NASA CONTRACTOR REPORT

NASA CR-2446

NASA CR-2446

HIGHLY LOADED MULTI-STAGE FAN DRIVE TURBINE - PERFORMANCE OF FINAL THREE CONFIGURATIONS

by D. G. Cherry and M. W. Thomas

Prepared by
GENERAL ELECTRIC COMPANY
Cincinnati, Ohio 45215
for Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1974

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-2446		

4. Title and Subtitle	5. Report Date
HIGHLY LOADED MULTI-STAGE FAN DRIVE TURBINE - PERFORMANCE OF FINAL THREE CONFIGURATIONS	SEPTEMBER 1974
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
D. G. Cherry and M. W. Thomas	GE73AEG481
	10. Work Unit No.
9. Performing Organization Name and Address	
General Electric Company 1 Jimson Road Cincinnati, Ohio 45215	11. Contract or Grant No. NAS 3-14304
	13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Final Report. Project Manager, Thomas P. Moffitt, Fluid System Components Division, NASA Lewis Research Center, Cleveland, Ohio

16. Abstract

Experimental results for a three-stage highly loaded fan drive turbine follow-on test program are presented. Three additional combinations of tandem and leaned bladerows were tested to further isolate their effects on three-stage turbine performance. The three-stage turbine with a tandem stator in stage two exhibited a total-to-total efficiency of approximately 0.887 as compared to 0.886 for the plain blade turbine base case. It is expected that a redesign of the stage three stator to accept flow from the two-stage tandem build without excessive angle of attack would result in an increase of approximately one-half of 1 percent in three-stage turbine total-to-total efficiency.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Turbine; High stage loading; Fan drive turbine; Tandem blading; Leaned stator	Unclassified - unlimited Category 28

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	116	$4.50

* For sale by the National Technical Information Service, Springfield, Virginia 22151

TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	2
AERODYNAMIC EVALUATION	3
Test Vehicle	3
Requirements	3
Configurations Tested	3
Test Apparatus and Instrumentation	4
Test Facility	4
Data Acquisition System	5
Instrumentation	5
Test Procedure	6
Data Reduction Procedure	8
Overall Performance	8
Rotor Exit Survey Calculations	8
Experimental Results and Discussion	9
Test Cell Repeatability	9
Overall Performance	9
Stage Performance	11
Rotor Exit Survey	12
Recommended Improvements	12
MECHANICAL EVALUATION	14
SUMMARY OF RESULTS	15
APPENDICES	16
A OVERALL PERFORMANCE CALCULATION PROCEDURE	16
B STAGE EFFICIENCY CALCULATION PROCEDURE	20
C ANALYSIS OF INCIDENCE LOSSES	23
D LIST OF SYMBOLS	25
REFERENCES	28
TABLES	29
ILLUSTRATIONS	42

LIST OF TABLES

Table		Page
I	Reduced Test Data and Calculated Performance Parameters, Configuration 1A (PPPPPP).	29
II	Reduced Test Data and Calculated Performance Parameters, Configuration 2A (PPPPLT).	32
III	Reduced Test Data and Calculated Performance Parameters, Configuration 3A (PPTPLP).	35
IV	Reduced Test Data and Calculated Performance Parameters, Configuration 4A (PPTPPP).	38
V	Reduced Test Data and Calculated Performance Parameters, Configuration 5A (PPTP).	39
VI	Overall and Stage Performance Summary.	41

LIST OF ILLUSTRATIONS

Figure		Page
1	Turbine Design Velocity Diagrams.	42
2	Three-Stage Turbine Flowpath.	43
3	Two-Stage Turbine Flowpath.	44
4	Plain Blade Airfoils.	45
5	Stage Two Tandem Stator Assembled.	46
6	Stage Three Tangentially Leaned Stator Airfoils Viewed Aft Looking Forward.	46
7	Stage Three Rotor Plain Blade.	47
8	Stage Three Rotor Tandem Blade.	47
9	Three-Stage Turbine Plain Blade Rotor Assembled.	48
10	Typical General Electric, Evendale Air Turbine Test Facility Configuration.	49
11	Air Turbine Test Instrumentation.	50
12	Equivalent Torque Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed, Base Cases Compared.	52
13	Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed, Base Cases Compared.	53
14	Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed, Base Cases Compared.	54
15	Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).	55
16	Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).	56
17	Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).	57
18	Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 1A (PPPPPP).	58
19	Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).	59

LIST OF ILLUSTRATIONS - CONTINUED

Figure		Page
20	Equivalent Specific Work Vs. Weight Flow-Speed Parameter, Configuration 1A (PPPPPP).	60
21	Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 2A (PPPPLT).	61
22	Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 2A (PPPPLT).	62
23	Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 2A (PPPPLT).	63
24	Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 2A (PPPPLT).	64
25	Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 2A (PPPPLT).	65
26	Equivalent Specific Work Vs. Weight Flow-Speed Parameter, Configuration 2A (PPPPLT).	66
27	Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 3A (PPTPLP).	67
28	Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 3A (PPTPLP).	68
29	Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 3A (PPTPLP).	69
30	Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 3A (PPTPLP).	70
31	Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 3A (PPTPLP).	71
32	Equivalent Specific Work Vs. Weight Flow-Speed Parameter, Configuration 3A (PPTPLP).	72
33	Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 4A (PPTPPP).	73
34	Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 4A (PPTPPP).	74
35	Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 4A (PPTPPP).	75

Figure		Page
36	Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 4A (PPTPPP).	76
37	Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 4A (PPTPPP).	77
38	Equivalent Specific Work Vs. Weight-Flow Speed Parameter, Configuration 4A (PPTPPP).	78
39	Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 5A (PPTP).	79
40	Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 5A (PPTP).	80
41	Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 5A (PPTP).	81
42	Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 5A (PPTP).	82
43	Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 5A (PPTP).	83
44	Predicted and Actual Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).	84
45	Predicted and Actual Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).	85
46	Predicted and Actual Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 1A (PPPPPP).	86
47	Predicted and Actual Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).	87
48	Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed, Three-Stage Turbine Configurations Compared.	88
49	Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed, Three-Stage Turbine Configurations Compared.	89
50a	Total-to-Total Efficiency Based on Measured Temperature Drop and Measured Inlet and Exit Total Pressures Vs. Measured Total-to-Total Pressure Ratio at Design Speed, Configuration 2 (PPPP) and Configuration 4 (PPTP) Compared.	90

Figure		Page
50b	Total-to-Total Efficiency Based on Measured Torque and Calculated Inlet and Exit Total Pressures Vs. Calculated Total-to-Total Pressure Ratio at Design Equivalent Speed, Configuration 2 (PPPP) and Configuration 5A (PPTP) Compared.	90
51	Normalized Static Pressure Vs. Axial Station, Configuration 1A (PPPPPP), at Design Equivalent Speed.	91
52	Normalized Static Pressure Vs. Axial Station, Configuration 2A (PPPPLT), at Design Equivalent Speed.	92
53	Normalized Static Pressure Vs. Axial Station, Configuration 3A (PPTPLP), at Design Equivalent Speed.	93
54	Normalized Static Pressure Vs. Axial Station, Configuration 4A (PPTPPP), at Design Equivalent Speed.	94
55	Turbine Efficiency Contour Plot, Configuration 1A (PPPPPP).	95
56	Turbine Efficiency Contour Plot, Configuration 2A (PPPPLT).	96
57	Turbine Efficiency Contour Plot, Configuration 3A (PPTPLP).	97
58	Turbine Efficiency Contour Plot, Configuration 5A (PPTP).	98
59	Turbine Exit Swirl Contour Plot, Configuration 1A (PPPPPP).	99
60	Turbine Exit Swirl Contour Plot, Configuration 2A (PPPPLT).	100
61	Turbine Exit Swirl Contour Plot, Configuration 3A (PPTPLP).	101
62	Turbine Exit Swirl Contour Plot, Configuration 4A (PPTPPP).	102
63	Turbine Exit Swirl Contour Plot, Configuration 5A (PPTP).	103
64	Turbine Exit Swirl Contour Plot, Configuration 2 (PPPP).	104

LIST OF ILLUSTRATIONS - CONCLUDED

Figure		Page
65	Radial Efficiency Profile, Configuration 7 (PPPPLP) Compared with Configuration 1 (PPPPPP).	105
66	Stage Three Incidence Angle Contour Plot, Typical for Two-Stage Tandem Turbine (PPTP).	106
67	Stage Three Incidence Angle Contour Plot, Typical for Two-Stage Plain Turbine (PPPP).	107
68	Cascade Efficiency Vs. Incidence Angle, Typical for a Plain Stator.	108

SUMMARY

This report describes additional experimental results for a program which was originally conducted to investigate aerodynamic means for increasing turbine stage loading and turbine blade loading consistent with high efficiency (Reference 1). Four additional highly loaded fan drive turbines were tested: 1) a three-stage turbine using all plain blading (base case), 2) a three-stage turbine with a ten-degree tangentially leaned stator and tandem rotor in stage three, 3) a three-stage turbine using a tandem stator in stage two, and 4) a three-stage turbine using a tandem stator in stage two and a ten-degree tangentially leaned stator in stage three. Each turbine was designed to the same velocity diagram, and each used the same constant inside-diameter flowpath.

At design equivalent speed (3169.0 rev/min) and design total-to-total pressure ratio (3.47) the turbine utilizing the stage two tandem stator (with all other bladerows plain) achieved an overall total-to-total efficiency of approximately 0.887 as compared to 0.886 for the all plain blade turbine. Although this represented the highest level of efficiency yet attained for a three-stage turbine in this program, it is well below the level predicted on the basis of previous tests results. Incidence loss on the stage three vane has been identified as the primary cause.

Retest of a two-stage turbine utilizng the stage two tandem stator confirmed the significant increase in two-stage total-to-total efficiency afforded by the use of this bladerow.

INTRODUCTION

The development of high-bypass-ratio turbofan engines for future aircraft propulsion schemes requires the development of fan turbines with increasingly higher work output. The requirements of smaller turbine diameters and reduced rotative speeds generate the need for turbines with higher aerodynamic loadings.

The NASA Highly Loaded Multi-Stage Fan Drive Turbine Program was established to investigate advanced turbine airfoil concepts to meet the requirements of higher loading while maintaining a high level of turbine aerodynamic performance.

During the initial planning of the program seven air turbine configurations were selected for testing which best represented the optimum test plan to evaluate the effects on overall turbine performance of the high lift devices which consisted of tandem stator and rotor airfoils and tangentially leaned stator airfoils.

The seven turbine configurations tested are described in detail in Reference 1. Test results are presented in tabular form in Table VIII of that report.

In view of the configurations that were tested, it became apparent that the testing of additional configurations with the existing airfoil hardware was required in order to completely isolate the individual effects of the tandem and leaned airfoils on the overall performance of the three stage turbine.

The program described herein was a nine-month follow-on investigation to provide additional experimental information on the performance of the existing airfoil bladerows.

The program was divided into three task items of activity. Under Task IA, Testing, five air turbine configurations were assembled and tested. Determination of the overall operating characteristics of these five configurations was accomplished under Task IIA, Data Reduction and Analysis. Task IIIA, Reporting, has as its purpose the orderly presentation of all test results and analyses and is completed with this report.

AERODYNAMIC EVALUATION

TEST VEHICLE

Requirements - The analysis and design of the three fan drive turbines which were investigated are presented in detail in References 3 through 5. An existing highly-loaded fan drive turbine rotating rig was modified for the test and performance phase of the program. The turbine design requirements were scaled for a turbine exit tip diameter of 28.4 inches in order to utilize the existing test rig. The full-size and scaled turbine design requirements are presented below:

Parameter	Full Size	Scaled
Average Pitch Loading, $\frac{gJ\Delta h}{2\Sigma U_p^2}$	1.5	1.5
Equivalent Specific Work, E/θ_{cr}, (Btu/lbm)	33.0	33.0
Equivalent Rotative Speed, $N/\sqrt{\theta_{cr}}$, (rev/min)	2000	3169
Equivalent Weight Flow, $W\sqrt{\theta_{cr}}\ \varepsilon/\delta$, (lbm/sec)	70	28
Inlet Swirl Angle (degrees)	0	0
Exit Swirl Angle Without Guide Vanes (degrees)	≤ 5	≤ 5
Maximum Tip Diameter (inches)	45.0	28.4
Number of Stages	3	3
$W\sqrt{T_T}/P_T$ at Inlet	108.4	43.16
$\Delta h/T_T$	0.0635	0.0635
$N/\sqrt{T_T}$	87.7	138.98

Configurations Tested - All bladerows tested in this program were designed to the three-stage turbine velocity diagrams presented in Figure 1. In order to further isolate the effects of the stage two tandem stator, the stage three tangentially leaned stator, and the stage three tandem rotor, a total of five configurations were tested. These configurations are described below.

Configuration	Symbol	Description
1A	PPPPPP	Three-stage turbine with plain blading in all bladerows. This configuration is shown in Figure 2 and is the same as Con-

		figuration 1 of the original test series. This turbine was run to verify test cell repeatability from the original test series.
2A	PPPPLT	Three-stage turbine with leaned stator and tandem rotor in stage three and plain blading in all other bladerows. This configuration was run to investigate the effects of the tandem rotor operating in the improved flow field generated by the leaned stator (see Fig. 88 in Reference 1)
3A	PPTPLP	Three-stage turbine with tandem stator in stage two, leaned stator in stage three, and plain blading in all other bladerows. This configuration was tested in anticipation of its representing the optimum combination of bladerows.
4A	PPTPPP	Three-stage turbine with tandem stator in stage two and plain blading in all other bladerows. This was an optional configuration (not contractually required) and was tested in order to investigate the effect of the stage two tandem stator operating in a three-stage turbine. In previous testing of a two-stage configuration, this bladerow was shown to be highly efficient relative to the stage two plain stator (see Table VI).
5A	PPTP	Two-stage turbine with tandem stage two stator and plain blading in all other bladerows. This configuration is shown in Figure 3 and is the same as Configuration 4 of the original test series (Reference 1). This turbine was tested in order to verify the presence of the significant performance payoff realized in the original test series using the tandem stage two stator and was also optional for this program.

Photographs of the turbine blading used in the testing of these five turbine configurations are presented in Figures 4 through 9.

TEST APPARATUS AND INSTRUMENTATION

Test Facility - The five turbine configurations were tested in the same General Electric Company's Evendale Air Turbine Test Facility as the original seven configurations. A typical test facility configuration is shown in Figure 10. A detailed description of the facility as configured for this program is presented in Reference 1.

Data Acquisition System - The data acquisition system for the test facility is capable of recording up to 200 temperatures and 350 pressures, in addition to other specific turbine performance parameters.

Temperature measurements are obtained using Chromel-Alumel thermocouple wire. Corrections for temperature recovery over the expected range of Mach numbers and for flow incidence angles are made in the cell data reduction program.

Pneumatic pressure signals from the turbine rig are fed to precision strain gage pressure transducers within the control room.

For a detailed description of the test cell data acquisition system and calibration techniques, see Reference 1.

Instrumentation - Figure 11 shows the location of the instrumentation used in the testing of the five turbine configurations. An instrumentation scheme was used which permitted removal of downstream turbine stages without requiring the reinstrumentation of upstream stages.

Turbine inlet instrumentation was affixed to the leading edge of the inlet strut frame on each of ten struts located 36 degrees apart, and approximately ten inches upstream of the first stage stator. Turbine inlet temperature was measured with 25 Chromel-Alumel thermocouples mounted in high recovery stagnation tubes affixed to the leading edge of the inlet strut frame on each of five struts 72 degrees apart. They were located radially at the area centers of five equal annular areas. Inlet total pressure was measured with 25 Kiel-type probes located in an identical manner as the total temperatures above, but on five alternate struts 72 degrees apart. These pressures were measured independently by means of the scanner-transducer system and then arithmetically averaged in the data reduction program. They were also pneumatically averaged, using a specially designed averaging block, measuring an average output on a single pressure transducer.

Inlet static pressure was measured with five equally spaced static pressure taps located on both the inner and outer flowpaths in a straight annular section about 1.7 inches upstream of the first stage stator. These static pressure taps were used to check the circumferential uniformity of the flow and to calculate the turbine inlet total pressure.

Interstage static pressures were measured with four static pressure taps installed on both inner and outer flowpath casings, approximately 90 degrees removed, in the cavity area before and after each stator.

Turbine outlet total temperature and total pressure were measured with six fixed circumferential arc rakes 60 degrees apart, located radially at the centers of six equal annular areas, and approximately four inches downstream of the last stage rotor. A total of 36 total temperatures and 72 total pressures were measured. Each rake contained twelve Kiel-type pressure elements located side-by-side, and six shielded thermocouple elements side-by-side. The total pressures were averaged both arithmetically and pneumatically in the same manner as the inlet pressure measurements.

Six turbine outlet static pressures were measured on both the inner and outer flowpaths. Elements were spaced 60 degrees apart and were located approximately four inches downstream of the last stage rotor.

Turbine outlet total temperature and total pressure were additionally measured by a radially and circumferentially traversing combination probe. A fast response pressure differential servo-system aligned the probe with the flow and provided an electrical output proportional to the flow angle. Total temperature, total pressure and flow angle were recorded on X-Y chart recorders as functions of either radial immersion or circumferential position. The probe was located approximately one inch downstream of the last stage rotor.

Air flow to the turbine was measured using a calibrated circular arc venturi which was operated at critical flow conditions. The venturi inlet pressure and temperature were measured using wall static pressure taps and Chromel-Alumel air thermocouple probes located upstream of the venturi throat.

Three independent speed measurements were provided by an indicating system consisting of a 60-tooth gear attached to the turbine shafting and three stationary magnetic sensors located very close to the gear teeth. Electrical impulses resulting from the passing of each tooth provided an electrical frequency proportional to turbine speed. Electrically time integrating this signal provided the speed indication, accurate within ± 1 rpm. During the course of each data reading, twelve different samples of speed were recorded and arithmetically averaged.

The torque measurement system consisted of a dual bridged shaft-mounted torque sensor. The strain sensitive spool section was located between the turbine shaft and the waterbrake shaft with a specially designed slip ring mounted behind the waterbrake to transmit electrical signals to the digital recorder. Each bridge was excited with its own independent electronics system and read out or displayed through the digital data acquisition system.

Torque calibrations were performed in place using a precision torque arm and dead weights, whose weight values are traceable to the National Bureau of Standards. Dead weight calibrations were conducted prior to each test run to verify repeatability of torque zeros and bridge linearity. In addition, extensive temperature calibrations were made to define torque zero and modulus changes over the operational temperature range, even though these effects are less than 0.25 percent.

TEST PROCEDURE

The turbine inlet conditions were set at 700° R and 30 psia at all test points.

The performance mapping of the turbine was accomplished by selecting test points within the following range of variables:

- Speed - from 80 to 120 percent of design speed
- Pressure ratio - from that corresponding to approximately 75 percent design ideal enthalpy drop to a pressure ratio corresponding to approximately 105 percent design ideal enthalpy drop except configuration 4A which was not tested below a pressure ratio corresponding to approximately 93 percent of design ideal enthalpy drop.

The following performance data were obtained at each test point:

- Turbine weight flow
- Rotative speed
- Torque
- Inlet total temperature
- Inlet total and static pressures
- Exit absolute flow angles
- Exit total and static pressures
- Exit total temperatures
- Flowpath hub and tip interstage static pressures

Three complete sets of data were recorded at each test point and processed through the on-line computer which permitted an immediate evaluation of the reduced data.

Key performance parameters were continually monitored to insure accuracy and consistency of the test data. The design point was periodically reset throughout the testing to monitor the repeatability of the facility and the design point calculations.

One radial and three circumferential traverses were made at each test point to record the turbine exit total pressure, total temperature and absolute flow angle. The circumferential traverses were taken at 10, 50, and 90 percent of the last stage rotor blade height.

A detailed rotor exit survey was made at the design speed and design pressure ratio for each of the four three-stage turbine configurations tested. The survey for each configuration included seven circumferential traverses of total temperature, total pressure, and flow angle at the radial centers of seven equal annular areas. The traverses encompassed at least two last stage stator wakes.

DATA REDUCTION PROCEDURE

Overall Performance - Two calculation schemes were used to reduce the overall performance data. The two methods differed in only one respect. The preliminary test cell data reduction program used measured exit total pressures for all performance calculations while the final data reduction was performed using calculated exit total pressure. This exit total pressure was calculated using continuity by determining an integrated average flow angle from the traverses and combining it with the exit total temperature based on measured torque and the average of measured exit hub and tip static pressures.

A more detailed description of all the calculation procedures used in the data reduction may be found in Appendix A.

The following overall performance parameters were calculated for each of the three readings taken at each test point.

1. Calculated total-to-total pressure ratio as obtained from indirect measurement.

2. Calculated total-to-static pressure ratio as obtained from indirect measurement.

3. Equivalent speed.

4. Equivalent weight flow.

5. Equivalent weight flow-speed parameter (product of equivalent speed and weight flow).

6. Equivalent torque

7. Equivalent specific work

8. Ideal equivalent specific work

9. Efficiency (total-to-total).

10. Blade-jet speed ratio

These parameters are presented in Tables I through V for turbine configurations 1A through 5A respectively.

Stage Performance - Calculations were performed to determine the efficiency of each stage of the various turbine configurations when the three stage turbine was operating at its design speed and design total-to-total pressure ratio. Design total-to-total pressure ratio for the three stage plain blade turbine (Configuration 1A) was defined to be that at which the design equivalent specific work of 33.0 Btu/lbm was extracted. All stage efficiency calculations were performed with a three-stage turbine total-to-total pressure ratio of 3.47. In order to determine the stage efficiencies, it was necessary to determine the key performance parameters of the two-stage and one-stage turbine when the three-stage turbine was operating at its design point. Basic to the stage efficiency calculation was the assumption that removal of downstream turbine stages did not alter the design point performance of the two-stage and one-stage turbines, e.g., the two-stage turbine behaved identically when run by itself and when run in the three-stage turbine.

A detailed outline of the stage efficiency calculation along with a sample calculation is presented in Appendix B.

Rotor Exit Survey Calculations - The rotor exit surveys of total pressure, total temperature, and absolute flow angle, which were taken at the design point of each turbine configuration, were used to construct contour plots of local efficiency and local absolute flow angle. Local efficiencies were calculated from the following parameters:

- Measured inlet total temperature
- Calculated inlet total pressure based on continuity using measured inlet static pressure and measured airflow
- Local exit total pressure measured by the traverse probe
- Local exit total temperature measured by the traverse probe

EXPERIMENTAL RESULTS AND DISCUSSION

Test Cell Repeatability - In order to verify the consistency of air turbing test facility data acquired during this test series with that acquired during the original test series, the three-stage turbine with all plain bladerows was rerun as a base case. Figures 12 through 14 present design speed curves of equivalent torque, equivalent weight flow, and turbine total-to-total efficiency versus turbine total-to-total pressure ratio for Configuration 1A (PPPPPP) of this series and Configuration 1 (also PPPPPP) of the original series. These plots confirm the test cell repeatability, thus establishing a base for comparison between the original turbine test series and this follow-on test series.

Overall Performance - The reduced data and calculated parameters are presented in the following curves for each turbine configuration:

1. Equivalent torque versus calculated total-to-total pressure ratio.
2. Equivalent weight flow versus calculated total-to-total pressure ratio.
3. Equivalent specific work versus calculated total-to-total pressure ratio.
4. Total-to-total effieiency versus calculated total-to-total pressure ratio.
5. Total-to-total effieiency versus blade-jet speed ratio.
6. Equivalent specific work versus equivalent weight flow - speed parameter with lines of constant calculated total-to-total pressure ratio, constant speed, and constant efficiency.

The above curves utilize constant values of equivalent speed as a parameter and are shown in Figures 15 through 43.

In Figures 44 through 47, some of the reduced data for the plain blade turbine build (Configuration 1A) are compared to the pretest predictions which were originally presented in Reference 3. The data show reasonable agreement with predictions in the vicinity of the design point, with some divergence occurring at far off-design points. The predictions were made with the use of an off-design turbine computer program (Reference 6) and some disagreement was expected because of the assumptions used in the program. The computer program uses constant loss coefficients (such as bladerow efficiencies and rotor and stator total pressure recovery factors) at each operating point. The differences seen in the equivalent weight flow versus pressure ratio curves was attributed partially to the coefficients used in the computer program, and partially to variations in bladerow throat areas in the assembled hardware compared to design intent.

In Figure 48, total-to-total efficiency versus total-to-total pressure ratio for the design equivalent speed line is compared for all three-stage turbine configurations. At the design point (Pressure ratio = 3.47 for Configuration 1A) the efficiencies fell within four-tenths of one-percent of each other. Configuration 2A (PPPPLT) exhibited the lowest design point efficiency of all the three-stage builds, due primarily to a lower bladerow efficiency for the stage three tandem rotor (see Stage Performance). Configuration 3A (PPTPLP) showed no significant increase in design point efficiency over the base case (Configuration 1A-PPPPPP), and Configuration 4A (PPTPPP) demonstrated an advantage of less than one-tenth of one-percent in design point efficiency over the base case. While this represents the highest level of efficiency yet attained in this program, it is well below the full one-percent increase predicted for Configuration 4A on the basis of test results from a two-stage turbine utilizing the stage two tandem stator (Table VIII, Reference 1). The discrepancy between the expected level of performance and the level realized during actual test can be partially explained by the fact that a high stage exit swirl from the two-stage turbine with a tandem stage two stator (see Rotor Exit Survey, this report) resulted in excessive positive incidence on the stage three stator, a bladerow which is characterized by its extreme sensitivity to positive incidence. A detailed analysis of the losses associated with the higher positive incidence is presented in Appendix C. Results of that analysis indicate that a loss of approximately one-half of one-percent in three-stage turbine efficiency is attributable to excessive positive incidence on the stage three stator. Thus most of the benefit derived from the improved performance of the tandem stage two is masked in the three-stage build by a poorly performing stage three. The fact that Configuration 3A (PPTPLP) performance is below that of Configuration 4A seems to indicate that the incidence problem is accentuated somewhat by stator lean.

In Figure 49, equivalent weight flow versus total-to-total pressure ratio for the design equivalent speed line is compared for all three-stage configurations. Note that the equivalent weight flow for the configurations utilizing the tandem stage two stator is lower than that for the configurations utilizing the plain stator in stage two. This difference in flow was also noticed during the original test series and is reported in Reference 1.

Figures 50a and 50b present total-to-total efficiency versus total-to-total pressure ratio for the two-stage turbines. Figure 50a compares efficiency based on measured total temperature drop across the turbine and measured inlet and exit total pressures for Configuration 4 (PPTP) and Configuration 2 (PPPP), both from the original test series. This is included to further substantiate the improved performance of the two-stage tandem turbine which was originally reported in Reference 1. Figure 50b compares efficiency based on measured torque and calculated inlet and exit total pressures for Configuration 5A (PPTP) and Configuration 2 (PPPP). Again, the advantage afforded by the tandem stator is obvious.

In Figures 51 through 54, curves of static pressure normalized by inlet total pressure versus axial station are presented for various turbine pressure ratios to illustrate the interstage hub and tip static pressure behavior of the 3-stage turbine configurations. Figure 51 (Configuration 1A - PPPPPP) indicates that the stage one rotor hub at lower pressure ratios had positive reaction and as pressure ratio increased, the reaction became negative. Stage one was designed for approximately eight percent positive hub reaction, while test data indicated slightly negative hub reaction at the design point. Figure 51 also indicates that the stage three rotor hub at lower pressure ratios had positive reaction which became negative reaction as the pressure ratio increased. In this case, the stage three rotor hub was designed for approximately twenty percent negative reaction. Figures 52 and 53, normalized static pressure for Configurations 2A (PPPPLT) and 3A (PPTPLP) respectively, illustrate the influence of the stage three tangentially leaned stator on reaction. Both of these leaned stator configurations had a positive reaction stage three rotor throughout their entire operating range.

Stage Performance - Stage performance calculations were performed to evaluate the performance of the all-plain third stage in Configuration 4A (PPTPPP) and of the leaned/tandem (/LT) third stage in Configuration 2A (PPPPLT).

In Appendix B of Reference 1, the stage efficiency of the all-plain third stage (/PP) was calculated to be 0.923 while operating in Configuration 1 (PPPPPP). In Appendix B of this report, however, the efficiency of that same state was calculated to be only 0.877 while operating in Configuration 4A (PPTPPP). The major part of this third stage performance decrement has been attributed to the positive incidence problem, previously discussed, that arises when the stage two tandem stator is used in the three-stage builds. The reader is again referred to Appendix C of this report for a more detailed analysis of the incidence loss problem.

The combination of the stage three tangentially leaned stator and stage three tandem rotor was calculated to have a stage efficiency of 0.909 while operating in Configuration 2A (PPPPLT), while the combination of the stage three plain stator and the stage three tandem rotor exhibited a stage efficiency of 0.918 operating in Configuration 5 (PPPPPT) of the original test series. Stage three efficiency attained utilizing all plain blading was 0.923. These results indicate that the stage three tandem rotor is inherently less efficient than the stage three plain rotor, even when operating in the improved pressure field generated by the leaned stator.

Results of stage performance calculations for this program and for the original program are summarized in Table VI of this report.

Rotor Exit Survey - Turbine efficiency contour plots showing local efficiency as a function of radius ratio and circumferential position for each turbine configuration design point are presented in Figures 55 through 58. These plots are useful for observing trends in so far as they indicate the regions of high efficiency at the pitchline between the last stage stator wakes and the regions of low efficiency in the vicinity of the tip, with a large decrease in efficiency toward the hub.

The temperature and pressure data used to construct these plots were manually read from the X-Y charts produced by the traversing survey probe. The accuracy of this technique is only sufficient to determine local trends and not absolute level of local efficiency; thus, the reader is cautioned against drawing conclusions about the relative performance of the various turbine configurations from these contour plots.

Figures 59 through 64 present contour plots showing local exit swirl angle as a function of radius ratio for each turbine configuration design point. The distinguishing characteristic among the three-stage turbines is the difference in swirl gradient from hub to tip for those turbines utilizing the stage three tangentially leaned stator (Configuration 2A-PPPPLT, and Configuration 3A-PPTPLP) as opposed to those utilizing the plain stator (Configuration 1A-PPPPPP, and Configuration 4A-PPTPPP). The stator lean tends to bring the hub and tip swirls closer to the pitch value. This trend was also reported in Reference 1.

The swirl contour for Configuration 2 (PPPP) of the original test series is included as Figure 64 to provide a comparison with Configuration 5A (PPTP), shown in Figure 63. This comparison clearly illustrates the increased level of swirl for the two-stage tandem turbine.

Recommended Improvements - The results of this follow-on series of air turbine tests together with the test results from the original program (see Reference 1) suggest the following areas of potential improvement in three-stage turbine performance:

1. Stator Redesign

   a) Redesign the stage two and stage three stators for slightly negative incidence as indicated by the results of the rotor exit survey and cascade test results (see Reference 2). The anticipated improvement in three-stage turbine design point efficiency resulting from such a redesign is one-half of one-percent (see Appendix C).

   b) Investigate a tandem arrangement for the stage three stator using the same solidity as the stage three plain stator.

   c) Redesign all stators using a curvilinear lean distribution, with positive lean at the hub and negative lean at the tip. Figure 65 presents the radial efficiency profiles for Configuration 1

(PPPPPP) and Configuration 7 (PPPPLP) of the original program. This comparison illustrates the improved performance in the hub region realized by using a stator with constant 10° positive tangential lean (see Figure 6). Note, however, that a definite performance penalty was incurred at the tip. Similar results were noted in Reference 7, where stators with curvilinear lean reduced losses significantly in annular cascades with sloped outer walls.

2. Rotor Redesign

Redesign all rotors for slightly negative incidence to provide a high level of performance at both design and off-design operating conditions. Cascade test results reported in Reference 2 indicate a high sensitivity to angle of attack.

3. Non-Free Vortex Velocity Diagram

Establish a radial work distribution to extract more work in the high performance pitch region and to unload the hub and tip regions. This would effectively decamber the bladerows near the endwalls, resulting in lower secondary losses in these regions. The radial efficiency profiles in Figure 65 provide some indication of the need to reduce the strong endwall secondary flow fields.

4. Redesign the Three-Stage Turbine to Include Outlet Guide Vanes (O.G.V.'s)

Addition of O.G.V.'s to the three-stage turbine would allow a more highly loaded third-stage, resulting in a more uniform stage energy split and a positive reaction stage three rotor, while keeping turbine exit swirl within desired limits. Reference 8 reports the test results for a very highly loaded 4-1/2-stage turbine in which the use of O.G.V.'s resulted in a loss of approximately one-half of one-percent in measured total-to-total efficiency relative to a four-stage configuration without O.G.V.'s. The concept of a 3-1/2-stage turbine involves a tradeoff between diffusion losses in the O.G.V.'s and the anticipated advantages to be gained from redistribution of energy splits. A parametric study incorporating the experimental results of Reference 8 into several different 3-1/2-stage turbine velocity diagrams is suggested to determine the practicality of such a design.

MECHANICAL EVALUATION

The plain and tandem rotor blades were vibration and fatigue tested as part of the original program in order to insure their mechanical integrity during test.

The vibration analysis consisted of bench testing to confirm analytically established natural frequencies and node patterns (see References 3 and 4) for the plain and tandem airfoils.

Bench fatigue endurance testing was carried out to isolate possible failure regions and corresponding stress levels.

Results of this testing are presented in Reference 1 and indicated that the blade rows possessed sufficient mechanical integrity for successful operation in the air turbine.

SUMMARY OF RESULTS

Four highly loaded fan drive turbines were tested: (1) a three-stage turbine using all plain blading (base case), (2) a three-stage turbine with a ten-degree tangentially leaned stator and a tandem rotor in stage three, (3) a three-stage turbine using a tandem stator in stage two, and (4) a three stage turbine using a tandem stator in stage two and a ten-degree tangentially lean stator in stage three. Each turbine was designed for the same velocity diagram and each used the same flowpath. The most significant results of the testing and evaluation are summarized below:

1. At the design speed and pressure ratio ($P_{T0}/P_{T3} = 3.47$, $N/\sqrt{\theta_{cr}} = 3169.0$) the plain blade turbine (Configuration 1A - PPPPPP) achieved an overall total-to-total efficiency of 0.886.

2. The significant increase in design point total-to-total efficiency which was predicted for the tandem turbines (Configuration 3A - PPTPLP and Configuration 4A - PPTPP) on the basis of previous testing of the stage two tandem stator did not materialize during test. Excessive positve incidence on the stage three stator in these configurations has been identified as the primary cause. Configuration 4A (PPTPPP) did, however, exhibit a design point efficiency of approximately 0.887, the highest level of performance yet attained in this program.

3. The use of a stage three tandem rotor in Configuation 2A (PPPPLT) resulted in a penalty of approximately two-tenths of one percent in total-to-total efficiency.

4. Retest of the two-stage tandem turbine (Configuration 5A-PPTP) confirmed the significant increase in two-stage turbine total-to-total efficiency afforded by the use of a tandem stator in stage two.

APPENDIX A

OVERALL PERFORMANCE CALCULATION

Flow Angle - In order to evaluate turbine performance on the basis of turbine exit total pressure calculated from continuity, an average turbine exit flow angle was determined. The turbine exit flowpath was divided into streamtubes, and measured values of swirl angles, total pressure, and total temperature were used to satisfy continuity within each streamtube. The turbine exit measured static pressure was assumed to vary linearly from hub to tip. The determination of the average turbine exit flow angle processed as follows:

$$\rho_{avg} V_{avg} A_{ann} \cos \Gamma_{avg} = \sum_{i=1}^{m} \rho_i V_i A_i \cos \Gamma_i$$

where:

$$\rho_i V_i = P_{S_i} \sqrt{\frac{\gamma g}{R T_{T_i}}} \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_T}{P_S}\right)_i^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right]} \sqrt{\left(\frac{P_T}{P_S}\right)_i^{\frac{\gamma-1}{\gamma}}}$$

P_T = Measured total pressure at center of i-th streamtube.

