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STATIC PERFORMANCE OF A 13.97-CM (5.5-INCH) DIAMETER MODEL VTOL LIFT FAN

by W. H. Lowe and R. W. Sanger

Prepared by
GENERAL DYNAMICS
San Diego, Calif. 92112
for Lewis Research Center

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Project Manager, Nestor Clough, V/STOL and Noise Division, NASA Lewis Research Center, Cleveland, Ohio

16. Abstract

A 13.97-cm (5.5-inch)-diameter tip-turbine-driven fan of the type currently being used in wind tunnel tests of VTOL lift fan models was tested. Values of thrust, weight flow, exit total and static pressure, exit swirl angle, and turbine temperature drop were measured as a function of fan speed for several inlet and exit configurations. A standard fan performance map was also obtained.

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STATIC PERFORMANCE OF A 13.97-CM (5.5-INCH) DIAMETER MODEL VTOL LIFT FAN

By W. H. Lowe and R. W. Sanger

SUMMARY

Thrust, weight flow, total and static exit pressures, turbine inlet and exit temperatures, and exit swirl angle were measured as a function of fan speed on a 13.97-cm (5.5-inch)-diameter tip-turbine-driven fan. These measurements were made at ambient discharge conditions over a design corrected fan speed range of 60 to 110 percent. Fan weight flow was obtained using a calibrated bellmouth inlet. The measured parameters as a function of a fan speed were obtained for two different discharge nozzle designs with various inlet and exit plates attached. One design consisted of a straight discharge duct and centerbody and the other was a low base drag nozzle designed to increase the base static pressure above ambient.

A standard fan performance map was obtained by operating the fan with the calibrate inlet bellmouth over a range of 70 to 110 percent of design corrected speed, and with exit static pressure to ambient pressure ratios of 0.9 to 1.15.

INTRODUCTION

Air-driven model fans are extensively used as propulsion simulation devices in a variety of wind tunnel programs. A commercially available 13.97-cm (5.5-inch)-diameter tip-turbine-driven lift fan is currently being used by NASA-LeRC in wind tunnel tests of model V/STOL propulsion units. These tests evaluate the effects of forward speed, cross-flow, and flow interactions on fan performance.

A test program was conducted to establish the static performance of a 13.97-cm (5.5-inch)-diameter tip-turbine lift fan assembly as used for model VTOL lift fan tests. The assembly tested consisted of a Tech Development Model TD-457 tip-turbine-driven fan with an extended duct and instrumentation. The purpose of the tests was to determine isolated fan performance using an accurate thrust-measuring device and a bellmouth inlet calibrated to measure fan weight flow. The isolated fan calibration provided base data to calibrate the installed (wind tunnel) fan instrumentation.

The tests were carried out in two phases. The primary purpose of the first phase was to calibrate the installed instrumentation for the determination of flow and thrust coefficients along the fan operating line at ambient discharge conditions. Flow coefficients were determined by comparing the mass flow measurements to computed values using the installed instrumentation. Therefore, the flow coefficients are really correction factors for the installed instrumentation.

A secondary objective of the first phase was to determine the sensitivity of fan performance to modifications made to the fan inlet and exit geometry. The inlet configurations consisted of a 50.8-cm (20-inch)-diameter thin plate mounted normal to the fan axis at the fan inlet plane, and a similar plate at the fan nozzle exit plane. Together these two plates simulate the inlet and exit environment of the wind tunnel installation of a fan-in-wing configuration. Using the inlet plate required the fan weight flow calculation to be based on fan duct instrumentation.

Most of the test runs used an exhaust nozzle configuration consisting of a cylindrical shroud and flat base hub designated as the standard nozzle. An alternate low base drag nozzle design consisting of a convergent shroud and hub with a concave base was also tested.

The fan assembly was mounted to a five-component strain-gage thrust balance and was operated at specific values of fan speed over a range of 60 to 110 percent of design corrected speed. Measurements included total corrected thrust, corrected fan and turbine weight flow, corrected fan speed, turbine inlet and exit temperatures, fan duct exit static and total pressures, and duct exit swirl angle.

In the second phase a complete performance map using the calibrated bellmouth inlet was developed. The fan assembly was mounted to a back-pressure control system consisting of an electro-hydraulic control throttle and ejector. The fan map was determined for the fan operating over a range of 70 to 110 percent of design corrected speed and duct exit static pressure to ambient pressure ratios of 0.90 to 1.15. No thrust measurements were recorded during this phase.

Presented herein for both nozzle designs and with the various inlet and exit plates attached are the measured values of fan discharge angle and pressures, fan weight flow, fan total thrust, turbine weight flow, and temperature drop across the turbine. Selected computed flow coefficients are presented, together with a complete fan performance map. A list of symbols used in the text is presented in Appendix A.

APPARATUS

Air Supply and Flow Control System

Clean, dry air was supplied to the bellmouth calibration fixture, the fan drive turbine, and the back pressure control ejector by the General Dynamics High Speed Wind

Tunnel (GDHSWT) compressor system. This system consists of a three-stage compressor driven by a 5966 kW (8000 hp) synchronous motor. The compressor can continuously supply air at a flow rate of 10 kg/s pressurized at 41 atmospheres. The dew point is -19.4°K (-35°F). The compressed air is stored in six storage tanks with a total storage capacity of 793 cubic meters (28,000 cubic feet) of dry air pressurized at 41 atmospheres. A schematic drawing of the air supply system used to provide air for the three test setup requirements is shown in Figure 1.

Turbine Air Supply. - For the model lift fan tests, the drive air was supplied to the turbine by a 5.08-cm (2-inch)-diameter line connected to the compressor discharge header. The air temperature at this connection point was approximately 328°K (130°F), which was higher than the 304°K (85°F) air temperature specified by NASA-LeRC. The temperature was maintained at ±3°K by manually mixing 284°K (50°F) air from the compressor chiller system. From the mixing valves, the air flowed through a 5.08-cm (2-inch)-diameter pipe approximately 46 meters (150 feet) long to a 10-micron filter bank and 3.8-cm (1.5-inch) dome pressure regulator. This valve was used to control fan speed by regulating the turbine supply pressure. From the regulator, the air flowed through a 2-cm (0.79-inch)-diameter ASME long-radius flow meter and 5.08-cm (2-inch)-diameter ball valve used to set the flow meter Mach number. The air was supplied to the turbine through two 1.9-cm (0.75-inch)-diameter steel braided flexible lines.

Ejector Air Supply. - Air was supplied to the ejector using compressed air from the storage tanks. This air was regulated using a 5.08-cm (2-inch)-diameter diaphram valve and a servo controller.

Air Supply for Bellmouth Calibration. - The air supply line used for the bellmouth calibration consisted of a 25.4-cm (10-inch)-diameter pipe connecting the storage tanks to a diaphram control valve. Immediately downstream of this valve the pipe diameter was reduced to 15.2 cm (6 inches). A 5.49-cm (2.16-inch)-diameter ASME flow meter was installed in this smaller pipe in accordance with the ASME Power Test Code, Part 5. This flow meter had previously been calibrated using the exit traverse method. A perforated sleeve was installed downstream of the flow meter to set the flow meter Mach number within ±0.05 of its calibration Mach number. From the perforated sleeve, the air discharged into a 61-cm (24-inch)-diameter duct.

Bellmouth Calibration Fixture

The bellmouth inlet was calibrated using the setup shown in Figure 2. This fixture basically consisted of a 61-cm (24-inch)-diameter by 5.6 meter (220-inch) long duct assembly that provided low velocity (8 m/s) metered air to the bellmouth. A fine mesh screen was installed between the perforated sleeve and bellmouth to establish uniform flow. Because of the large duct-bellmouth throat area ratio (19), the duct static pressure was assumed to equal the bellmouth inlet stagnation pressure. The bellmouth inlet contour was the quadrant of an ellipse and had a contraction ratio equal to ten. A dummy fan section was mounted at the bellmouth exit to simulate fan interference on the bellmouth static pressure measurements. This section simulated the fan passage to the fan rotor exit station. The hub diameter thereafter was reduced to avoid choking within the required test range of flow rates.

Thrust Balance

During the first test phase, the lift fan was mounted to an existing five-component strain-gaged balance (Convair C-4.8-5) shown in Figures 3 and 4. The balance was wired so that thrust was directly proportional to the signal output. The other four components — normal force, normal moment, thrust moment, and rolling moment — were calibrated and recorded to allow computing a resultant thrust force if the fan thrust axis were not aligned with the balance thrust axis. Axis alignment was verified by the test data. Static loads were applied to the balance using the fan as a calibration fixture from zero to 667 newtons (0 to 150 lbf). Calibrations were conducted with the turbine supply hose pressure at ambient and 27 atmospheres. Also, all instrumentations leads were installed. Thus, the deadweight calibration results reflect the interference caused by bridging the metric and non-metric elements of the test setup. The turbine supply hoses were aligned to eliminate the pressure-area effect on thrust. The calibration results were a function of turbine supply line stiffness, which was related to line pressure. A small correction was applied to the thrust measurements based on this effect (see Appendix B).

Back Pressure Control System

For the fan performance map test phase, the lift fan was mounted to an assembly consisting of an adapter section and an existing electro-hydraulic inlet control system, shown in Figures 5 and 6. This inlet control system incorporated a remotely actuated plug used to adjust the duct exit static pressure to ambient pressure ratio. An annular ejector system was used to reduce the back pressure below ambient pressure.

Model Description

The lift fan model tested was 13.97-cm (5.5-inch)-diameter tip-turbine-driven fan (Tech Development Model TD-457). The fan was rated at 3749 rad/s (35,800 rpm) with overspeed capability of 110 percent of rated speed. The fan total pressure ratio at design speed was 1.25 with a corrected fan weight flow of 2.52 kg/s (5.55 lbm/sec). Fan thrust capability was about 667 newtons (150 lbf). Maximum turbine drive air flow was rated at 0.5 kg/s (1.1 lbm/sec) supplied by two diametrically-opposed lines.

The fan was supplied by NASA-LeRC with installed instrumentation and modifications identical to those used in their wind tunnel studies. The inlet of Tech Development Model TD-457 fan was modified, and a duct extension was added to the fan.

A sketch showing the basic model configurations and dimensions is presented in Figure 7. The two inlet configurations consisted of a bellmouth and a 50.8-cm (20-inch)-diameter thin plate mounted normal to the fan axis at the fan inlet plane. A similar flat plate was mounted at the fan nozzle exit plane. Together, these two plates were intended to simulate the inlet and exit environments of a fan-in-wing configuration being tested concurrently in the LeRC wind tunnel.

Two exhaust nozzle types were tested. One of these consisted of a straight cylindrical shroud and flat base hub. The second type consisted of a convergent shroud and concave base hub. These two configurations were designated standard nozzle and low base drag nozzle, respectively.

Instrumentation

Flow-meter instrumentation for the air supply lines measured upstream static pressure ($P_{u,\ fm}$), throat differential pressure (Δp_{fm}), and stagnation temperature (T_{fm}). Stagnation temperature was determined by means of an iron-constantan thermocouple.

The bellmouth instrumentation (Figures 2 and 7) included one ring of four manifolded static pressure orifices (P_{B2}) located at the bellmouth throat. A second ring of four manifolded static pressure orifices (P_{B1}) was located 5.1 cm (2 inches) upstream of the bellmouth throat to determine the effect of the dummy fan on the throat static pressure measurements. A ring of four manifolded static pressure orifices ($\bar{P}_D$), located 30.5 cm (12 inches) upstream of the bellmouth inlet, measured the bellmouth inlet stagnation pressure. Bellmouth total temperature (T_D) was measured in the duct downstream of the perforated sleeve using a chromel-alumel thermocouple. A five-probe total pressure rake was used to measure the pressure distribution at the bellmouth inlet plane prior to the installation of the bellmouth in the duct.

