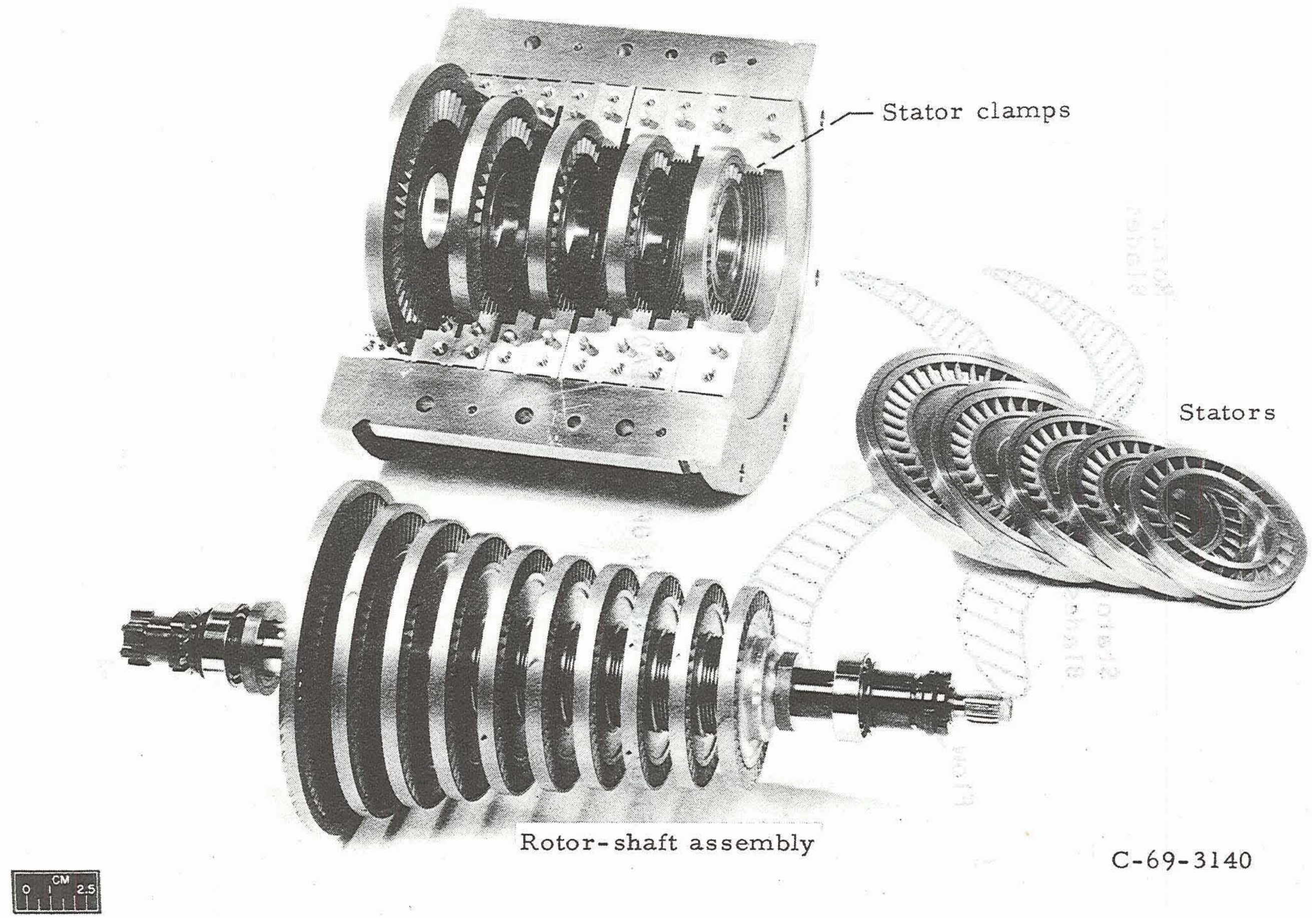

Figure 2. - Ten-stage turbine components.