P_S = Static pressure at center of i-th streamtube based on linear variation in measured static pressure from hub to tip

T_T = Measured total temperature at center of i-th streamtube

Γ = Swirl angle

ρ = Density

V = Absolute velocity

A = Area

m = Number of streamtubes

i = Subscript denoting streamtube value

ann = Subscript denoting average value for total annulus

The average velocity representing the turbine exit flow field was calculated by conserving the axial and tangential components of momentum, such that

$$V_{avg} = \left(V_{u_{avg}}^2 + V_{z_{avg}}^2\right)^{1/2}$$

where $$V_{u_{avg}} = \left(\sum_{i=1}^{m} W_i \; V_i \; \sin \Gamma_i\right) \Big/ \sum_{i=1}^{m} W_i$$

$$V_{z_{avg}} = \left(\sum_{i=1}^{m} W_i \; V_i \; \cos \Gamma_i\right) \Big/ \sum_{i=1}^{m} W_i$$

and $$V_i = \sqrt{2g \; Jc_p \; T_{Ti} \left[1 - \left(\frac{P_S}{P_T}\right)_i^{\frac{\gamma-1}{\gamma}}\right]}$$

V_u = Tangential component of absolute velocity

V_z = Axial component of absolute velocity

W_i = Weight flow through i-th streamtube = $\rho_i V_i A_i \cos \Gamma_i$

The average turbine exit total temperature was determined through an energy balance of the annular streamtubes.

$$T_{T_{avg}} = \left(\sum_{i=1}^{m} W_i \; T_{Ti}\right) \Big/ \sum_{i=1}^{m} W_i$$

The average density at the turbine exit was obtained from the equation of state.

$$\rho_{avg} = \frac{P_{S_{avg}}}{R \; T_{S_{avg}}}$$

where $$T_{S_{avg}} = T_{T_{avg}} - \frac{V_{avg}^2}{2g \; Jc_p}$$

Overall Performance - After obtaining the average turbine exit flow angle, the exit total pressure was calculated in the following manner:

$$P_{T_3} = P_{S_3}\left(1 + \frac{\gamma-1}{2} M_3^2\right)^{\gamma/\gamma-1}$$

Turbine exit Mach number, M_3, was determined from the following relationship:

$$\frac{W\sqrt{R\ T_{T_3}}}{P_S\ A_{ann}\ \cos\Gamma_{avg}} = \sqrt{\gamma g}\ \ M_3\sqrt{1 + \frac{\gamma-1}{2} M_3^2}$$

Turbine exit total temperature, T_{T_3}, was determined as follows:

$$T_{T_3} = T_{T_{oo}} - \frac{\Delta h}{c_p}$$

where $\Delta h = \frac{2\pi\ N\tau}{60\ JW}$

N = Turbine rotative speed, rev/min

τ = Measured torque, ft-lbf

$T_{T_{oo}}$ = Measured turbine inlet total temperature, ° R

W = Measured turbine weight flow, lbm/sec

Turbine inlet total pressure was calculated in the same manner as the turbine exit total pressure. The calculation used measured airflow, measured inlet total temperature, the average of measured hub and tip static pressures, and the assumption of zero inlet swirl angle.

The remaining parameters used in the overall performance calculation were obtained as follows:

$\delta = P_{T_o}/14.696$

$\theta_{cr} = T_{T_{oo}}/518.688$

$\varepsilon = 1.0$ (for $\gamma = 1.4$)

Equivalent Speed, N EQV = $N/\sqrt{\theta_{cr}}$

Equivalent Weight Flow, WA EQV = $W\sqrt{\theta_{cr}}\ \varepsilon/\delta$

Weight Flow-Speed Parameter, WAN EQV = $WN\varepsilon/60\delta$

Equivalent Torque, TQ EQV = $\tau\varepsilon/\delta$

Equivalent Specific Work, DH EQV = $\dfrac{E}{\theta_{cr}} = \dfrac{2\pi\ N\tau}{60\ J\ \theta_{cr}\ W}$

Ideal Equivalent Specific Work, DHI EQV =

$$\left(\frac{E}{\theta_{cr}}\right)_{ideal} = c_p\ T_{T_{oo}}\left[1-\left(\frac{P_{T_3}}{P_{T_o}}\right)^{\frac{\gamma-1}{\gamma}}\right]\Bigg/\theta_{cr}$$

Total-to-total Efficiency, ETA TT =

$$\eta_{TT} = \left(\frac{E}{\theta_{cr}}\right)\Bigg/\left(\frac{E}{\theta_{cr}}\right)_{ideal}$$

Blade-Jet Speed Ratio, U/CO =

$$\nu = \left\{\frac{KN^2}{c_p\ T_{T_{oo}}\left[1-\left(\frac{P_{S_3}}{P_{T_0}}\right)^{\frac{\gamma-1}{\gamma}}\right]}\right\}^{1/2}$$

where: $K = \sum_{i=1}^{m}\left(\frac{\pi\ D_{p_i}}{720}\right)^2\Big/2g\ J$

where: m = number of turbine stages

D_p = pitchline diameter of the i-th rotor

APPENDIX B

STAGE EFFICIENCY CALCULATION

Calculations were performed to determine the efficiency of the third stage of Configuration 2A (PPPPLT) and of Configuration 4A (PPTPPP) with both three stage turbines operating at the design point. In order to compare the stage efficiencies on an equal basis, calculations were performed for a three-stage turbine total-to-total pressure ratio of 3.47. This is the pressure ratio at which the design equivalent specific work of 33.0 Btu/lbm is extracted when the three-stage plain blade turbine operates at the design equivalent speed.

The calculation procedure is outlined below:

1. Enter curves of equivalent specific work versus total-to-total pressure ratio at design equivalent speed for the three-stage turbines to obtain equivalent specific work at a pressure ratio of 3.47.

2. Enter three-stage turbine curves of normalized static pressure versus total-to-total pressure ratio at a pressure ratio of 3.47 to determine normalized static pressure at the hub and tip of stage two exit.

3. At the stage two normalized hub and tip exit static pressures, enter curves of normalized static pressuer versus total-to-total pressure ratios across the two-stage turbines.

4. Enter curves of equivalent specific work versus total-to-total pressure ratio for the two-stage turbine to determine its equivalent specific work.

5. Using the above information and Keenan and Kaye's <u>Gas Tables</u> (Reference 9), calculate the stage efficiencies.

The following example shows how the efficiency of the all plain third stage (/PP) operating behind the two-stage tandem combination (PP/TP) was calculated using test results for configuration 4A (PPTPPP) and Configuration 5A (PPTP).

1. At $(P_{T_0}/P_{T_3})_{4A} = 3.47$, $(E/\theta_{cr})_{4A} = 33.05$ Btu/lbm.

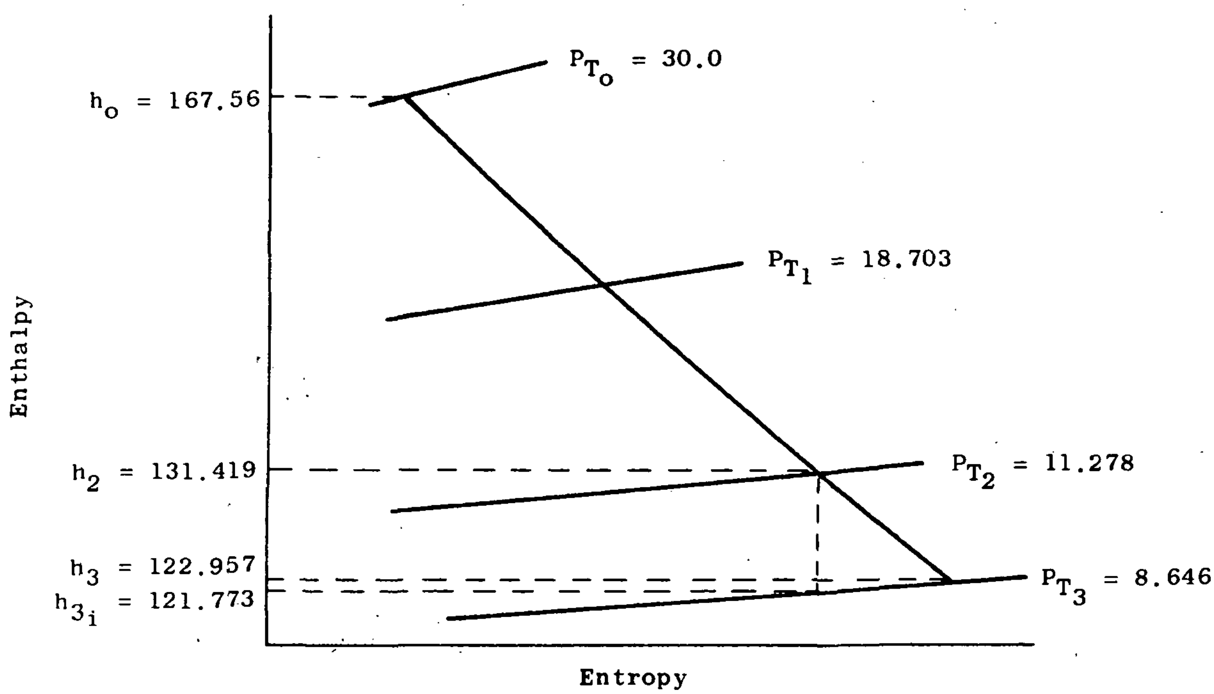
2. At Stage Two exit, $P_s/P_{T_0} = 0.300$

3. For the two-stage turbine, $(P_{T_o}/P_{T_{1.5}})_{5A} = 2.66$

4. For the two-stage turbine, $(E/\theta_{cr})_{5A} = 26.78$

5. Stage efficiencies are calculated from the above information and the accompanying sketch which was constructed using Table I of Reference 9.

Configuration 4A	E/θ_{cr}	Δh
Stage 1 & Stage 2	26.78	36.141
Stage 3	6.27	8.462
Total	33.05	44.603



Stage Three Efficiency Calculation

$$\eta_{TT_{4A}} = \frac{h_2 - h_3}{h_2 - h_{3i}} = \frac{131.419 - 122.957}{131.419 - 121.773} = .877$$

Similar calculations for Configuration 2A (PPPPLT) yield the following results:

Configuration 3A	E/θ_{cr}	Δh
Stage 1 + Stage 2	26.38	35.601
Stage 3	6.52	8.799
Total	32.90	44.400

$$\eta_{TT_{2A}} = \frac{h_{T1.5} - h_{T3}}{h_{T1.5} - h_{T3i}} = \frac{131.959 - 123.16}{131.959 - 122.276} = .909$$

These results have been incorporated into Table VIII of Reference 1 which is presented as Table VI of this report.

APPENDIX C

ANALYSIS OF INCIDENCE LOSSES

As a result of the significant increase in performance of the two-stage tandem turbine (PPTP) over the two-stage plain turbine (PPPP) which was noted during the original test series, it became highly desirable to test the stage two tandem stator in a three-stage build. Based on stage performance analyses a full one-percent increase in design point total-to-total efficiency was expected. During actual test of this turbine (Configuration 4A-PPTPPPP), however, less than one-tenth of one-percent increase in efficiency was realized (see Figure 48).

Data reduction and analysis have revealed that excessive positive incidence on the stage three plain stator accounted for approximately one-half of one-percent of this performance decrement. A review of that analysis is presented below.

Figures 66 and 67 present contour plots showing incidence of the stage three stator as a function of radius ratio and percent circumferential location. Figure 66 shows that, at the design point, a typical two-stage tandem turbine (PPTP) produces an average of about five and one-half degrees positive incidence on the stage three vane, while Figure 67 shows an average of about three degrees for the two-stage plain turbine (PPPP).

Figure 68 presents a plot of vane cascade efficiency, η_v, versus incidence angle, i, for a typical plain stator as cross-plotted from cascade data in Reference 2. Note the sharp drop off in η_v with increasingly positive incidence, a result of suction side separation.

Using Figures 66, 67, and 68, the incidence angle, i, and stage three stator cascase efficiency, η_{v3}, can be tabulated as follows:

Configuration	(i) Stage 3	η_{v3}
PPPPPP	3.0°	.9580
PPTPPP	5.5°	.9375

A velocity diagram study was conducted using Reference 6 to determine the derivative of three-stage turbine efficiency, η_{TT}, with respect to stage three vanes efficiency, η_{v3}. Results of this study indicate that, for a one-percent change in stage three vane efficiency, a resulting change of one-quarter of one-percent in three-stage turbine efficiency would occur.

Applying this efficiency derivative to the values of η_{v3}, in the table, the penalty in three-stage turbine efficiency due to excessive positive incidence can be calculated as follows:

$$\Delta\eta_{TT} = \frac{\partial\eta_{TT}}{\partial\eta_{v3}}\ \Delta\eta_{v3} = (.25)(.9375-.9580) = -.0051$$

The results of this analysis, therefore, indicate that a loss of one-half of one percent in three-stage turbine total-to-total efficiency is attributable to incidence loss.

APPENDIX D

LIST OF SYMBOLS

A	Area (in.^{2})
c_p	Specific heat at constant pressure (ft^2/sec^2 °R)
D	Diameter (in.)
d_o	Bladerow throat dimension (in.)
Δh	Turbine energy extraction (Btu/lbm)
Δh_{stg}	Stage energy extraction (Btu/lbm)
h_{ex}	Height of bladerow at exit (in.)
h_{th}	Height of bladerow at throat (in.)
i	Incidence angle (degrees)
L	Tangetially leaned bladerow
M	Mach number
m	Number of bladerows, streamtubes, or stages
N	Rotational speed (rev/min)
n	Number of vanes or blades
P	Plain bladerow
P_s	Static pressure (psia)
P_{S_3}	Turbine exit static pressure
P_T	Total pressure (psia)
P_{T_o}	Turbine inlet total pressure
P_{T_3}	Turbine exit total pressure
R	Gas constant (ft^2/sec^2 °R)
T	Tandem bladerow
T_S	Static temperature (°R)

T_T	Total temperature (°R)
$T_{T_{oo}}$	Turbine inlet total temperature
T_{T_3}	Turbine exit total temperature
t	Spacing (in.)
U	Wheel speed (ft/sec)
V	Absolute velocity (ft/sec)
W	Mass flow rate (lbm/sec)
E/θ_{cr}	Equivalent specific work (Btu/lbm)
$W\sqrt{\theta_{cr}}\,\varepsilon/\delta$	Equivalent weight flow (lbm/sec)
$N/\sqrt{\theta_{cr}}$	Equivalent rotative speed (rev/min)
$WN\varepsilon/60\delta$	Weight flow - speed parameter (lbm/sec^2)
$gJ\Delta h/2U^2$	Loading factor
α_o	Vane inlet absolute flow angle (degrees)
α_1	Vane exit absolute flow angle (degrees)
β_1	Blade inlet relative flow angle (degrees)
β_2	Blade exit relative flow angle (degrees)
Γ	Stage leaving swirl angle (degrees)
γ	Specific heat ratio
δ	Ratio of turbine pressure to pressure at standard sea level conditions
ε	Function of γ defined as $\frac{\gamma_{SL}}{\gamma}\left[\left(\frac{\gamma+1}{2}\right)^{\gamma/\gamma-1}\Big/\left(\frac{\gamma_{SL}+1}{2}\right)^{\gamma_{SL}/\gamma_{SL}-1}\right]$
η_{TT}	Total-to-total efficiency based on measured torque and calculated inlet and exit total pressures.
η_{TT}'	Total-to-total efficiency based on measured temperature drop and measured inlet and exit total pressures.
η_V	Cascade efficiency
θ_{cr}	Squared ratio of critical velocity at turbine inlet temperature to critical velocity at standard sea level temperature

μ Viscosity (lbm/sec-ft)

ν Blade-jet speed ratio

ρ Density (lbm/ft^3)

τ Torque (ft-lbf)

τ_{eq} Equivalent torque (ft-lbf), $\tau_{eq} = \tau\varepsilon/\delta$

Subscripts

h Hub

i Current axial station, stage, streamtube, or ideal

p Pitch

r Radial component

t Tip

u Tangential component

z Axial component

REFERENCES

1. Wolfmeyer, G.W., and Thomas, M.W., "Highly Loaded Multi-Stage Fan Drive Turbine - Performance of Initial Seven Configurations," NASA CR-2362, July 1973.

2. Cherry, D.G., Staley, T.K., and Thomas, M.W., "Highly Loaded Multi-Stage Fan Drive Turbine - Cascade Test Program," NASA CR-2171, January 1973.

3. Evans, D.C. and Wolfmeyer, G.W., "Highly Loaded Multi-Stage Fan Drive Turbine - Plain Blade Configuration Design," NASA CR-1964, February 1972.

4. Evans, D.C. and Wolfmeyer, G.W., "Highly Loaded Multi-Stage Fan Drive Turbine - Tandem Blade Configuration Design," NASA CR-2097, August 1972.

5. Evans, D.C. and Wolfmeyer, G.W., "Highly Loaded Multi-Stage Fan Drive Turbine - Lean Stator Configuration Design," NASA CR-2096, July 1972.

6. Flagg, E.E., "Analytical Procedure and Computer Program for Determining the Off-Design Performance of Axial - Flow Turbines," NASA CR-710, March 1966.

7. Deich, M.E. and Gubarev, A.V., "A New Method of Profiling the Guide Cascades of Stages with Small Ratios of Diameter to Length," Teploenergetika, No. 8, August 1962.

8. Walker, N.D. and Thomas, M.W., "Experimental Investigation of a 4-1/2-Stage Turbine With Very High Stage Loading Factor - Turbine Performance," NASA CR-2363, March 1973.

9. Keenan, J.H. and Kaye, J., Gas Tables, John Wiley and Sons, Inc., New York, 1948.

Table I. Reduced Test Data and Calculated Performance Parameters, Configuration 1A (PPPPPP).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
39	99	29.94	3.482	3.834	3152.76	27.981	1470.27	2180.18	33.059	37.329	0.8856	0.3686	8.87
40	100	29.94	3.484	3.836	3163.14	27.976	1474.89	2174.46	33.086	37.340	0.8861	0.3698	8.89
41	100	29.95	3.484	3.838	3161.72	27.984	1474.62	2177.85	33.113	37.344	0.8867	0.3696	9.14
45	120	29.95	3.477	3.825	3803.39	27.460	1740.66	1776.36	33.111	37.289	0.8879	0.4450	13.58
46	120	29.96	3.471	3.817	3788.19	27.472	1734.50	1784.60	33.116	37.245	0.8891	0.4435	13.72
47	120	29.95	3.473	3.820	3797.85	27.462	1738.30	1783.30	33.188	37.263	0.8906	0.4446	13.64
48	110	29.97	3.483	3.830	3478.12	27.789	1610.90	1981.72	33.379	37.335	0.8940	0.4068	9.52
49	110	29.97	3.483	3.830	3472.65	27.802	1609.13	1983.25	33.336	37.330	0.8930	0.4062	9.58
50	110	29.98	3.483	3.830	3475.19	27.789	1609.56	1980.31	33.327	37.335	0.8926	0.4064	9.57
51	90	29.90	3.469	3.827	2841.50	28.066	1329.17	2380.41	32.432	37.231	0.8711	0.3324	11.03
52	90	29.90	3.467	3.825	2841.34	28.065	1329.05	2390.83	32.573	37.218	0.8752	0.3325	11.20
53	90	29.89	3.467	3.825	2841.32	28.069	1329.20	2388.08	32.532	37.220	0.8740	0.3324	11.17
54	80	29.89	3.444	3.815	2533.17	28.088	1185.87	2539.64	30.823	37.053	0.8318	0.2966	14.53
55	80	29.89	3.435	3.802	2533.06	28.096	1186.13	2548.31	30.919	36.990	0.8359	0.2969	14.40
56	80	29.90	3.446	3.817	2533.68	28.090	1186.18	2562.20	31.101	37.069	0.8390	0.2966	14.60
57	100	29.88	3.486	3.839	3170.50	27.980	1478.50	2171.16	33.108	37.354	0.8863	0.3705	9.00
58	100	29.89	3.491	3.846	3174.49	27.971	1479.92	2169.38	33.132	37.393	0.8861	0.3708	8.82
59	100	29.89	3.488	3.842	3170.12	27.976	1478.10	2169.33	33.081	37.369	0.8853	0.3704	8.75
60	100	29.88	3.483	3.836	3168.19	27.981	1477.50	2169.90	33.063	37.337	0.8855	0.3704	8.86
61	100	29.89	3.486	3.839	3178.50	27.972	1481.79	2165.03	33.108	37.353	0.8864	0.3715	8.89
62	100	29.89	3.486	3.839	3172.51	27.968	1478.82	2164.76	33.045	37.354	0.8847	0.3708	9.03
63	99	29.87	3.142	3.397	3152.52	27.971	1469.68	2031.78	30.816	34.728	0.8873	0.3833	9.15
64	100	29.87	3.143	3.399	3157.77	27.966	1471.83	2029.50	30.839	34.739	0.8877	0.3838	9.29
65	99	29.87	3.142	3.398	3149.06	27.973	1468.15	2034.26	30.818	34.730	0.8874	0.3828	9.32
66	120	29.86	3.124	3.389	3810.25	27.358	1737.38	1629.56	30.542	34.579	0.8832	0.4636	19.38
67	120	29.87	3.130	3.397	3814.56	27.347	1738.62	1628.78	30.574	34.630	0.8829	0.4638	19.38
68	121	29.87	3.127	3.393	3821.19	27.346	1741.55	1627.76	30.610	34.611	0.8844	0.4647	19.33
69	110	29.90	3.131	3.389	3479.47	27.731	1608.17	1827.93	30.865	34.639	0.8910	0.4234	14.24
70	110	29.89	3.131	3.390	3481.37	27.745	1609.82	1827.03	30.852	34.643	0.8906	0.4236	14.22
71	110	29.90	3.133	3.392	3483.58	27.723	1609.58	1826.45	30.885	34.656	0.8912	0.4238	14.26
72	90	29.89	3.134	3.392	2846.44	28.054	1330.90	2208.30	30.152	34.667	0.8698	0.3463	9.21
73	90	29.89	3.135	3.392	2845.13	28.062	1330.68	2207.84	30.124	34.671	0.8688	0.3461	9.06
74	90	29.88	3.133	3.390	2846.84	28.066	1331.64	2207.02	30.127	34.658	0.8692	0.3463	8.99
75	80	29.89	3.125	3.388	2532.13	28.091	1185.51	2386.46	28.949	34.587	0.8370	0.3081	11.34
76	80	29.88	3.123	3.386	2531.16	28.090	1185.00	2386.60	28.941	34.576	0.8370	0.3081	11.26
77	80	29.88	3.122	3.385	2530.58	28.095	1184.95	2386.28	28.925	34.567	0.8368	0.3080	11.19
78	100	29.88	3.477	3.827	3166.16	27.989	1476.99	2168.97	33.018	37.290	0.8854	0.3704	8.78
79	100	29.88	3.480	3.831	3165.54	27.993	1476.90	2172.28	33.057	37.312	0.8860	0.3702	8.75
80	100	29.88	3.492	3.848	3168.69	27.994	1478.38	2175.06	33.132	37.401	0.8859	0.3701	8.75
81	100	29.88	2.804	2.991	3167.80	27.902	1473.15	1849.54	28.258	31.764	0.8896	0.4034	13.93
82	100	29.88	2.804	2.990	3159.90	27.896	1469.16	1850.86	28.214	31.760	0.8883	0.4025	13.85
83	100	29.88	2.803	2.990	3158.52	27.904	1468.94	1851.85	28.208	31.756	0.8883	0.4023	13.90
84	120	29.89	2.790	2.993	3794.69	27.152	1717.24	1469.42	27.636	31.635	0.8736	0.4831	24.77
85	120	29.89	2.788	2.991	3792.34	27.161	1716.71	1473.06	27.679	31.616	0.8755	0.4830	24.80
86	120	29.89	2.788	2.990	3789.79	27.166	1715.87	1471.95	27.634	31.610	0.8742	0.4827	24.79
87	110	29.89	2.796	2.989	3488.35	27.569	1602.84	1647.68	28.056	31.684	0.8855	0.4444	19.67
88	110	29.89	2.794	2.988	3472.76	27.589	1596.84	1658.17	28.088	31.673	0.8868	0.4424	19.68
89	110	29.89	2.795	2.989	3477.20	27.581	1598.42	1655.26	28.083	31.682	0.8864	0.4429	19.73
90	90	29.89	2.804	2.988	2850.12	28.048	1332.35	2031.49	27.780	31.767	0.8745	0.3631	10.02
91	90	29.89	2.806	2.990	2850.39	28.041	1332.15	2031.93	27.795	31.782	0.8746	0.3630	9.94

Table I. Reduced Test Data and Calculated Performance Parameters, Configuration 1A (PPPPPP) (Continued).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
92	90	29.89	2.805	2.989	2852.10	28.040	1332.87	2031.02	27.801	31.776	0.8749	0.3633	9.88
93	80	29.87	2.796	2.980	2529.33	28.087	1184.00	2208.46	26.764	31.687	0.8447	0.3226	9.42
94	80	29.87	2.796	2.980	2529.72	28.092	1184.40	2207.39	26.750	31.690	0.8441	0.3226	9.30
95	80	29.87	2.796	2.979	2529.36	28.088	1184.07	2207.06	26.747	31.684	0.8442	0.3226	9.37
96	100	29.90	3.478	3.828	3167.03	27.981	1476.95	2170.65	33.063	37.296	0.8865	0.3705	8.72
97	100	29.90	3.477	3.827	3162.30	27.981	1474.72	2173.70	33.060	37.289	0.8866	0.3700	8.76
98	100	29.90	3.480	3.832	3161.11	27.990	1474.64	2175.06	33.058	37.309	0.8861	0.3697	9.25
99	80	29.90	3.458	3.830	2531.64	28.089	1185.20	2540.73	30.816	37.151	0.8295	0.2961	13.54
100	80	29.90	3.451	3.820	2531.36	28.091	1185.16	2538.25	30.780	37.101	0.8296	0.2963	13.43
101	80	29.90	3.457	3.827	2531.55	28.089	1185.14	2539.79	30.804	37.145	0.8293	0.2961	13.19
102	100	29.90	2.465	2.600	3163.42	27.708	1460.87	1633.66	25.100	28.285	0.8874	0.4273	20.37
103	100	29.89	2.462	2.597	3162.37	27.715	1460.73	1633.06	25.076	28.251	0.8876	0.4274	20.34
104	100	29.90	2.465	2.600	3163.20	27.711	1460.94	1633.27	25.089	28.288	0.8869	0.4272	20.33
105	120	29.89	2.441	2.599	3798.22	26.771	1694.70	1262.61	24.107	28.019	0.8604	0.5132	32.91
106	120	29.90	2.441	2.598	3798.36	26.768	1694.60	1261.86	24.096	28.018	0.8600	0.5132	32.90
107	120	29.90	2.441	2.598	3797.54	26.764	1693.94	1260.98	24.078	28.014	0.8595	0.5131	32.89
108	110	29.91	2.457	2.600	3480.30	27.247	1580.49	1437.79	24.714	28.202	0.8763	0.4701	26.14
109	110	29.91	2.458	2.600	3482.28	27.242	1581.05	1436.89	24.718	28.203	0.8764	0.4703	26.15
110	110	29.90	2.457	2.599	3482.47	27.252	1581.71	1437.18	24.715	28.193	0.8766	0.4704	26.14
111	90	29.92	2.466	2.595	2846.47	27.969	1326.87	1818.75	24.910	28.302	0.8801	0.3848	14.16
112	90	29.93	2.466	2.595	2845.97	27.959	1326.18	1818.95	24.916	28.303	0.8804	0.3847	14.23
114	80	29.92	2.470	2.596	2532.43	28.068	1184.67	1993.54	24.205	28.336	0.8542	0.3423	9.52
115	80	29.92	2.470	2.596	2532.64	28.066	1184.68	1993.80	24.212	28.337	0.8545	0.3423	9.57
116	80	29.92	2.469	2.595	2532.19	28.068	1184.57	1993.18	24.198	28.333	0.8541	0.3423	9.43
117	100	29.91	3.474	3.825	3158.53	27.992	1473.57	2173.17	32.999	37.273	0.8853	0.3696	8.95
118	100	29.92	3.476	3.826	3167.85	27.977	1477.12	2166.97	33.020	37.283	0.8857	0.3706	8.91
119	100	29.92	3.482	3.834	3166.35	27.988	1477.00	2170.84	33.050	37.327	0.8854	0.3702	8.85
120	100	29.95	2.102	2.197	3167.28	27.051	1427.96	1321.62	20.824	23.810	0.8746	0.4660	29.19
121	100	29.97	2.103	2.197	3166.88	27.057	1427.06	1320.51	20.815	23.815	0.8740	0.4659	29.16
122	100	29.96	2.102	2.197	3167.27	27.051	1427.97	1321.68	20.825	23.810	0.8746	0.4660	29.21
123	120	29.97	2.071	2.196	3800.35	25.905	1640.78	982.84	19.404	23.373	0.8302	0.5593	43.52
124	120	29.98	2.071	2.197	3797.92	25.903	1639.65	983.27	19.401	23.385	0.8296	0.5588	43.53
125	120	29.98	2.071	2.196	3796.69	25.897	1638.68	982.54	19.385	23.372	0.8294	0.5587	43.52
126	110	29.99	2.090	2.198	3477.07	26.444	1532.48	1141.73	20.202	23.639	0.8546	0.5114	37.06
127	110	29.98	2.089	2.197	3478.05	26.455	1533.52	1142.47	20.213	23.627	0.8555	0.5117	37.07
128	110	29.99	2.090	2.198	3479.76	26.446	1533.75	1141.40	20.211	23.640	0.8550	0.5118	37.05
129	90	29.94	2.110	2.197	2848.88	27.582	1309.65	1518.95	21.113	23.919	0.8827	0.4191	21.75
130	90	29.99	2.113	2.200	2849.62	27.583	1310.02	1519.92	21.131	23.951	0.8823	0.4189	21.73
131	90	29.98	2.114	2.201	2849.83	27.592	1310.53	1522.25	21.158	23.968	0.8828	0.4188	21.79
132	80	29.94	2.113	2.195	2533.35	27.936	1179.54	1710.17	20.870	23.951	0.8714	0.3729	15.06
133	80	29.94	2.113	2.196	2533.24	27.926	1179.04	1710.08	20.876	23.959	0.8713	0.3728	15.04
134	80	29.94	2.113	2.195	2532.60	27.925	1178.73	1709.36	20.862	23.952	0.8710	0.3728	15.04
135	100	29.93	3.474	3.823	3167.00	27.903	1477.05	2169.50	33.042	37.266	0.8866	0.3706	8.84
136	100	29.93	3.484	3.836	3170.34	27.980	1478.43	2169.35	33.079	37.338	0.8859	0.3706	8.70
137	100	29.93	3.480	3.831	3171.20	27.974	1478.53	2167.05	33.059	37.314	0.8860	0.3709	8.57
138	100	29.98	3.687	4.111	3165.23	27.981	1476.10	2251.28	34.271	38.737	0.8847	0.3625	9.17
139	100	29.98	3.686	4.110	3164.44	27.987	1476.05	2251.57	34.260	38.733	0.8845	0.3624	9.29
140	100	29.97	3.685	4.108	3166.41	27.986	1476.92	2251.23	34.277	38.725	0.8851	0.3627	9.15
141	120	29.97	3.690	4.102	3797.95	27.499	1740.65	1857.84	34.530	38.758	0.8909	0.4353	11.20
142	120	29.97	3.692	4.105	3797.97	27.493	1740.28	1858.75	34.555	38.774	0.8912	0.4352	11.31

Table I. Reduced Test Data and Calculated Performance Parameters, Configuration 1A (PPPPPP) (Concluded).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
143	120	29.97	3.693	4.106	3798.01	27.492	1740.26	1859.66	34.573	38.781	0.8915	0.4351	11.29
144	110	29.97	3.686	4.098	3488.34	27.796	1616.04	2049.72	34.617	38.731	0.8938	0.3999	8.58
145	110	29.97	3.690	4.105	3482.12	27.803	1613.54	2054.79	34.632	38.761	0.8935	0.3990	8.67
146	110	29.97	3.693	4.108	3485.07	27.800	1614.73	2053.39	34.642	38.777	0.8934	0.3992	8.51
147	90	29.98	3.665	4.098	2849.12	28.056	1332.26	2435.66	33.286	38.592	0.8625	0.3266	11.84
148	90	29.98	3.669	4.104	2849.99	28.059	1332.78	2437.18	33.314	38.621	0.8626	0.3266	11.79
149	90	29.97	3.669	4.103	2850.08	28.062	1332.99	2436.34	33.299	38.619	0.8622	0.3266	11.62
150	80	29.97	3.643	4.098	2531.37	28.075	1184.47	2615.08	31.731	38.445	0.8254	0.2902	15.99
151	80	29.97	3.645	4.100	2531.09	28.085	1184.78	2615.32	31.718	38.456	0.8248	0.2901	15.91
152	80	29.97	3.640	4.094	2531.02	28.087	1184.79	2613.30	31.692	38.428	0.8247	0.2902	15.77
153	100	29.96	3.476	3.826	3163.69	27.986	1475.63	2178.28	33.138	37.285	0.8888	0.3701	8.74
154	100	29.97	3.483	3.834	3163.01	27.980	1475.01	2172.43	33.049	37.331	0.8853	0.3698	8.62
155	100	29.96	3.482	3.834	3163.81	27.985	1475.68	2175.07	33.091	37.328	0.8865	0.3699	8.62