Fan assembly instrumentation is shown in Figure 7. Fan exit total pressure ($\bar{P}_R$) was measured by four uniformly spaced total pressure rakes, each consisting of five manifolded probes. The probes were so distributed that each was at the center of an equal area. Four manifolded static pressure orifices on the fan shroud ($\bar{p}_{s2}$), and four manifolded static pressure orifices on the fan hub ($\bar{p}_{h2}$), were used to determine the duct exit static pressure ($\bar{p}_3$). The low base drag nozzle had an additional set of shroud ($\bar{p}_{s1}$) and hub ($\bar{p}_{h1}$) manifolded static pressure orifices located approximately at the duct rake station. Base pressure (p_b) was measured at the center of the hub.

A calibrated three-tube yaw probe mounted in the center of the duct was used to measure exit swirl angle (β).

All pressures were measured using strain-gage pressure transducers. The transducers were calibrated against a dead weight tester. The results of the calibration were fitted with polynomial curves using the method of least squares. A separate transducer was used for each pressure orifice. Absolute transducers were used for all pressure measurements except the flow meter, bellmouth throat static, and yaw probe pressures. Differential transducers were used for these measurements. The transducers and calibration ranges were selected based on the expected test ranges for each measurement. The transducers were connected to the orifices with approximately one meter of 0.12 cm (0.049 inch)outside diameter steel and plastic tubing.

Two fan bearing temperatures (T_b), two turbine inlet temperatures (T_i), and two exit temperatures (T_e) were determined by iron-constantan thermocouples. All thermocouples were referenced to melting ice.

Ambient pressure (P_o) and temperature (T_o) were also measured.

An electromagnetic tachometer provided two pulses per fan revolution. The output of the fan was converted to a dc voltage proportional to speed.

Data Acquisition and Monitoring System

A block diagram of the data acquisition and monitoring system is shown in Figure 8. Electrical signals from the pressure transducers, balance, thermocouples, and tachometer were processed by the GDHSWT data acquisition and digital computer systems for on-site data reduction.

The analog signals were converted into digital form and time-domain multiplexed at a rate of 25,000 channels per second. The data system resolution and linearity was ±0.01 percent of ±5 volts, full range.

Each signal was pre-conditioned using separate high quality low-level dc amplifiers. The amplifiers were of differential type with high stability and common mode rejection. Insertion voltage calibrations provided accuracies to ±0.03 percent of full range.

The test data were digitized and transferred to the disk of an on-line computer system. Computed final data were available within 15 minutes after a run. Tabulated and plotted data formats were used.

Fan corrected speed, turbine supply pressure and temperature, fan exit static pressure ratio, and fan bearing temperatures were recorded by the GDHSWT analog computer. The analog computer converted these signals to English units on-line and displayed them on a strip chart. Fan corrected speed was also displayed digitally.

Safety interlocks were also built into the analog computer program logic to limit fan speed to 4189 rad/s (40,000 rpm) and bearing temperature to 436°K (325°F). At these limits the analog computer triggered a solenoid valve that dumped the dome loading air of the turbine air supply regulator.

Precision of Measurements

The estimated precision of the test measurements is included in the following table. These estimates are determined from a statistical analysis of instrumentation calibration results only and are based on a 95 percent confidence level.

Model pressures	=	±206.8 N/m^2	(±0.03 psi)
Fan weight flow	=	±0.011 kg/s	(±0.025 lbm/sec)
Turbine weight flow	=	±0.0034 kg/s	(±0.0075 lbm/sec)
Thrust	=	±0.89 N	(±0.2 lbf)
Swirl angle	=	±0.007 rad	(±0.4 degree)
Temperature	=	±1.11° K	(±2° R)
Fan speed	=	±754 rad/s	(±120 rpm)

PROCEDURE

Bellmouth Calibration Procedure

One run was made with the five-probe duct rake to verify the flow uniformity at the bellmouth inlet plane. This rake was removed before installing the bellmouth. The bellmouth was calibrated through a weight flow range of 1.1 kg/s (2.5 lbm/sec) to 2.9 kg/s (6.5 lbm/sec) by adjusting the supply pressure upstream of the flow meter. Runs were conducted with and without the dummy fan section.

Fan Calibration Procedure

The following six model configurations were tested:

Model 1	Bellmouth inlet + standard nozzle
Model 2	Bellmouth inlet + standard nozzle + flat plate exit
Model 3	Bellmouth inlet + standard nozzle + flat plate exit + swirl angle probe
Model 4	Flat plate inlet + standard nozzle + flat plate exit
Model 5	Flat plate inlet + standard nozzle + flat plate exit + swirl angle probe
Model 6	Flat plate inlet + low base drag nozzle + flat plate exit

Thrust, temperature, and pressure measurements were recorded on each of the six model configurations at 60, 70, 80, 90, 95, 100, 105, and 110 percent design fan speed. Repeat points were taken at 95, 100, and 105 percent. Occasionally, the safety interlock system stopped the fan and invalidated a run. Three data points were recorded at each condition when the fan speed had stabilized. Also, fan speed was maintained at most levels for several minutes to allow the rotor shroud icing to stabilize before recording the data. This delay was based on the bearing temperature level and rise rate; e.g., at 110 percent the bearing temperature level coupled with the rapid temperature rise required the data to be taken within a few seconds of stabilizing the fan speed. Turbine inlet temperature was maintained at 304 ± 3°K (85 ± 5°F).

Fan Map Procedures

Using the bellmouth inlet and standard nozzle, a fan map was obtained. The fan was operated at values of percent design corrected speed of 70, 80, 90, 100, and 110; and duct exit static pressure ratios of 0.90, 0.93, 0.95, 0.98, 1.0, 1.03, 1.05, 1.08, 1.10, and 1.13. Runs were conducted by maintaining a constant fan speed as the exit static pressure ratio was varied from 0.90 to 1.13.

Minimum back pressure was obtained with the ejector set for maximum pumping. The fan back pressure was increased by reducing the ejector supply pressure until the exit static pressure ratio was approximately 1.0. At this condition the ejector was turned off. The exhaust duct opening was reduced by the throttle to reach exit static pressure ratios above 1.0.

Data were recorded based on the same procedure used for the fan calibration test phase.

DATA REDUCTION

All of the test data were computed on-line using the GDHSWT data acquisition system. The on-line print-out consisted of all primary measurements in both English units and SI units. Various thrust, pressure, and flow coefficients were computed using the procedure given in Appendix B. Selected data were computer plotted as a function of percent design corrected speed. A complete set of tabulated data have been forwarded to the NASA-LeRC Project Manager.

RESULTS AND DISCUSSION

Bellmouth Calibration

The results of the bellmouth calibration are shown in Figure 9. This is a plot of discharge coefficients, $C_{D_{B1}}$ and $C_{D_{B2}}$, as a function of Reynolds number. Figure 9 shows that the dummy fan section affects the bellmouth static pressure and that the discharge coefficients are nearly independent of Reynolds number. All of the fan weight flow calculations, W_f, were based on the upstream bellmouth static pressure since it is less sensitive to disturbances at the throat. It was also assumed that the discharge coefficient determined with the dummy fan section installed best represented the actual test conditions.

Fan Calibration

The results of the fan calibration tests are summarized in Figures 10 through 22. These curves are fairings of the test data. Each parameter is shown as a function of percent design corrected speed, $\% N/\sqrt{\theta}$.

Figure 10 is a plot of the fan total pressure ratio $\overline{P}_R/P_o$. These data show that inlet and exit modifications, using the standard nozzle, had only minor effects on the fan operating characteristics. At 100 percent design-corrected speed, the maximum pressure ratio was 1.21 using the bellmouth inlet and standard nozzle configuration. The design-speed pressure ratio obtained using the low base drag nozzle was 1.18.

The effects of inlet and exit geometry modifications on fan performance are also shown by the thrust measurements summarized in Figure 11. At 100 percent design corrected speed, the fan developed a corrected thrust equal to 505 newtons (112.5 lbf).

The variation of exit swirl angle is shown in Figure 12. Since the maximum value is only -0.03 radian (-1.7 degrees) and $\cos 1.7 = 0.999$, the exit swirl angle need not be included in performance calculations.

The variation of total corrected weight flow is shown in Figures 13 and 14. For Figure 13, the weight flow calculations were based on the bellmouth and turbine flow rates. The data shown in Figure 14 are for fan configurations without the bellmouth inlet. For these configurations, the total weight flow calculations were based on fan duct instrumentation assuming ideal flow (see Appendix B). These calculations may be adjusted using the data given in Figure 15. This figure is a plot of the variation of average duct discharge coefficient ($C_{D_D} = W_3/W_D$) obtained by calibrating the duct instrumentation against the bellmouth weight flow measurements.

The variation of the fan duct and hub static pressures is shown in Figures 16 through 19. Of particular interest are the hub static pressure measurements for the low base drag nozzle shown in Figure 19. The characteristic of this nozzle is to turn the flow radially inward toward the centerline. The reactive force of redirecting the flow axially is balanced by the hub base pressure. This effect is clearly shown in comparing low base drag nozzle hub pressure with the standard nozzle hub pressure shown in Figure 18. Also, a study of Figure 19 shows an apparent longitudinal pressure gradient in the fan duct. However, the differences between the upstream and exit static pressures reflect the reduction in the three-dimensional flow path area at the low base drag nozzle exit.

The turbine air flow requirements are shown in Figure 20. A maximum turbine-corrected weight flow of 0.54 kg/s was required to drive the fan at 100 percent design corrected speed.

The temperature drop across the turbine is shown in Figure 21. This figure illustrates one problem in operating the fan: the temperature drop varies between 44 and 105° K. By operating the fan at a turbine supply temperature of 304° K, the range of turbine exhaust temperature is 260 to 199° K. This low temperature will cause ice to form on the shroud, thus modifying the shroud contour. It is therefore important to maintain a constant speed for a sufficient length of time to ensure that the icing condition has stabilized (see Procedure).

Any direct comparison between the standard and low base drag nozzles must be qualified. The fan was designed to operate at an ambient exit back pressure. The three-dimensional flow path area at the exit of the low base drag nozzle was less than the fan duct area. This restriction at the nozzle exit raised the effective exit static pressure above ambient (see Figure 19) thereby decreasing fan weight flow. Because of the fan sensitivity to operating off design, there is a deterioration of fan performance as indicated by the thrust measurements shown in Figure 11.

Fan Map

The fan discharge performance map using the bellmouth inlet and standard nozzle is shown in Figure 22. This figure is a plot of fan total pressure ratio ($\overline{P}_R/P_0$) as a function of corrected fan total weight flow ($W_3\sqrt{\theta}/\delta$) at constant percent fan corrected speed ($\%N/\sqrt{\theta}$). The total weight flow is the sum of the fan inlet and turbine flow rates. The duct total pressure rakes provide an area-averaged total pressure measurement that is a function of both fan and turbine discharge pressures.