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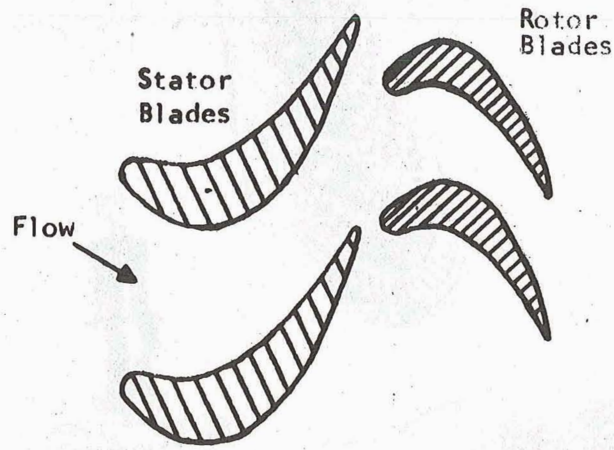

Figure 3 - SKETCH OF STAGE BLADE PROFILES

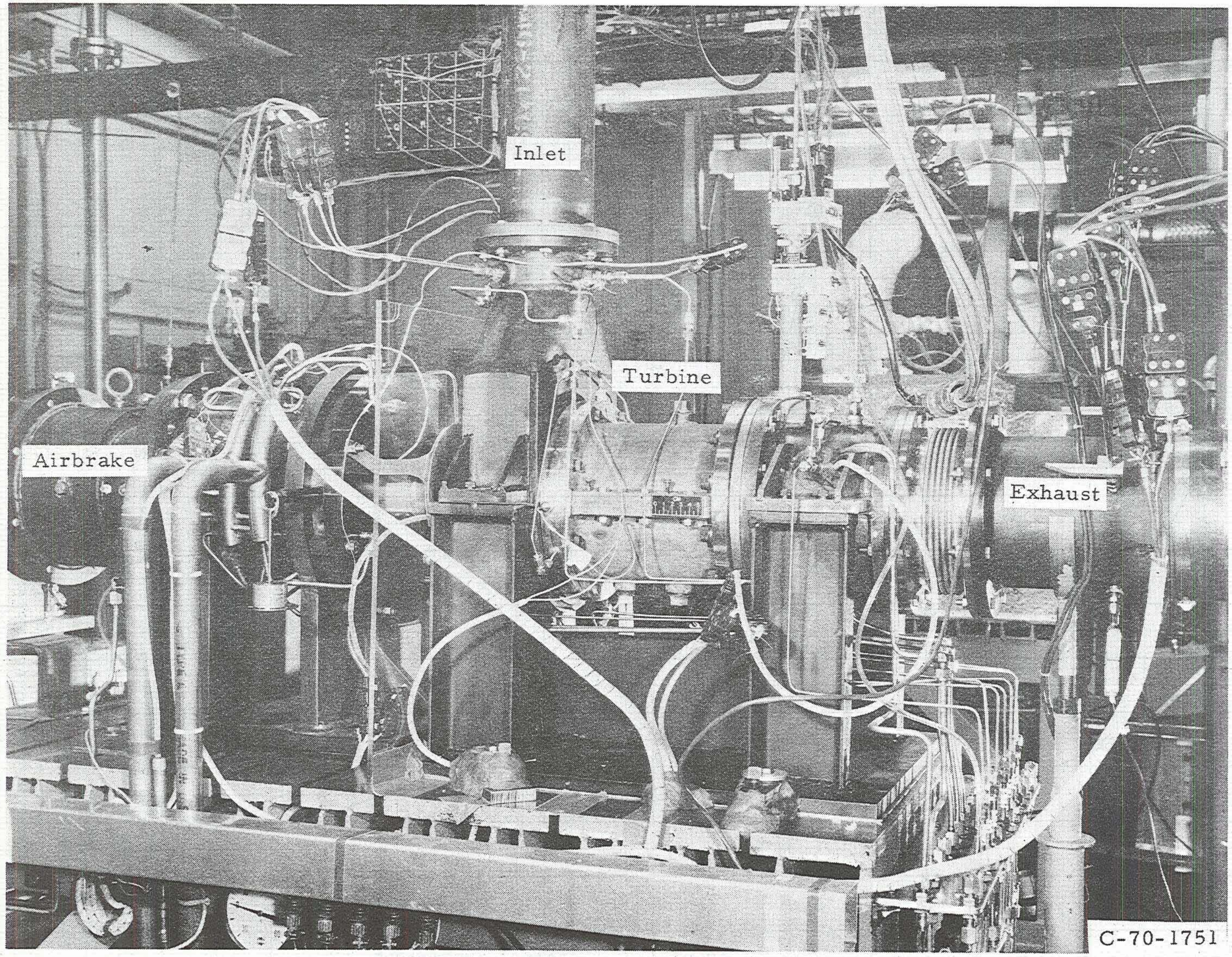