Table II. Reduced Test Data and Calculated Performance Parameters, Configuration 2A (PPPPLT).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
213	100	29.91	3.454	3.825	3170.76	28.006	1480.02	2150.25	32.761	37.128	0.8824	0.3710	16.44
214	100	29.92	3.453	3.823	3163.21	28.007	1476.54	2153.81	32.736	37.120	0.8819	0.3702	16.26
215	100	29.92	3.450	3.821	3156.69	28.002	1473.23	2155.98	32.707	37.100	0.8816	0.3695	16.55
216	120	29.87	3.441	3.819	3799.39	27.458	1738.72	1765.97	32.884	37.031	0.8880	0.4448	21.89
217	120	29.89	3.440	3.819	3798.17	27.451	1737.71	1765.07	32.866	37.026	0.8876	0.4446	22.12
218	120	29.87	3.439	3.818	3799.57	27.462	1739.07	1764.38	32.851	37.019	0.8874	0.4448	22.01
219	110	29.87	3.447	3.816	3480.48	27.795	1612.31	1956.57	32.971	37.075	0.8893	0.4075	18.15
220	110	29.88	3.453	3.823	3483.20	27.782	1612.84	1957.08	33.020	37.121	0.8895	0.4076	17.95
221	110	29.88	3.451	3.821	3483.79	27.791	1613.62	1956.31	33.003	37.105	0.8894	0.4078	18.03
222	90	29.88	3.454	3.830	2849.49	28.065	1332.85	2338.23	31.948	37.127	0.8605	0.3333	16.21
223	90	29.89	3.446	3.818	2849.31	28.056	1332.34	2331.87	31.870	37.071	0.8597	0.3336	15.84
224	90	29.89	3.446	3.819	2849.49	28.063	1332.75	2333.22	31.882	37.065	0.8602	0.3335	16.40
225	80	29.91	3.437	3.822	2532.43	28.093	1185.73	2514.23	30.500	37.000	0.8243	0.2964	17.75
226	80	29.90	3.434	3.818	2531.80	28.101	1185.78	2512.26	30.460	36.981	0.8237	0.2964	17.50
227	80	29.09	2.575	2.713	2532.63	24.504	1034.33	2392.51	33.277	29.482	1.1287	0.3357	32.92
228	90	29.91	3.470	3.852	2848.32	28.071	1332.58	2347.95	32.061	37.243	0.8609	0.3325	16.25
229	90	29.91	3.451	3.827	2848.68	28.054	1331.93	2340.07	31.978	37.105	0.8618	0.3332	16.61
230	90	29.91	3.450	3.826	2848.57	28.064	1332.36	2339.43	31.956	37.099	0.8614	0.3333	16.36
231	100	29.92	3.454	3.825	3157.44	27.991	1473.00	2159.18	32.777	37.128	0.8828	0.3694	16.50
232	100	29.92	3.458	3.830	3163.28	27.987	1475.48	2158.42	32.831	37.151	0.8837	0.3700	16.61
233	100	29.91	3.455	3.826	3156.65	27.992	1472.69	2160.44	32.786	37.132	0.8830	0.3693	16.58
234	100	29.93	3.116	3.391	3165.03	27.963	1475.04	2010.13	30.619	34.520	0.8870	0.3850	18.61
235	100	29.92	3.116	3.391	3163.83	27.965	1474.61	2010.17	30.605	34.519	0.8866	0.3849	18.67
236	100	29.92	3.114	3.388	3164.63	27.966	1475.03	2008.24	30.582	34.501	0.8864	0.3851	18.51
237	120	29.94	3.095	3.393	3793.74	27.353	1729.52	1630.57	30.434	34.346	0.8861	0.4614	27.19
238	120	29.94	3.097	3.394	3798.23	27.357	1731.82	1629.21	30.440	34.363	0.8858	0.4619	27.06
239	120	29.94	3.099	3.397	3798.70	27.348	1731.46	1630.00	30.469	34.379	0.8863	0.4618	27.16
240	110	29.94	3.115	3.396	3483.04	27.716	1608.91	1818.86	30.761	34.508	0.8914	0.4235	21.78
241	110	29.94	3.111	3.392	3482.29	27.714	1608.44	1817.30	30.730	34.479	0.8913	0.4236	21.76
242	110	29.94	3.112	3.392	3483.28	27.710	1608.71	1816.97	30.736	34.480	0.8914	0.4237	21.79
243	90	29.93	3.121	3.395	2846.81	28.055	1331.14	2195.18	29.976	34.560	0.8674	0.3462	16.68
244	90	29.93	3.122	3.394	2848.73	28.052	1331.89	2194.55	29.991	34.586	0.8676	0.3464	16.32
245	90	29.93	3.117	3.389	2848.76	28.051	1331.83	2193.24	29.975	34.529	0.8681	0.3466	16.51
246	80	29.92	3.112	3.386	2530.07	28.082	1184.18	2372.37	28.763	34.482	0.8342	0.3079	16.52
247	80	29.92	3.114	3.390	2530.21	28.084	1184.29	2374.93	28.795	34.504	0.8345	0.3078	16.67
248	80	29.92	3.113	3.387	2530.83	28.085	1184.63	2372.01	28.765	34.489	0.8340	0.3080	16.45
249	100	29.95	3.457	3.827	3161.44	27.982	1474.38	2158.56	32.819	37.145	0.8835	0.3698	16.31
250	100	29.96	3.459	3.829	3158.42	27.976	1472.65	2159.79	32.814	37.160	0.8831	0.3694	16.24
252	100	29.94	2.791	2.994	3163.17	27.883	1469.98	1844.43	28.158	31.637	0.8900	0.4027	21.66
253	100	29.95	2.793	2.996	3159.80	27.879	1468.22	1846.19	28.159	31.659	0.8894	0.4021	21.56
254	100	29.94	2.791	2.993	3163.22	27.879	1469.80	1844.35	28.161	31.637	0.8901	0.4027	21.59
255	120	29.95	2.756	2.993	3788.94	27.154	1714.74	1468.75	27.580	31.305	0.8810	0.4824	33.39
256	120	29.95	2.758	2.996	3793.85	27.151	1716.77	1467.17	27.589	31.327	0.8807	0.4828	33.33
257	120	29.29	2.227	2.339	3790.54	24.073	1520.81	1305.11	27.656	25.453	1.0865	0.5390	41.04
258	110	29.91	2.774	2.991	3479.45	27.567	1598.66	1647.31	27.980	31.477	0.8889	0.4431	27.51
259	110	29.92	2.774	2.991	3479.04	27.563	1598.19	1647.81	27.990	31.479	0.8892	0.4430	27.62
260	110	29.92	2.772	2.989	3479.32	27.571	1598.81	1647.51	27.979	31.463	0.8892	0.4432	27.56
261	90	29.92	2.795	2.993	2846.44	28.037	1330.08	2025.20	27.670	31.679	0.8734	0.3624	18.23
262	90	29.92	2.794	2.991	2846.11	28.036	1329.90	2025.69	27.674	31.666	0.8739	0.3625	18.16
263	90	29.93	2.795	2.993	2846.15	28.066	1331.32	2026.93	27.662	31.677	0.8732	0.3623	18.34

Table II. Reduced Test Data and Calculated Performance Parameters, Configuration 2A (PPPPLT) (Continued)

RDG	PCT NDES	PTO	PTO/PTS	PTO/PSS	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
264	80	29,93	2,799	2,996	2528,72	28,097	1184,17	2202,21	26,672	31,717	0,8409	0,3218	16,09
265	80	29,92	2,800	2,996	2528,96	28,086	1183,82	2203,75	26,704	31,721	0,8418	0,3218	16,22
266	80	29,92	2,798	2,994	2529,37	28,079	1183,72	2202,20	26,696	31,709	0,8419	0,3220	16,10
267	100	29,94	3,460	3,832	3156,56	27,972	1471,59	2162,10	32,834	37,171	0,8833	0,3691	16,46
268	100	29,93	3,456	3,826	3172,68	27,980	1479,52	2152,93	32,853	37,143	0,8845	0,3712	16,36
269	100	29,94	3,457	3,827	3160,79	27,978	1473,88	2159,87	32,837	37,145	0,8840	0,3697	16,50
270	100	29,97	3,468	3,837	3165,19	27,981	1476,10	2159,10	32,867	37,225	0,8829	0,3700	15,29
271	100	29,98	3,459	3,827	3163,82	27,982	1475,49	2156,61	32,815	37,163	0,8830	0,3701	15,49
272	100	29,98	3,460	3,827	3164,54	27,986	1476,05	2157,03	32,823	37,167	0,8831	0,3702	15,47
273	120	29,98	3,467	3,838	3795,79	27,453	1736,77	1773,15	32,993	37,221	0,8864	0,4437	19,23
274	120	29,98	3,466	3,837	3795,07	27,456	1736,64	1772,99	32,979	37,213	0,8862	0,4436	19,29
275	120	29,99	3,465	3,835	3796,58	27,450	1736,95	1772,75	32,995	37,204	0,8869	0,4439	19,31
276	110	29,98	3,464	3,831	3481,33	27,790	1612,42	1964,40	33,117	37,200	0,8902	0,4071	16,64
277	110	29,97	3,461	3,827	3480,33	27,789	1611,93	1963,35	33,090	37,176	0,8901	0,4071	16,75
278	110	29,99	3,466	3,834	3481,12	27,785	1612,03	1964,07	33,115	37,214	0,8899	0,4070	16,65
279	100	29,99	2,454	2,599	3166,09	27,681	1460,66	1624,71	25,008	28,167	0,8879	0,4278	25,18
280	100	29,99	2,456	2,601	3163,79	27,691	1460,15	1627,59	25,025	28,184	0,8879	0,4273	25,24
281	100	29,99	2,456	2,601	3163,10	27,702	1460,42	1628,50	25,023	28,183	0,8879	0,4272	25,20
282	120	30,00	2,425	2,600	3793,36	26,784	1693,32	1262,38	24,060	27,833	0,8645	0,5123	37,48
283	120	30,01	2,426	2,602	3794,09	26,786	1693,83	1263,11	24,077	27,843	0,8647	0,5123	37,59
284	120	30,01	2,425	2,601	3793,67	26,781	1693,29	1261,69	24,052	27,836	0,8641	0,5123	37,58
285	110	29,92	2,435	2,591	3483,53	27,236	1581,29	1427,42	24,569	27,951	0,8790	0,4713	31,45
286	110	29,92	2,438	2,595	3476,89	27,259	1579,62	1433,31	24,602	27,988	0,8790	0,4700	31,48
287	110	29,93	2,440	2,597	3479,29	27,252	1580,28	1432,68	24,615	28,009	0,8788	0,4702	31,51
288	90	29,94	2,458	2,595	2837,61	27,957	1322,17	1813,07	24,765	28,210	0,8779	0,3836	19,90
289	90	29,93	2,460	2,597	2855,10	27,953	1330,12	1809,59	24,874	28,233	0,8810	0,3858	19,99
290	90	29,93	2,461	2,598	2841,97	27,951	1323,95	1813,92	24,819	28,244	0,8788	0,3840	19,83
291	80	29,93	2,462	2,595	2536,93	28,046	1185,85	1981,47	24,120	28,247	0,8539	0,3430	16,65
292	80	29,93	2,462	2,596	2536,24	28,054	1185,86	1982,25	24,116	28,256	0,8535	0,3428	16,61
293	80	29,94	2,463	2,597	2537,35	28,050	1186,22	1981,91	24,126	28,266	0,8535	0,3429	16,55
294	100	29,94	3,467	3,837	3163,80	27,972	1474,97	2161,33	32,897	37,218	0,8839	0,3698	15,60
295	100	29,93	3,472	3,843	3163,72	27,975	1475,08	2163,41	32,925	37,253	0,8838	0,3696	15,58
296	100	29,93	3,477	3,850	3163,35	27,976	1474,94	2165,22	32,948	37,291	0,8835	0,3694	15,44
300	100	29,94	2,077	2,188	3161,70	27,017	1423,66	1313,21	20,681	23,457	0,8817	0,4662	37,39
301	100	29,94	2,077	2,189	3163,02	27,015	1424,15	1313,17	20,691	23,465	0,8817	0,4663	37,38
302	100	29,94	2,079	2,191	3168,69	27,009	1426,38	1312,27	20,718	23,493	0,8819	0,4669	37,35
303	120	29,94	2,096	2,187	3796,32	25,894	1638,38	981,67	19,368	23,727	0,8163	0,5599	31,68
304	120	29,93	2,097	2,189	3795,67	25,906	1638,86	982,75	19,377	23,742	0,8162	0,5596	31,71
305	120	29,93	2,099	2,191	3794,90	25,901	1638,20	984,70	19,415	23,764	0,8170	0,5592	31,70
306	110	29,94	2,109	2,195	3481,93	26,440	1534,35	1137,27	20,155	23,906	0,8431	0,5125	26,01
307	110	29,94	2,109	2,195	3482,24	26,429	1533,86	1137,66	20,172	23,907	0,8438	0,5126	25,98
308	110	29,94	2,110	2,196	3481,99	26,434	1534,04	1137,41	20,163	23,923	0,8428	0,5124	25,97
309	90	29,95	2,117	2,196	2846,87	27,556	1307,48	1514,59	21,057	24,009	0,8771	0,4189	14,09
310	90	29,95	2,117	2,197	2848,05	27,571	1308,71	1514,65	21,056	24,011	0,8769	0,4190	13,92
311	90	29,96	2,086	2,197	2847,92	27,562	1308,22	1514,40	21,058	23,588	0,8927	0,4189	35,34
312	80	29,94	2,106	2,193	2530,74	27,916	1177,48	1702,45	20,770	23,861	0,8704	0,3727	20,63
313	80	29,94	2,107	2,194	2531,32	27,911	1177,52	1702,01	20,773	23,871	0,8702	0,3727	20,70
314	80	29,95	2,106	2,194	2530,89	27,911	1177,32	1702,71	20,778	23,864	0,8707	0,3726	20,81
315	100	29,94	3,458	3,825	3163,31	27,968	1474,51	2157,20	32,835	37,156	0,8837	0,3701	15,57
316	100	29,93	3,461	3,830	3166,21	27,979	1476,46	2156,58	32,842	37,179	0,8833	0,3703	15,53

Table II. Reduced Test Data and Calculated Performance Parameters, Configuration 2A (PPPPLT) (Concluded).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
317	100	29.93	3.463	3.831	3165.60	27.973	1475.85	2157.36	32.855	37.189	0.8834	0.3702	15.56
318	100	29.98	3.649	4.085	3167.84	27.982	1477.39	2227.29	33.932	38.483	0.8817	0.3635	15.48
319	100	29.98	3.656	4.096	3167.01	27.980	1476.88	2230.63	33.977	38.534	0.8818	0.3631	15.60
320	100	29.98	3.662	4.103	3167.51	27.974	1476.79	2231.57	34.004	38.572	0.8816	0.3630	15.42
321	120	29.98	3.674	4.110	3791.92	27.482	1736.81	1850.35	34.358	38.651	0.8889	0.4343	17.58
322	120	29.98	3.690	4.132	3791.83	27.483	1736.82	1854.44	34.432	38.759	0.8884	0.4337	17.39
323	120	29.97	3.677	4.114	3792.11	27.489	1737.35	1852.47	34.390	38.670	0.8893	0.4342	17.56
324	109	29.97	3.669	4.105	3469.97	27.799	1607.69	2047.59	34.395	38.619	0.8906	0.3976	15.67
325	110	29.97	3.671	4.107	3471.93	27.801	1608.70	2046.74	34.398	38.630	0.8905	0.3978	15.58
326	110	29.96	3.669	4.105	3479.99	27.796	1612.19	2042.29	34.408	38.618	0.8910	0.3987	15.65
327	90	29.92	3.641	4.093	2845.17	28.055	1330.34	2417.53	32.994	38.434	0.8585	0.3263	17.08
328	90	29.91	3.649	4.102	2841.26	28.052	1328.37	2421.42	33.005	38.483	0.8576	0.3256	16.88
329	90	29.91	3.643	4.095	2844.16	28.055	1329.87	2418.45	32.995	38.446	0.8582	0.3261	17.02
330	80	29.91	3.622	4.099	2532.53	28.073	1184.95	2590.46	31.448	38.304	0.8210	0.2903	20.27
331	80	29.91	3.620	4.097	2529.45	28.084	1183.96	2592.98	31.428	38.289	0.8208	0.2900	20.33
332	80	29.94	3.608	4.080	2529.26	28.081	1183.76	2586.93	31.356	38.206	0.8207	0.2903	20.39
333	100	29.92	3.458	3.825	3161.83	27.976	1474.24	2158.64	32.832	37.157	0.8836	0.3699	15.50
335	100	29.92	3.459	3.825	3162.57	27.977	1474.64	2157.37	32.819	37.159	0.8832	0.3700	15.38
336	100	29.93	3.460	3.826	3162.10	27.970	1474.05	2158.02	32.832	37.166	0.8834	0.3699	15.44
337	100	29.93	3.458	3.824	3161.58	27.974	1474.01	2157.04	32.808	37.152	0.8831	0.3699	15.44
338	100	29.92	3.457	3.823	3161.64	27.982	1474.46	2157.89	32.812	37.146	0.8833	0.3700	15.48
339	100	29.93	3.456	3.822	3161.80	27.977	1474.28	2158.66	32.831	37.141	0.8840	0.3700	15.43
340	100	29.93	3.457	3.823	3161.88	27.982	1474.57	2158.31	32.821	37.147	0.8835	0.3700	15.45
341	100	29.93	3.459	3.826	3161.75	27.985	1474.68	2159.56	32.835	37.163	0.8835	0.3699	15.48
342	100	29.93	3.458	3.824	3161.83	27.982	1474.54	2158.22	32.819	37.151	0.8834	0.3700	15.52
343	100	29.92	2.791	2.994	3159.94	27.889	1468.81	1846.29	28.151	31.640	0.8897	0.4022	21.65
344	100	29.92	2.791	2.994	3160.24	27.899	1469.43	1846.71	28.151	31.637	0.8898	0.4023	21.68
345	100	29.92	2.792	2.995	3160.59	27.888	1469.06	1845.87	28.152	31.649	0.8895	0.4023	21.52

Table III. Reduced Test Data and Calculated Performance Parameters, Configuration 3A (PPTPLP).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
413	100	29.99	3.467	3.827	3160.97	27.918	1470.78	2161.32	32.932	37.218	0.8848	0.3698	13.66
414	100	30.00	3.470	3.830	3159.64	27.919	1470.25	2163.67	32.952	37.237	0.8849	0.3696	13.42
415	100	30.00	3.466	3.825	3160.44	27.921	1470.72	2161.28	32.922	37.212	0.8847	0.3698	13.35
416	120	29.96	3.468	3.823	3796.21	27.297	1727.09	1767.31	33.075	37.225	0.8885	0.4443	17.21
417	120	29.97	3.471	3.827	3795.83	27.293	1726.68	1766.22	33.056	37.250	0.8874	0.4441	17.12
418	120	29.97	3.472	3.828	3797.38	27.304	1728.05	1766.45	33.062	37.257	0.8874	0.4442	16.99
419	110	29.99	3.479	3.836	3476.58	27.681	1603.93	1966.95	33.245	37.302	0.8912	0.4064	14.30
420	110	30.00	3.478	3.834	3475.06	27.679	1603.11	1966.55	33.226	37.295	0.8909	0.4063	14.16
421	110	30.01	3.476	3.831	3473.79	27.675	1602.26	1965.43	33.200	37.282	0.8905	0.4063	13.91
422	90	29.99	3.463	3.833	2843.50	28.047	1329.19	2357.00	32.158	37.187	0.8648	0.3325	14.63
423	90	30.00	3.459	3.828	2843.34	28.041	1328.85	2354.79	32.133	37.164	0.8646	0.3326	14.59
424	90	29.99	3.461	3.830	2842.41	28.045	1328.59	2356.64	32.143	37.177	0.8646	0.3324	14.53
425	80	29.94	3.440	3.825	2527.45	28.090	1183.27	2534.56	30.690	37.024	0.8289	0.2957	17.55
426	80	29.96	3.440	3.826	2528.56	28.078	1183.27	2533.48	30.703	37.026	0.8292	0.2958	17.79
427	80	29.95	3.442	3.827	2528.56	28.081	1183.41	2534.29	30.710	37.040	0.8291	0.2958	17.52
428	100	29.99	3.474	3.837	3160.41	27.931	1471.24	2164.67	32.961	37.269	0.8844	0.3694	13.62
429	100	29.99	3.475	3.839	3160.53	27.938	1471.65	2167.32	32.995	37.275	0.8852	0.3694	13.98
430	100	29.99	3.480	3.846	3159.75	27.936	1471.16	2168.27	33.004	37.316	0.8845	0.3691	13.70
431	100	29.96	3.131	3.394	3161.39	27.896	1469.85	2016.22	30.749	34.644	0.8876	0.3845	14.22
432	100	29.96	3.130	3.392	3160.73	27.894	1469.43	2015.86	30.739	34.636	0.8875	0.3844	14.22
433	100	29.97	3.131	3.394	3160.78	27.892	1469.36	2015.34	30.734	34.642	0.8872	0.3844	14.27
434	120	29.97	3.128	3.401	3791.43	27.211	1719.49	1628.50	30.535	34.612	0.8822	0.4608	21.66
435	120	29.99	3.132	3.406	3791.50	27.190	1718.20	1628.18	30.553	34.649	0.8818	0.4605	21.71
436	120	29.99	3.131	3.404	3791.54	27.196	1718.59	1628.88	30.560	34.636	0.8823	0.4606	21.78
437	110	29.95	3.137	3.404	3477.39	27.598	1599.46	1820.90	30.876	34.691	0.8900	0.4225	17.52
438	110	29.96	3.136	3.403	3476.81	27.603	1599.50	1820.27	30.855	34.681	0.8897	0.4225	17.51
439	110	29.96	3.136	3.403	3475.82	27.600	1598.90	1820.18	30.847	34.684	0.8894	0.4223	17.38
440	90	29.97	3.133	3.399	2843.68	28.041	1328.99	2208.27	30.137	34.653	0.8697	0.3457	13.60
441	90	29.98	3.134	3.400	2843.90	28.038	1328.94	2208.99	30.153	34.666	0.8698	0.3456	13.48
442	90	29.97	3.133	3.399	2843.31	28.042	1328.85	2209.20	30.145	34.659	0.8698	0.3456	13.41
443	80	29.97	3.129	3.404	2526.93	28.088	1182.92	2394.14	28.986	34.625	0.8371	0.3070	15.15
444	80	29.97	3.128	3.402	2527.49	28.081	1182.90	2393.85	28.996	34.615	0.8377	0.3071	15.01
445	80	29.97	3.127	3.401	2527.43	28.087	1183.13	2393.60	28.986	34.605	0.8376	0.3071	15.31
446	100	29.94	3.462	3.823	3159.73	27.929	1470.81	2164.78	32.958	37.186	0.8863	0.3698	14.06
447	100	29.94	3.474	3.837	3159.17	27.934	1470.81	2165.89	32.963	37.273	0.8844	0.3693	13.54
448	100	29.93	3.474	3.838	3158.74	27.945	1471.17	2166.58	32.957	37.271	0.8843	0.3692	13.66
449	100	29.92	2.807	3.000	3159.55	27.829	1465.43	1849.06	28.252	31.796	0.8885	0.4019	16.84
450	100	29.91	2.807	2.999	3159.61	27.823	1465.16	1848.39	28.248	31.788	0.8886	0.4020	16.93
451	100	29.91	2.806	2.998	3159.15	27.828	1465.19	1850.06	28.264	31.783	0.8893	0.4019	16.99
452	120	29.90	2.778	2.986	3791.24	26.987	1705.26	1457.77	27.559	31.514	0.8745	0.4831	27.47
453	120	29.90	2.784	2.993	3791.76	26.985	1705.36	1457.07	27.552	31.574	0.8726	0.4827	27.37
454	120	29.90	2.783	2.992	3791.29	26.993	1705.61	1456.97	27.539	31.562	0.8725	0.4828	27.36
455	110	29.95	2.801	3.000	3476.00	27.440	1589.72	1649.14	28.113	31.735	0.8859	0.4422	21.87
456	110	29.95	2.801	3.000	3476.25	27.439	1589.77	1650.37	28.137	31.738	0.8865	0.4422	21.91
457	110	29.94	2.803	3.003	3476.23	27.443	1589.99	1651.22	28.147	31.757	0.8863	0.4420	21.90
458	90	29.97	2.808	2.999	2841.80	27.999	1326.10	2039.39	27.856	31.802	0.8759	0.3615	14.52
459	90	29.96	2.806	2.997	2841.63	28.013	1326.73	2040.42	27.854	31.780	0.8764	0.3616	14.59
460	90	29.96	2.807	2.998	2841.42	28.013	1326.60	2040.66	27.855	31.790	0.8762	0.3615	14.59
461	80	29.95	2.805	2.997	2526.97	28.076	1182.45	2223.98	26.938	31.769	0.8479	0.3215	14.01
462	80	29.95	2.805	2.998	2527.03	28.072	1182.33	2222.47	26.923	31.775	0.8473	0.3215	13.89

Table III. Reduced Test Data and Calculated Performance Parameters, Configuration 3A (PPTPLP) (Continued).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
463	80	29.95	2.804	2.997	2527.09	28.072	1182.35	2222.09	26.920	31.766	0.8474	0.3216	13.99
464	100	29.96	3.476	3.838	3157.09	27.928	1469.54	2169.62	33.005	37.281	0.8853	0.3690	13.44
465	100	29.96	3.473	3.835	3157.37	27.928	1469.63	2168.70	32.995	37.264	0.8854	0.3691	13.64
466	100	29.96	3.477	3.840	3157.66	27.925	1469.62	2169.68	33.016	37.293	0.8853	0.3690	13.42
467	100	29.95	2.457	2.594	3157.50	27.572	1450.95	1623.18	25.015	28.196	0.8872	0.4269	22.60
468	100	29.95	2.458	2.596	3157.30	27.584	1451.50	1623.90	25.014	28.211	0.8867	0.4268	22.65
469	100	29.96	2.455	2.592	3157.39	27.573	1450.95	1622.25	24.999	28.175	0.8873	0.4271	22.66
470	120	29.96	2.435	2.596	3792.47	26.543	1677.75	1244.64	23.931	27.947	0.8563	0.5126	34.73
471	120	29.96	2.435	2.596	3792.51	26.545	1677.87	1244.58	23.929	27.949	0.8562	0.5126	34.72
472	120	29.96	2.435	2.597	3792.27	26.563	1678.93	1245.53	23.929	27.953	0.8561	0.5125	34.73
473	110	29.96	2.446	2.593	3479.02	27.073	1569.79	1421.76	24.587	28.075	0.8758	0.4705	28.83
474	110	29.96	2.446	2.593	3480.17	27.069	1570.09	1421.05	24.586	28.073	0.8758	0.4707	28.81
475	110	29.96	2.446	2.593	3479.29	27.076	1570.09	1421.36	24.579	28.072	0.8756	0.4706	28.83
476	90	29.95	2.462	2.594	2847.94	27.932	1325.81	1816.95	24.930	28.255	0.8823	0.3851	17.35
477	90	29.95	2.463	2.595	2849.03	27.928	1326.14	1816.27	24.934	28.261	0.8823	0.3852	17.36
479	80	29.94	2.466	2.597	2534.01	28.043	1184.36	1998.66	24.304	28.295	0.8589	0.3424	15.08
480	80	29.94	2.466	2.597	2534.28	28.063	1185.31	1999.16	24.296	28.293	0.8587	0.3425	15.04
482	100	29.92	3.471	3.833	3166.05	27.915	1473.01	2164.53	33.037	37.249	0.8869	0.3702	13.95
483	100	29.91	3.466	3.826	3166.07	27.900	1472.24	2162.67	33.027	37.210	0.8876	0.3704	14.09
484	100	29.93	3.453	3.809	3165.02	27.925	1473.05	2156.08	32.886	37.118	0.8860	0.3708	13.95
485	100	29.93	2.090	2.186	3165.19	26.806	1414.08	1300.58	20.667	23.639	0.8743	0.4670	31.56
486	100	29.92	2.093	2.190	3166.79	26.824	1415.76	1303.80	20.714	23.683	0.8747	0.4668	31.65
487	100	29.93	2.096	2.193	3167.12	26.834	1416.43	1305.50	20.736	23.722	0.8741	0.4664	31.62
489	120	29.93	2.068	2.191	3796.03	25.619	1620.87	964.54	19.233	23.333	0.8243	0.5593	43.89
490	120	29.93	2.067	2.191	3796.12	25.616	1620.67	965.35	19.252	23.326	0.8253	0.5594	43.88
491	110	29.93	2.079	2.185	3482.10	26.175	1519.05	1122.26	20.091	23.483	0.8556	0.5138	38.01
492	110	29.94	2.085	2.194	3482.21	26.180	1519.40	1121.66	20.077	23.579	0.8515	0.5128	38.00
493	110	29.95	2.085	2.193	3484.35	26.229	1523.17	1121.25	20.045	23.571	0.8504	0.5131	38.01
494	90	29.93	2.110	2.200	2846.85	27.444	1302.13	1515.48	21.156	23.919	0.8845	0.4185	24.36
495	90	29.94	2.110	2.199	2846.87	27.447	1302.30	1515.05	21.147	23.912	0.8844	0.4186	24.33
496	90	29.94	2.111	2.200	2846.78	27.451	1302.47	1515.84	21.155	23.929	0.8841	0.4184	24.30
497	80	29.93	2.111	2.196	2532.37	27.863	1175.97	1708.76	20.900	23.929	0.8734	0.3727	18.25
498	80	29.92	2.111	2.196	2532.04	27.868	1176.07	1710.13	20.910	23.929	0.8738	0.3726	18.21
499	80	29.93	2.113	2.198	2531.60	27.862	1175.59	1709.87	20.908	23.954	0.8728	0.3724	18.17
500	100	29.93	3.466	3.825	3165.07	27.908	1472.16	2162.58	33.006	37.210	0.8870	0.3703	13.71
501	100	29.93	3.470	3.831	3163.89	27.916	1472.05	2164.85	33.019	37.243	0.8866	0.3700	13.73
502	100	29.82	3.075	3.517	3163.97	27.486	1449.42	2173.80	33.674	34.174	0.9854	0.3802	41.82
503	100	29.94	3.628	4.044	3163.19	27.886	1470.16	2221.21	33.907	38.344	0.8843	0.3640	13.85
504	100	29.94	3.616	4.030	3164.00	27.923	1472.45	2226.35	33.950	38.264	0.8872	0.3645	14.08
505	100	29.79	3.227	3.542	3164.60	27.315	1440.70	2236.63	34.871	35.414	0.9847	0.3794	26.06
506	120	29.92	3.672	4.088	3798.83	27.331	1730.42	1839.45	34.407	38.643	0.8904	0.4358	15.01
507	120	29.93	3.673	4.089	3798.19	27.331	1730.16	1840.07	34.412	38.646	0.8904	0.4357	15.00
508	120	29.92	3.677	4.095	3798.60	27.327	1730.08	1841.65	34.451	38.674	0.8908	0.4356	15.10
509	110	29.94	3.670	4.091	3479.80	27.681	1605.44	2038.68	34.488	38.628	0.8928	0.3991	13.45
510	110	29.93	3.670	4.090	3481.66	27.681	1606.24	2038.08	34.498	38.628	0.8931	0.3993	13.42
511	110	29.94	3.671	4.091	3478.45	27.647	1602.82	2038.73	34.519	38.636	0.8934	0.3990	13.44
512	90	29.93	3.645	4.086	2847.80	28.029	1330.36	2427.70	33.193	38.457	0.8631	0.3267	15.52
513	90	29.93	3.653	4.099	2847.53	28.031	1330.34	2428.69	33.201	38.515	0.8620	0.3264	15.62
514	90	29.94	3.649	4.096	2846.90	28.066	1331.70	2426.10	33.117	38.489	0.8604	0.3264	15.62
515	80	29.92	3.622	4.093	2530.41	28.072	1183.91	2604.08	31.588	38.306	0.8246	0.2902	19.56

Table III. Reduced Test Data and Calculated Performance Parameters, Configuration 3A (PPTPLP) (Concluded).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/Co	FLOWANG
516	80	29.92	3.616	4.085	2536.99	28.078	1187.24	2600.03	31.615	38.264	0.8262	0.2911	19.76
517	80	29.92	3.616	4.084	2529.98	28.081	1184.07	2603.47	31.566	38.260	0.8250	0.2903	19.61
518	100	29.95	3.473	3.834	3161.32	27.912	1470.67	2164.52	32.991	37.262	0.8854	0.3696	13.45
519	100	29.94	3.469	3.829	3160.53	27.912	1470.30	2164.10	32.976	37.235	0.8856	0.3697	13.36
520	100	29.96	3.460	3.816	3160.81	27.909	1470.23	2158.19	32.893	37.166	0.8850	0.3701	13.28

Table IV. Reduced Test Data and Calculated Performance Parameters, Configuration 4A (PPTPPP).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
156	100	29.93	3.478	3.828	3157.28	27.960	1471.27	2171.93	33.006	37.300	0.8849	0.3693	8.45
157	100	29.93	3.479	3.828	3159.59	27.948	1471.71	2169.71	33.010	37.305	0.8849	0.3696	8.32
158	100	29.93	3.476	3.825	3165.42	27.951	1474.61	2166.42	33.017	37.287	0.8855	0.3704	8.50
162	110	29.91	3.481	3.827	3484.12	27.680	1607.32	1967.70	33.331	37.321	0.8931	0.4076	10.81
163	110	29.90	3.480	3.826	3488.86	27.686	1609.86	1965.40	33.330	37.313	0.8933	0.4082	10.70
164	110	29.90	3.481	3.827	3486.03	27.691	1608.85	1966.00	33.307	37.317	0.8926	0.4078	10.69
168	90	29.92	3.467	3.824	2850.51	28.052	1332.69	2358.22	32.248	37.222	0.8664	0.3336	10.09
169	90	29.92	3.477	3.836	2850.59	28.047	1332.51	2362.73	32.316	37.288	0.8667	0.3332	10.23
170	90	29.92	3.477	3.836	2850.71	28.049	1332.66	2362.10	32.307	37.289	0.8664	0.3333	10.14
171	80	29.91	3.452	3.823	2530.48	28.090	1184.68	2542.49	30.823	37.112	0.8305	0.2961	13.63
172	80	29.91	3.449	3.819	2529.32	28.086	1183.97	2542.02	30.808	37.090	0.8306	0.2961	13.79
173	80	29.91	3.463	3.837	2539.55	28.082	1188.59	2542.47	30.942	37.189	0.8320	0.2968	13.87
174	100	29.91	3.480	3.829	3164.31	27.927	1472.83	2168.51	33.065	37.312	0.8862	0.3701	8.75
175	100	29.90	3.481	3.831	3164.11	27.940	1473.41	2168.57	33.049	37.316	0.8856	0.3700	8.72
176	100	29.90	3.484	3.835	3160.66	27.940	1471.81	2171.94	33.065	37.341	0.8855	0.3695	8.77
177	100	29.90	3.483	3.833	3162.23	27.938	1472.44	2171.08	33.070	37.332	0.8858	0.3698	8.67
178	100	29.90	3.487	3.839	3164.26	27.936	1473.30	2170.38	33.083	37.359	0.8855	0.3698	8.83
179	100	29.90	3.487	3.839	3164.25	27.938	1473.38	2171.30	33.094	37.362	0.8858	0.3698	8.74
180	100	29.91	3.140	3.395	3167.14	27.896	1472.49	2018.77	30.844	34.717	0.8885	0.3851	9.86
181	100	29.91	3.136	3.390	3168.17	27.897	1473.05	2017.98	30.841	34.680	0.8893	0.3855	10.01
182	100	29.92	3.144	3.399	3166.10	27.893	1471.85	2020.56	30.865	34.745	0.8883	0.3848	9.98
183	120	29.93	3.125	3.391	3792.53	27.219	1720.51	1629.29	30.550	34.588	0.8833	0.4614	20.36
184	120	29.92	3.123	3.390	3799.48	27.209	1723.00	1624.08	30.520	34.577	0.8827	0.4623	20.40
185	120	29.92	3.122	3.388	3791.64	27.223	1720.32	1628.12	30.517	34.563	0.8829	0.4614	20.36
186	110	29.94	3.133	3.393	3479.97	27.606	1601.13	1821.60	30.902	34.654	0.8917	0.4233	15.68
187	110	29.94	3.135	3.396	3480.17	27.611	1601.54	1822.51	30.913	34.675	0.8915	0.4232	15.60
188	110	29.93	3.136	3.397	3483.07	27.611	1602.84	1821.64	30.925	34.683	0.8916	0.4235	15.55
189	90	29.93	3.140	3.397	2843.94	28.029	1328.57	2214.54	30.238	34.714	0.8710	0.3458	8.53
190	90	29.93	3.141	3.398	2844.14	28.031	1328.76	2215.39	30.249	34.723	0.8712	0.3457	8.41
192	80	29.95	3.128	3.390	2530.57	28.072	1183.98	2396.84	29.076	34.619	0.8399	0.3079	10.29
193	80	29.95	3.128	3.389	2532.80	28.075	1185.14	2395.63	29.084	34.615	0.8402	0.3082	10.32
194	80	29.94	3.127	3.388	2532.60	28.076	1185.09	2395.40	29.078	34.608	0.8402	0.3082	10.23
195	100	29.99	3.467	3.812	3170.07	27.905	1474.34	2160.61	33.031	37.222	0.8874	0.3713	8.73
196	100	29.98	3.469	3.813	3169.13	27.903	1473.78	2161.89	33.044	37.232	0.8875	0.3711	8.61
197	100	29.98	3.474	3.820	3171.42	27.900	1474.71	2162.73	33.083	37.271	0.8876	0.3712	8.50
198	100	29.94	3.663	4.075	3170.90	27.905	1474.73	2244.72	34.326	38.581	0.8897	0.3641	9.47
199	100	29.95	3.690	4.112	3173.03	27.916	1476.31	2245.18	34.342	38.762	0.8860	0.3634	8.99
200	100	29.95	3.694	4.118	3170.27	27.919	1475.17	2247.46	34.344	38.787	0.8855	0.3629	9.00
201	120	29.96	3.692	4.105	3799.39	27.359	1732.49	1849.01	34.554	38.774	0.8912	0.4353	12.65
202	120	29.96	3.691	4.104	3798.91	27.360	1732.30	1848.34	34.537	38.767	0.8909	0.4353	12.65
203	120	29.96	3.696	4.110	3799.98	27.359	1732.70	1848.05	34.543	38.802	0.8902	0.4352	12.34
204	110	29.91	3.685	4.094	3486.18	27.692	1609.01	2042.16	34.597	38.728	0.8933	0.3997	8.71
205	110	29.90	3.681	4.089	3484.77	27.708	1609.25	2041.75	34.557	38.702	0.8929	0.3997	8.58
206	110	29.91	3.681	4.089	3484.31	27.705	1608.90	2042.31	34.565	38.701	0.8931	0.3997	8.59
207	90	29.90	3.656	4.083	2851.11	28.047	1332.75	2435.07	33.312	38.533	0.8645	0.3272	11.27
208	90	29.90	3.653	4.080	2850.49	28.054	1332.81	2434.51	33.288	38.516	0.8643	0.3272	11.31
209	90	29.90	3.662	4.091	2849.95	28.053	1332.49	2436.91	33.316	38.576	0.8636	0.3269	11.00
210	100	29.89	3.475	3.824	3162.01	27.935	1472.19	2169.93	33.053	37.280	0.8866	0.3700	8.72
211	100	29.90	3.474	3.822	3163.85	27.947	1473.69	2167.97	33.028	37.271	0.8862	0.3703	8.34
212	100	29.89	3.476	3.823	3159.91	27.934	1471.14	2169.75	33.030	37.281	0.8860	0.3698	8.50

Table V. Reduced Test Data and Calculated Performance Parameters, Configuration 5A (PPTP).