APPENDIX A

SYMBOLS

A	cross sectional area, meter^2
C_D	discharge coefficient
F	thrust force, newtons
g	gravitational constant
M	Mach number
N	fan speed, radians/second
Δp	differential pressure, newtons/meter^2
p	static pressure, newtons/meter^2
P	stagnation pressure, newtons/meters^2
R	gas constant
Re	Reynolds number
ΔT	temperature drop across turbine, $(T_e - T_i)$, °K
T	stagnation temperature, °K
W	weight flow, kilograms/second
β	swirl angle, radians
γ	ratio of specific heat for air = 1.4
δ	pressure correction factor, $P_o/1.013 \times 10^5$
θ	temperature correction factor, $T_o/370.5$
Overbar	average or manifold

Subscripts

b	hub base or fan bearing
B	bellmouth
D	duct
e	turbine exit

f	fan
fm	flow meter
h	hub
i	turbine inlet
R	duct rake
s	shroud
t	turbine
u	upstream
o	ambient
3	fan duct exit

APPENDIX B

DATA REDUCTION EQUATIONS

All of the model data were processed on line utilizing the General Dynamics High Speed Wind Tunnel data acquisition system. Selected data were computer plotted as a function of design corrected speed

where

$$(N/\sqrt{\theta})\ \% = (N/\sqrt{\theta}) \times (100/3749)$$

Model pressures were converted to pressure ratios p/P_o and P/P_o.

The following relations were computed to determine fan performance:

Average fan total pressure

$$\overline{P}_R = 0.25 \sum_{n=1}^{4} P_{R_n} \tag{1}$$

where n is the rake number

Average duct exit static pressure

$$\overline{p}_3 = 0.5\,(p_{h_2} + p_{s_2}) \tag{2}$$

Corrected turbine weight flow

$$W_t\sqrt{\theta}/\delta = \sqrt{\frac{\gamma g}{R}} \left\{ M \left[1 + \frac{\gamma-1}{2} M^2\right]^{1/2} (T_t)^{1/2} \quad C_D\, Ap \right\}_{fm} \left(\frac{\sqrt{\theta}}{\delta}\right) \tag{3}$$

where

$$M_{fm} = \left[5 \left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} -5 \right]_{fm}^{1/2}$$

$C_{D_{fm}}$ = 0.995 (discharge coefficient determined by calibration)

A_{fm} = 3.16×10^{-4} meter^2 (0.4902 in^2)

Corrected fan weight flow was based on the upstream bellmouth static pressure instrumentation and the correction factor, C_{DB1}. This correction factor was determined to be a linear function of the Reynolds number. It was assumed that the calibration data obtained using the dummy turbine section best represented the actual test conditions. These equations are defined as:

$$(W_f \sqrt{\theta}/\delta) = \sqrt{\frac{\gamma g}{R}} \left(\frac{\sqrt{\theta}}{\delta}\right) T_o^{-1/2} A_B \left\{ C_D\, p\, M \left[1 + \frac{\gamma-1}{2} M^2\right]^{1/2} \right\}_B \qquad (4)$$

where

$$M_B = \left[5 \left(\frac{P_o}{p}\right)^{\frac{\gamma-1}{\gamma}} -5\right]_B^{1/2}$$

$$C_{D_{B1}} = 0.9516 - 0.0138\, Re \times 10^{-6} \text{ (see Figure 9)}$$

Corrected fan duct exit weight flow was defined by the equation:

$$W_D \sqrt{\theta}/\delta = 0.25\, \bar{p}_3\, A_D \quad (\sqrt{\theta}/\delta) \sqrt{\frac{\gamma g}{RT_D}} \sum_{n=1}^{4} \left\{ M \left[1 + \frac{\gamma-1}{2} M^2\right]^{1/2} \right\}_n \qquad (5)$$

where

$$M_n = \left[5 \left(\frac{P_{R_n}}{\bar{p}_3}\right)^{\frac{\gamma-1}{\gamma}} -5\right]_n \qquad n = \text{rake number}$$

T_D = mass averaged duct temperature based on the assumption of turbine work equals fan rotor work. Four iterations were required based on the following expressions:

$W_R' = f\,(\sqrt{T_R'})$ (use eq. (5))

$\Delta T_f' = -\,(W_t\, \Delta T_t)/(W_R' - W_t)$ = temp rise due to fan work

$T_R'' = \left[(T_o + \Delta T_f')\,(W_R' - W_t) + W_t\, T_e \right] / W_R'$

$W_R'' = f\,(\sqrt{T_R''})$ = second approximation, etc. At start of iteration procedure, $T_R' = T_o$

Swirl angle, β, was defined by the relation:

$$\beta = \frac{1}{57.3} \left[0.884 + 19.77 \left(\Delta p_2 - \Delta p_1\right)/\Delta p_2 + \Delta p_1)\right], \text{ radians} \tag{6}$$

where the coefficients were obtained from a least squares fit of calibration data provided by NASA.

The indicated thrust measurement was corrected for turbine supply line interaction. This effect, always less than 0.5 lb (2.2 newtons), was determined by applying static thrust loads to the fan-thrust balance assembly at several turbine supply pressures. The correction was based on the combined effect of thrust and turbine supply line pressure as by

$$F_f = T_i + 1.256 \times 10^{-9} \left(p_{fm} \ T_i\right) \tag{7}$$

where it was assumed that the supply line pressure was best represented by the flow meter throat static pressure, p_{fm} (see Figure 1).

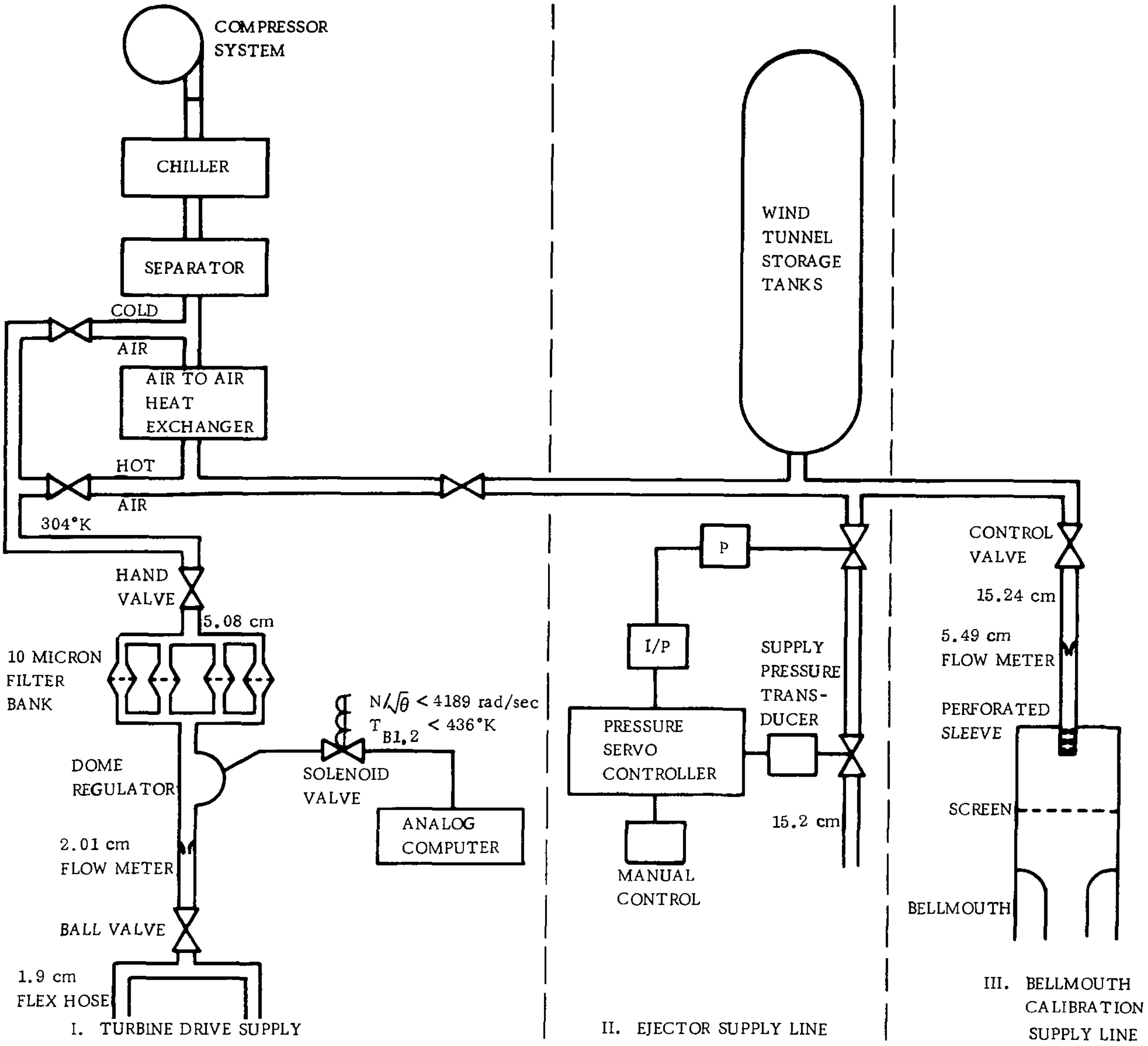
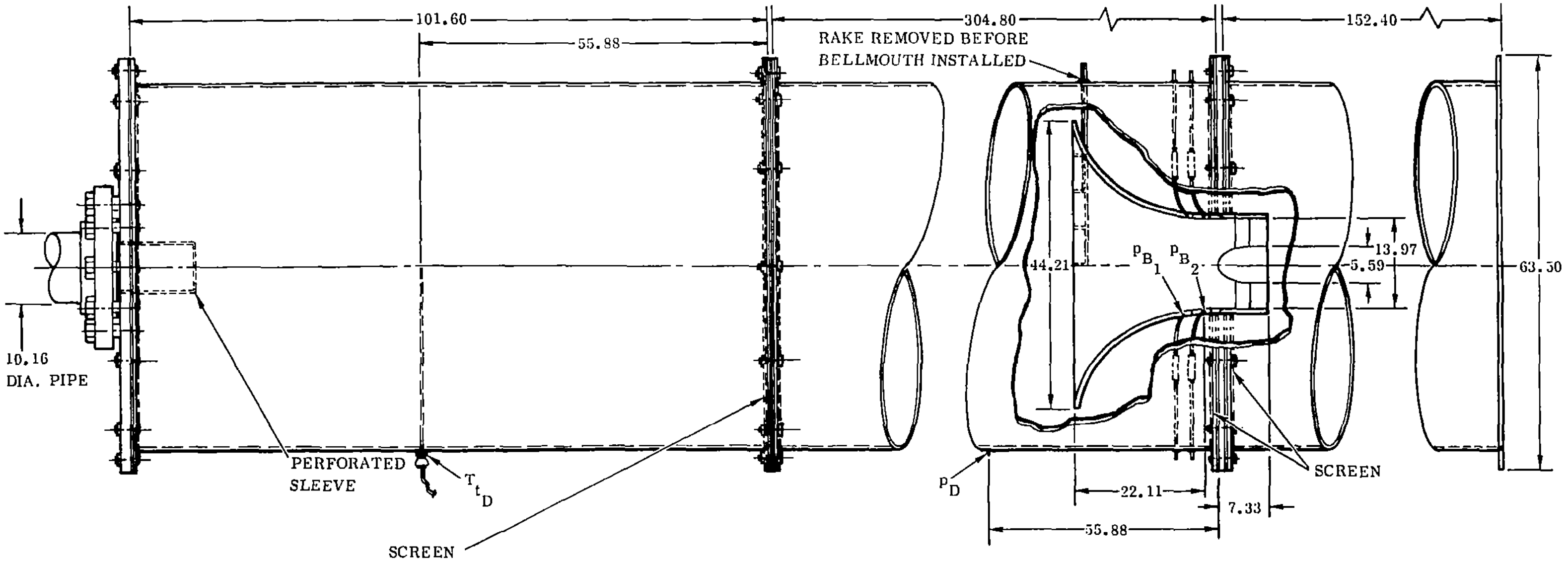


Figure 1. Schematic of General Dynamics High Speed Wind Tunnel Air Supply System.