Figure 4. - Turbine test facility.

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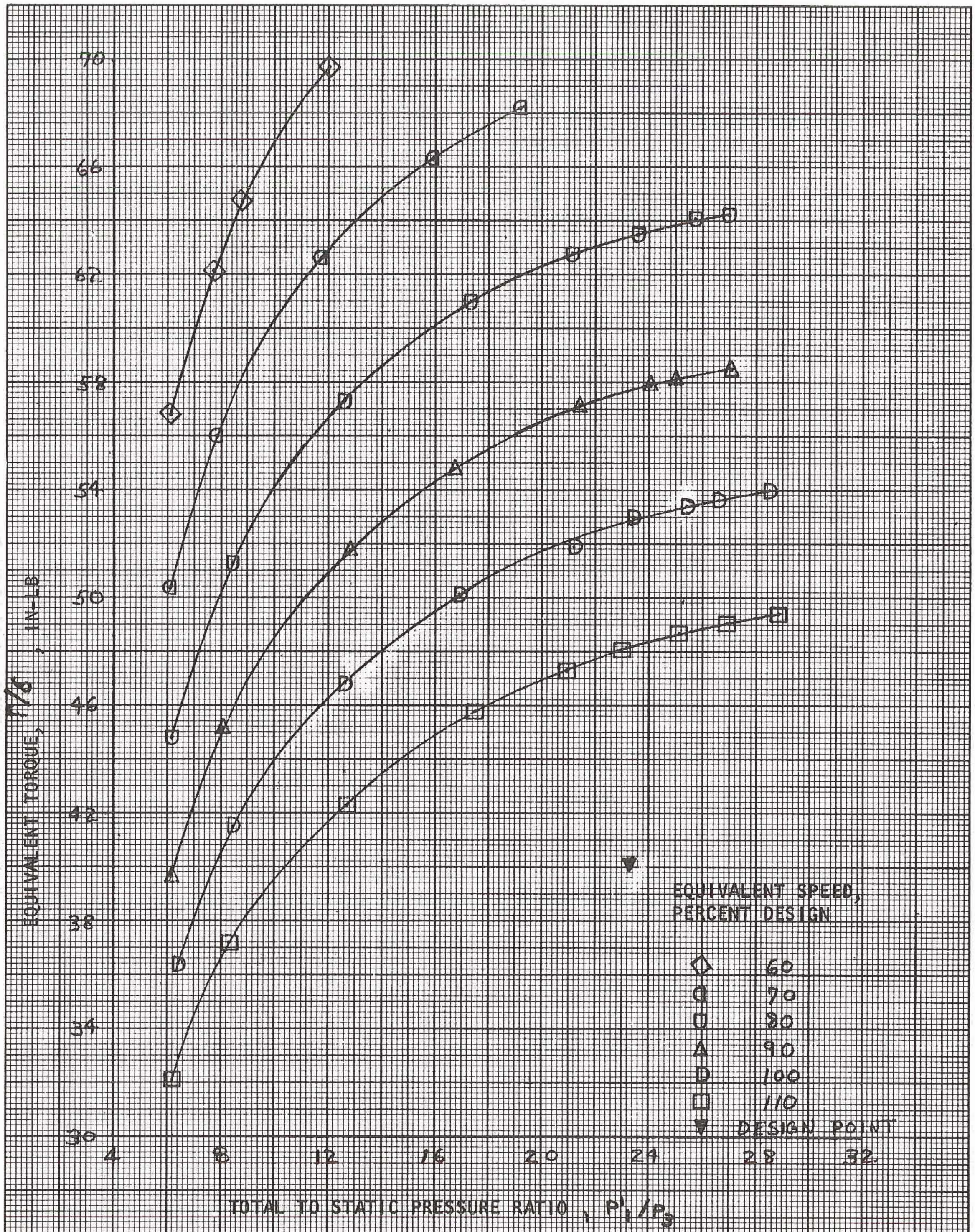

Figure 5. - VARIATION OF TORQUE WITH TOTAL TO STATIC PRESSURE RATIO AND SPEED.