RDG	PCT NDES	PTO	PTO/PTS	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
521	100	29.96	2.731	3.382	3161.60	27.943	1472.42	1779.33	27.093	31.058	0.8723	0.3058	44.23
522	100	29.96	2.729	3.380	3161.36	27.951	1472.71	1779.10	27.079	31.043	0.8723	0.3059	44.24
523	100	29.97	2.730	3.380	3160.88	27.939	1471.84	1778.82	27.083	31.050	0.8722	0.3058	44.24
524	120	29.97	2.849	3.384	3790.64	27.395	1730.77	1515.96	28.228	32.184	0.8771	0.3666	38.15
525	120	29.97	2.848	3.381	3790.29	27.399	1730.87	1515.88	28.220	32.171	0.8772	0.3666	38.16
526	120	29.96	2.844	3.376	3791.62	27.405	1731.82	1508.65	28.089	32.136	0.8741	0.3670	38.16
527	80	29.96	2.610	3.380	2526.45	28.087	1182.68	2017.68	24.424	29.842	0.8184	0.2444	48.92
528	80	29.96	2.612	3.389	2526.64	28.104	1183.46	2018.38	24.420	29.869	0.8176	0.2442	48.92
529	80	29.96	2.608	3.378	2528.19	28.092	1183.68	2018.29	24.444	29.829	0.8195	0.2446	48.92
530	100	29.92	2.729	3.383	3162.56	27.965	1474.03	1779.89	27.088	31.038	0.8727	0.3059	44.32
531	100	29.92	2.731	3.387	3162.26	27.962	1473.72	1780.09	27.091	31.063	0.8721	0.3057	44.31
532	100	29.91	2.717	3.360	3160.31	27.971	1473.30	1776.56	27.012	30.923	0.8735	0.3064	44.32
533	100	29.91	2.871	3.790	3171.84	27.961	1478.14	1842.30	28.124	32.386	0.8684	0.2956	46.23
534	100	29.92	2.871	3.789	3176.78	27.959	1480.33	1839.96	28.134	32.385	0.8687	0.2961	46.22
535	100	29.91	2.871	3.790	3165.84	27.952	1474.87	1843.95	28.105	32.390	0.8677	0.2951	46.22
536	120	29.90	3.024	3.796	3802.26	27.407	1736.83	1581.93	29.534	33.742	0.8753	0.3542	41.13
537	120	29.89	3.026	3.800	3800.07	27.417	1736.44	1583.50	29.536	33.757	0.8750	0.3539	41.12
538	120	29.90	3.025	3.800	3802.74	27.415	1737.55	1582.98	29.549	33.756	0.8754	0.3542	41.12
539	100	29.88	2.723	3.373	3160.14	27.941	1471.64	1780.31	27.097	30.983	0.8746	0.3059	44.43
540	100	29.88	2.723	3.374	3162.52	27.942	1472.81	1779.01	27.096	30.987	0.8744	0.3061	44.42
541	100	29.88	2.720	3.368	3167.11	27.945	1475.06	1775.76	27.084	30.955	0.8749	0.3068	44.44
542	100	29.88	2.721	3.371	3159.84	27.943	1471.58	1778.14	27.060	30.968	0.8738	0.3060	44.43
543	100	29.88	2.720	3.368	3161.23	27.941	1472.11	1778.46	27.078	30.958	0.8747	0.3062	44.43
544	100	29.88	2.721	3.369	3164.43	27.935	1473.32	1777.01	27.089	30.960	0.8750	0.3065	44.44
545	100	29.89	2.501	2.889	3163.82	27.893	1470.78	1655.17	25.265	28.681	0.8809	0.3245	40.39
546	100	29.88	2.500	2.888	3163.94	27.897	1471.07	1654.98	25.260	28.669	0.8811	0.3245	40.38
547	100	29.87	2.499	2.887	3163.37	27.902	1471.09	1655.18	25.253	28.663	0.8810	0.3245	40.38
548	120	29.87	2.588	2.893	3808.40	27.267	1730.74	1383.09	25.996	29.610	0.8779	0.3904	31.67
549	120	29.87	2.589	2.894	3808.45	27.246	1729.43	1383.70	26.028	29.622	0.8787	0.3903	31.67
550	120	29.88	2.589	2.894	3808.66	27.259	1730.33	1382.17	25.989	29.622	0.8773	0.3903	31.67
551	80	29.87	2.418	2.899	2530.76	28.075	1184.17	1903.97	23.097	27.761	0.8320	0.2592	46.46
552	80	29.87	2.417	2.897	2534.41	28.075	1185.89	1902.52	23.112	27.747	0.8330	0.2596	46.46
553	80	29.86	2.416	2.896	2530.69	28.084	1184.53	1904.56	23.096	27.738	0.8326	0.2593	46.46
554	100	29.86	2.263	2.496	3160.10	27.769	1462.54	1496.46	22.917	25.905	0.8847	0.3456	35.64
555	100	29.87	2.263	2.496	3160.26	27.758	1462.03	1495.24	22.909	25.904	0.8844	0.3456	35.65
556	100	29.86	2.261	2.493	3161.35	27.761	1462.69	1494.72	22.907	25.883	0.8850	0.3459	35.66
557	120	29.86	2.320	2.498	3810.55	26.950	1711.59	1221.41	23.240	26.607	0.8735	0.4166	24.10
558	120	29.87	2.319	2.497	3808.73	26.951	1710.85	1222.59	23.251	26.598	0.8742	0.4165	24.09
559	120	29.86	2.320	2.497	3808.22	26.956	1710.89	1222.94	23.251	26.601	0.8740	0.4164	24.10
560	80	29.86	2.204	2.497	2536.18	28.066	1186.34	1749.31	21.273	25.166	0.8453	0.2773	43.08
561	80	29.87	2.205	2.497	2536.45	28.055	1186.00	1748.65	21.275	25.171	0.8452	0.2773	43.08
562	80	29.86	2.204	2.496	2532.98	28.064	1184.77	1749.31	21.247	25.155	0.8446	0.2770	43.07
563	100	29.86	2.725	3.388	3160.86	27.946	1472.21	1783.66	27.149	31.007	0.8756	0.3056	44.68
564	100	29.86	2.723	3.382	3160.95	27.930	1471.44	1782.23	27.143	30.984	0.8761	0.3058	44.68
565	100	29.86	2.724	3.383	3160.58	27.937	1471.60	1782.43	27.137	30.989	0.8757	0.3057	44.68
566	100	29.89	2.049	2.190	3164.04	27.368	1443.24	1310.20	20.384	23.070	0.8836	0.3705	29.53
567	100	29.88	2.051	2.192	3164.84	27.367	1443.53	1310.00	20.387	23.092	0.8829	0.3704	29.54
568	100	29.89	2.050	2.191	3163.84	27.373	1443.40	1310.69	20.387	23.086	0.8831	0.3703	29.56
569	120	29.91	2.083	2.193	3796.23	26.388	1669.57	1049.90	20.326	23.543	0.8634	0.4441	16.91
570	120	29.91	2.085	2.195	3796.66	26.390	1669.88	1051.87	20.365	23.566	0.8642	0.4439	16.89

Table V. Reduced Test Data and Calculated Performance Parameters, Configuration 5A (PPTP) (Concluded).

RDG	PCT NDES	PTO	PTO/PT3	PTO/PS3	N EQV	WA EQV	WAN EQV	TQ EQV	DH EQV	DHI EQV	ETA TT	U/CO	FLOWANG
571	120	29.91	2.085	2.196	3796.97	26.384	1669.65	1051.50	20.364	23.577	0.8637	0.4439	16.92
572	80	29.93	2.010	2.195	2532.04	27.973	1180.47	1580.99	19.259	22.507	0.8557	0.2961	39.23
573	80	29.93	2.009	2.194	2532.50	27.971	1180.61	1579.77	19.248	22.494	0.8557	0.2962	39.24
574	80	29.93	2.008	2.193	2532.36	27.976	1180.73	1579.07	19.236	22.483	0.8556	0.2963	39.24
575	100	29.92	2.734	3.383	3165.88	27.910	1472.67	1777.63	27.135	31.091	0.8728	0.3062	44.15
576	100	29.91	2.734	3.382	3167.73	27.914	1473.72	1777.70	27.149	31.088	0.8733	0.3064	44.15
577	100	29.91	2.736	3.386	3167.30	27.914	1473.54	1778.08	27.150	31.109	0.8728	0.3062	44.14
578	100	29.91	2.880	3.798	3167.89	27.923	1474.31	1844.25	28.157	32.472	0.8671	0.2951	46.06
579	100	29.91	2.881	3.798	3166.46	27.919	1473.41	1844.95	28.159	32.475	0.8671	0.2950	46.05
580	100	29.91	2.882	3.802	3167.16	27.932	1474.40	1845.91	28.167	32.485	0.8671	0.2949	46.06
581	88	29.89	2.801	3.786	2791.77	28.037	1304.55	1987.37	26.631	31.735	0.8392	0.2603	48.16
582	88	29.89	2.799	3.781	2791.31	28.037	1304.34	1988.25	26.638	31.719	0.8398	0.2604	48.17
583	88	29.89	2.801	3.787	2791.01	28.038	1304.24	1988.12	26.633	31.738	0.8391	0.2602	48.16
584	88	29.88	2.804	3.794	2789.49	28.044	1303.79	1989.49	26.631	31.759	0.8385	0.2599	48.16
585	88	29.88	2.802	3.791	2790.17	28.046	1304.24	1989.13	26.630	31.747	0.8388	0.2600	48.16
586	88	29.88	2.803	3.795	2789.77	28.052	1304.32	1989.63	26.628	31.757	0.8385	0.2599	48.16
587	100	29.87	1.817	1.895	3162.85	26.452	1394.41	1062.22	17.092	19.532	0.8751	0.4060	20.67
588	100	29.87	1.817	1.895	3164.87	26.454	1395.41	1060.37	17.072	19.529	0.8742	0.4063	20.68
589	100	29.87	1.817	1.895	3164.43	26.454	1395.18	1061.65	17.090	19.533	0.8749	0.4062	20.70
590	100	29.88	2.725	3.370	3162.22	27.934	1472.20	1776.73	27.067	31.002	0.8731	0.3062	44.23
591	100	29.88	2.728	3.376	3162.21	27.934	1472.23	1778.72	27.097	31.032	0.8732	0.3061	44.23
592	100	29.87	2.726	3.373	3162.16	27.944	1472.70	1778.43	27.083	31.014	0.8733	0.3062	44.23

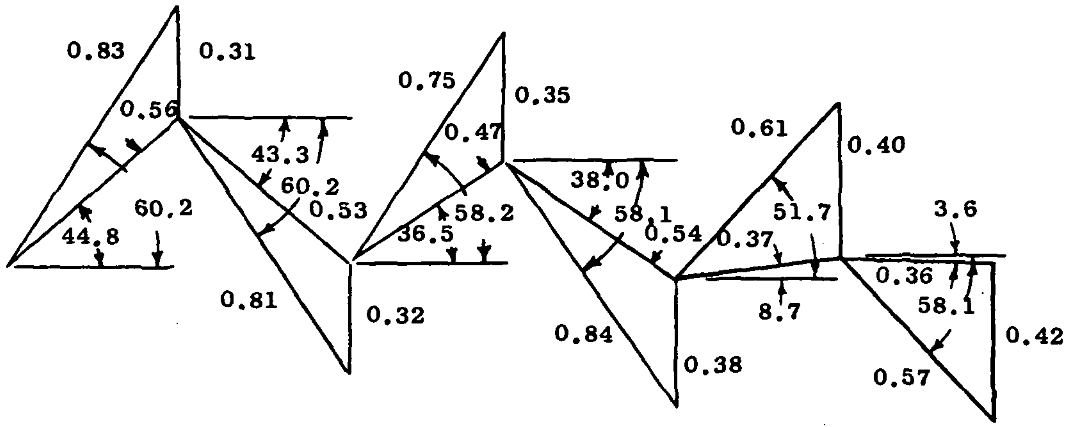
Table VI. Overall and Stage Performance Summary.

Stage	Configuration	Equivalent Specific Work, E/θ_{cr}	Total-to-Total Pressure Ratio	Total-to-Total Efficiency, η_{TT}
OVERALL PERFORMANCE				
1	3-PP	13.76	1.604	0.875
1 + 2	2-PPPP	26.38	2.66	0.868
1 + 2	4-PPTP	26.78	2.66	0.880
1 + 2 + 3	1-PPPPPP	33.00	3.47	0.886
1 + 2 + 3	5-PPPPPT	32.97	3.47	0.885
1 + 2 + 3	6-PPTPTT	32.90	3.47	0.883
1 + 2 + 3	7-PPPPLP	33.00	3.47	0.886
1 + 2 + 3	2A-PPPPLT	32.90	3.47	0.883
1 + 2 + 3	3A-PPTPLP	33.00	3.47	0.886
1 + 2 + 3	4A-PPTPPP	33.05	3.47	0.887
STAGE PERFORMANCE				
1	PP/	13.76	1.604	0.875
2	/PP/	12.62	1.658	0.846
2	/TP/	13.02	1.658	0.873
3	/PP[1]	6.62	1.305	0.923
3	/PT	6.62	1.305	0.918
3	/TT	6.12	1.305	0.856
3	/LP[2]	6.62	1.305	0.923
3	/LT	6.52	1.305	0.909
3	/PP[3]	6.35	1.305	0.877

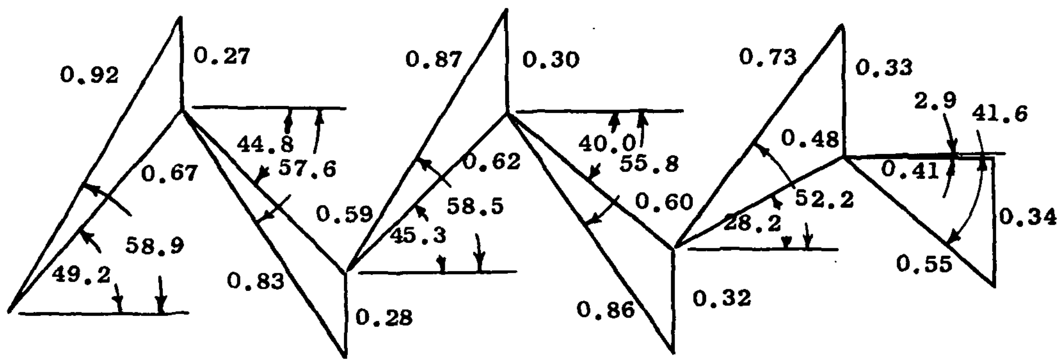
[1] As tested in Configuration 1 (PPPPPP).

[2] As tested in Configuration 7 (PPPPLP).

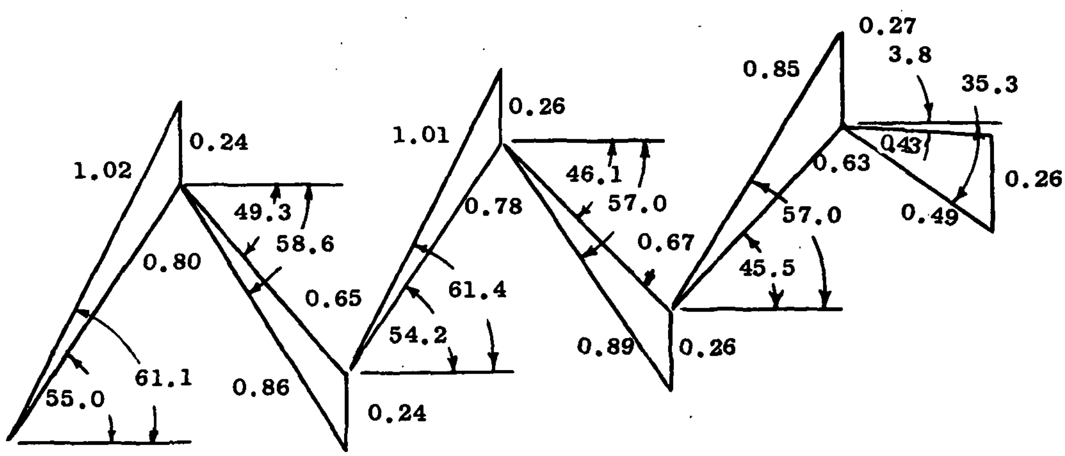
[3] As tested in Configuration 4A (PPTPPP).



TIP



PITCH



HUB

Numbers Shown on Velocity Diagrams are Angles in Degrees and Mach Numbers

Figure 1. Turbine Design Velocity Diagrams.

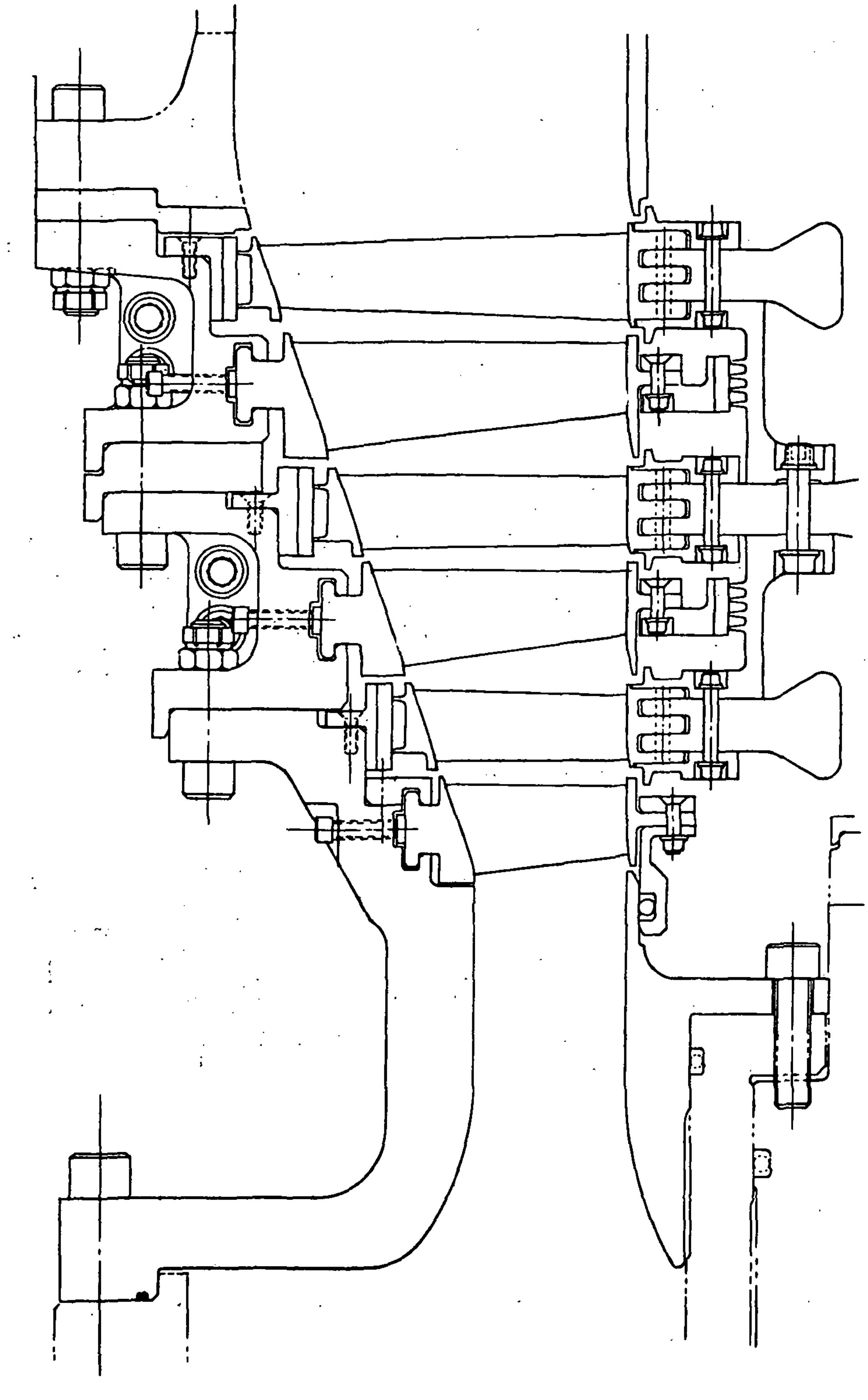


Figure 2. Three-Stage Turbine Flowpath.

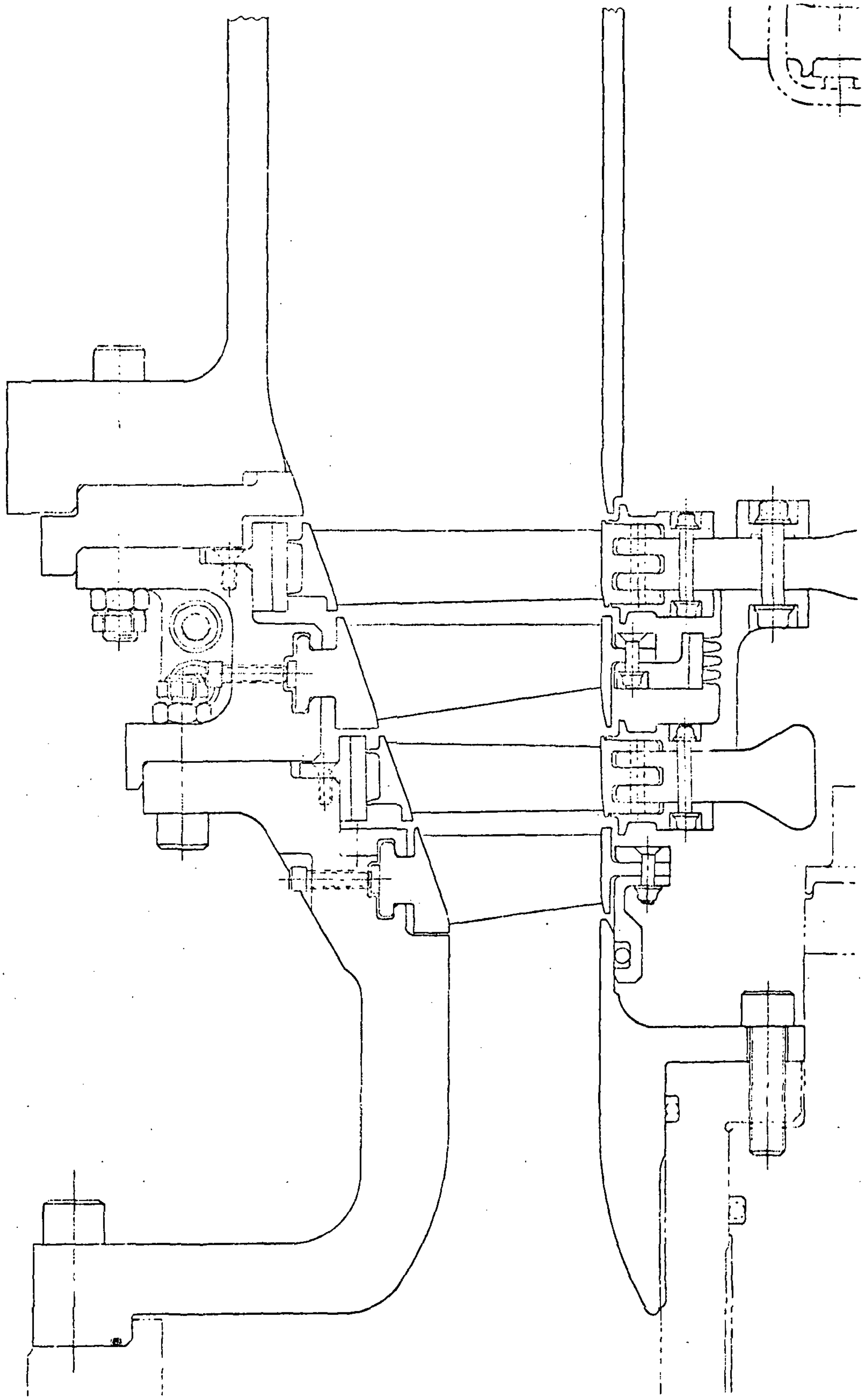


Figure 3. Two-Stage Turbine Flowpath.

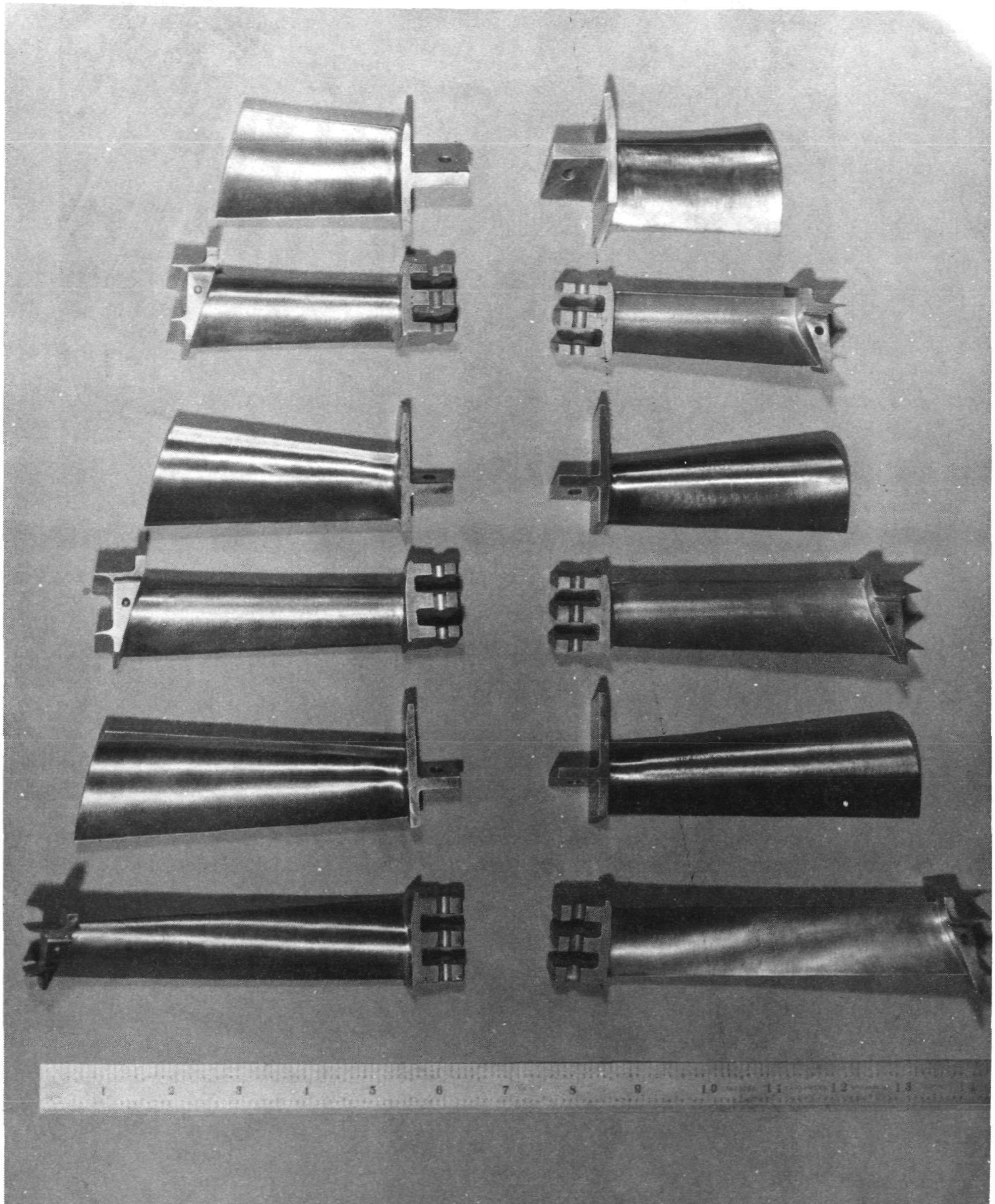


Figure 4. Plain Blade Airfoils.

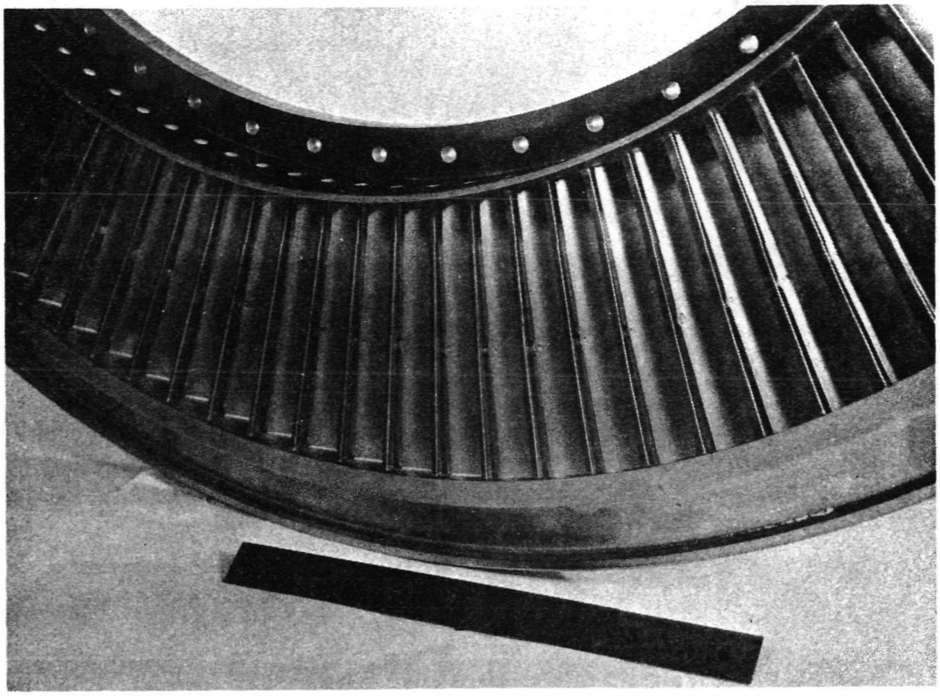


Figure 5. Stage Two Tandem Stator Assembled.

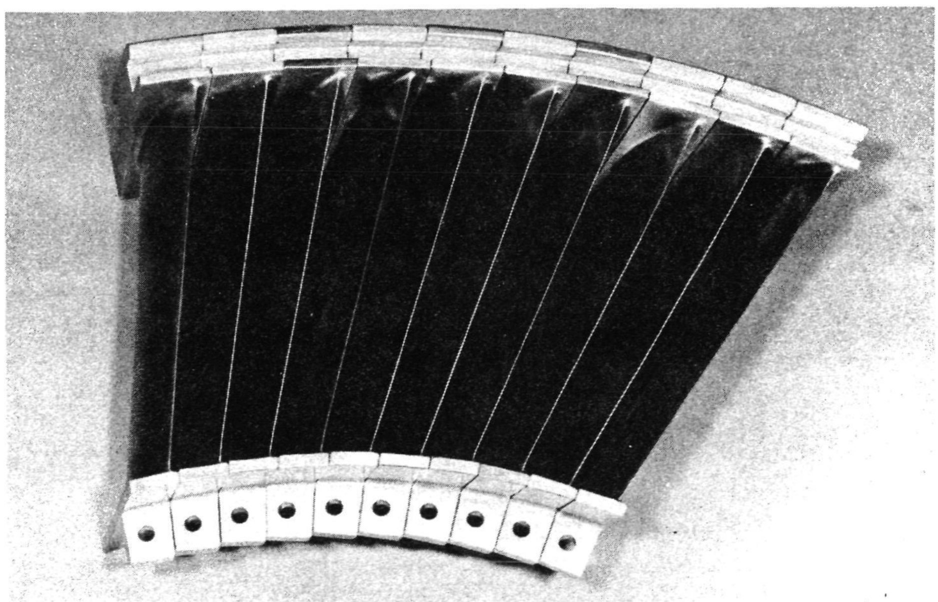


Figure 6. Stage Three Tangentially Leaned Stator Airfoils Viewed Aft Looking Forward.

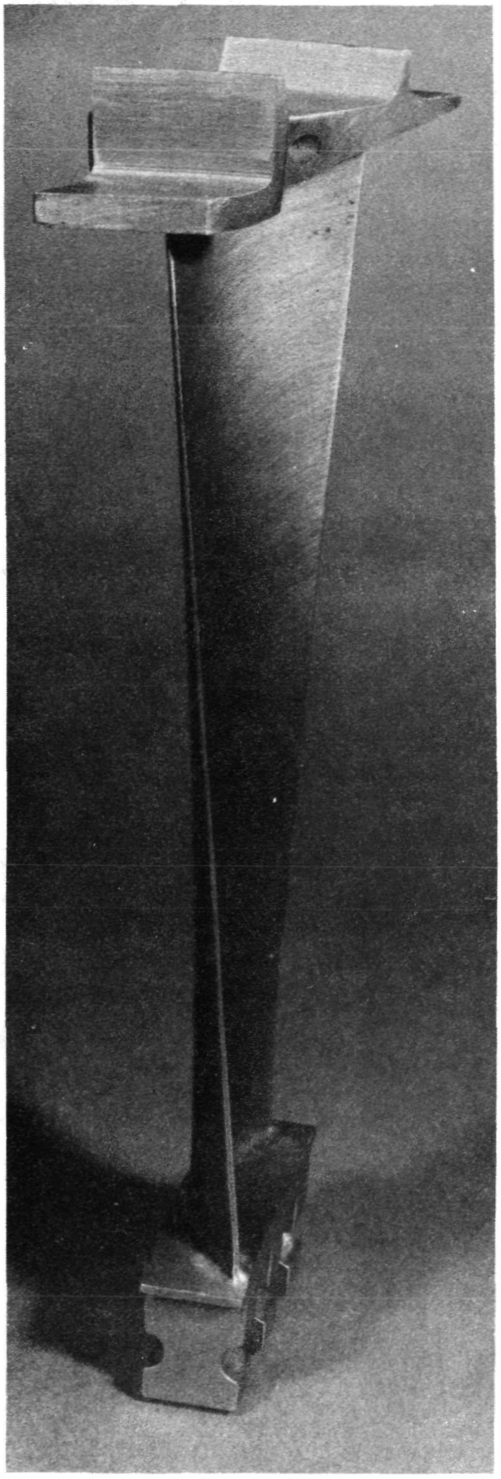


Figure 7. Stage Three Rotor Plain Blade.