ALL DIMENSIONS IN CENTIMETERS

Figure 2. Bellmouth Calibration Fixture.

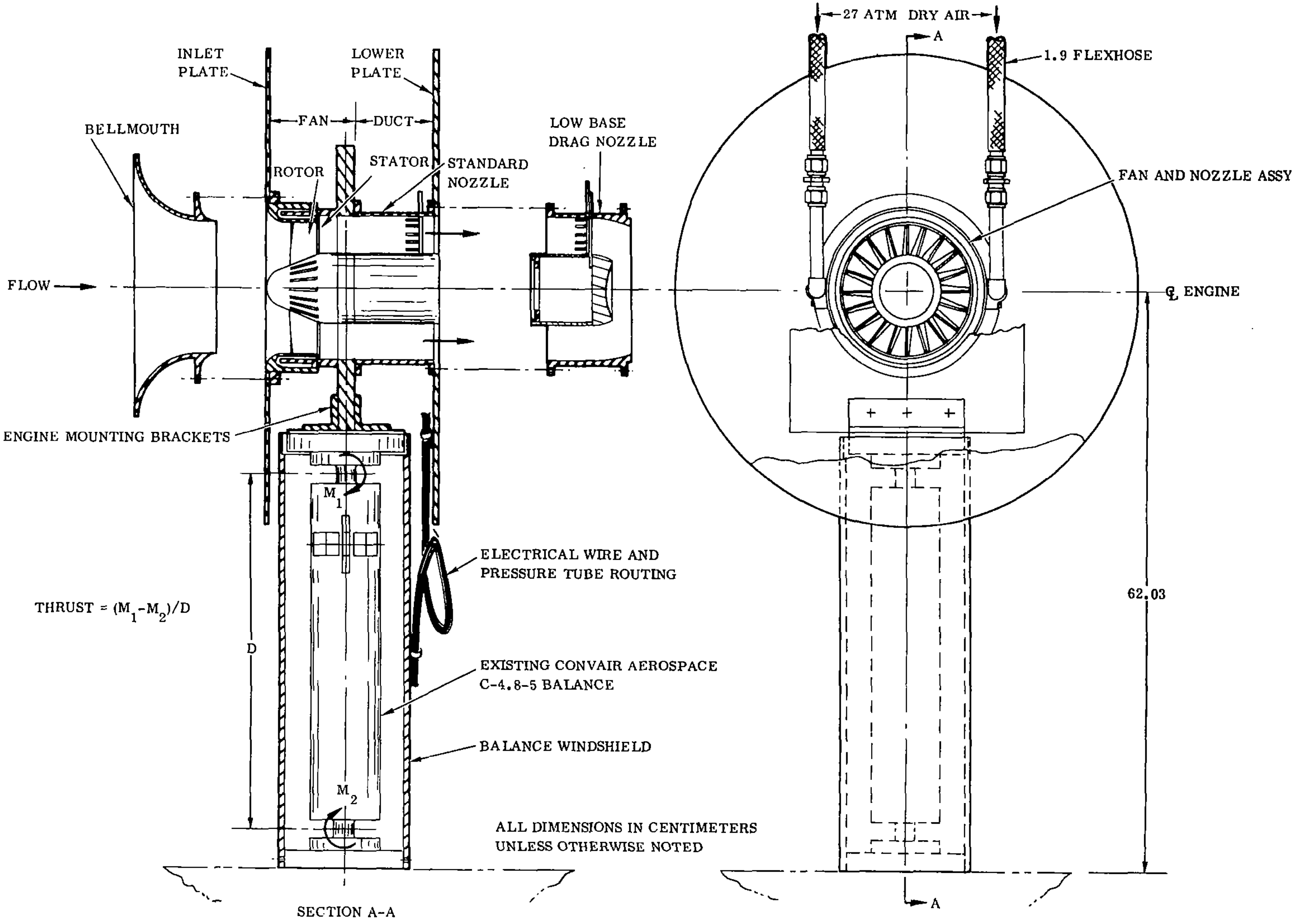


Figure 3. Fan and Thrust Balance Assembly.

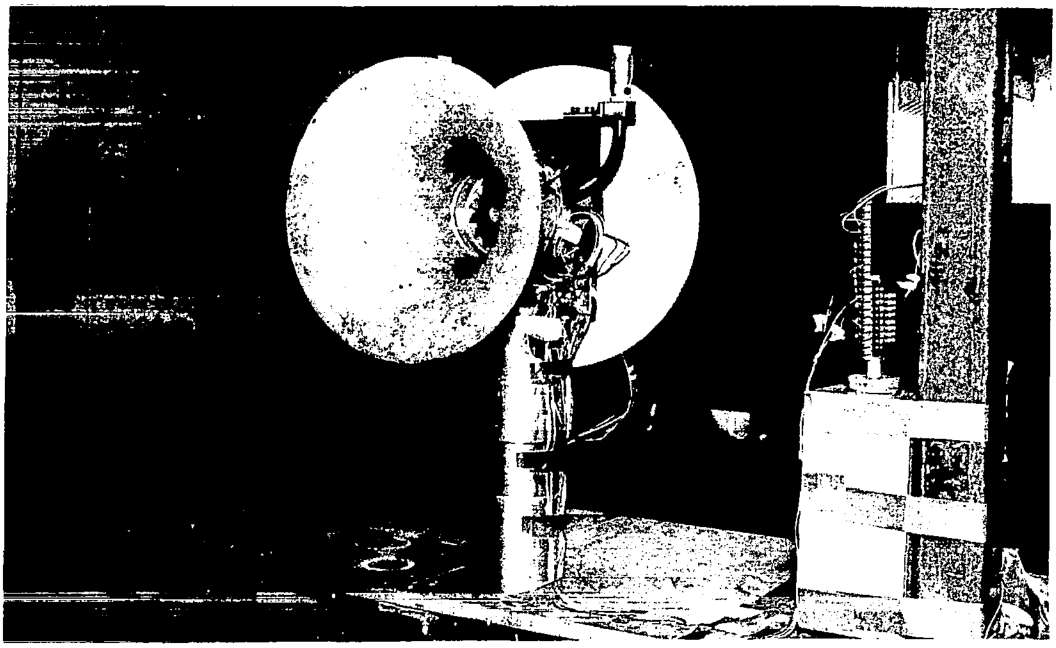


Figure 4. Fan Calibration Setup.

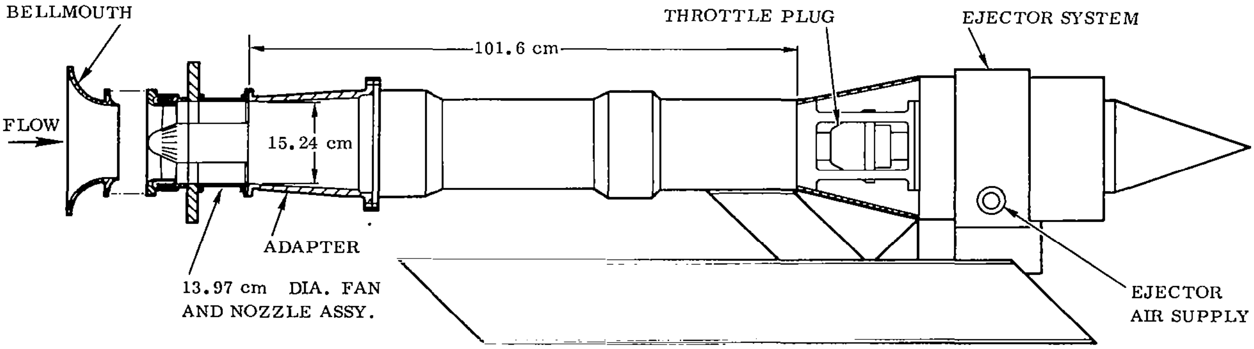


Figure 5. Fan and Back Pressure Control Assembly.

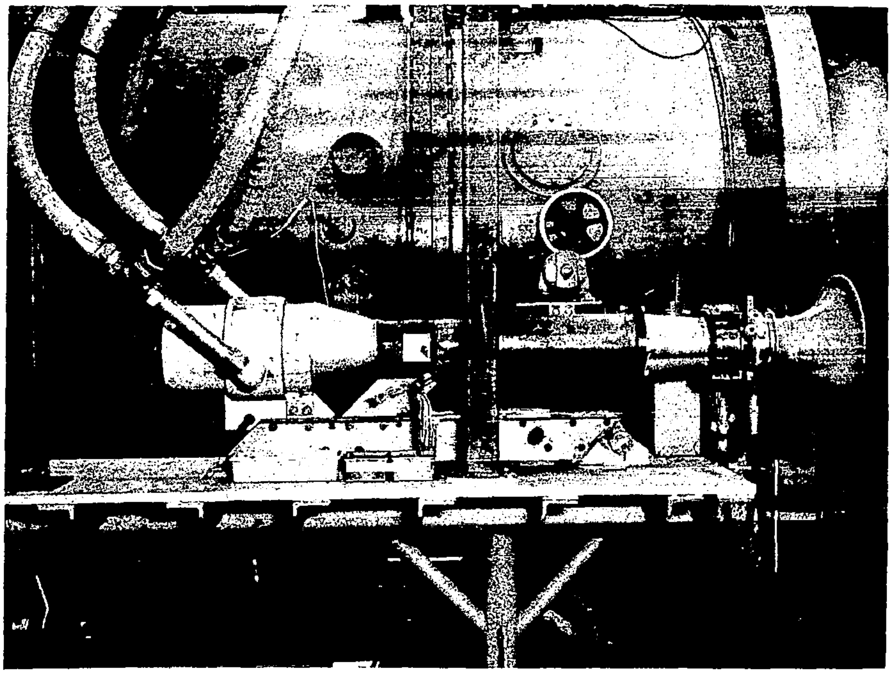
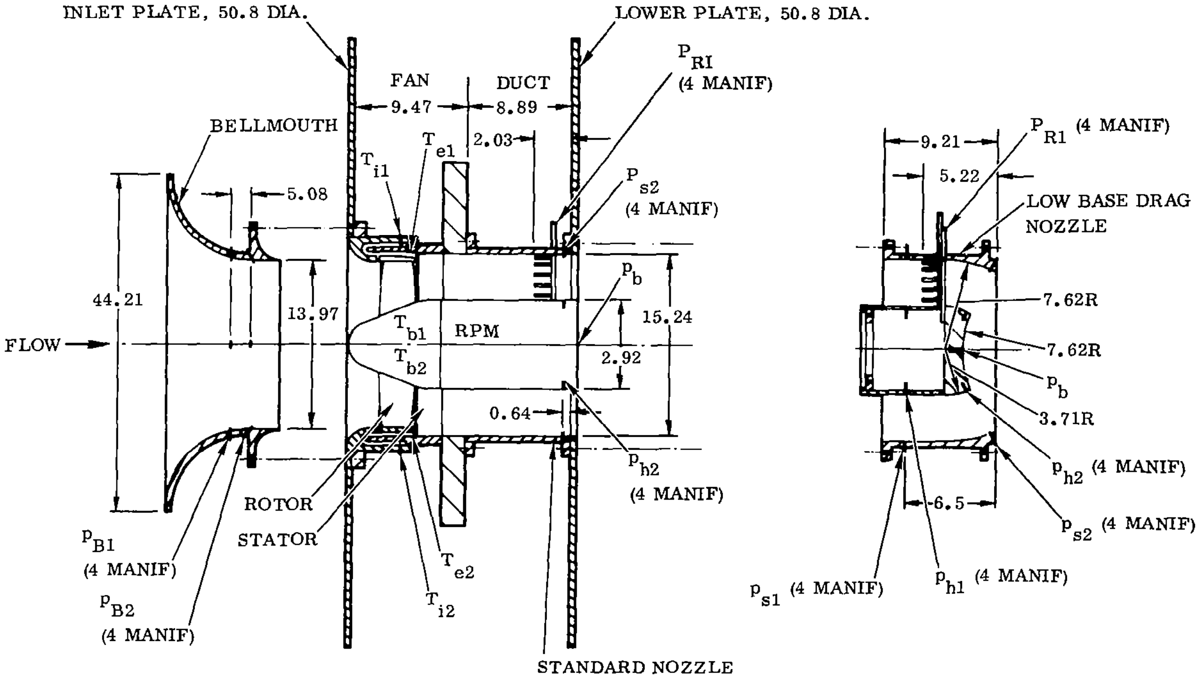


Figure 6. Test Setup Used to Obtain Fan Performance Map.