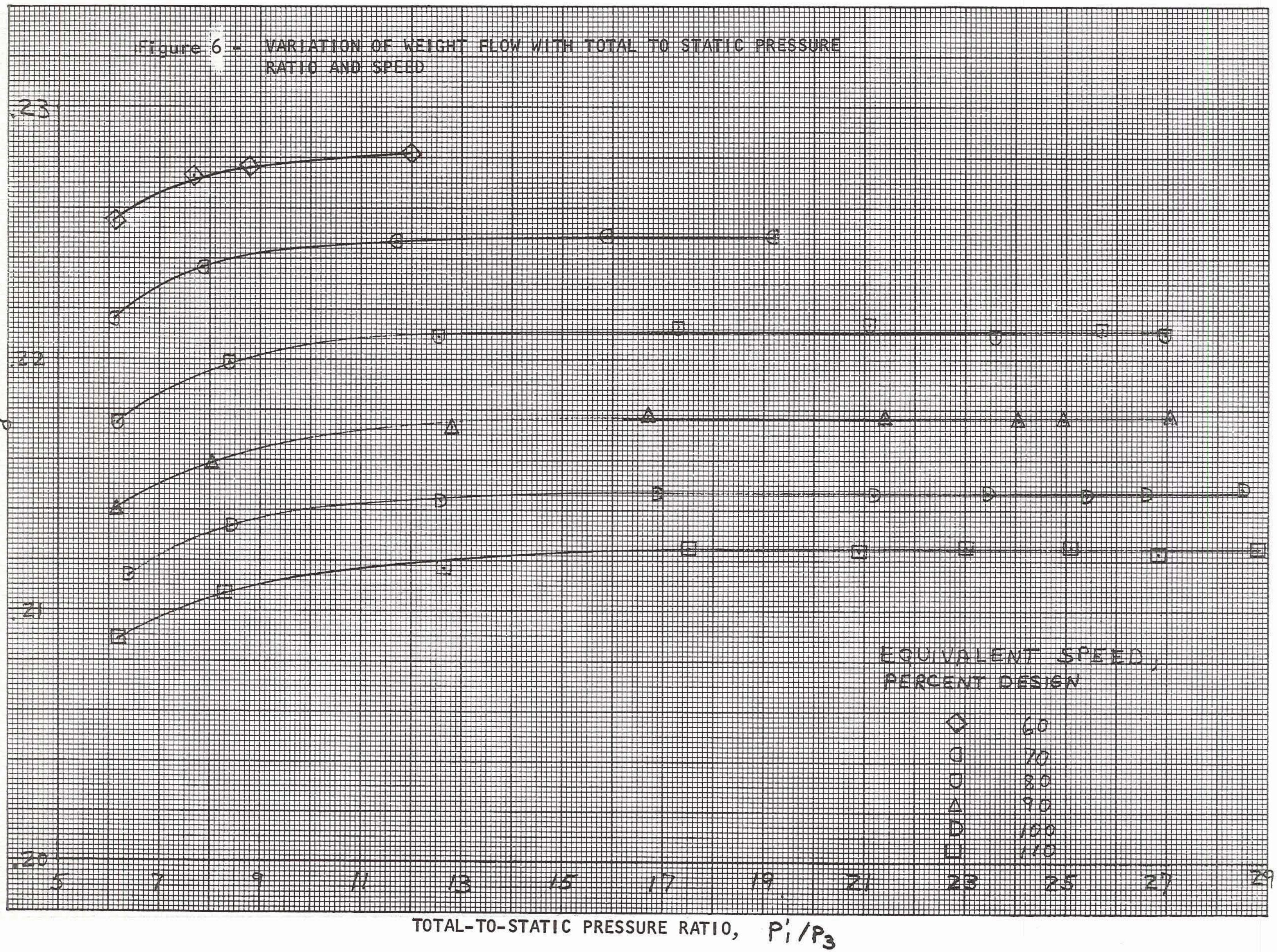
Figure 6 - VARIATION OF WEIGHT FLOW WITH TOTAL TO STATIC PRESSURE RATIO AND SPEED
EQUIVALENT WEIGHT FLOW, $\frac{\omega\sqrt{\theta_{cr}}}{\delta}$, LB/SEC
.23
.22
.21
.20
5
7
9
11
13
15
17
19
21
23
25
27
29
TOTAL-TO-STATIC PRESSURE RATIO, P_1'/P_3
EQUIVALENT SPEED, PERCENT DESIGN
60
70
80
90
100
110