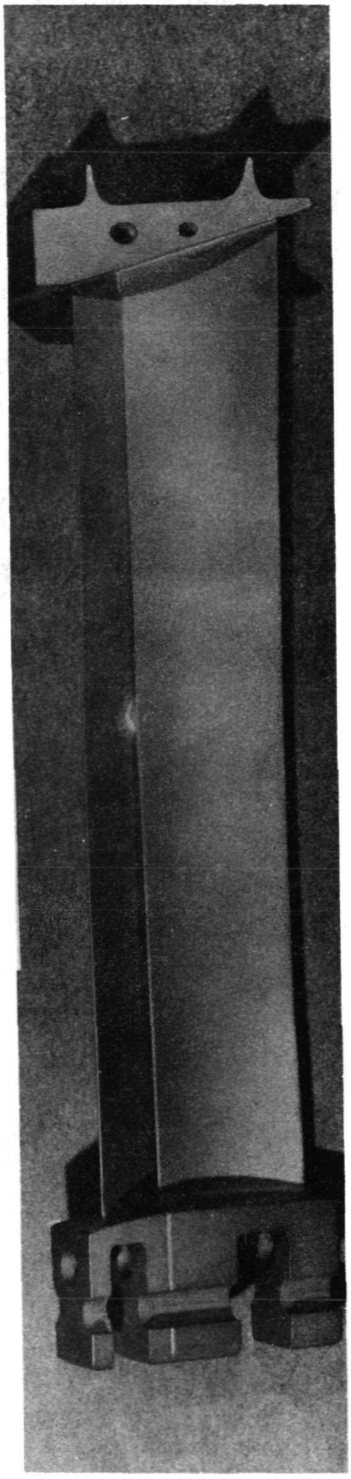


Figure 8. Stage Three Rotor Tandem Blade.

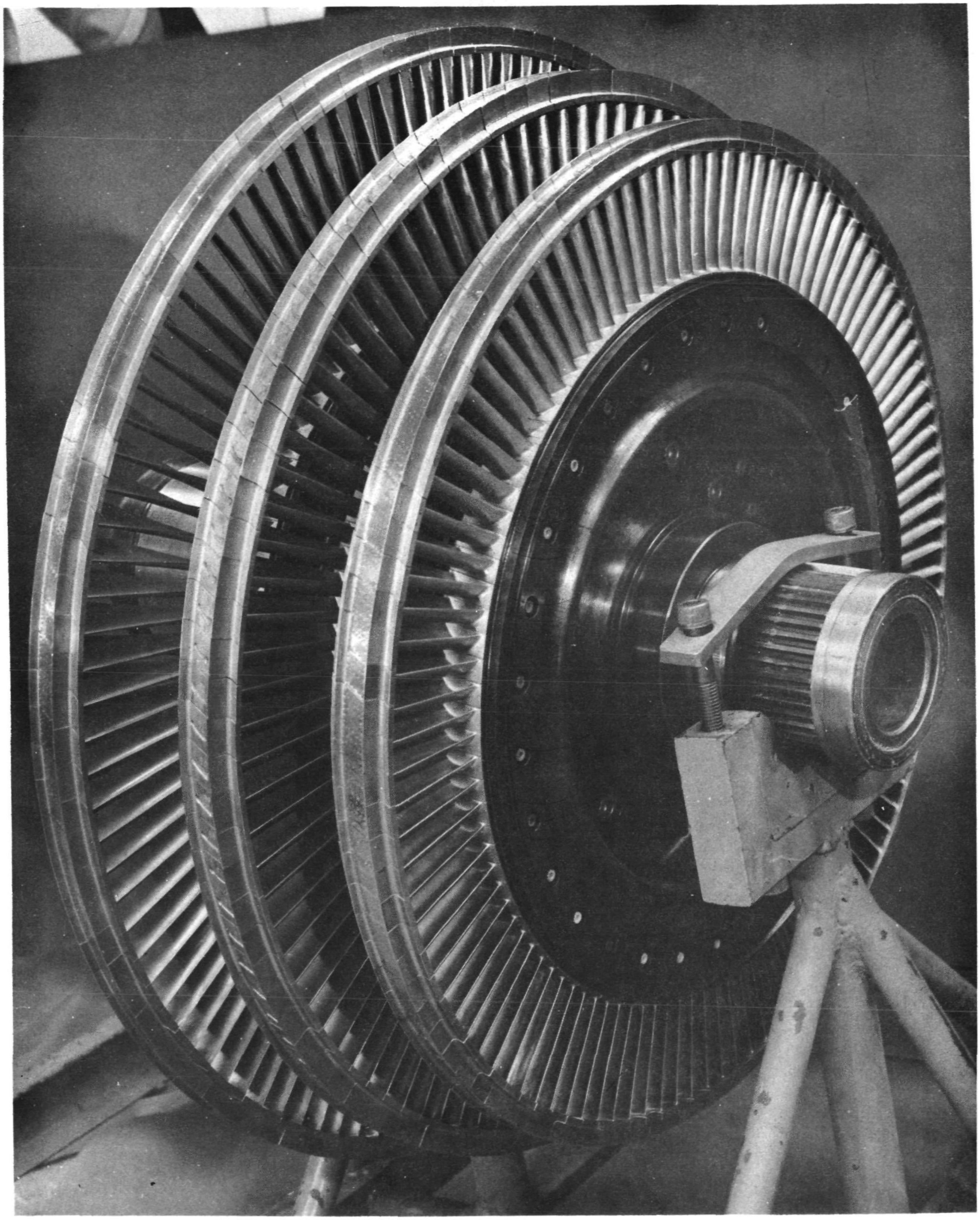


Figure 9. Three-Stage Turbine Plain Blade Rotor Assembled.

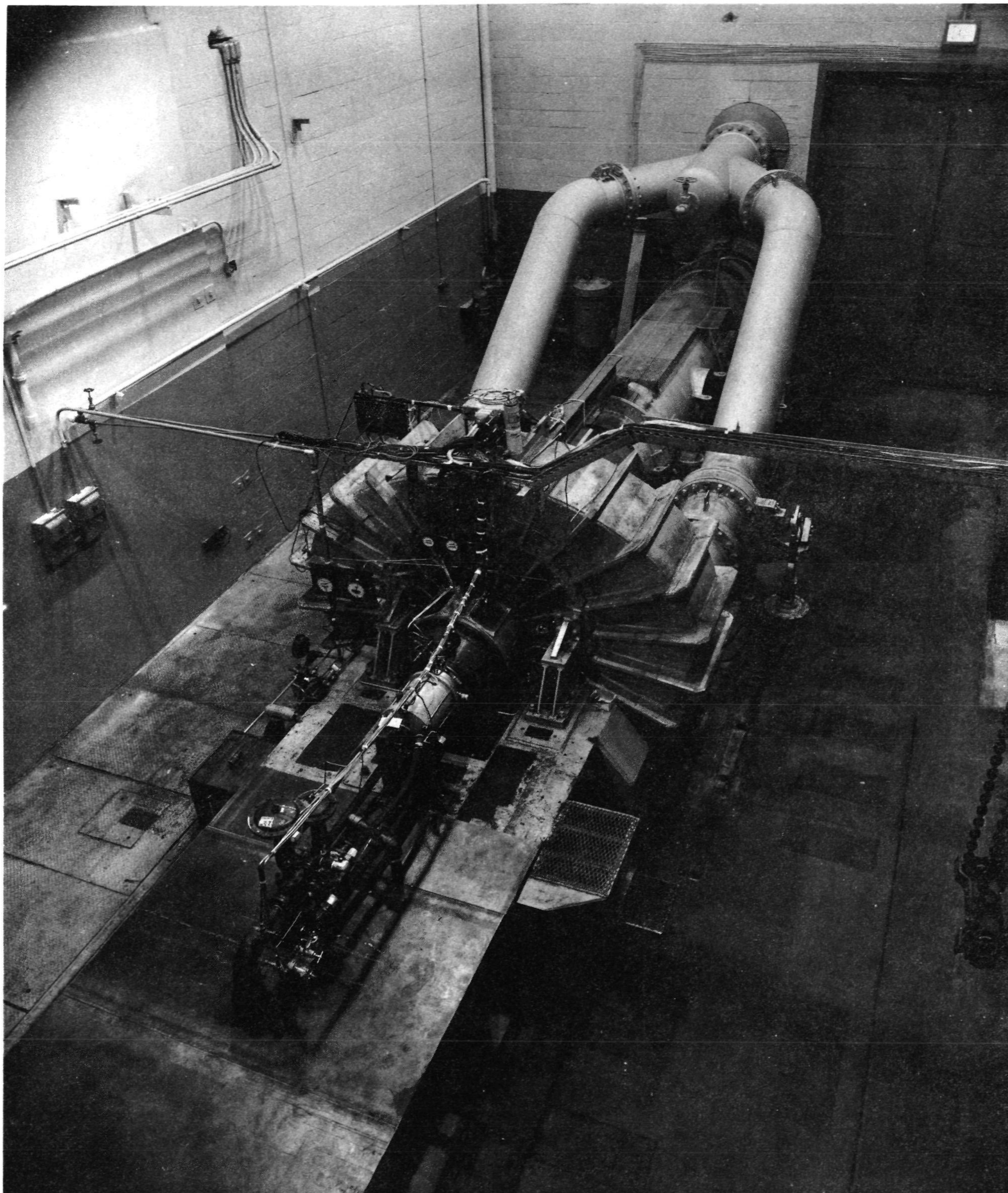


Figure 10. Typical General Electric, Evendale, Air Turbine Test Facility Configuration.

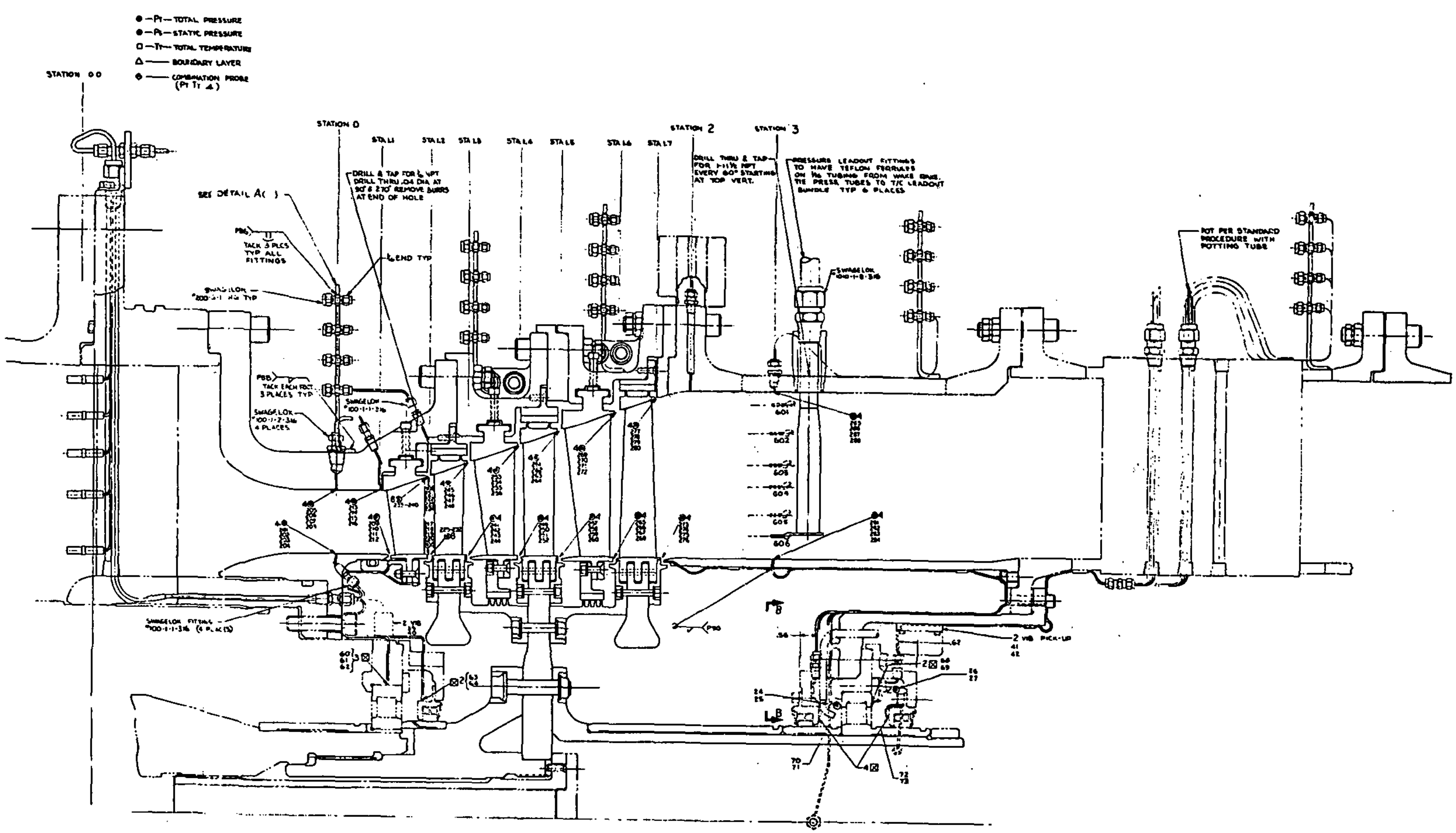


Figure 11. Air Turbine Test Instrumentation.

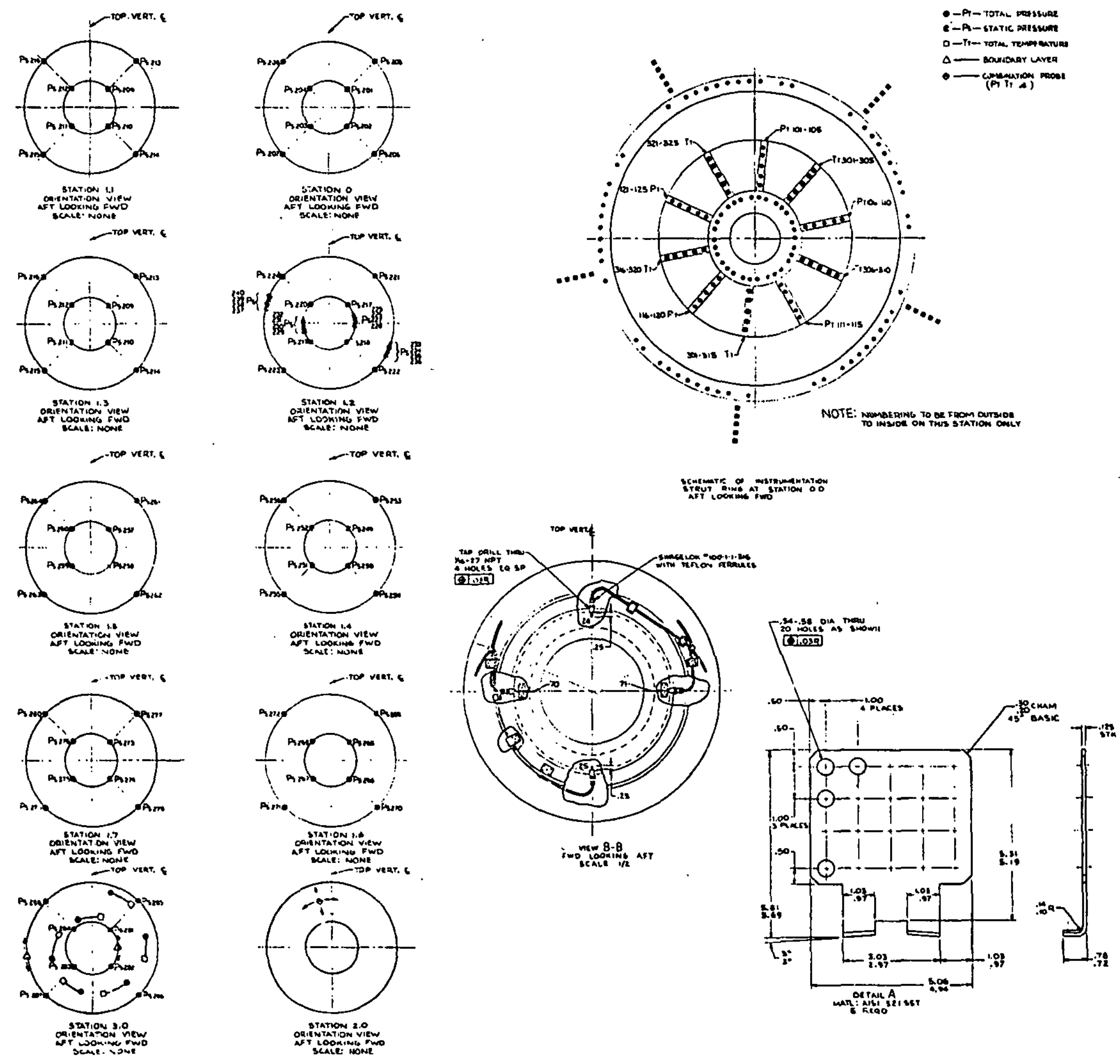


Figure 11. Air Turbine Test Instrumentation (Concluded).

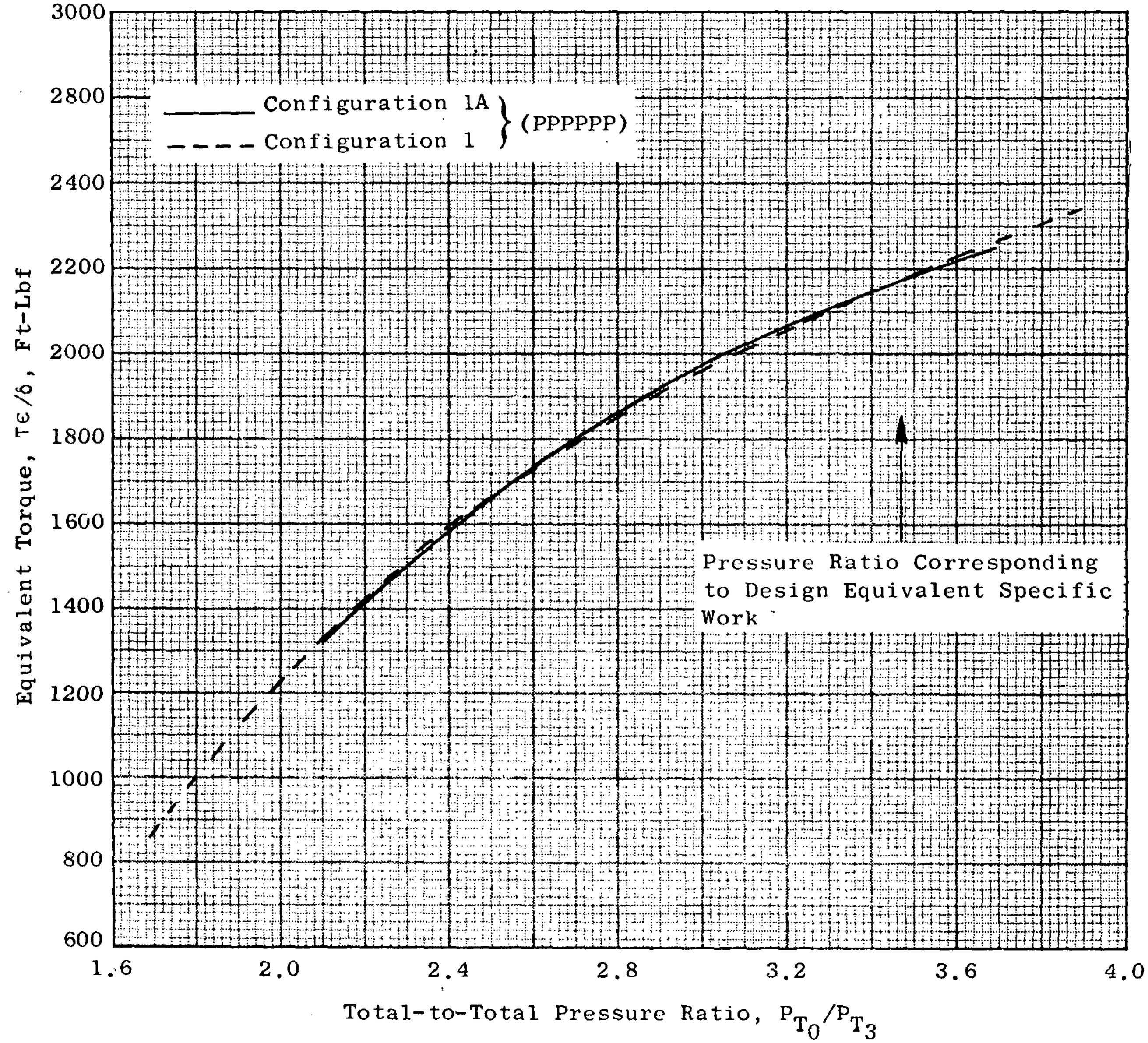


Figure 12. Equivalent Torque Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed, Base Cases Compared.

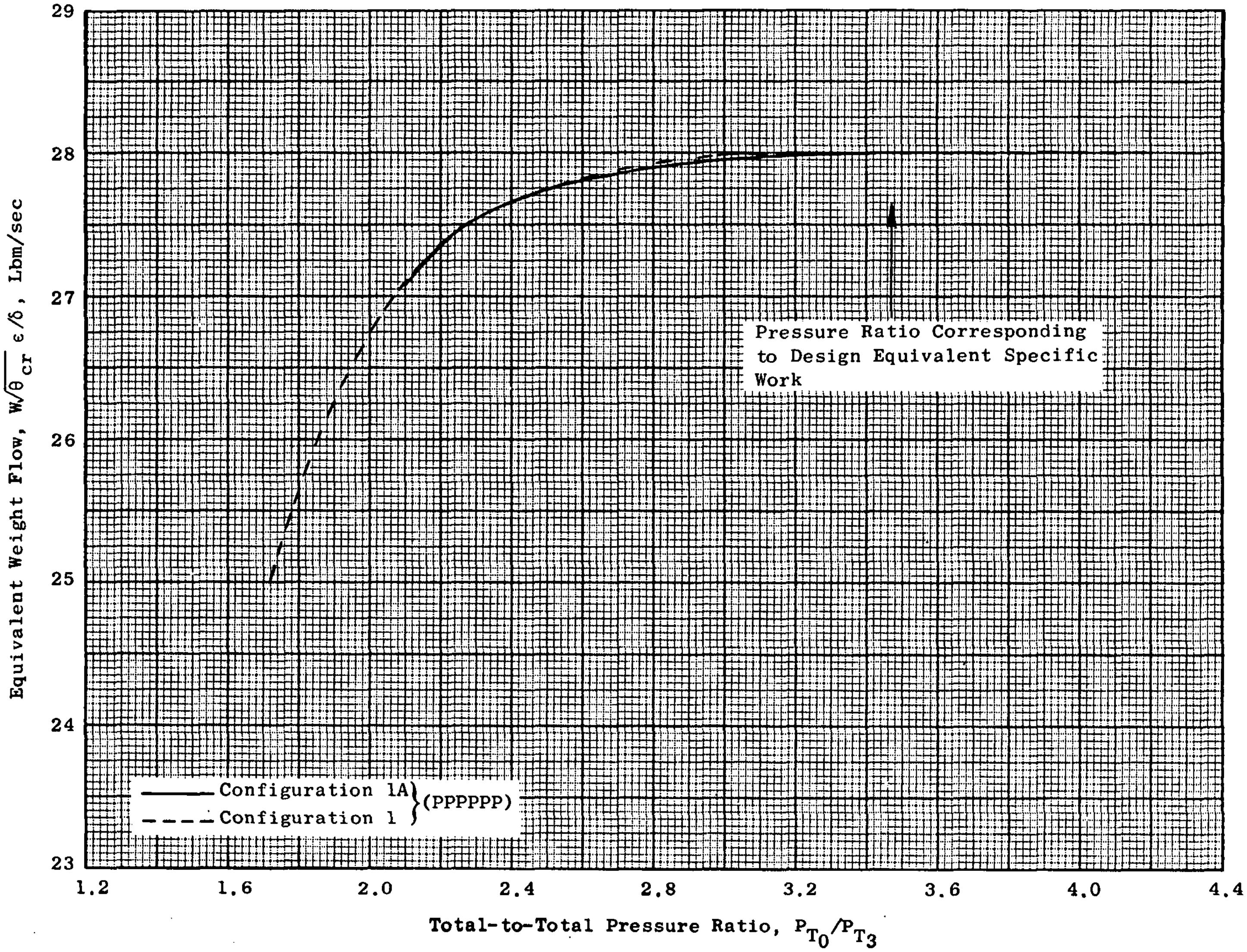


Figure 13. Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed, Base Cases Compared.

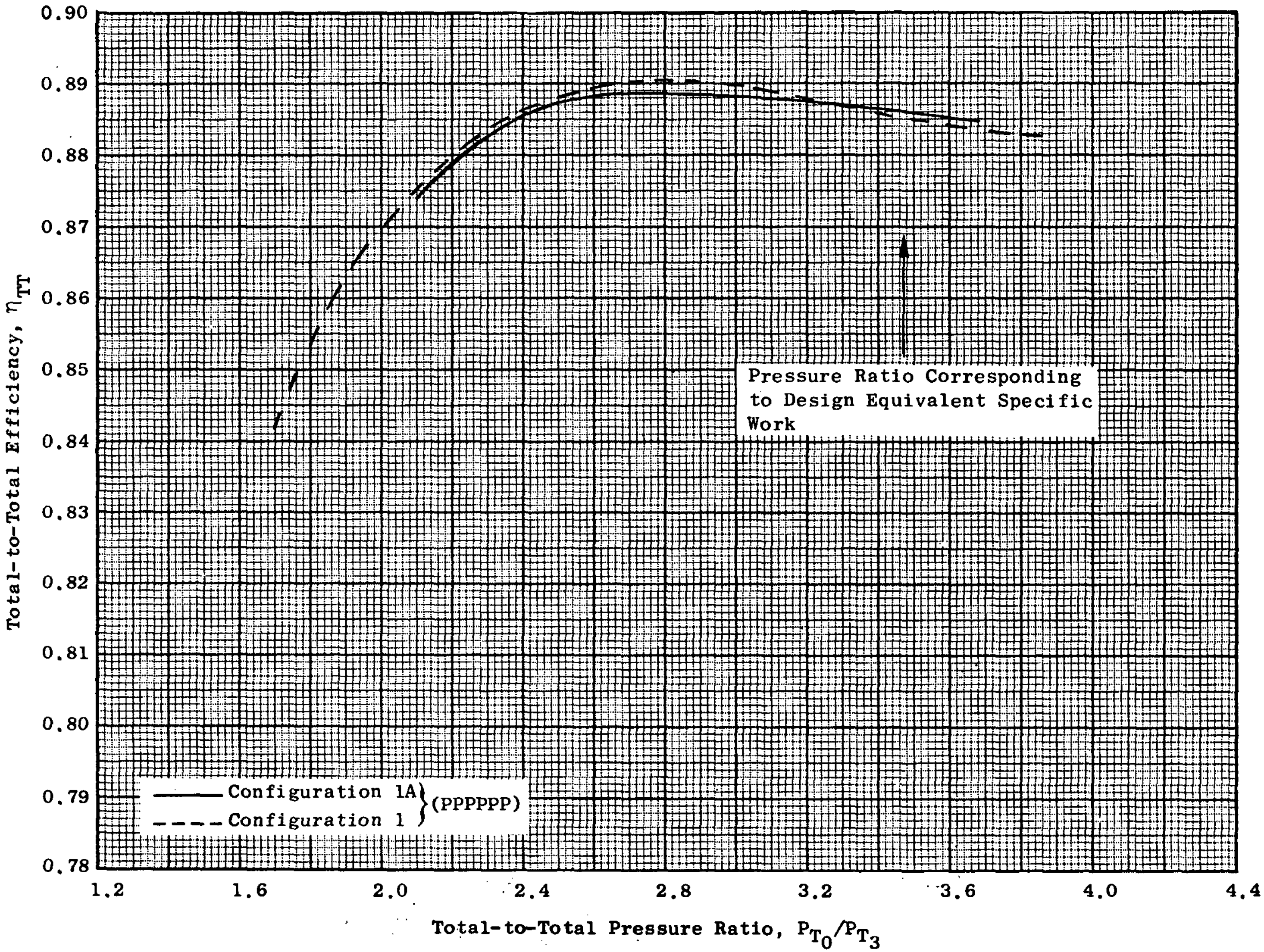


Figure 14. Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed. Base Cases Compared.

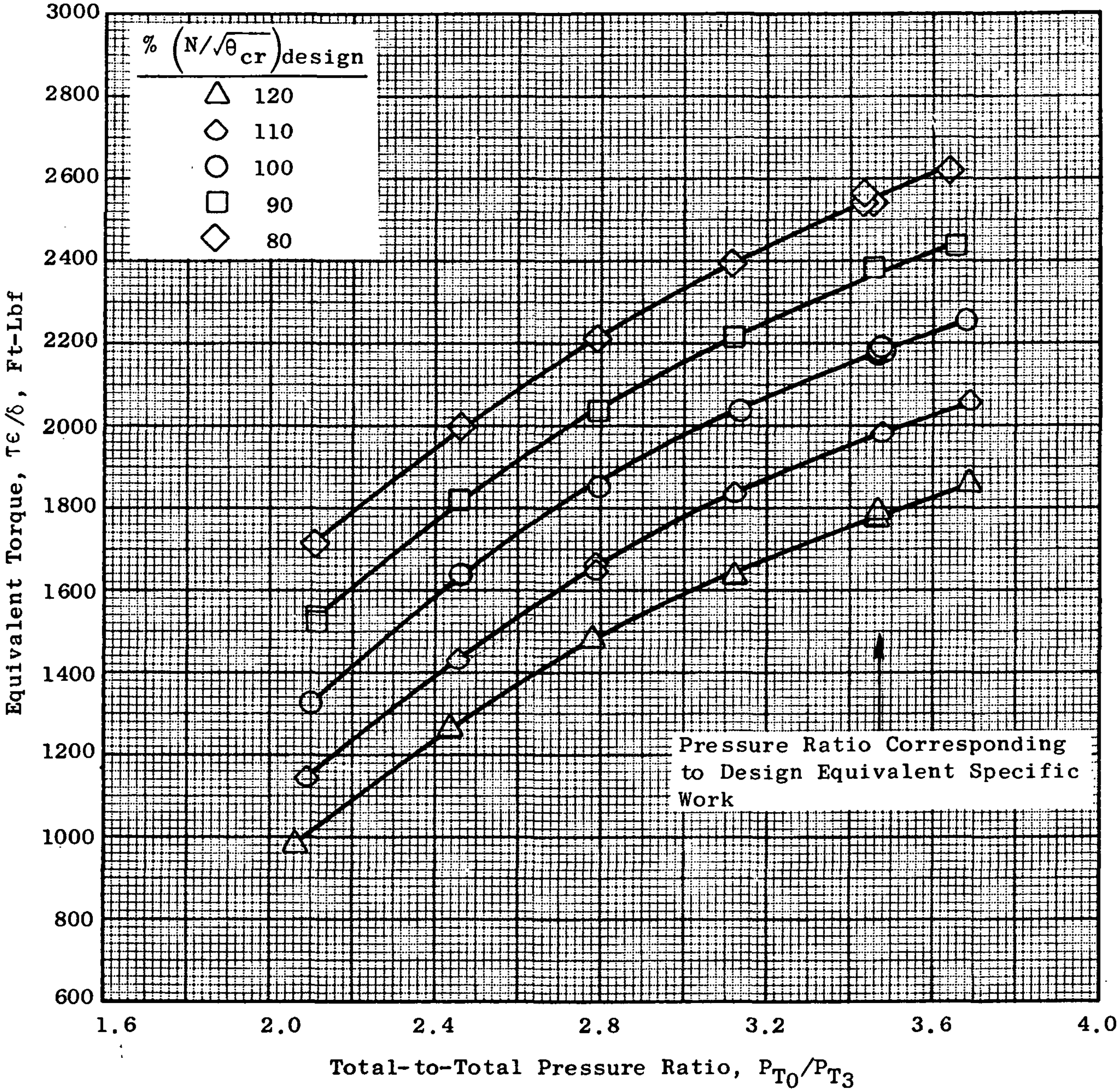


Figure 15. Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).

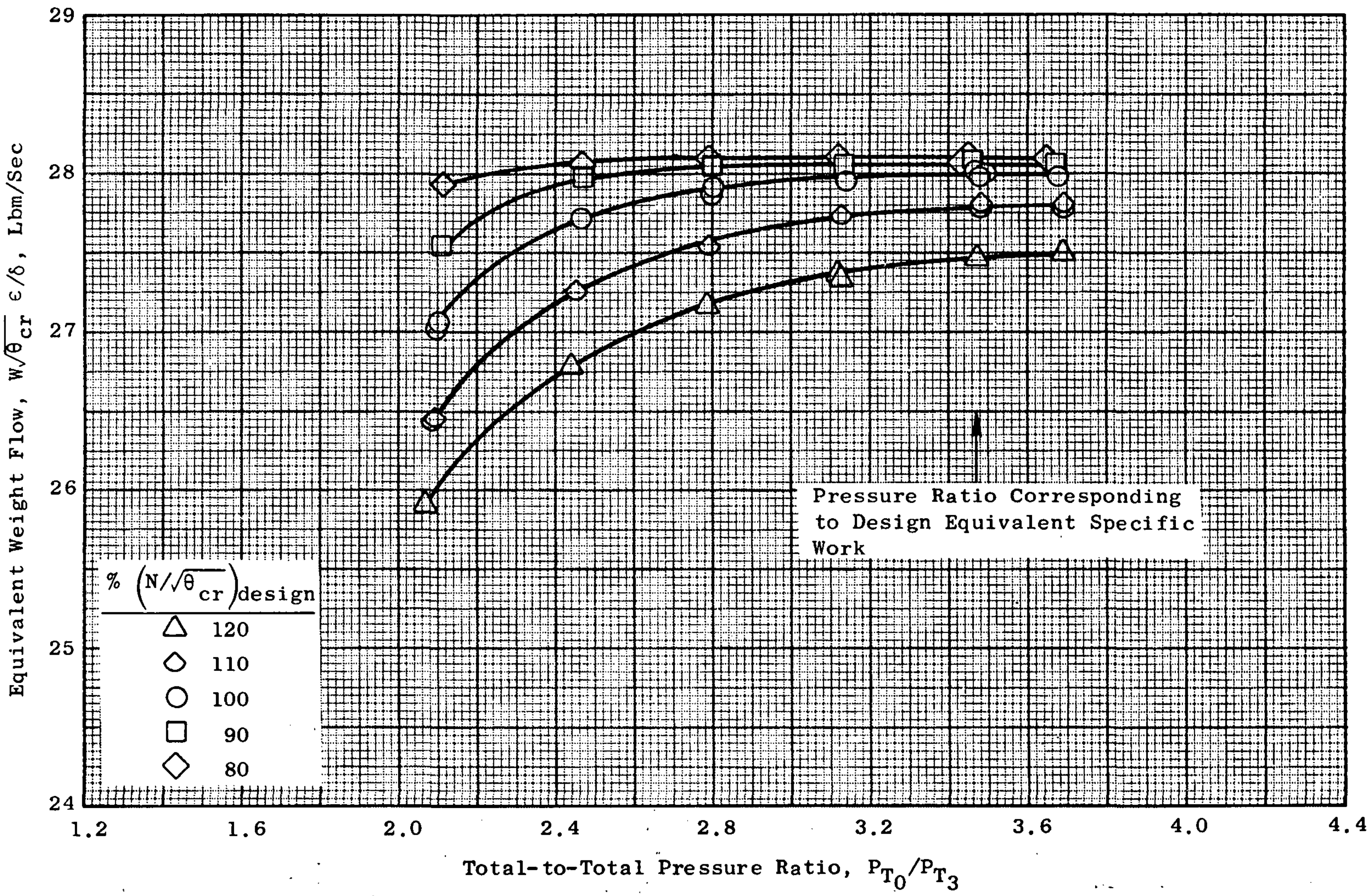


Figure 16. Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).