ALL DIMENSIONS IN CENTIMETERS UNLESS OTHERWISE NOTED

Figure 7. Details of Fan and Instrumentation Location.

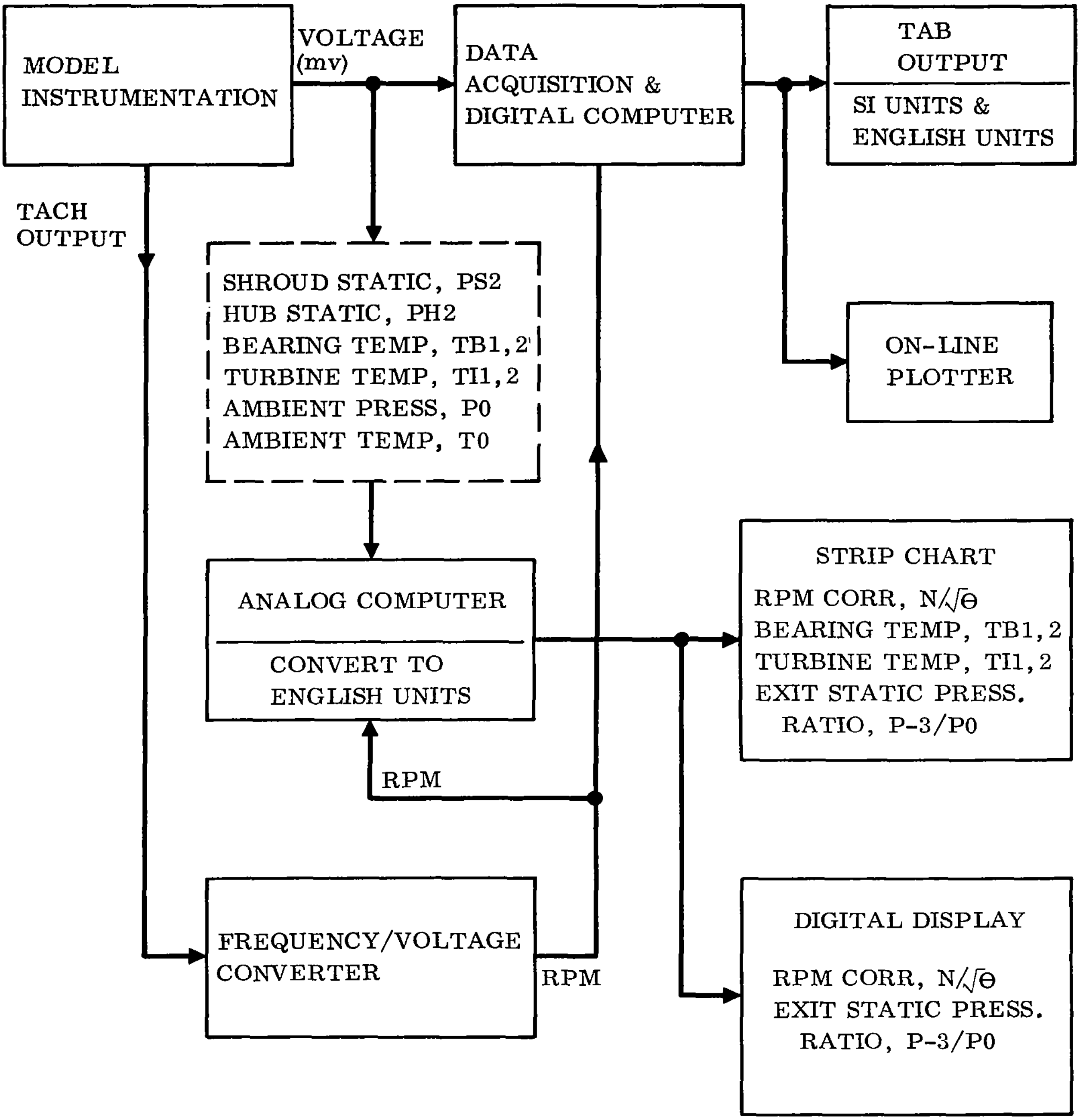
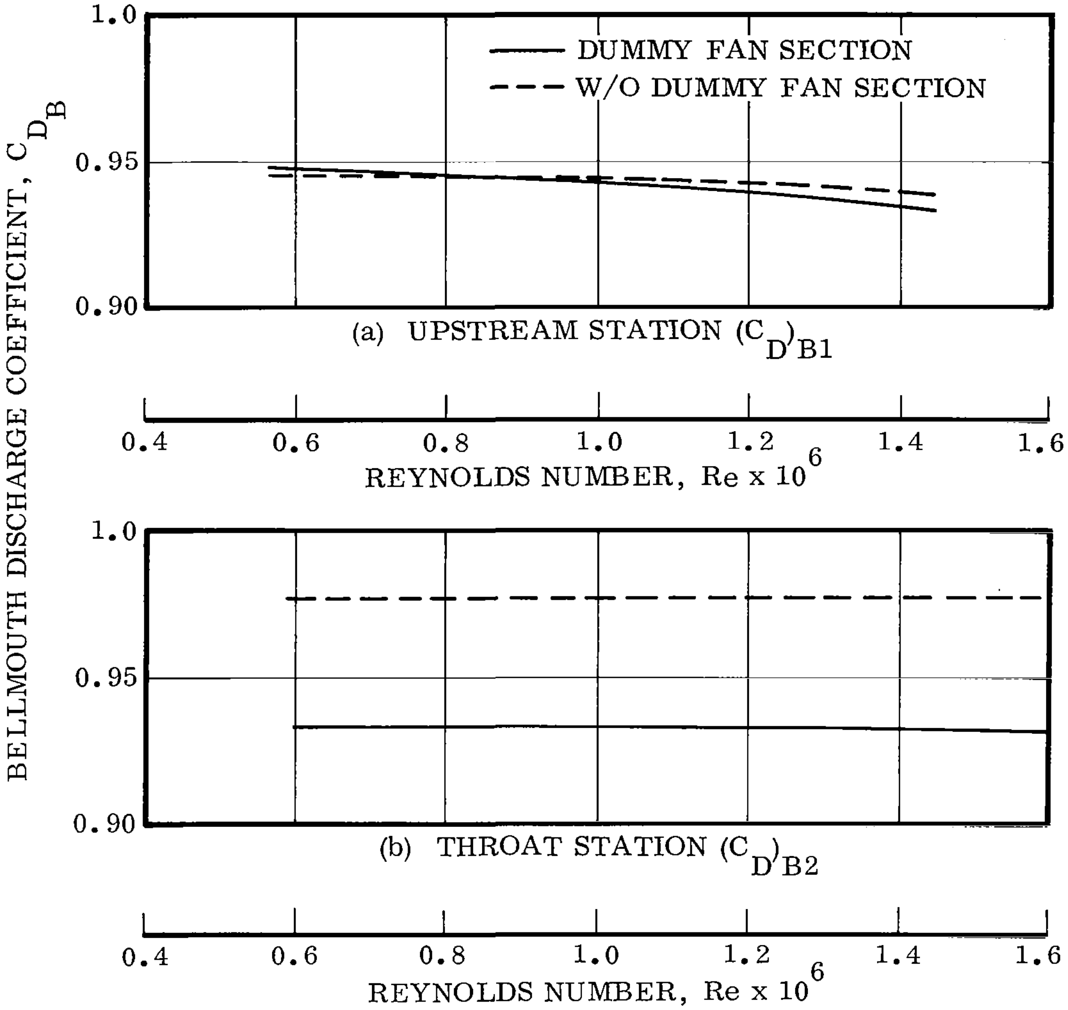


Figure 8. Data Acquisition and Instrumentation Schematic.



(a) UPSTREAM STATION $(C_D)_{B1}$

(b) THROAT STATION $(C_D)_{B2}$

Figure 9. Variation of Bellmouth Discharge Coefficient as Function of Reynolds Number.