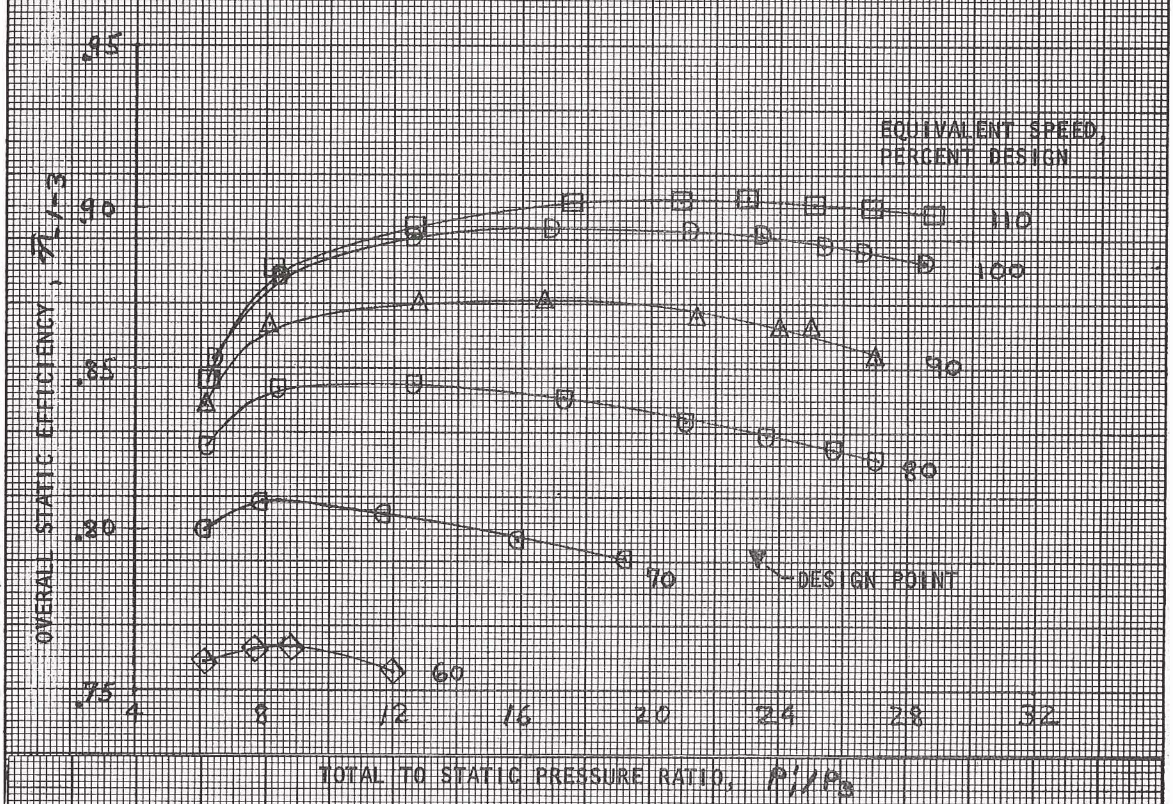

Figure 7 - VARIATION OF STATIC EFFICIENCY WITH TOTAL TO STATIC PRESSURE RATIO AND SPEED.

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