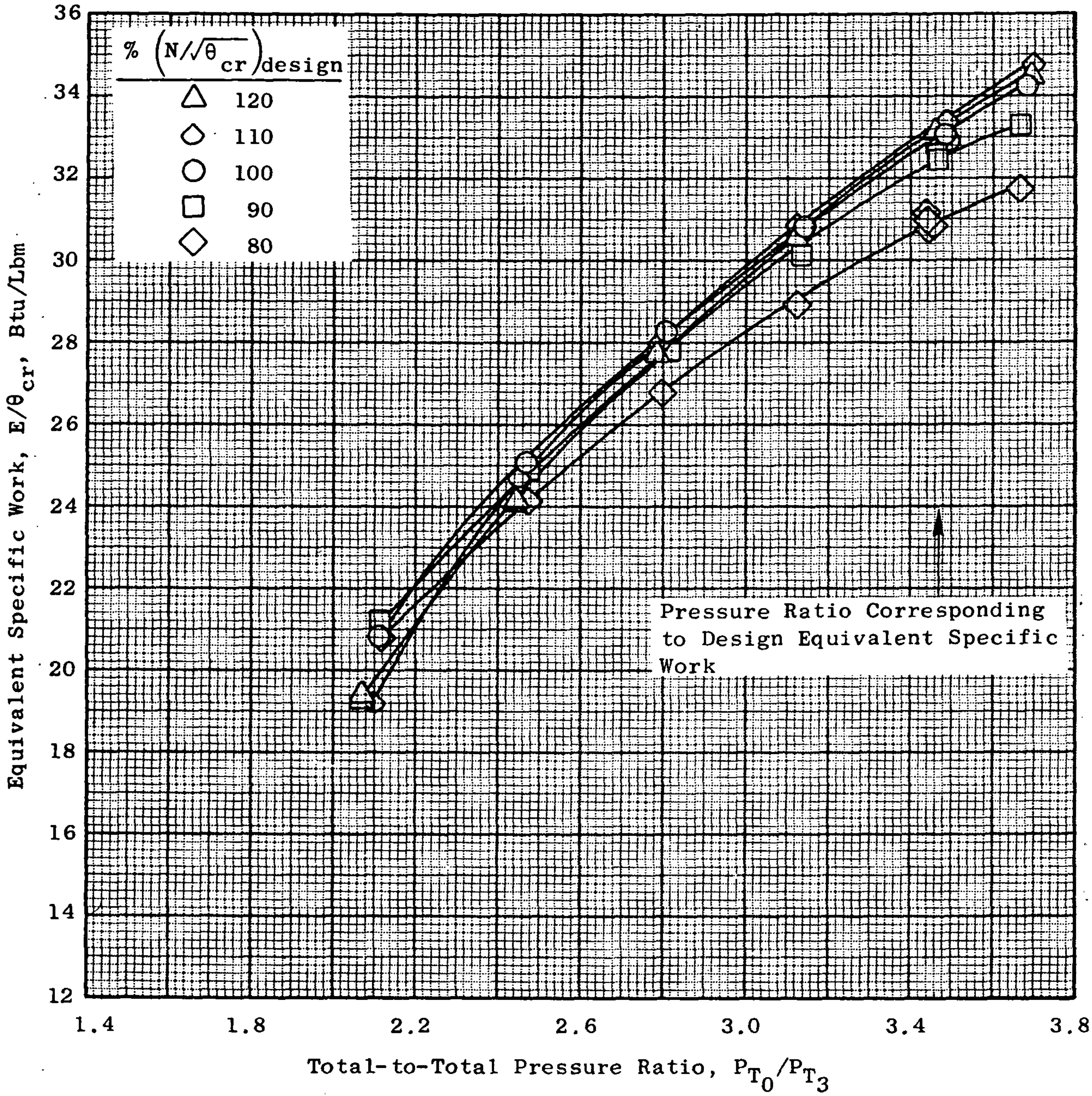


Figure 17. Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).

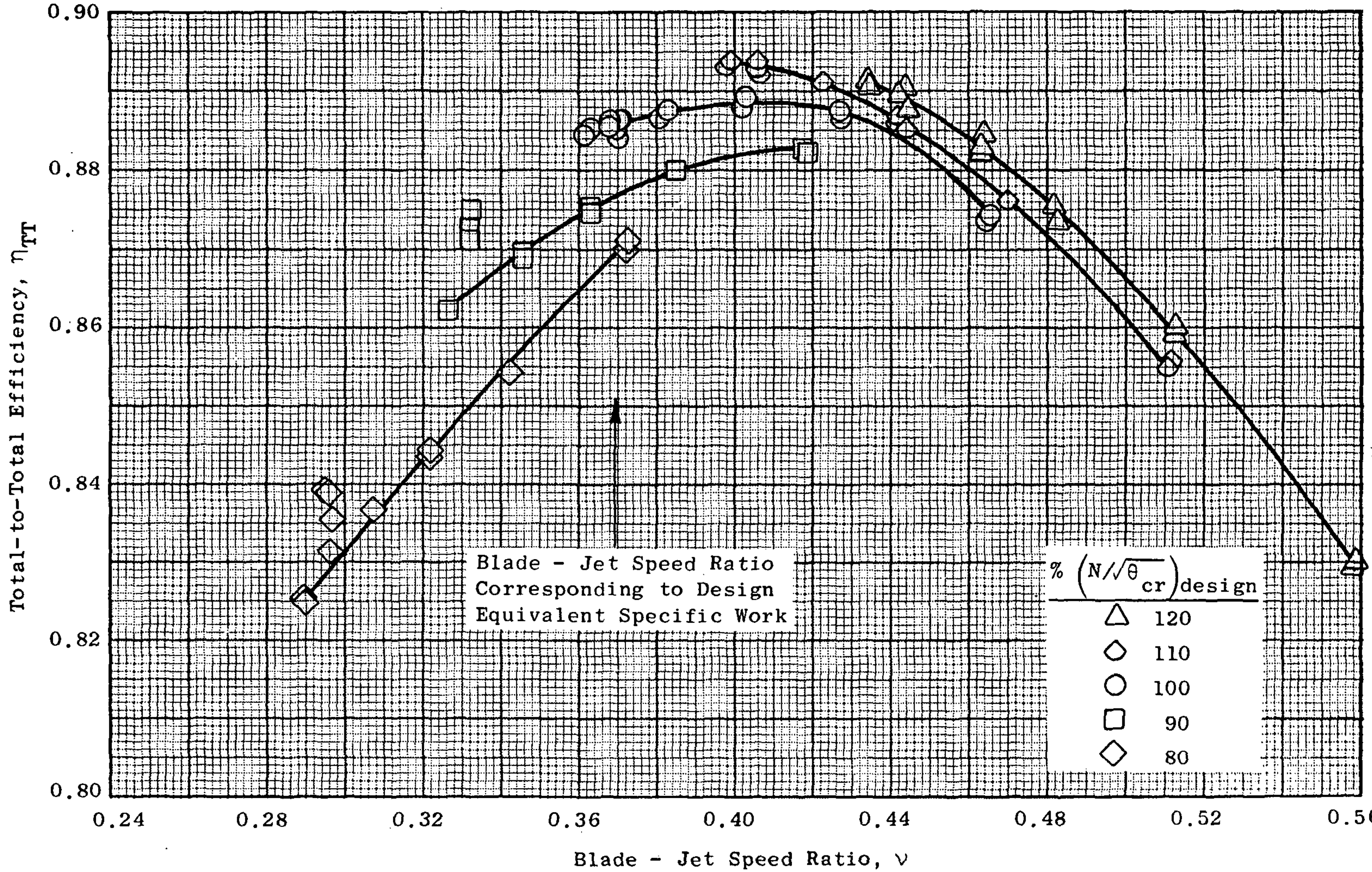


Figure 18. Total-to-Total Efficiency Vs. Blade - Jet Speed Ratio, Configuration 1A (PPPPPP).

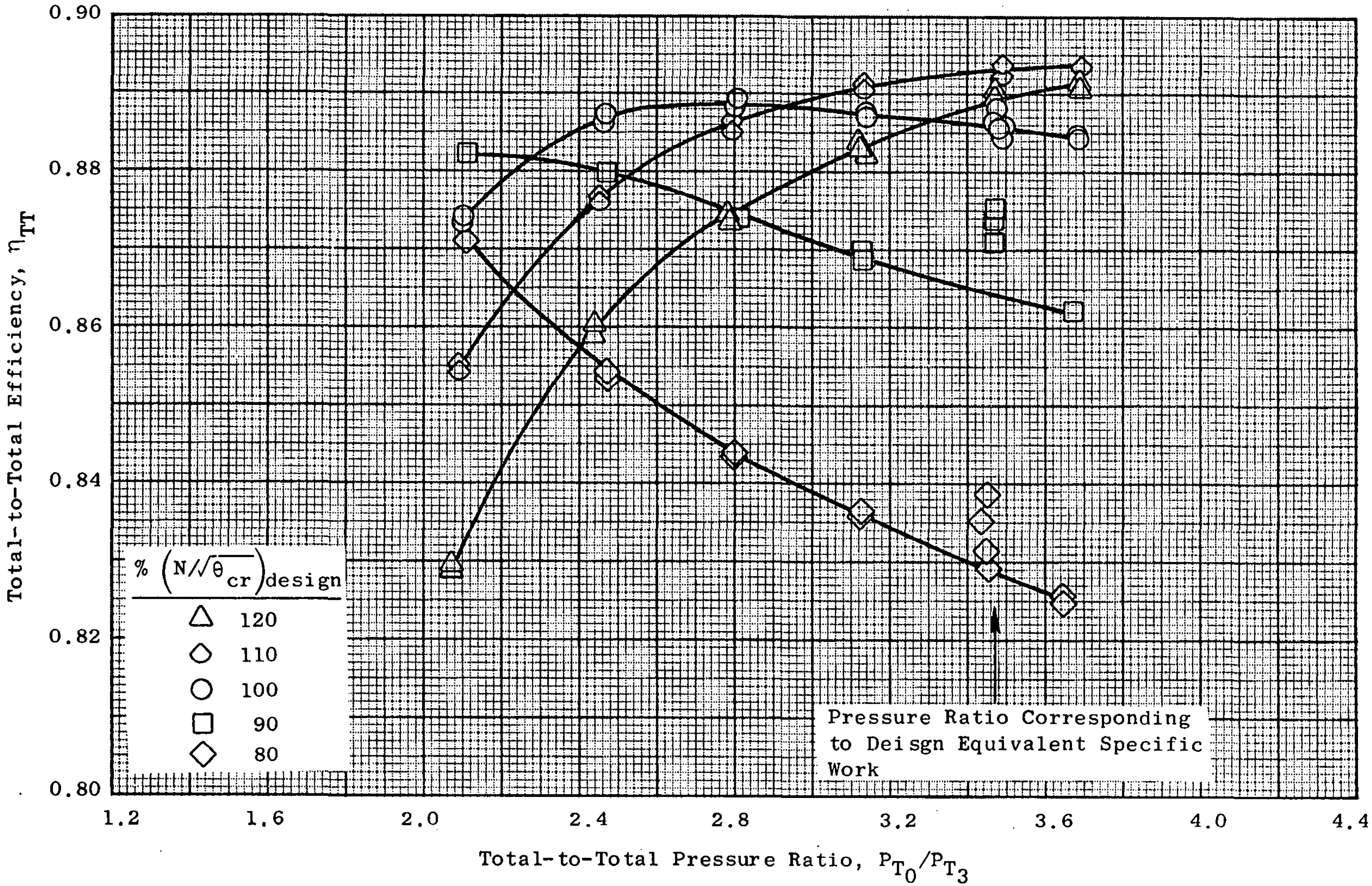


Figure 19. Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).

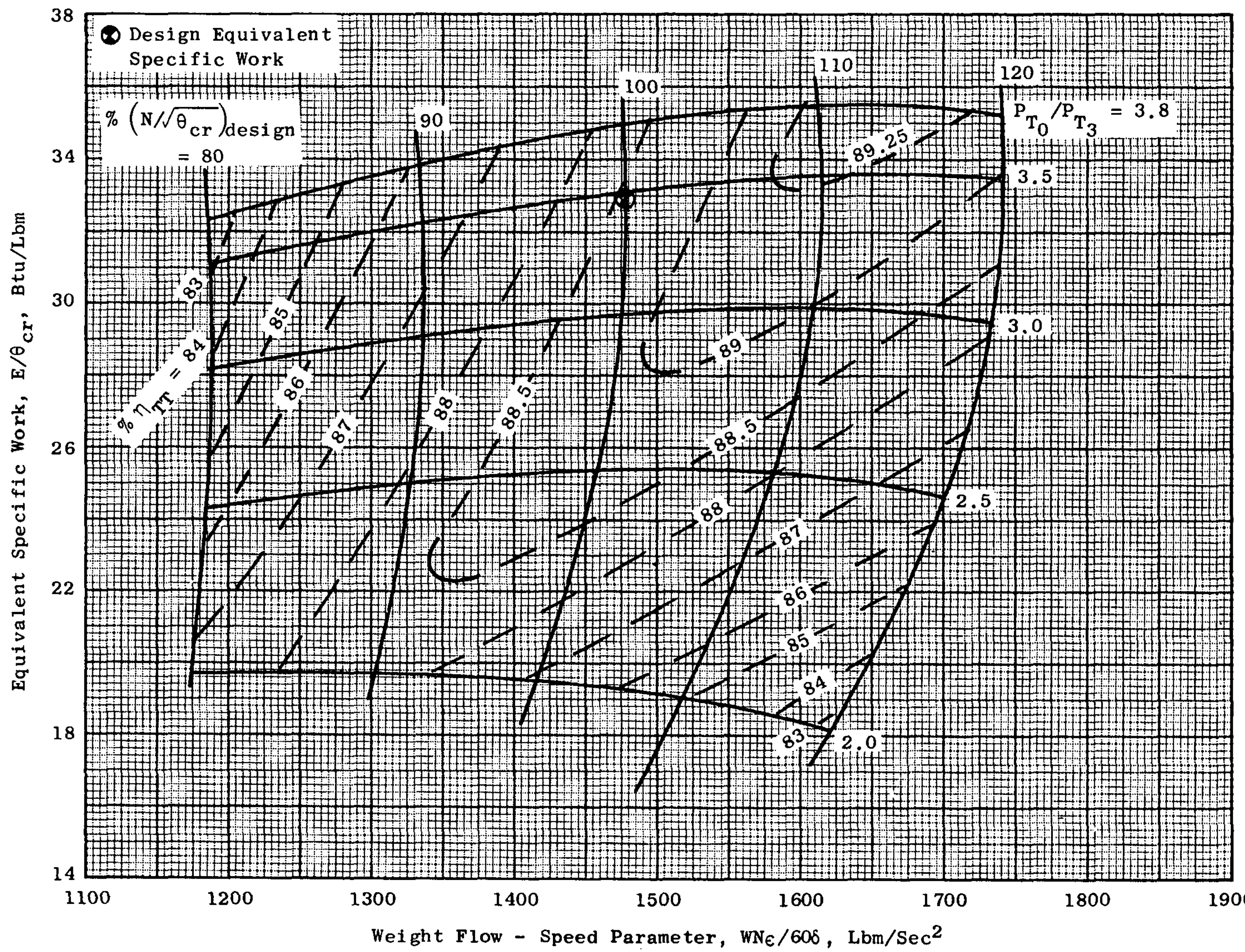


Figure 20. Equivalent Specific Work Vs. Weight Flow - Speed Parameter, Configuration 1A (PPPPPP).

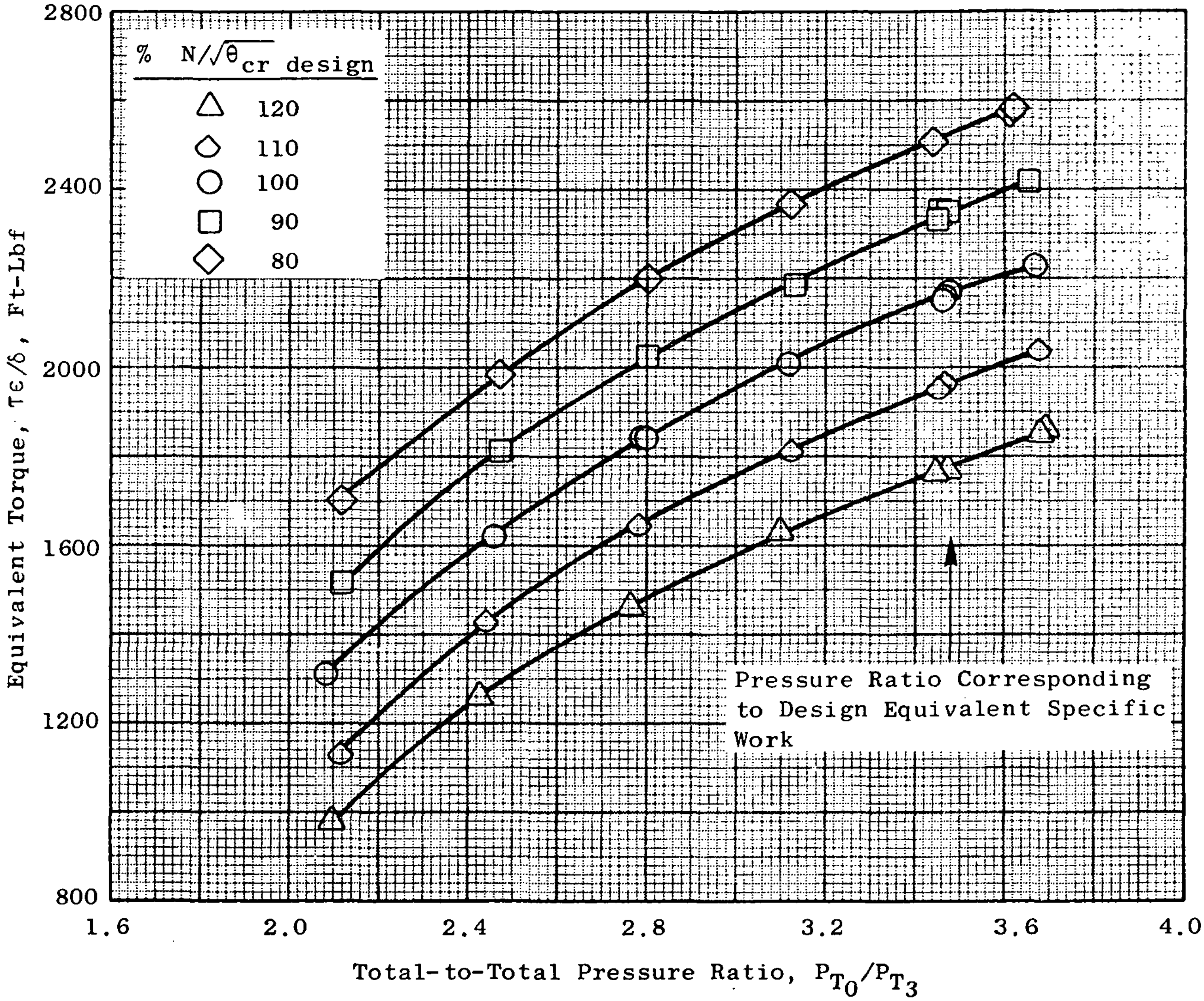


Figure 21. Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 2A (PPPPLT).

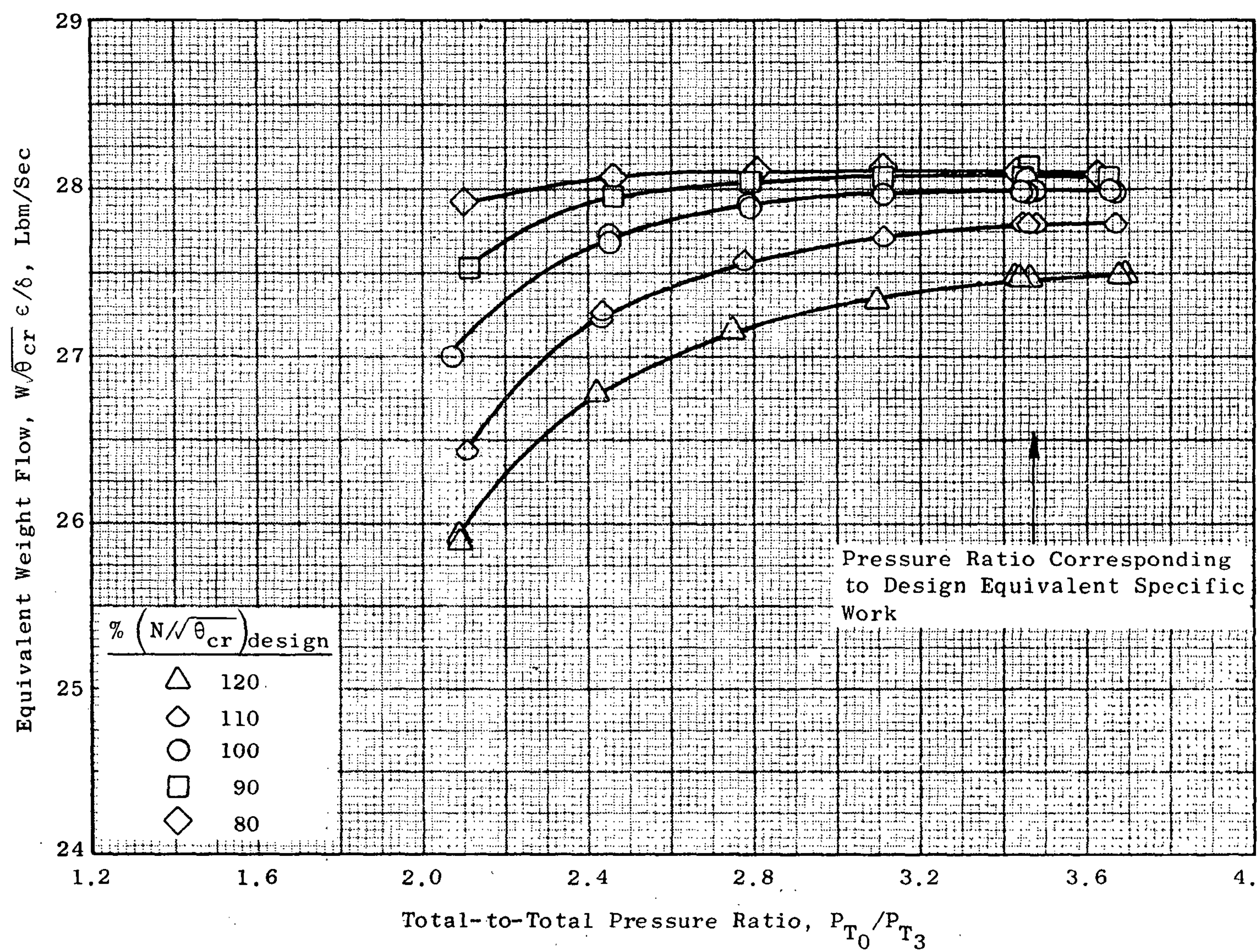


Figure 22. Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 2A (PPPPLT).

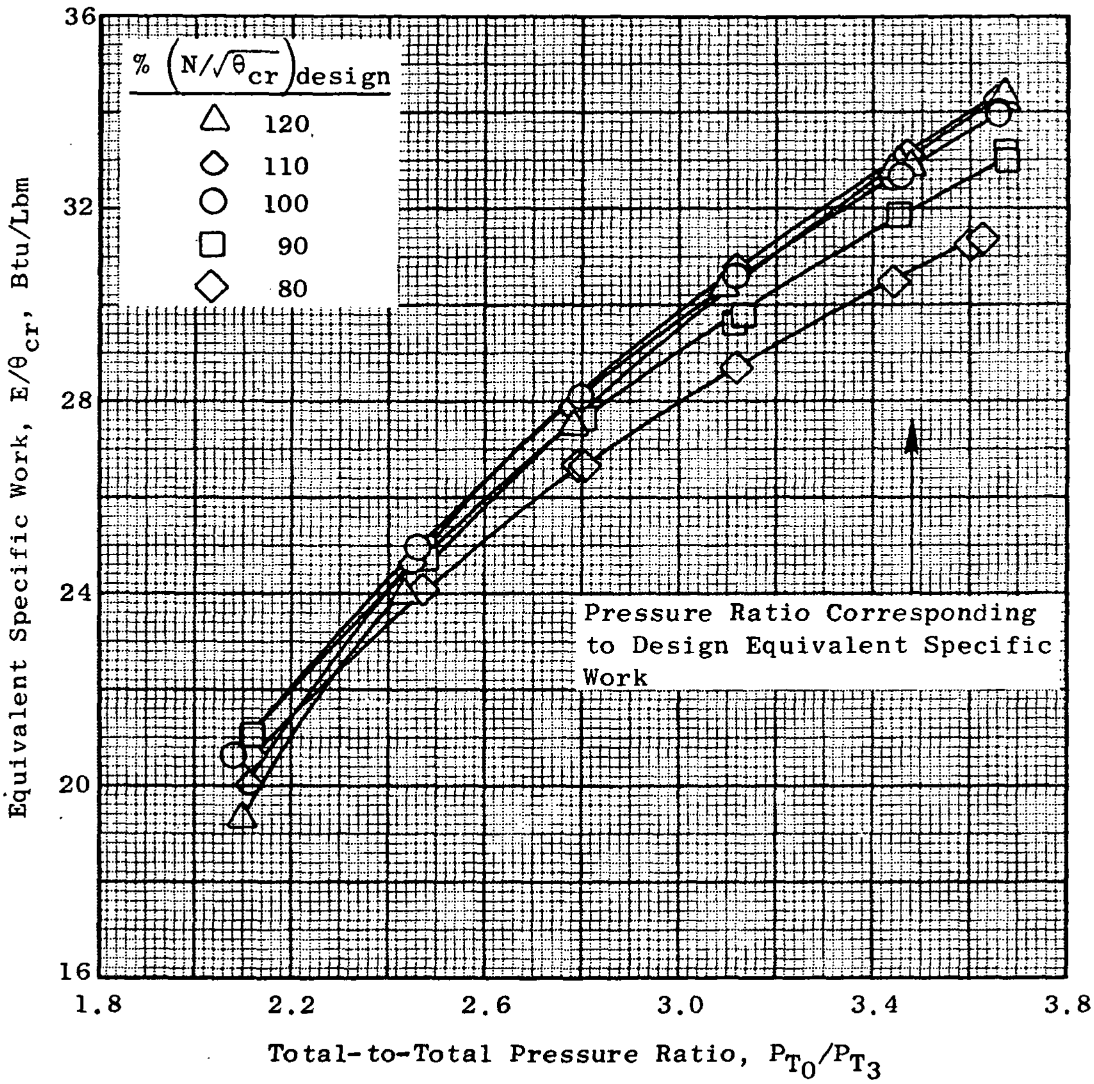


Figure 23. Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 2A (PPPPLT).

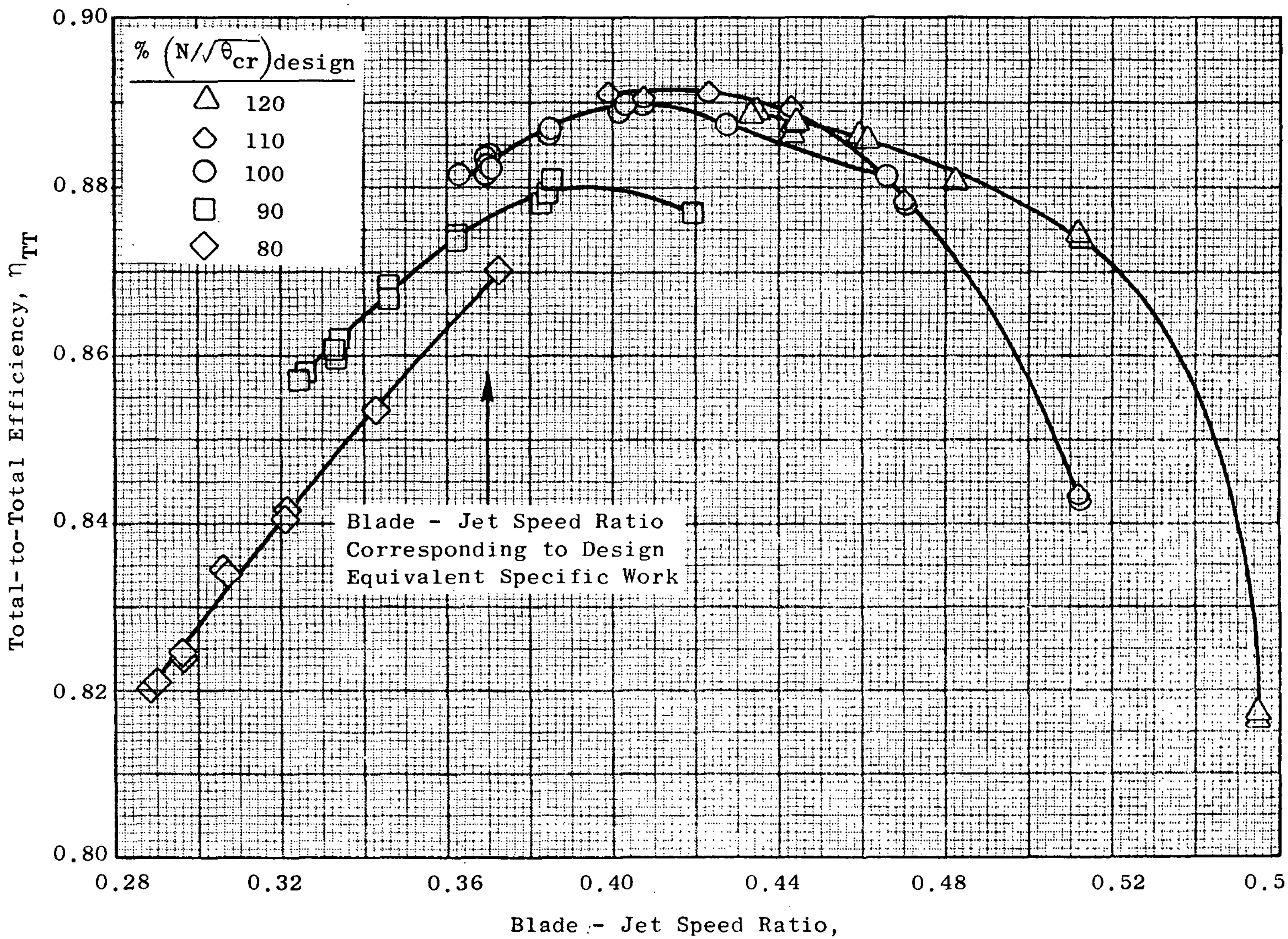


Figure 24. Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 2A (PPPPLT).

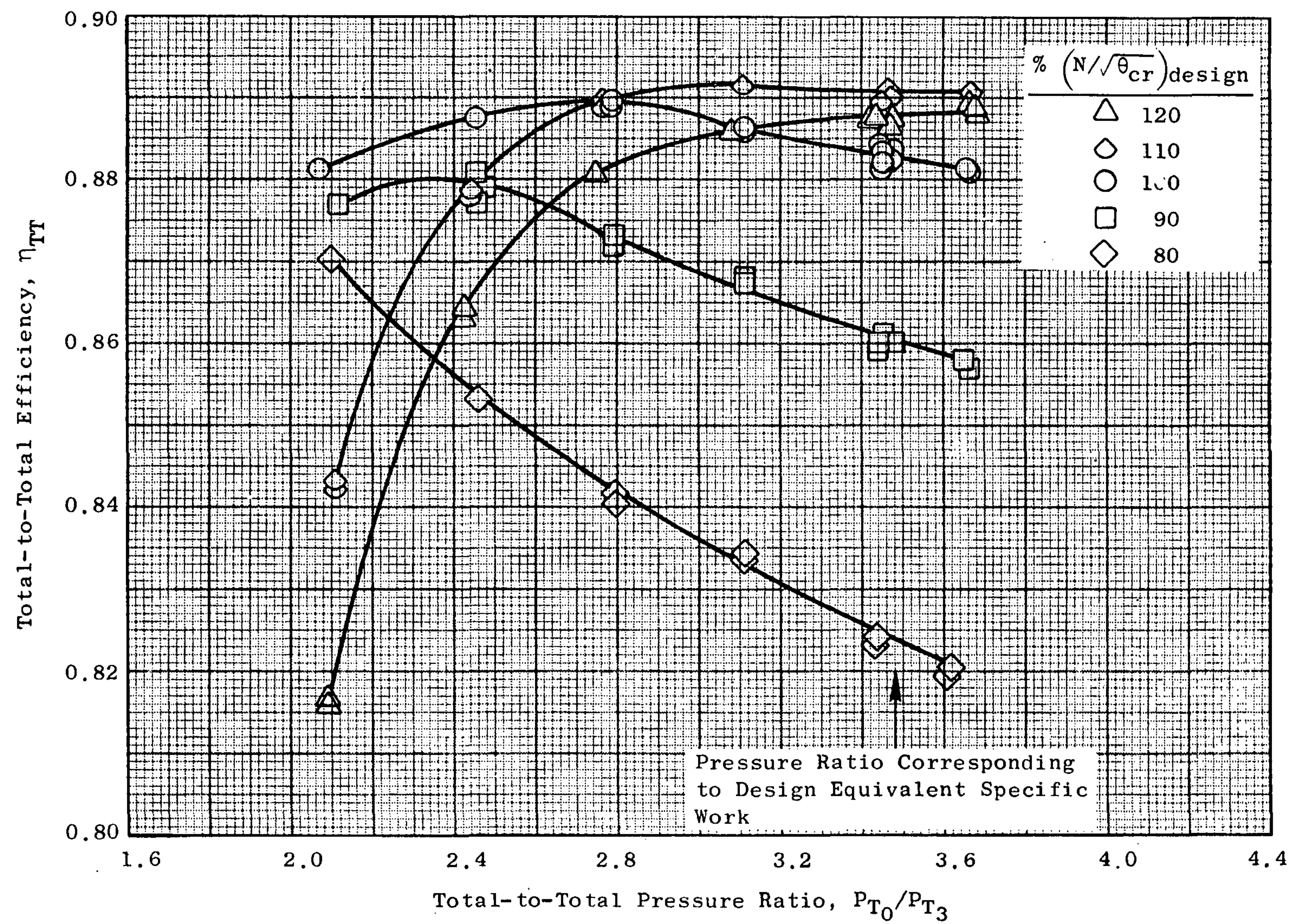


Figure 25. Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 2A (PPPPLT).