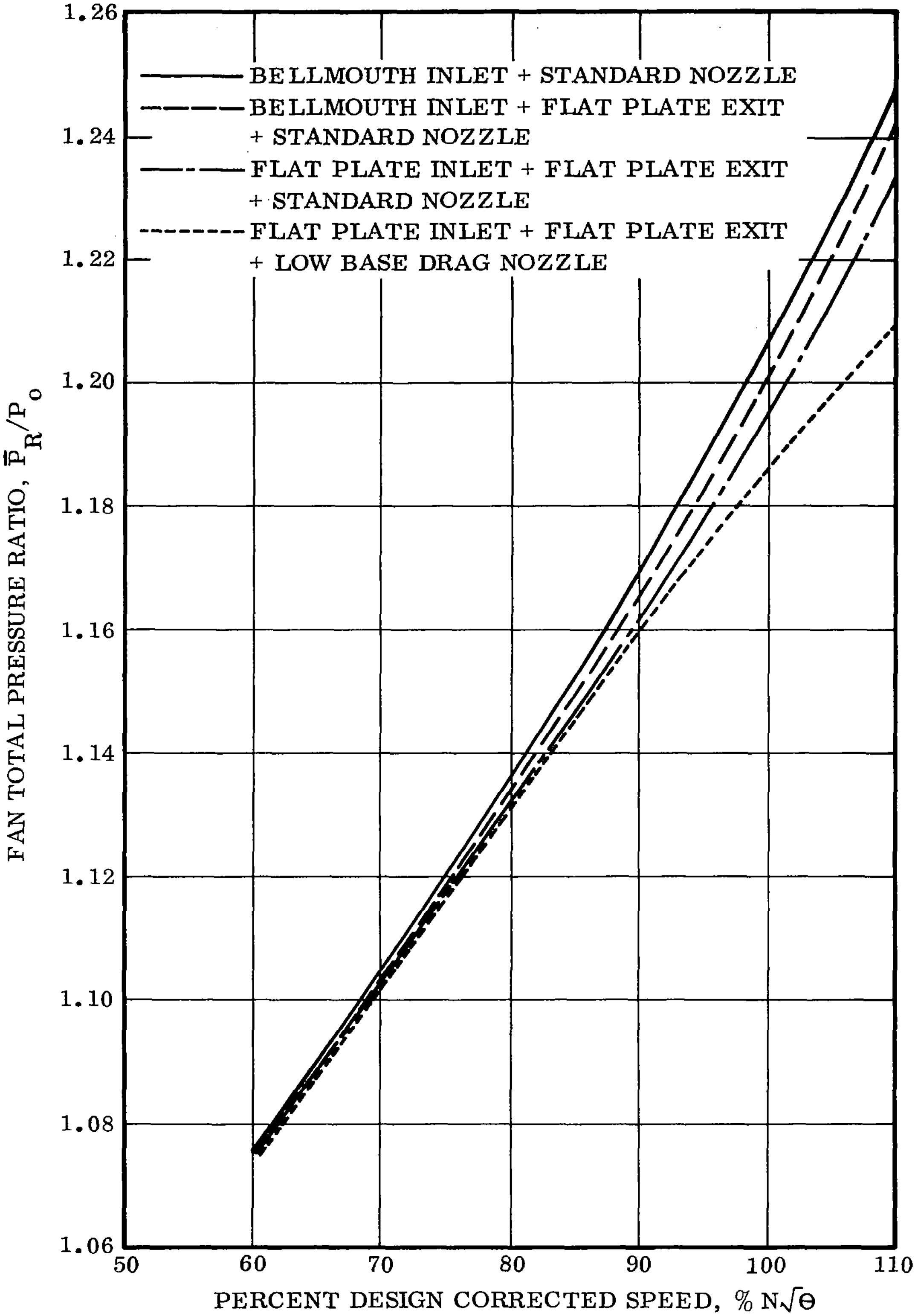


Figure 10. Fan Total Pressure Ratio Variation as Function of Percent Design Corrected Speed.

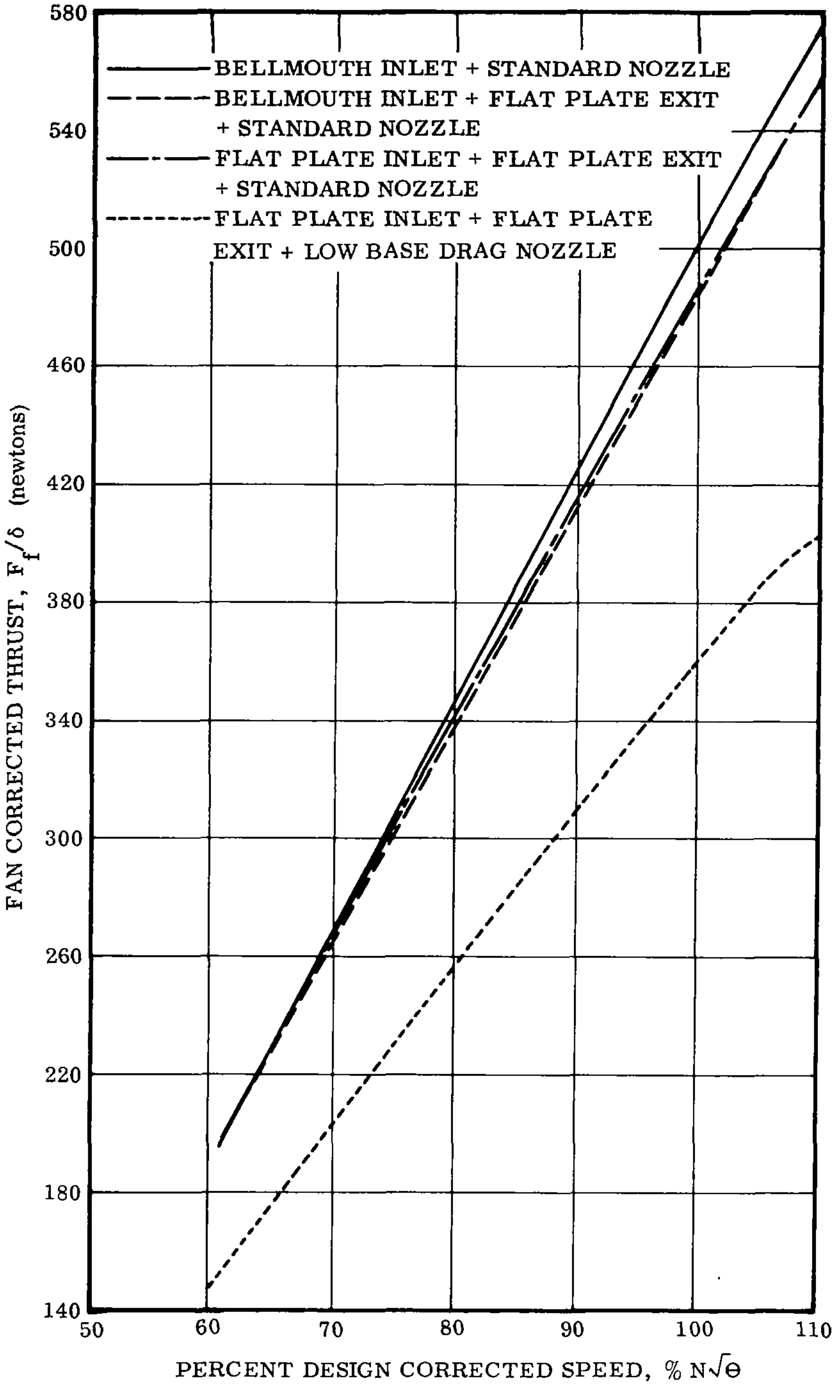


Figure 11. Fan Corrected Thrust Variation as Function of Percent Design Corrected Speed.

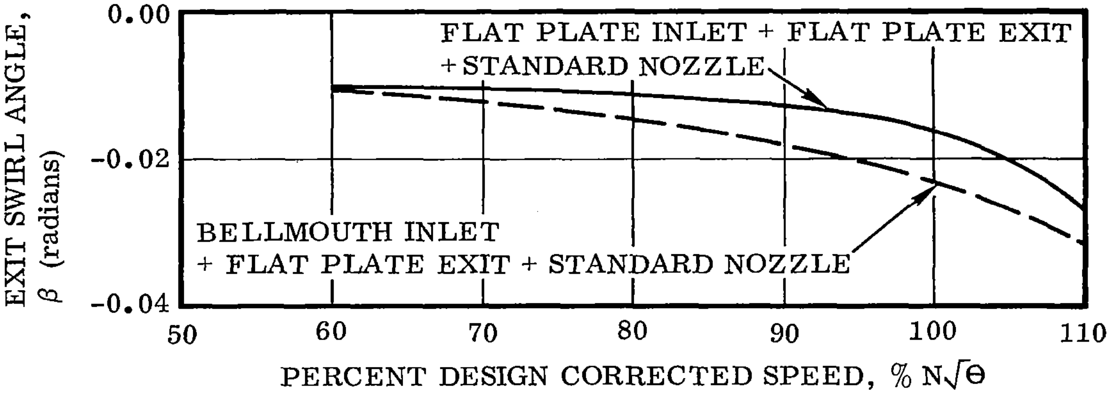


Figure 12. Exit Swirl Angle Variation as Function of Percent Design Corrected Speed.

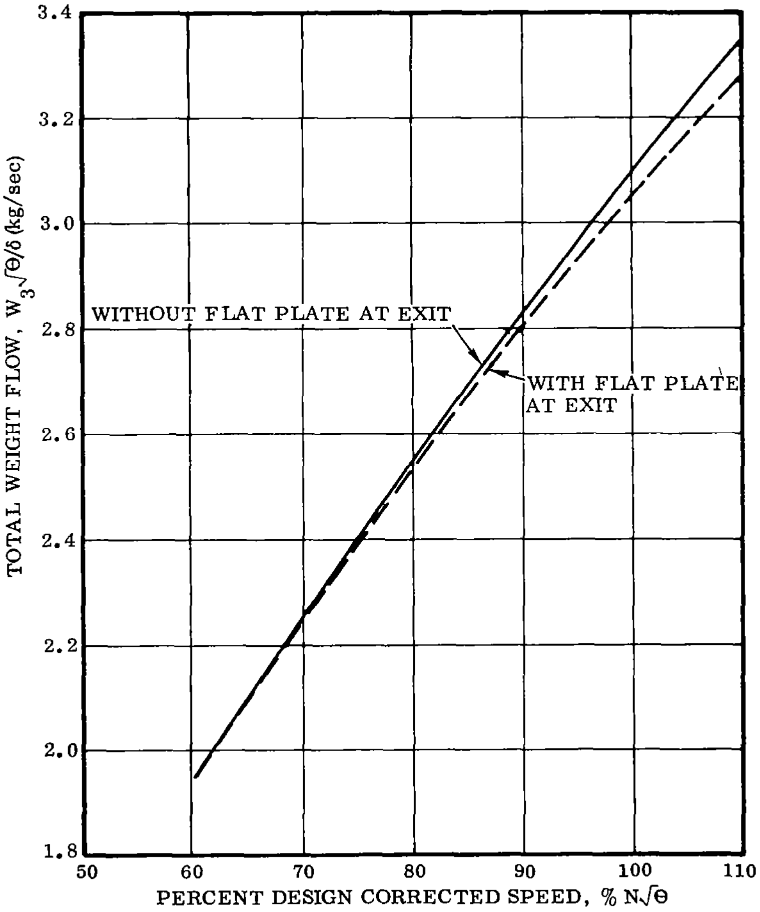


Figure 13. Total Weight Flow Variation as Function of Percent Design Corrected Speed for Fan With Bellmouth Inlet.

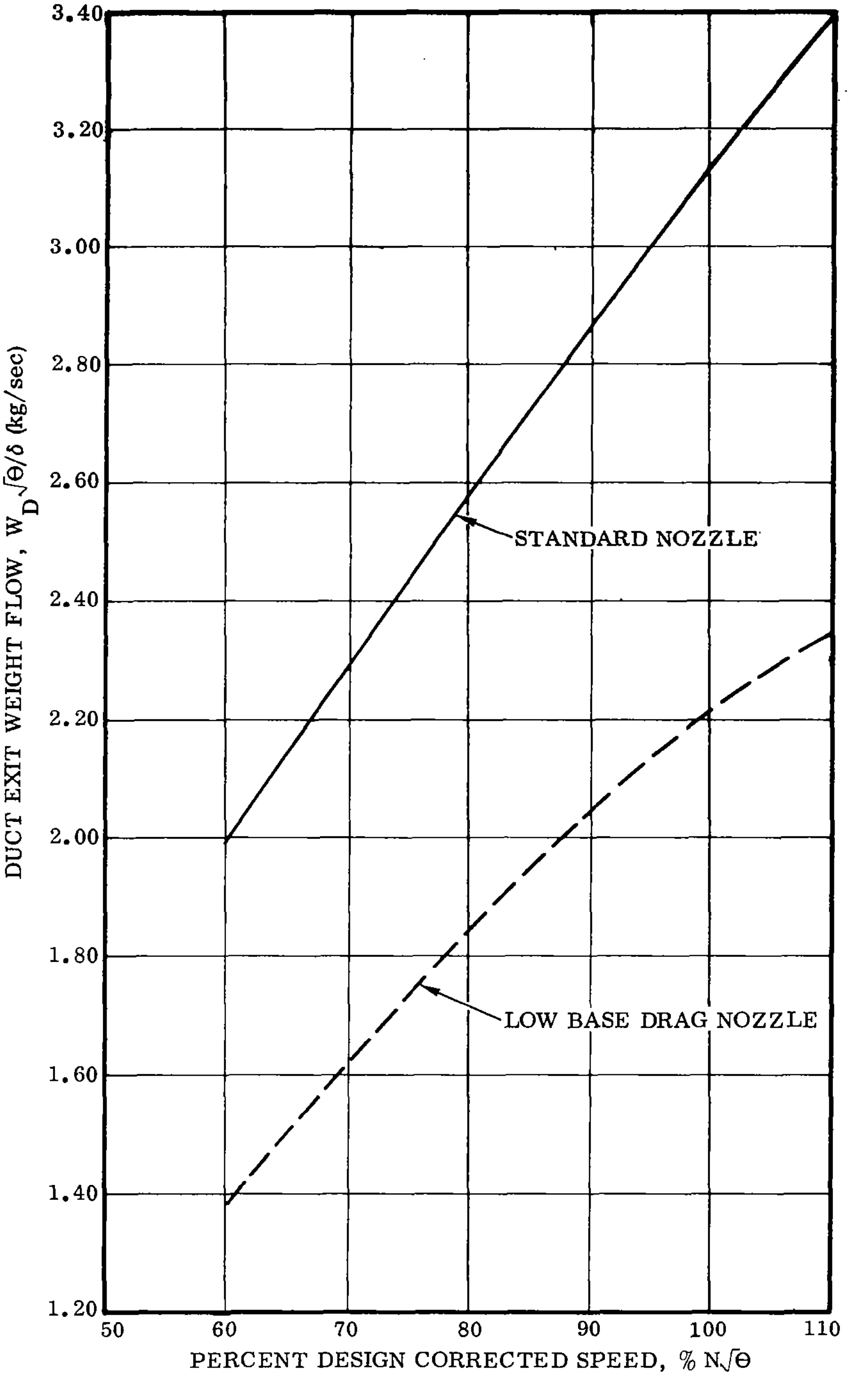


Figure 14. Calculated Duct Exit Weight Flow Variation as Function of Percent Design Corrected Speed for Fan With Flat Plate Inlet and Exit.

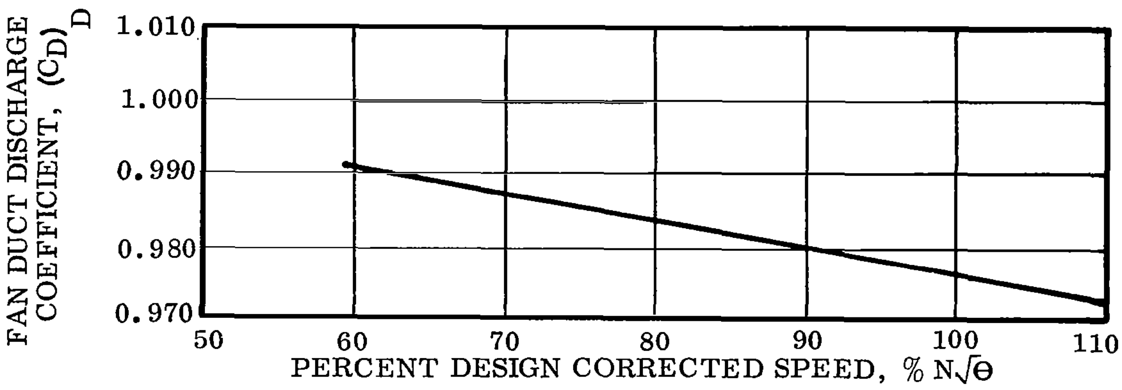


Figure 15. Average Duct Discharge Coeefficient Variation as Function of Percent Design Corrected Speed.

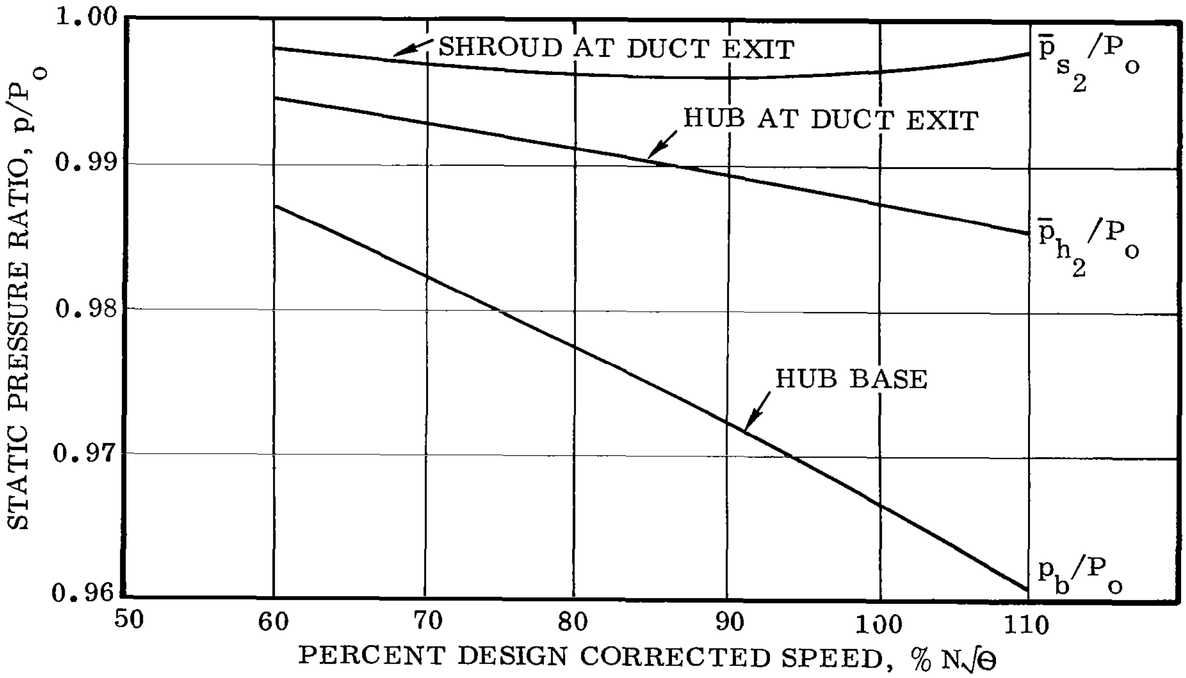


Figure 16. Static Pressure Variation as Function of Percent Design Corrected Speed for Fan With Bellmouth Inlet and Standard Nozzle.

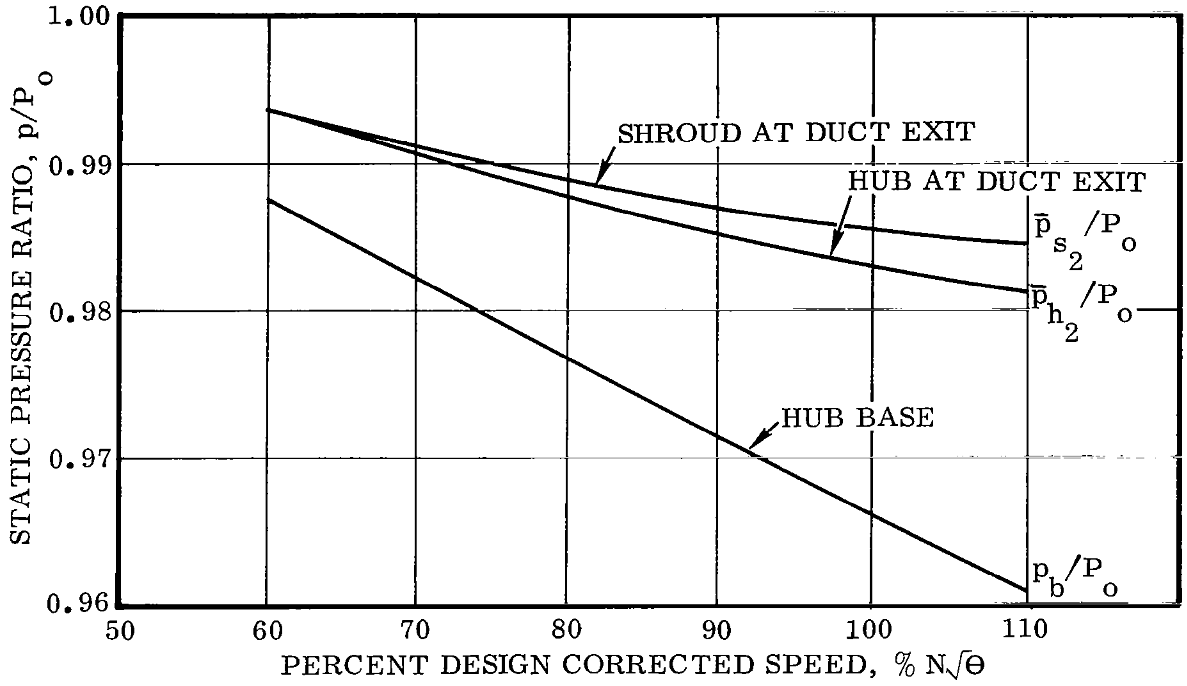


Figure 17. Static Pressure Variation as Function of Percent Design Corrected Speed for Fan With Bellmouth Inlet, Standard Nozzle and Flat Plate Exit.

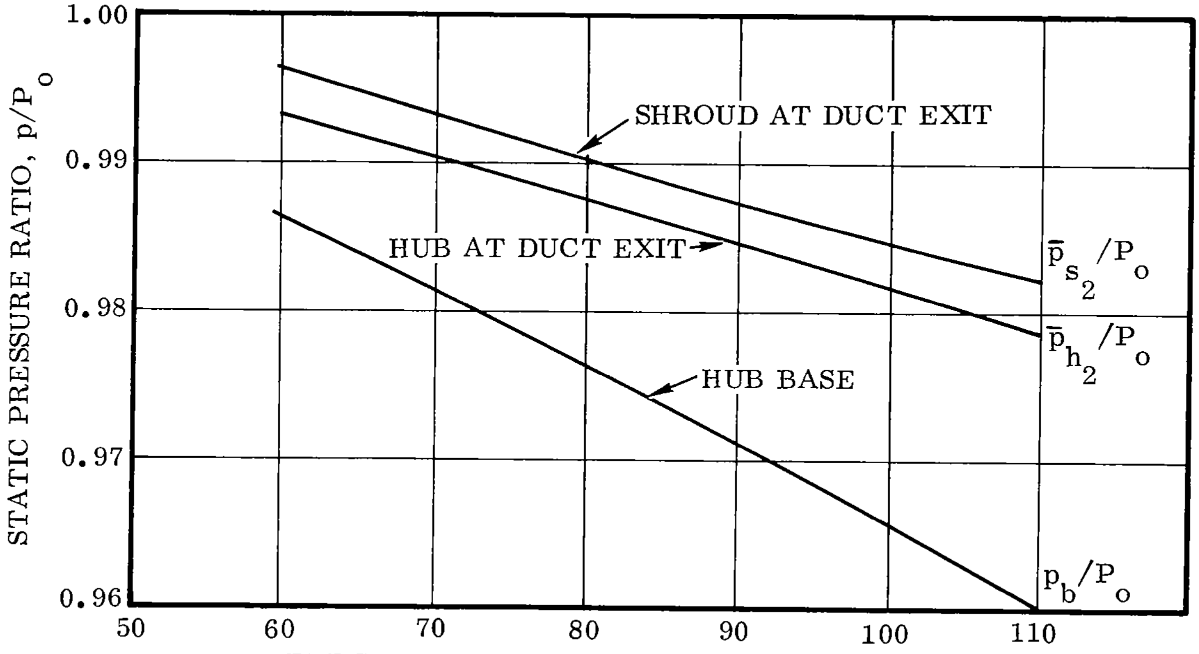


Figure 18. Static Pressure Variation as Function of Percent Design Corrected Speed for Fan With Flat Plate Inlet, Standard Nozzle and Flat Plate Exit.