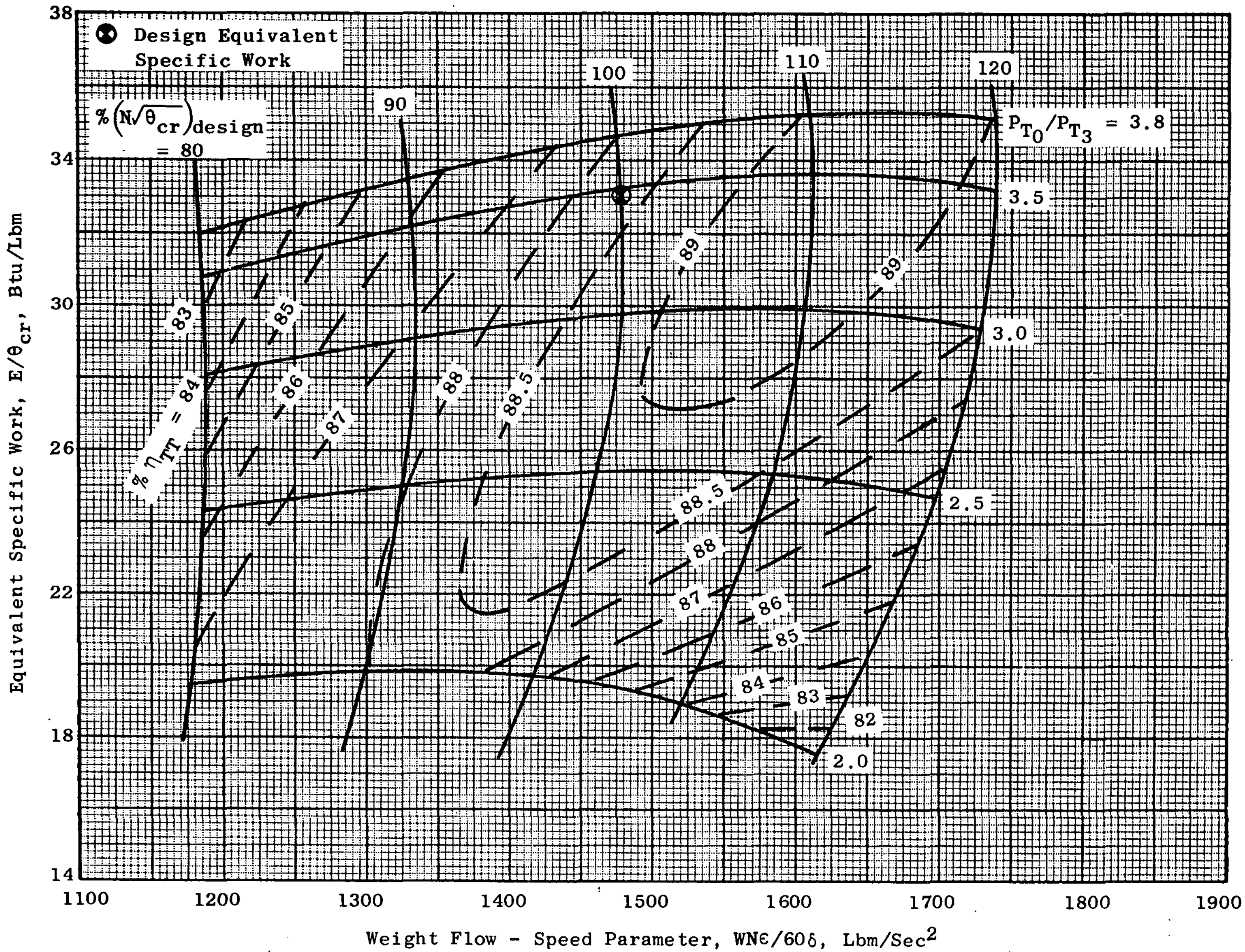


Figure 26. Equivalent Specific Work Vs. Weight Flow-Speed Parameter, Configuration 2A (PPPPLT).

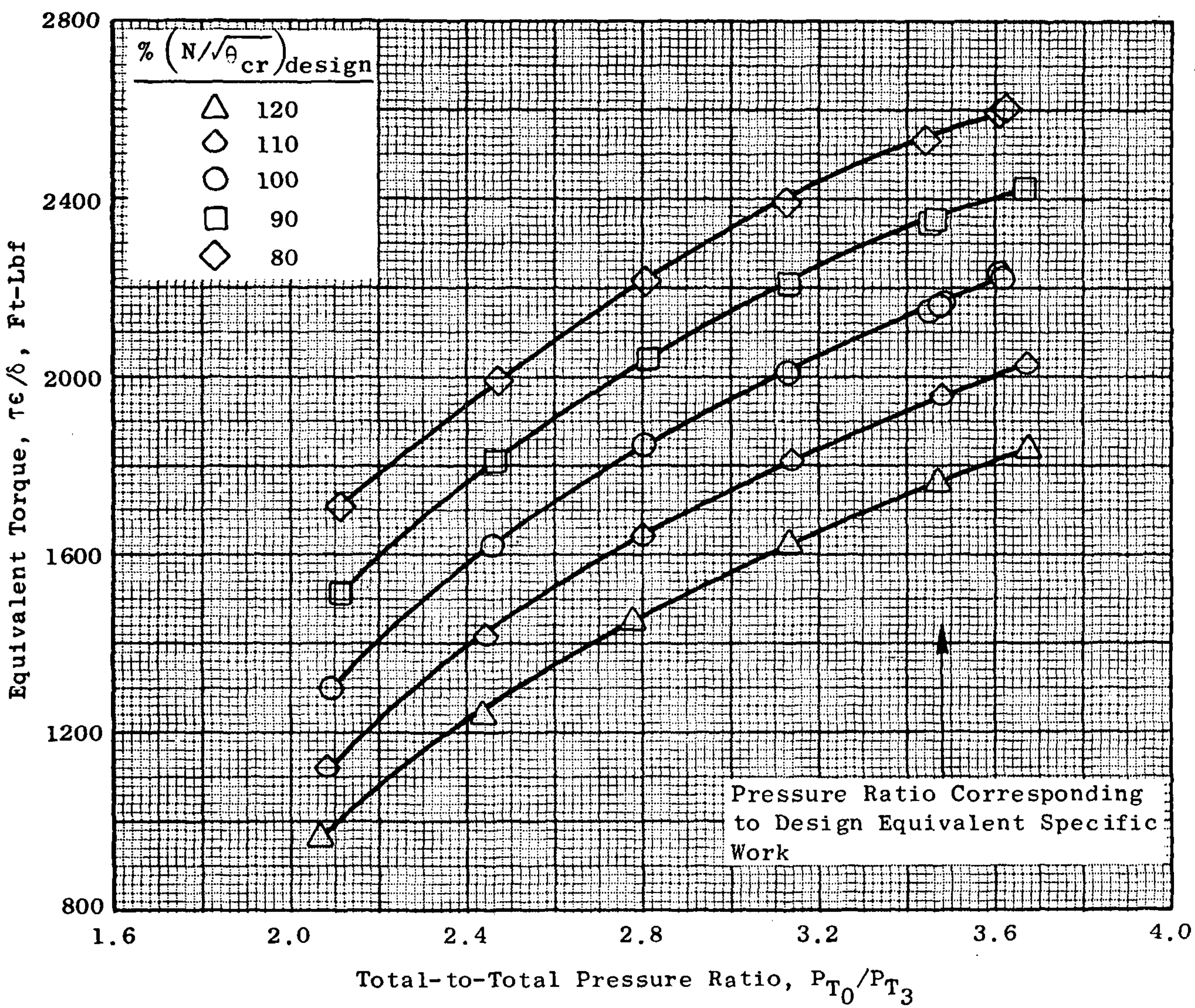


Figure 27. Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 3A (PPTPLP).

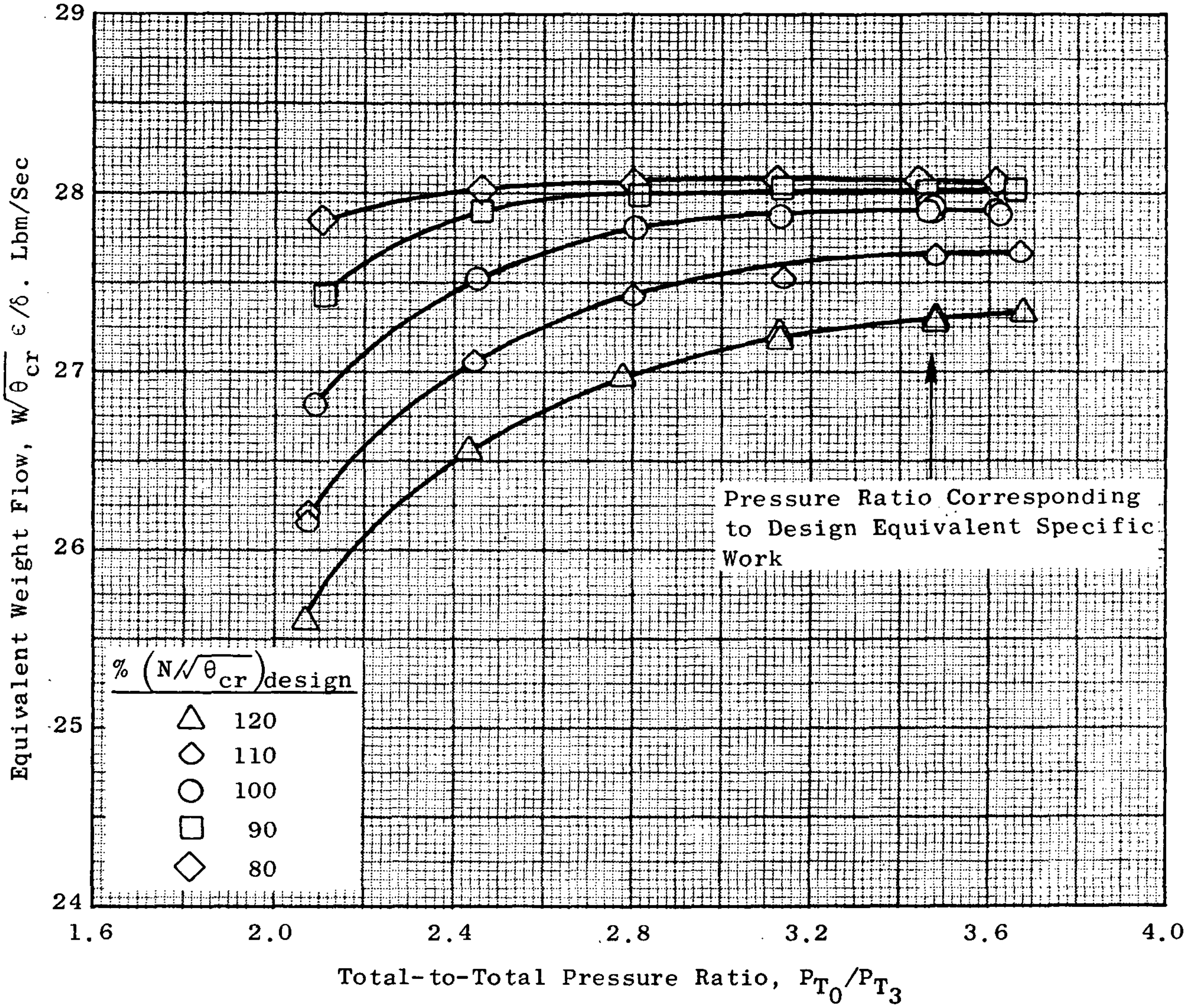


Figure 28. Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 3A (PPTPLP).

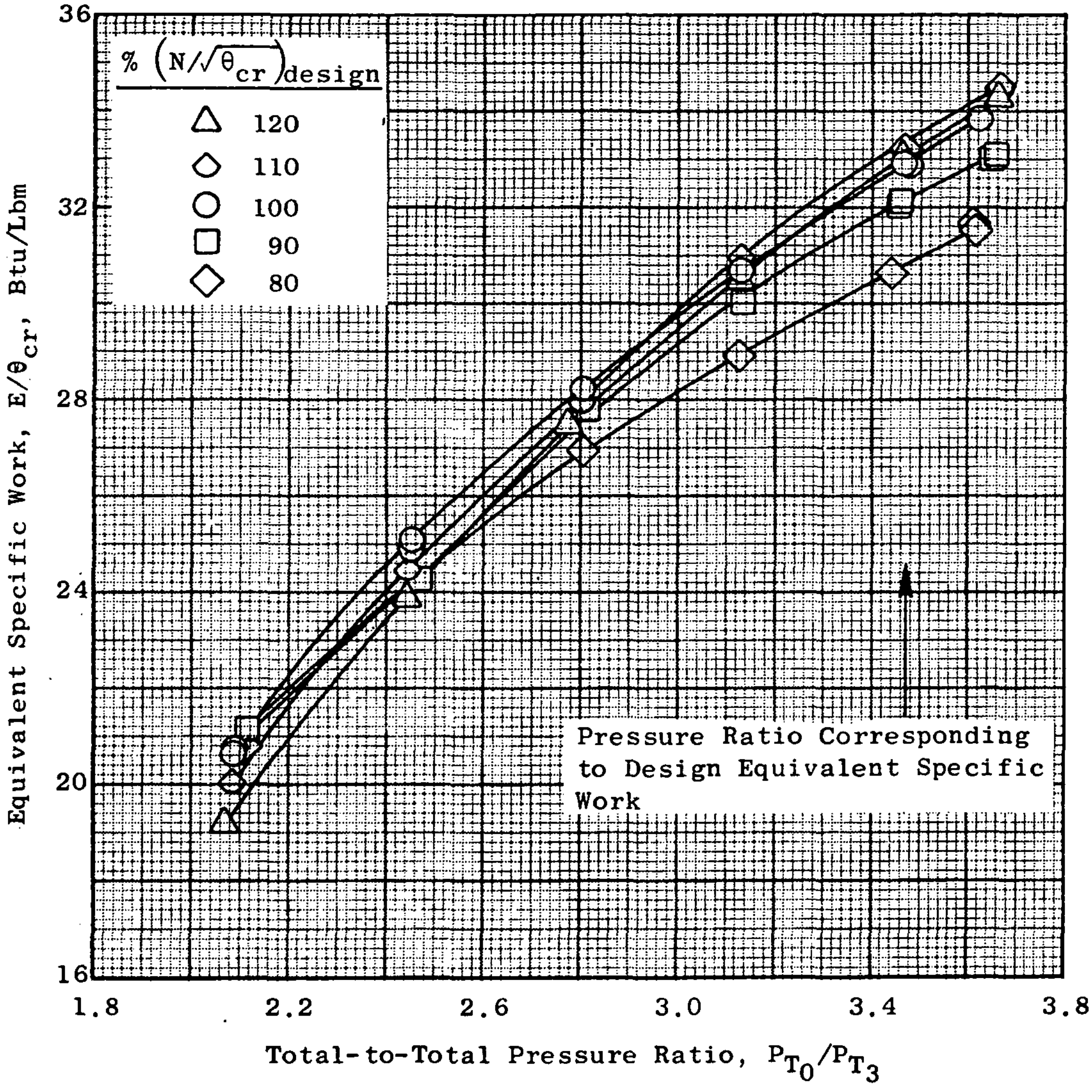


Figure 29. Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 3A (PPTPLP).

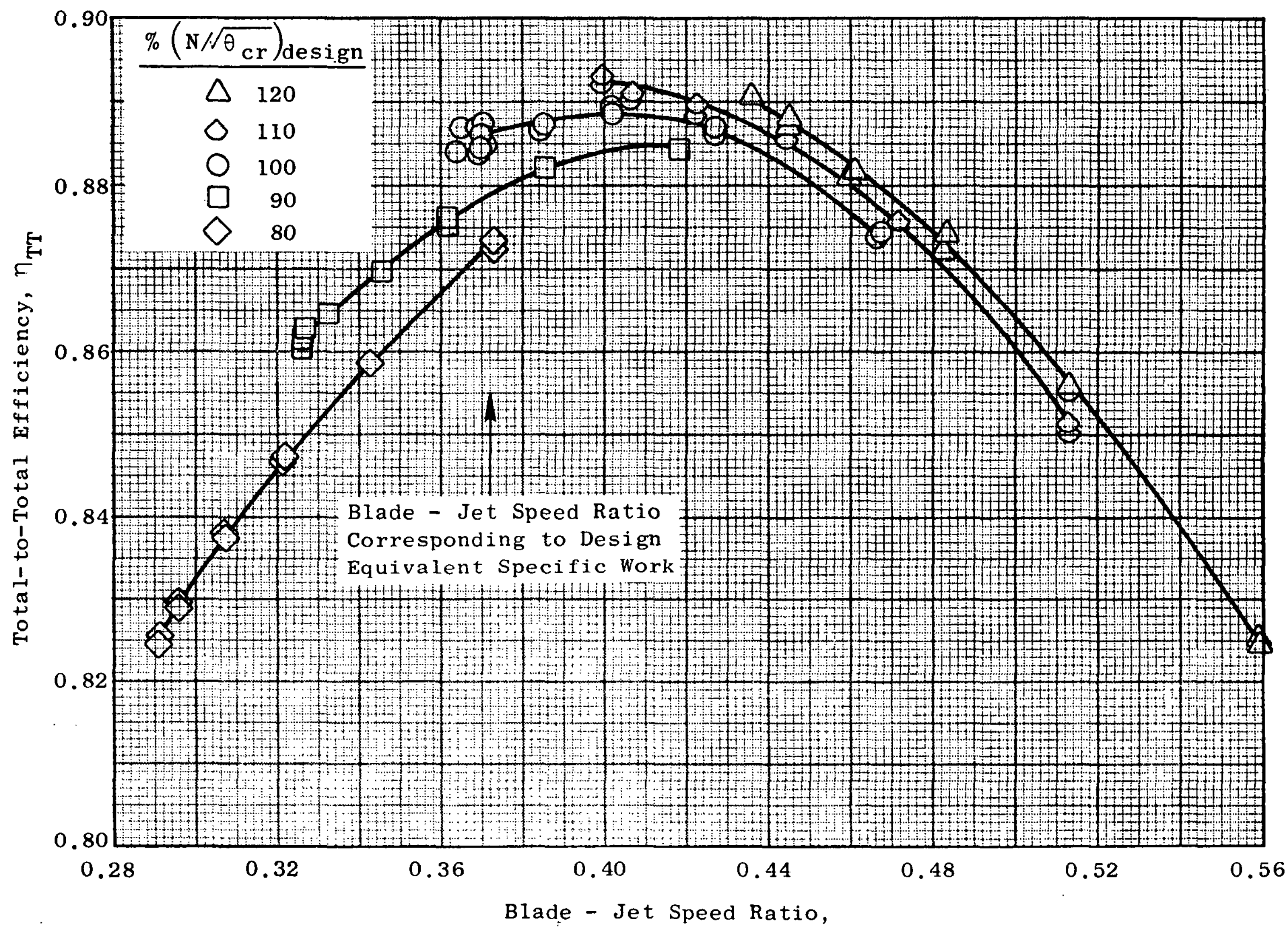


Figure 30. Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 3A (PPTPLP).

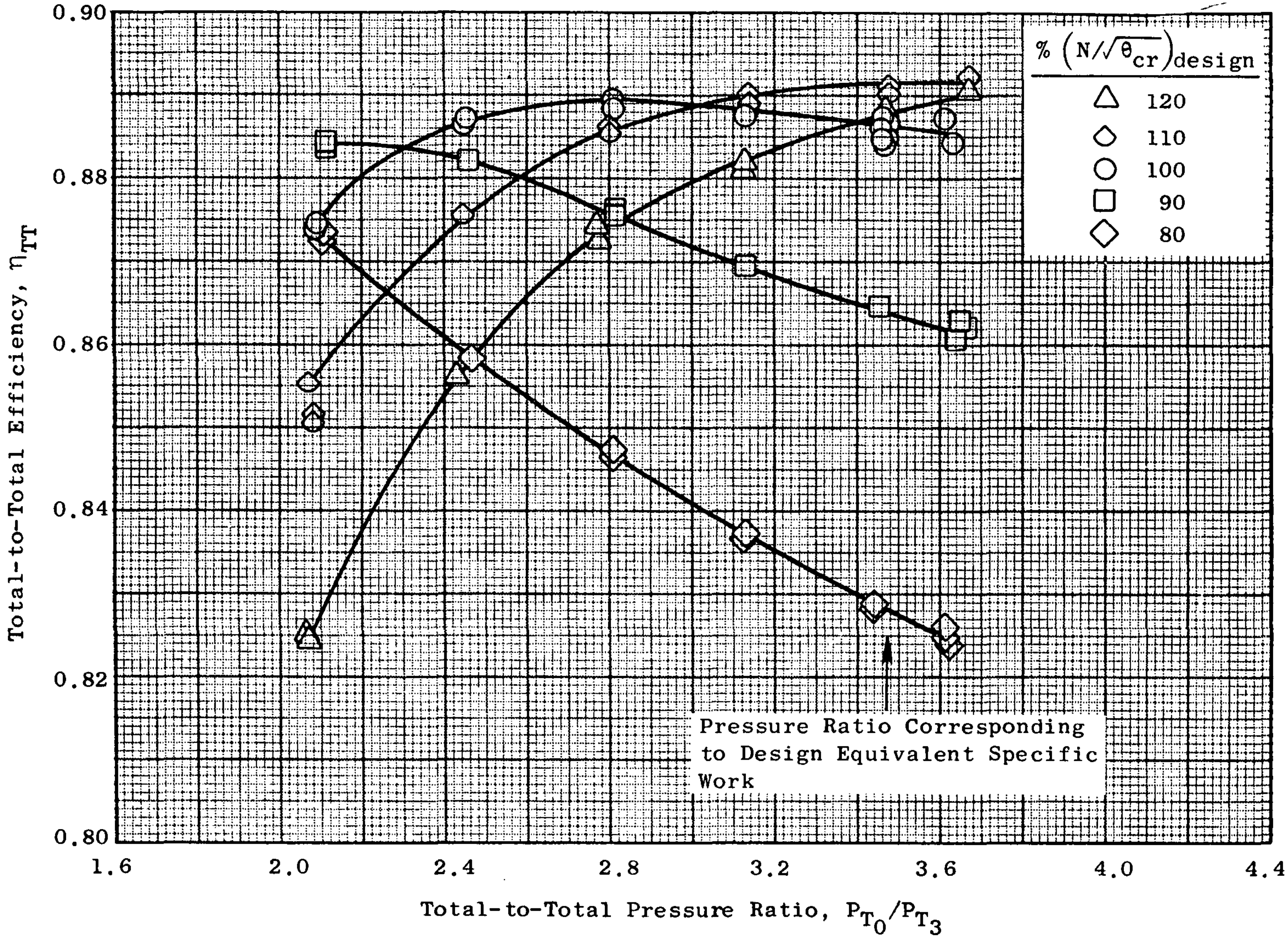


Figure 31. Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 3A (PPTPLP).

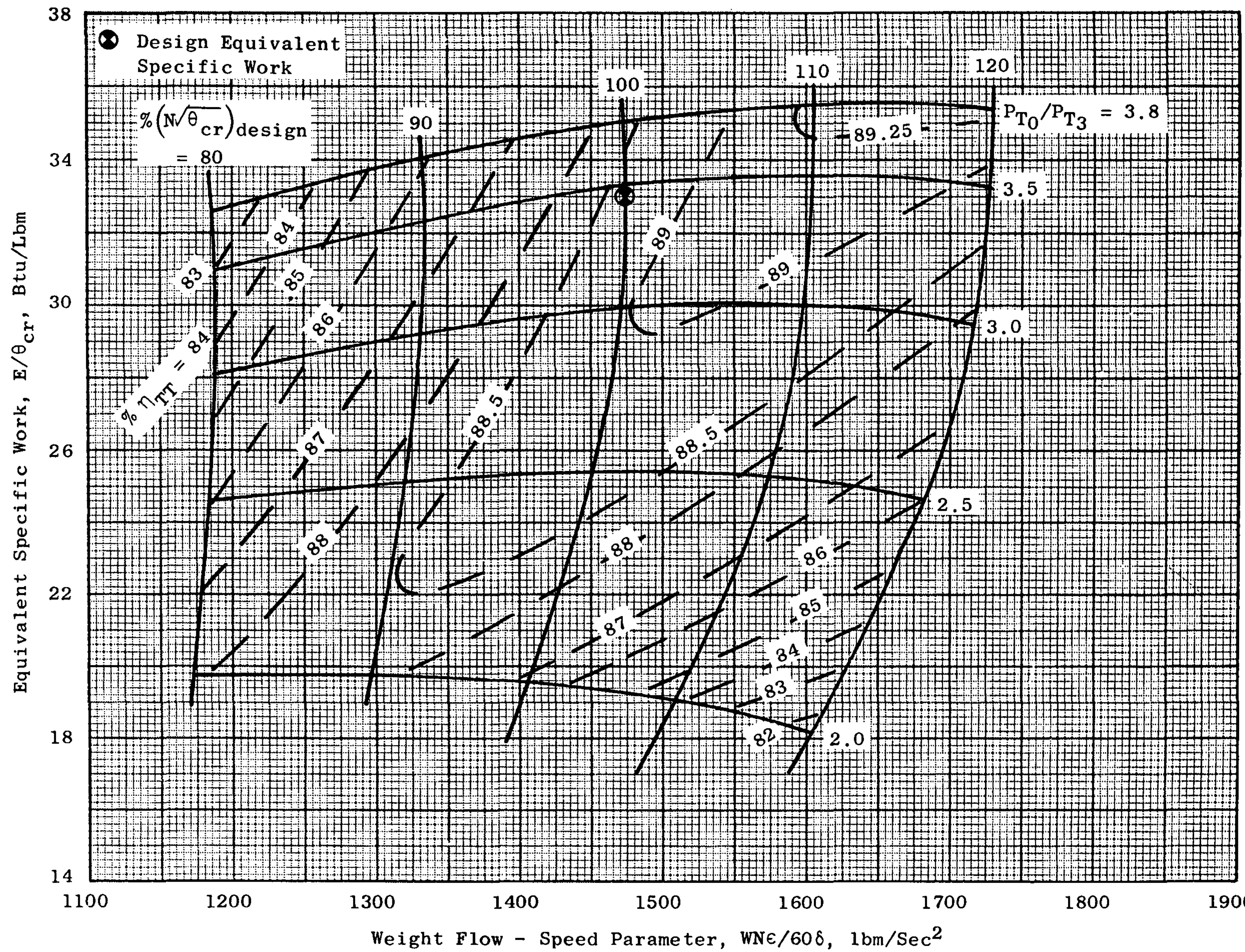


Figure 32. Equivalent Specific Work Vs. Weight Flow - Speed Parameter, Configuration 3A (PPTPLP).

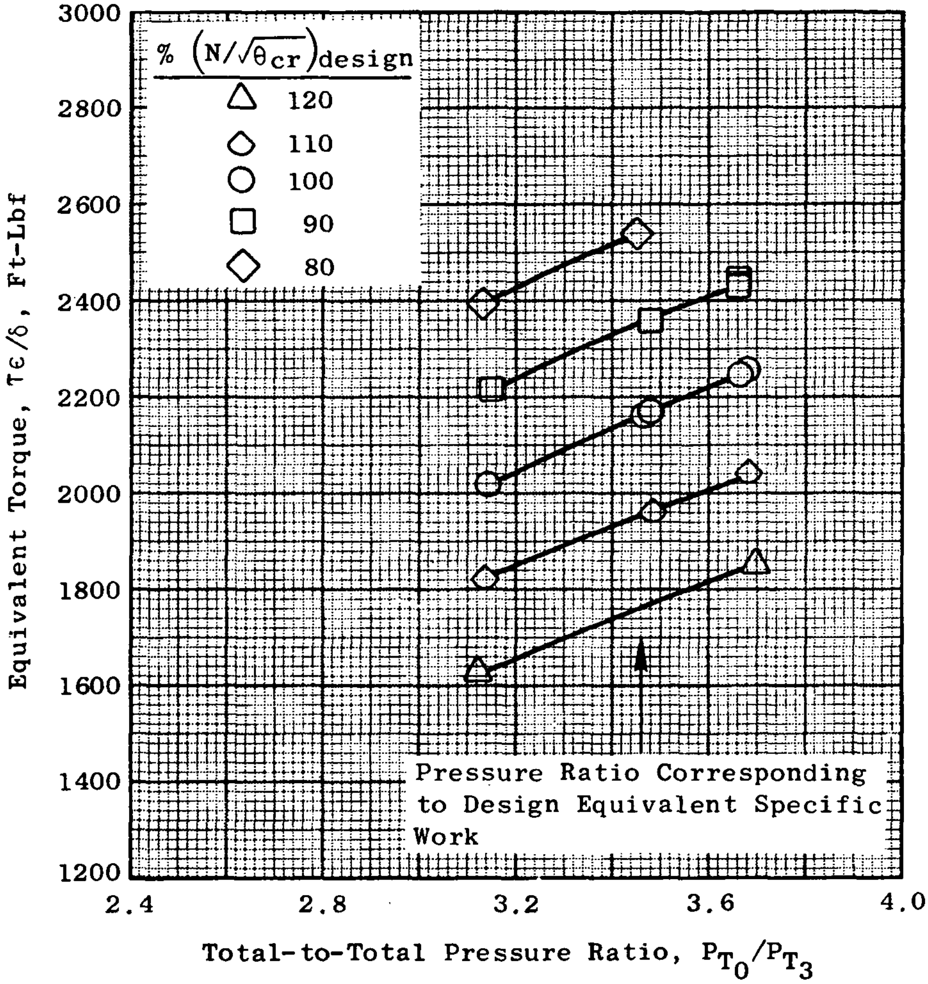


Figure 33. Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 4A (PPTPPP).

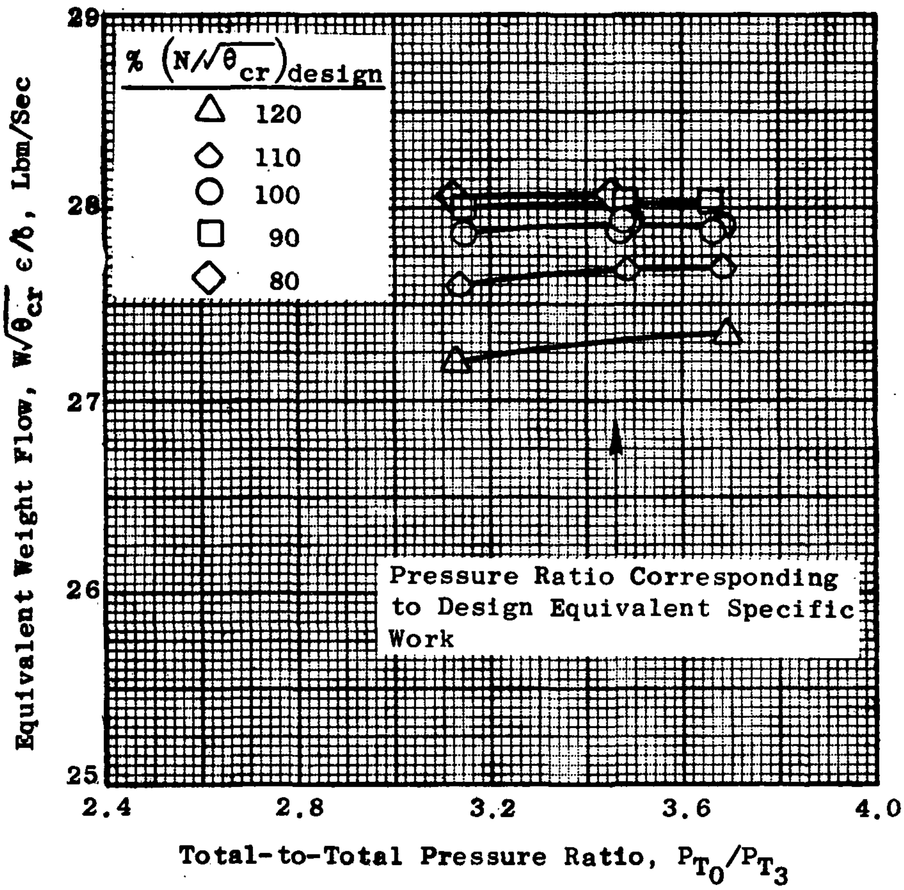


Figure 34. Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 4A (PPTPPP).

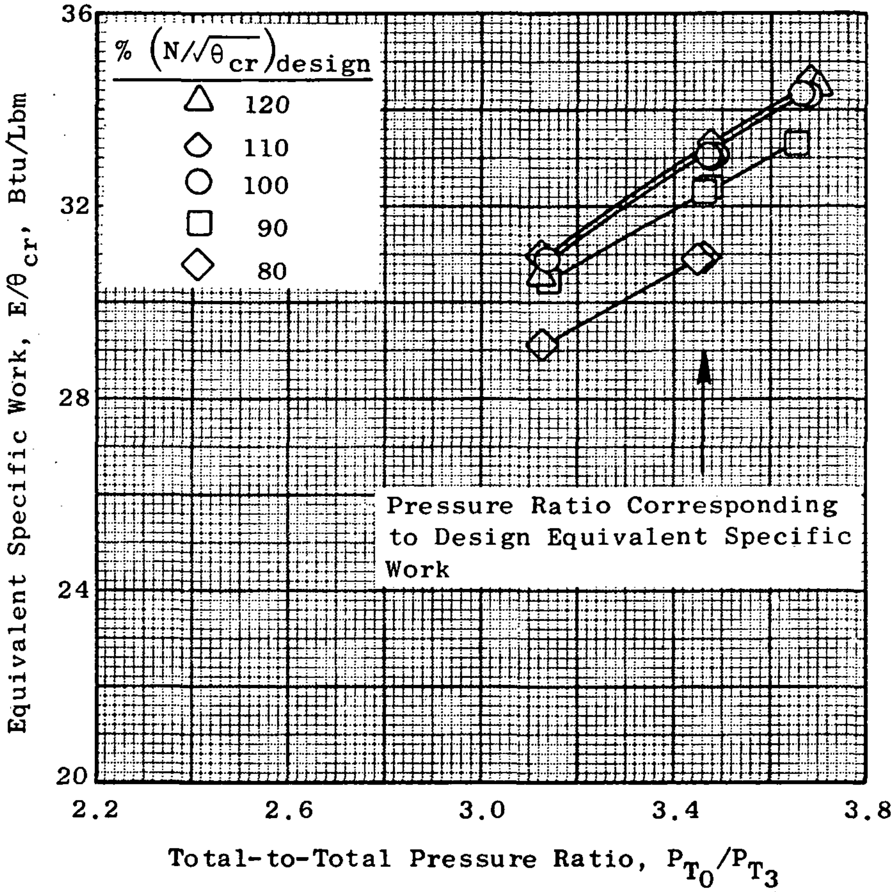


Figure 35. Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 4A (PPTPPP).

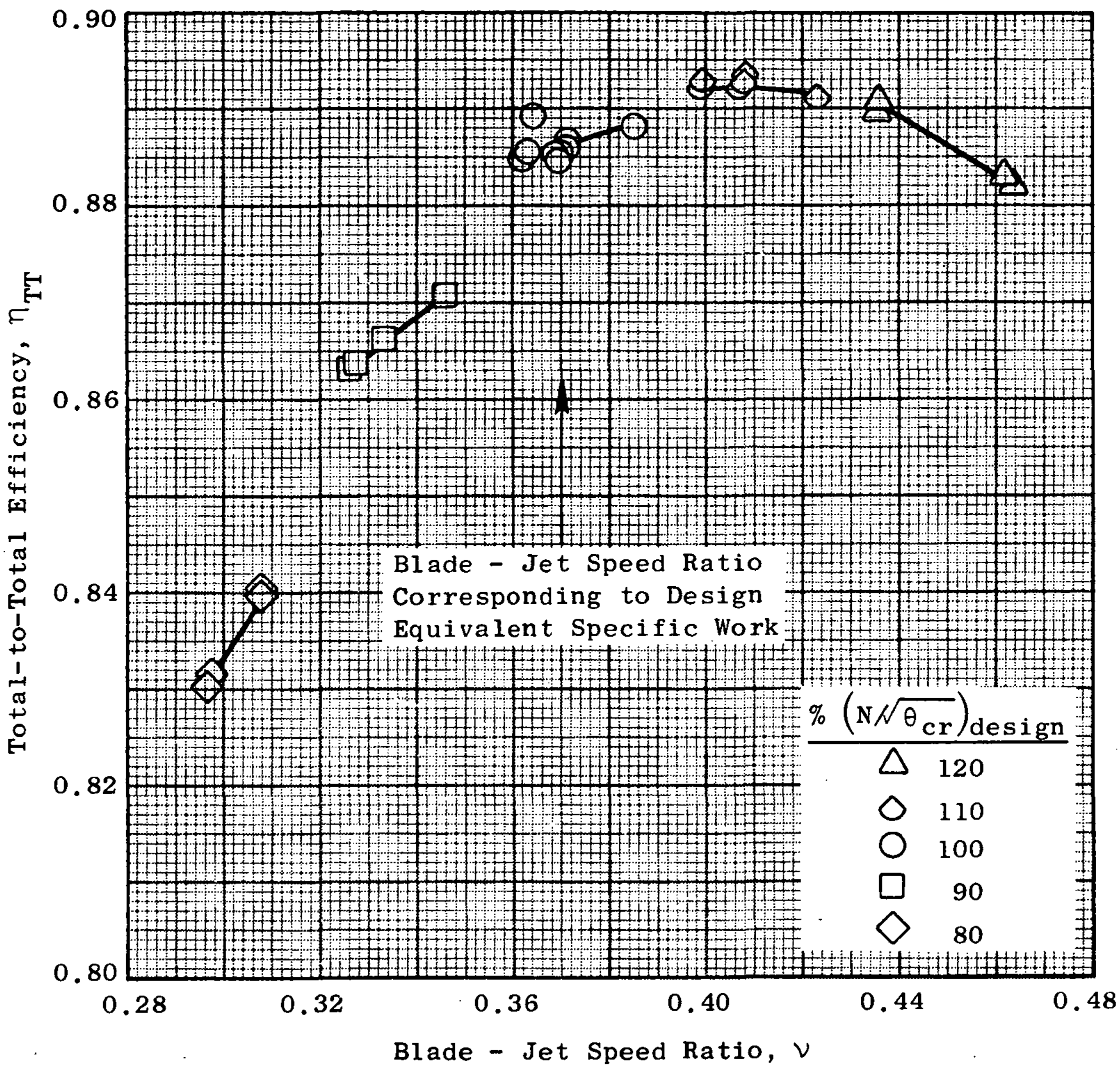


Figure 36. Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 4A (PPTPPP).