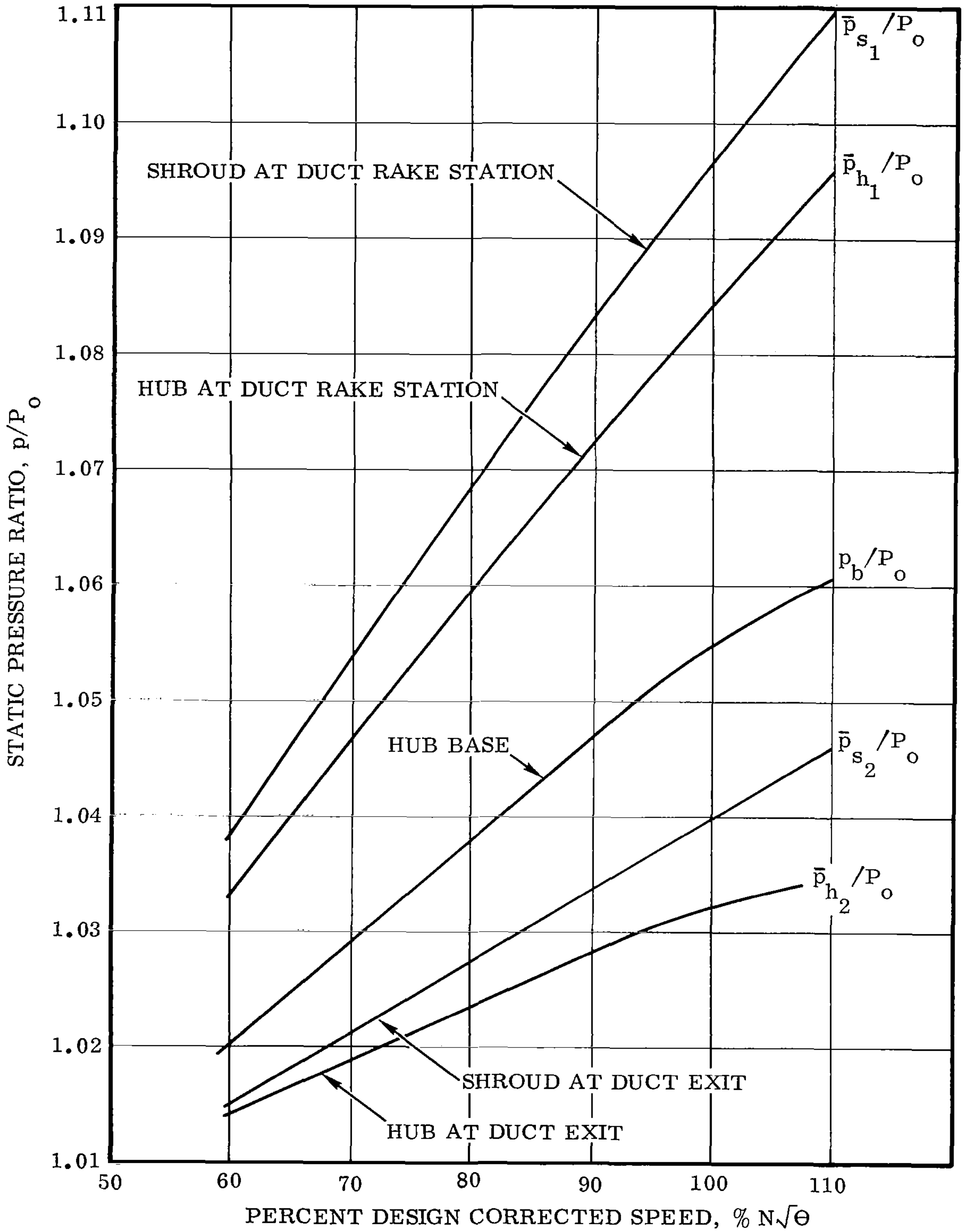


Figure 19. Static Pressure Variation as Function of Percent Design Corrected Speed for Fan With Flat Plate Inlet, Flat Plate Exit and Low Base Drag Nozzle.

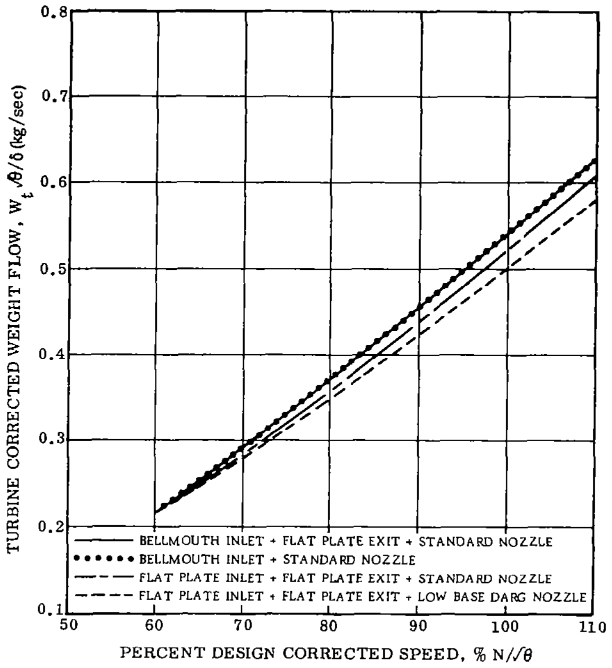


Figure 20. Turbine Corrected Weight Flow Variation as Function of Percent Design Corrected Speed.

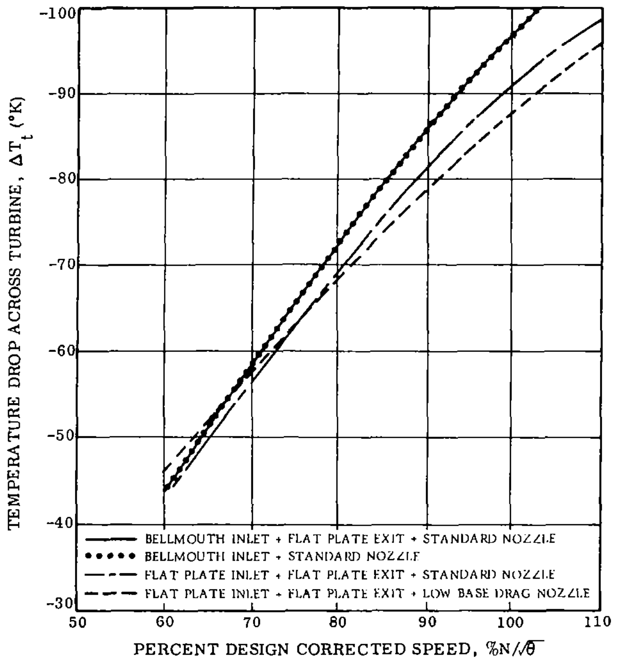


Figure 21. Temperature Drop Across Turbine Variation as Function of Percent Design Corrected Speed.

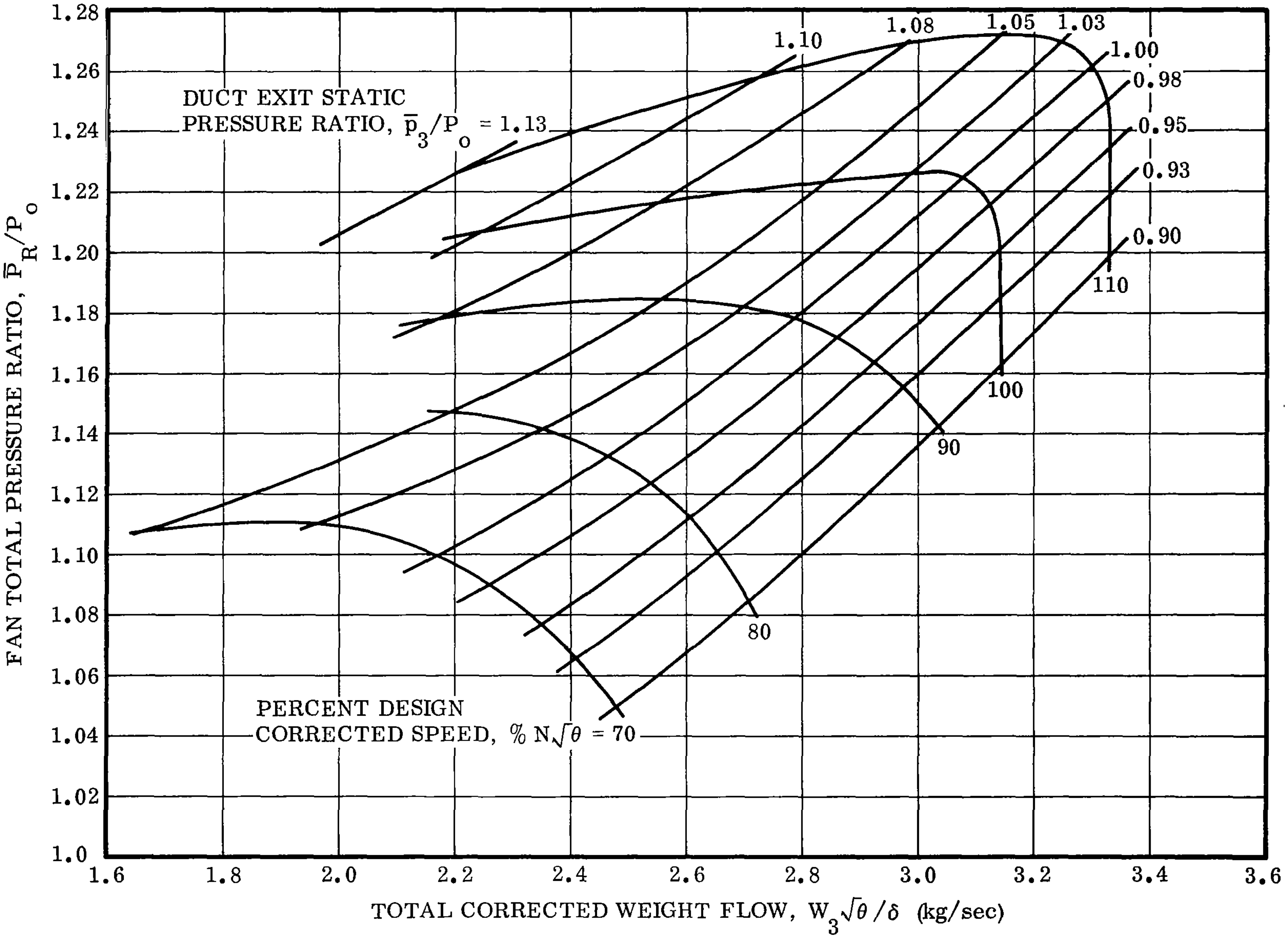


Figure 22. Fan Discharge Performance Map for Fan With Bellmouth Inlet and Standard Nozzle.

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