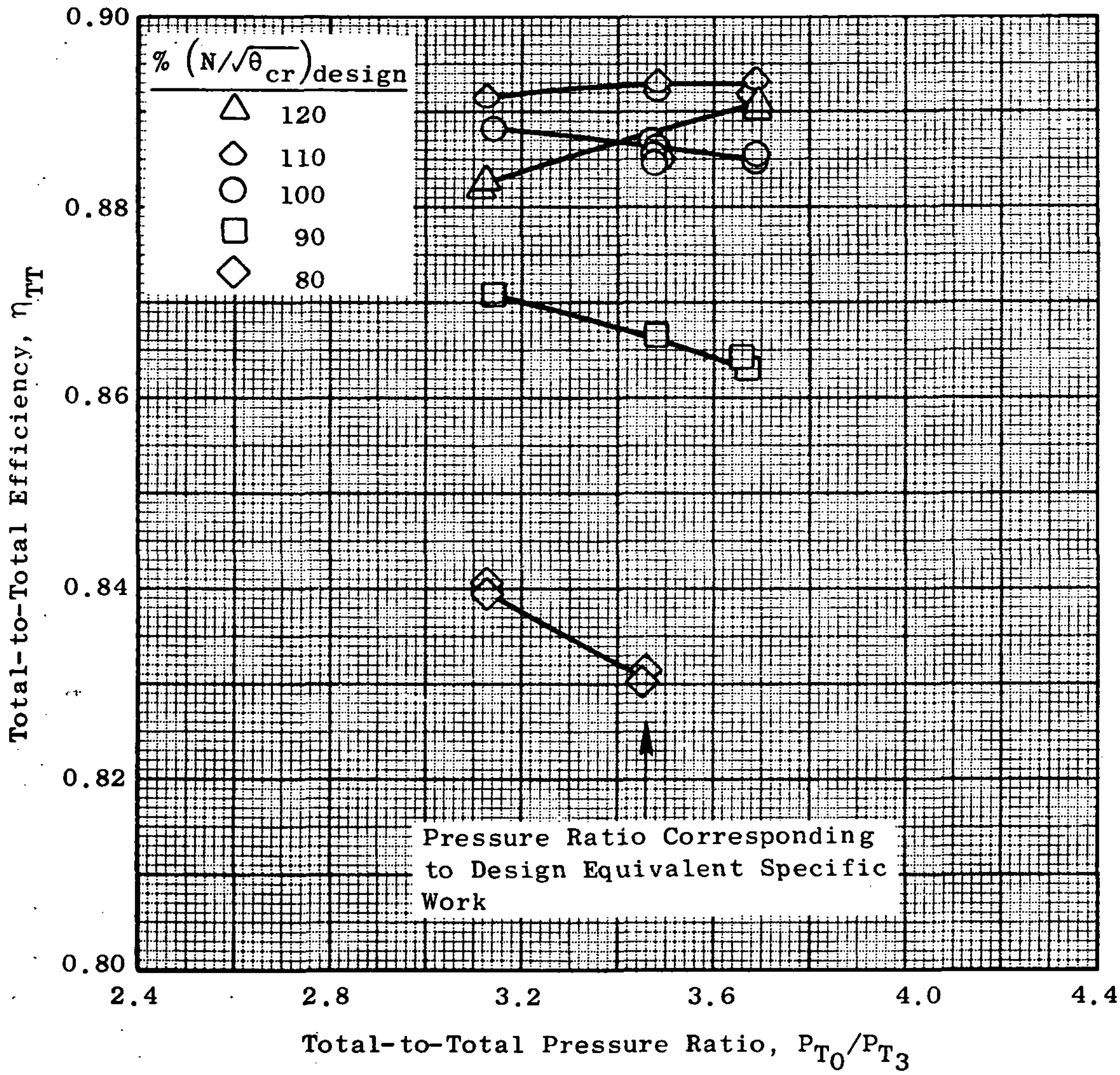


Figure 37. Total-to-Total Efficiency vs. Total-to-Total Pressure Ratio, Configuration 4A (PPTPPP).

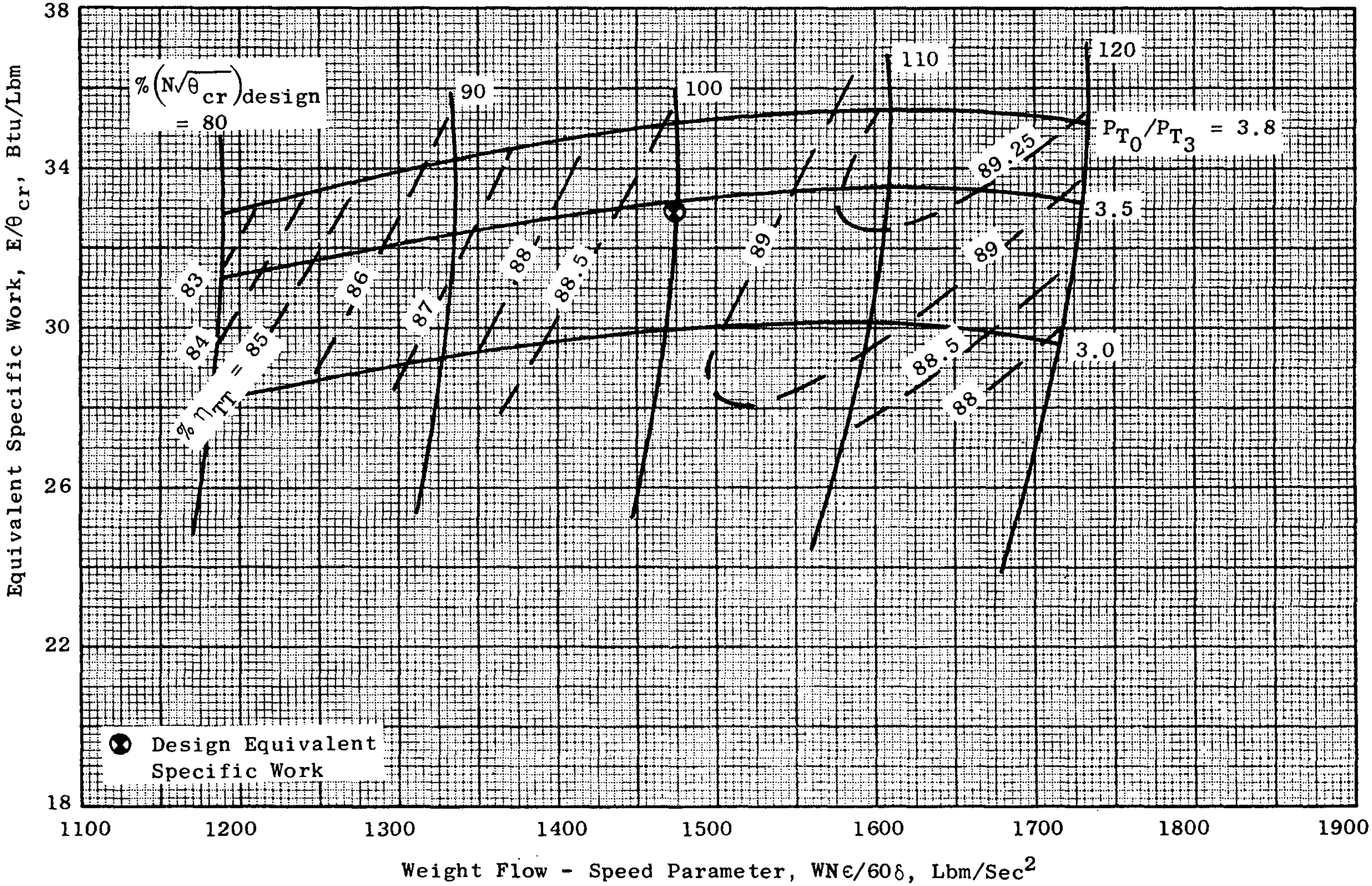


Figure 38. Equivalent Specific Work Vs. Weight - Flow Speed Parameter, Configuration 4A (PPTPPP).

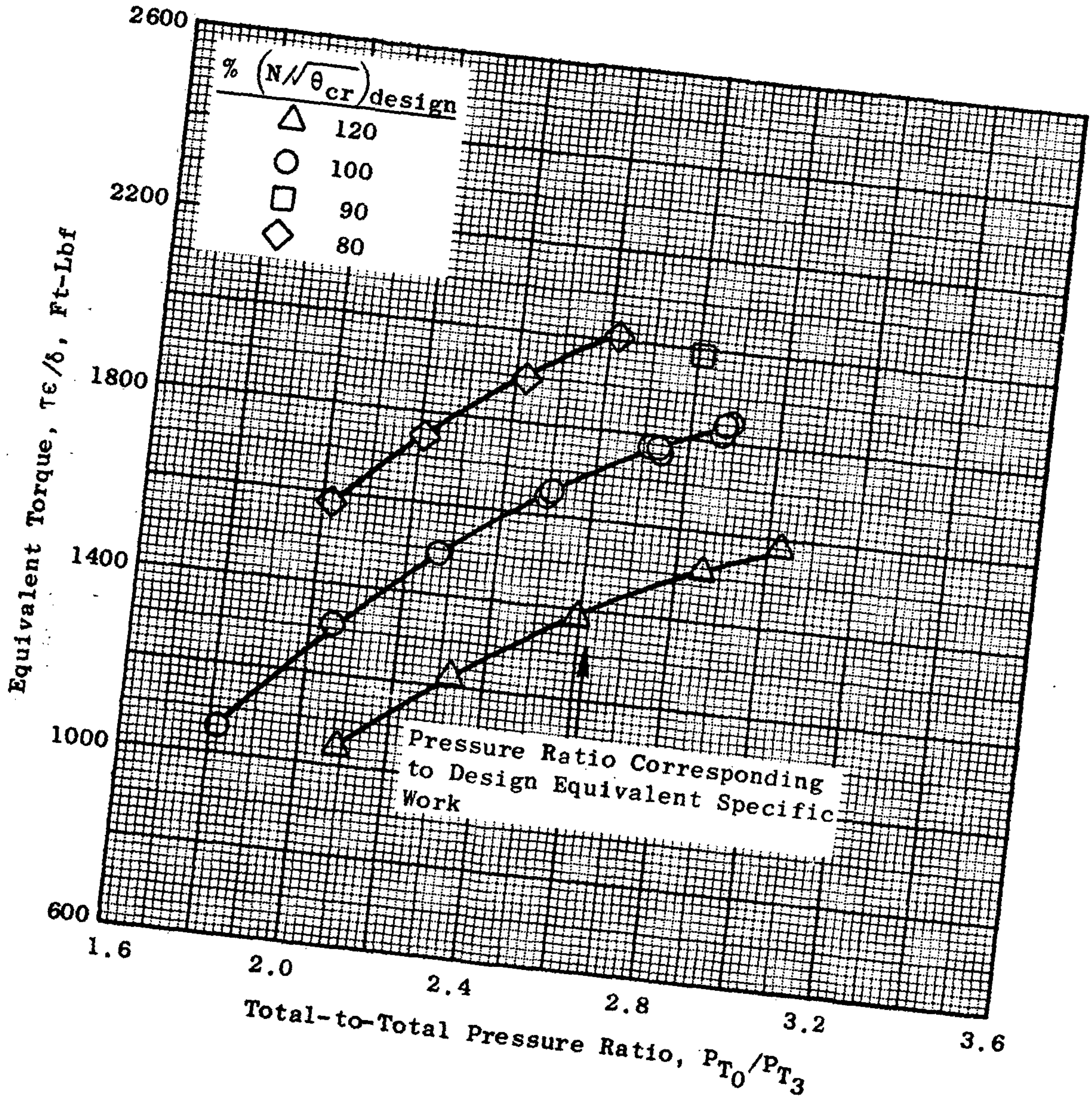


Figure 39. Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 5A (PPTP).

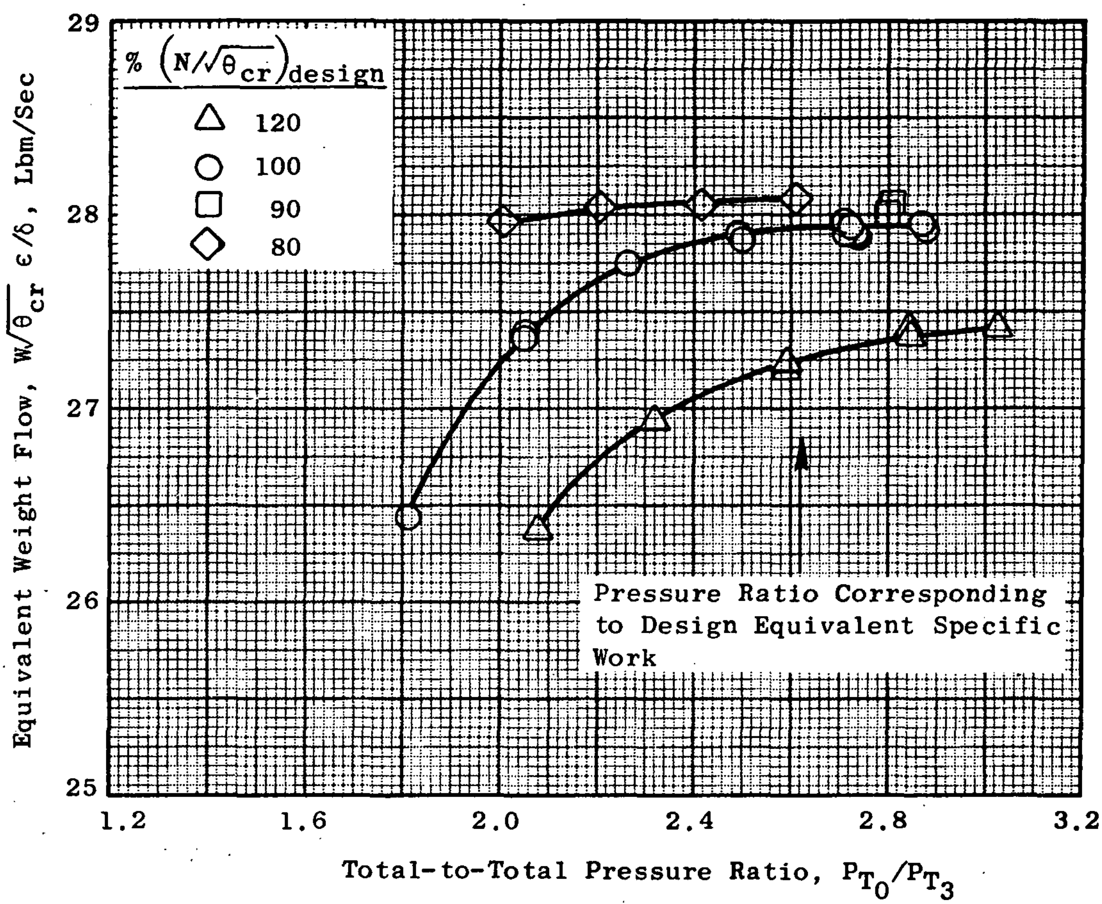


Figure 40. Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 5A (PPTP).

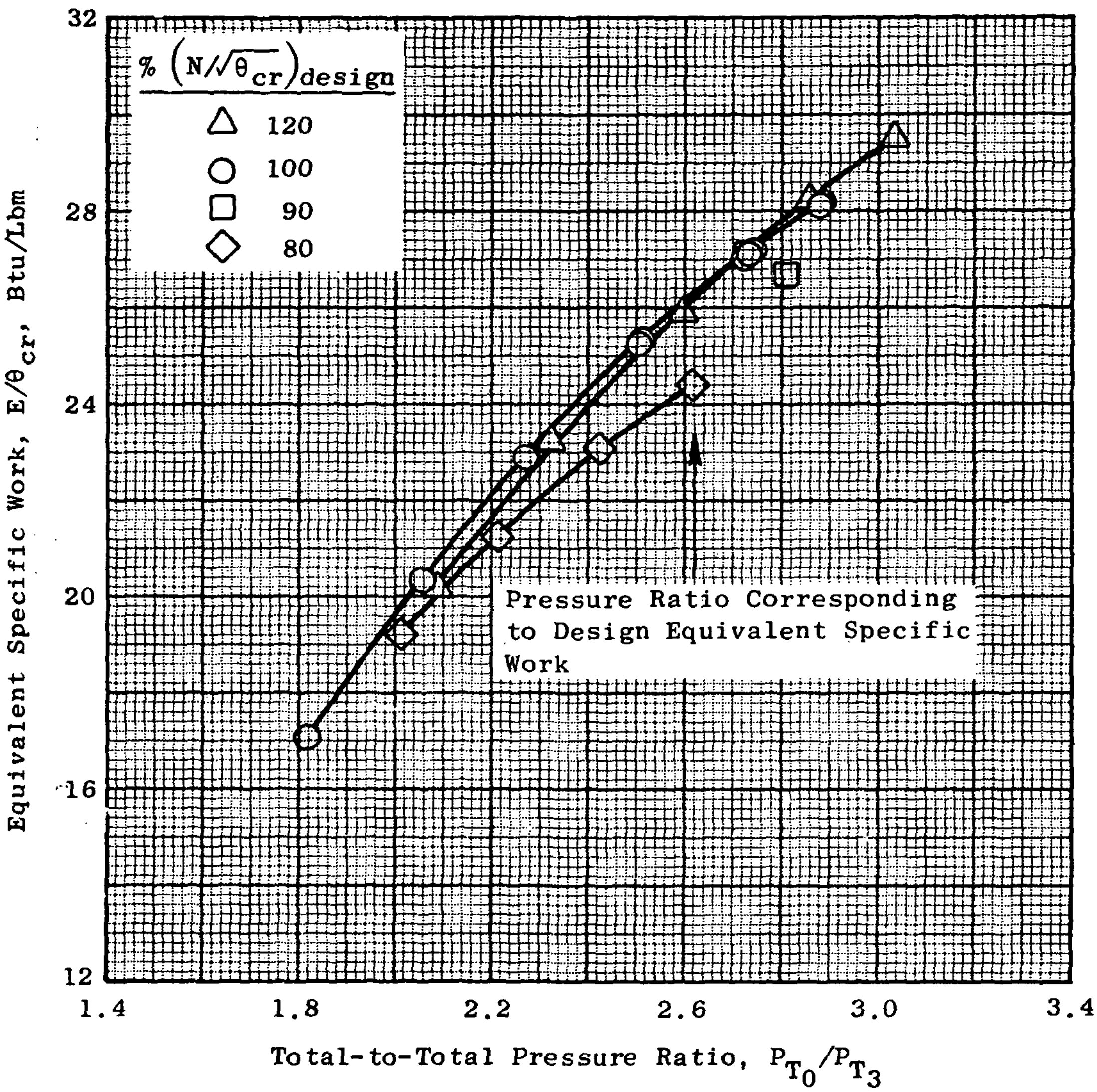


Figure 41. Equivalent Specific Work Vs. Total-to-Total Pressure Ratio, Configuration 5A (PPTP).

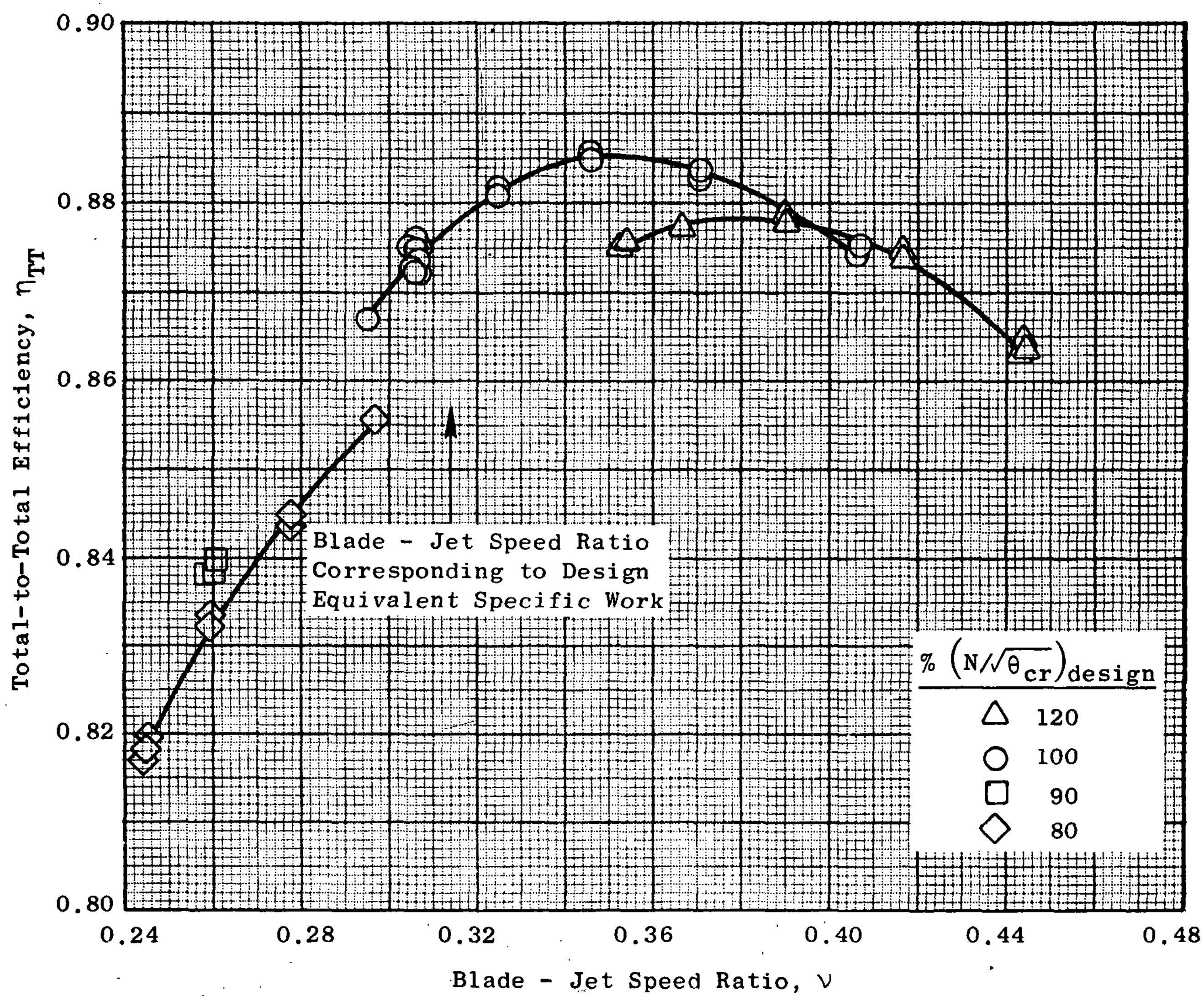


Figure 42. Total-to-Total Efficiency Vs. Blade-Jet Speed Ratio, Configuration 5A (PPTP).

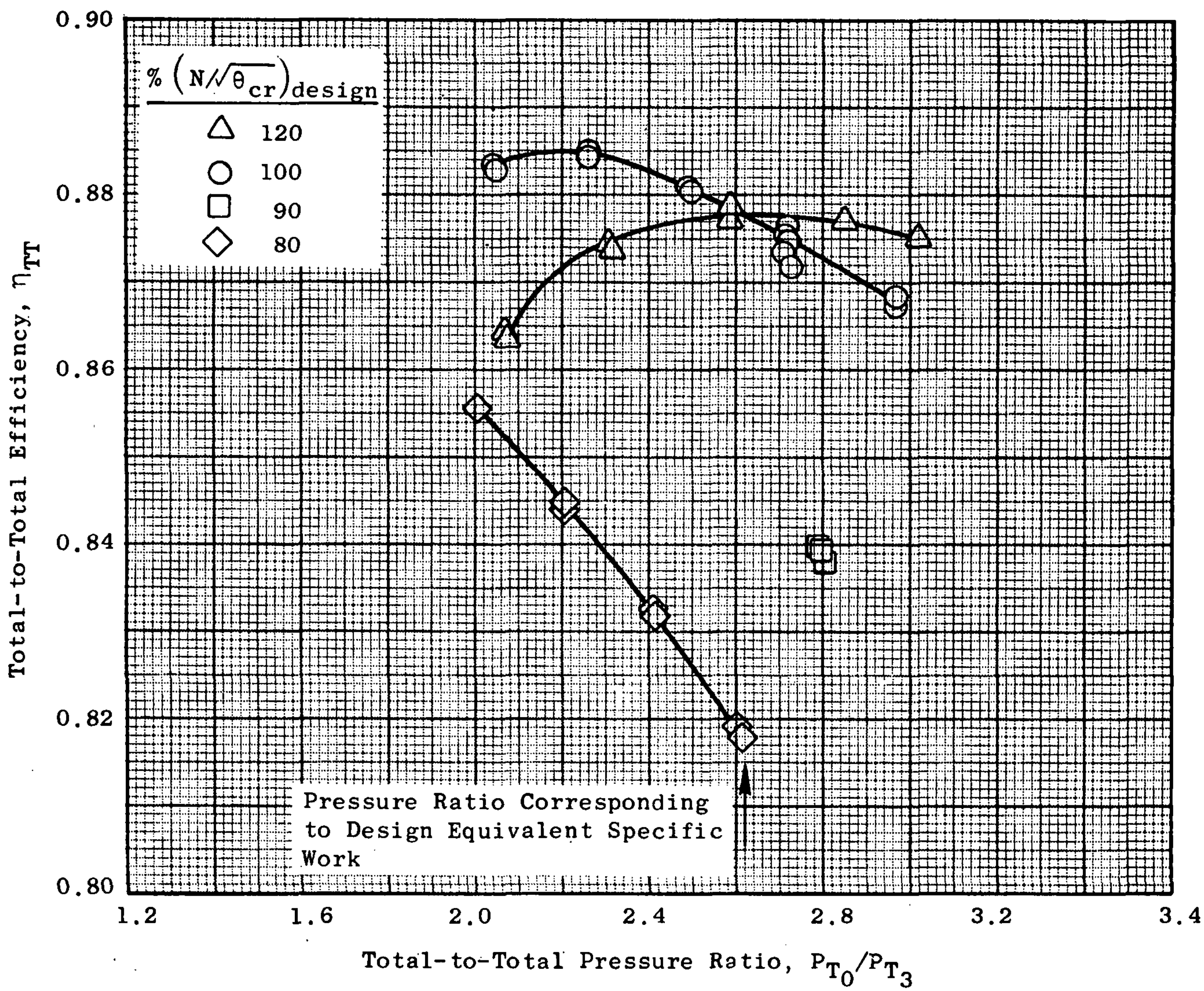


Figure 43. Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 5A (PPTP).

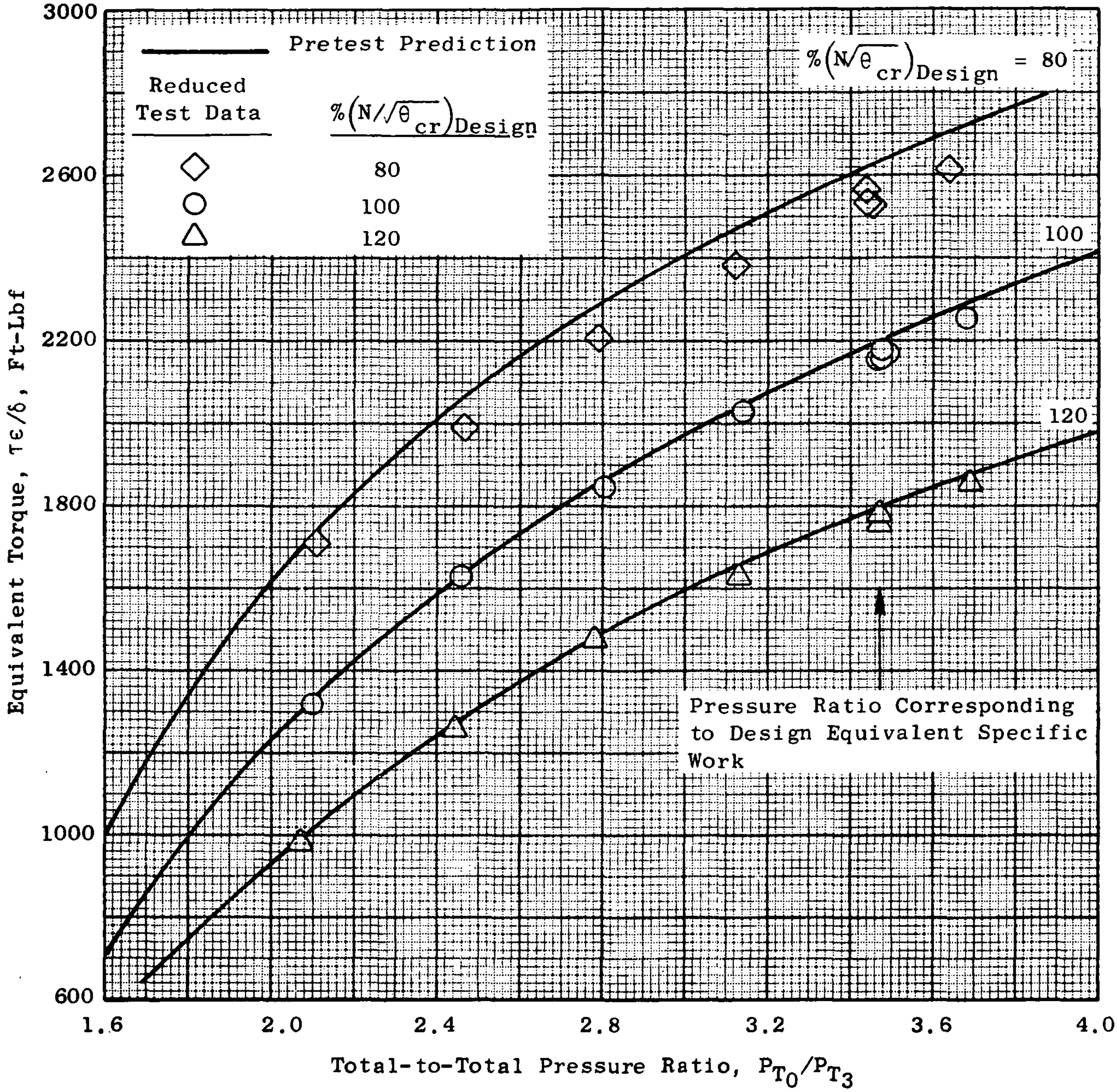


Figure 44. Predicted and Actual Equivalent Torque Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).

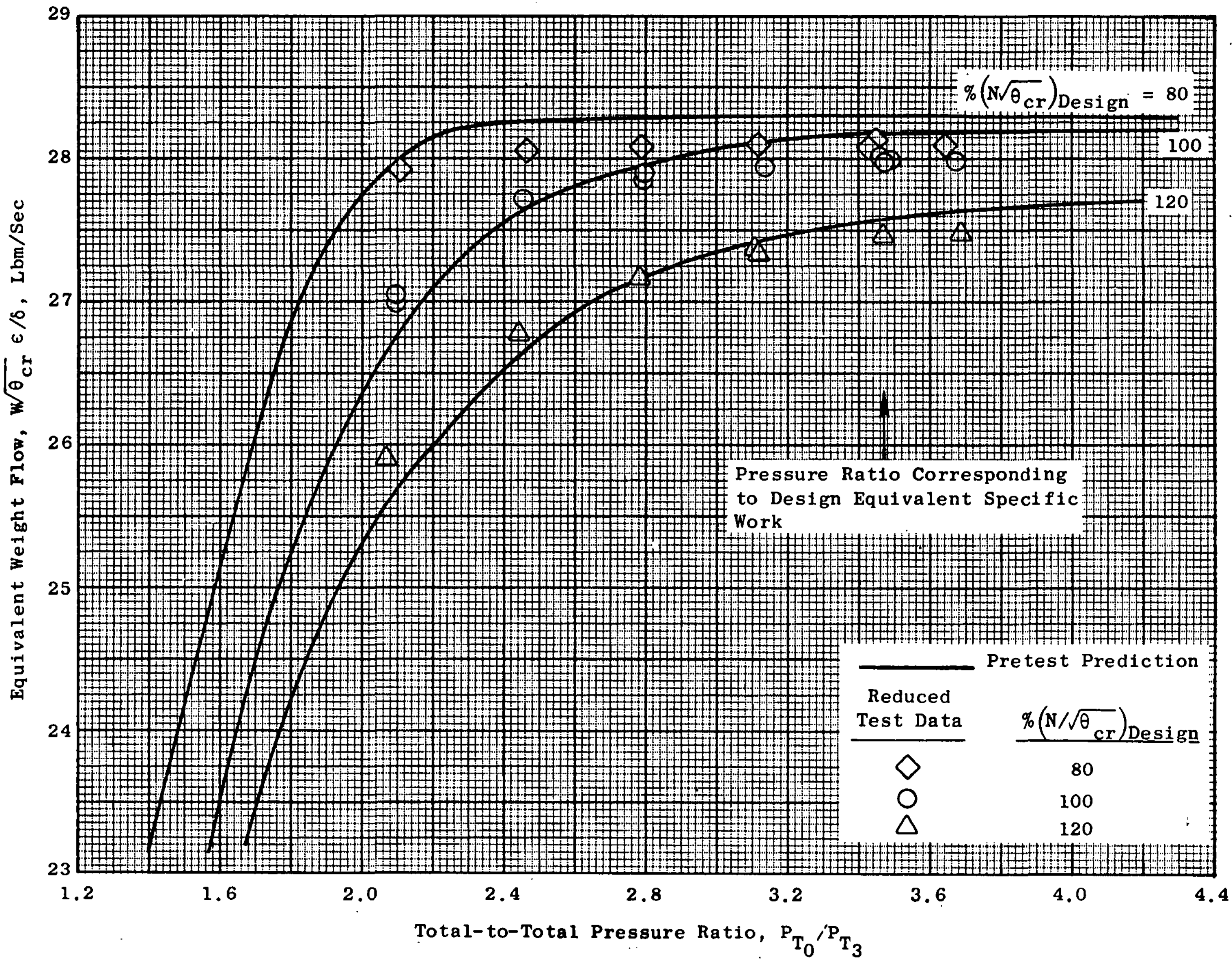


Figure 45. Predicted and Actual Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).

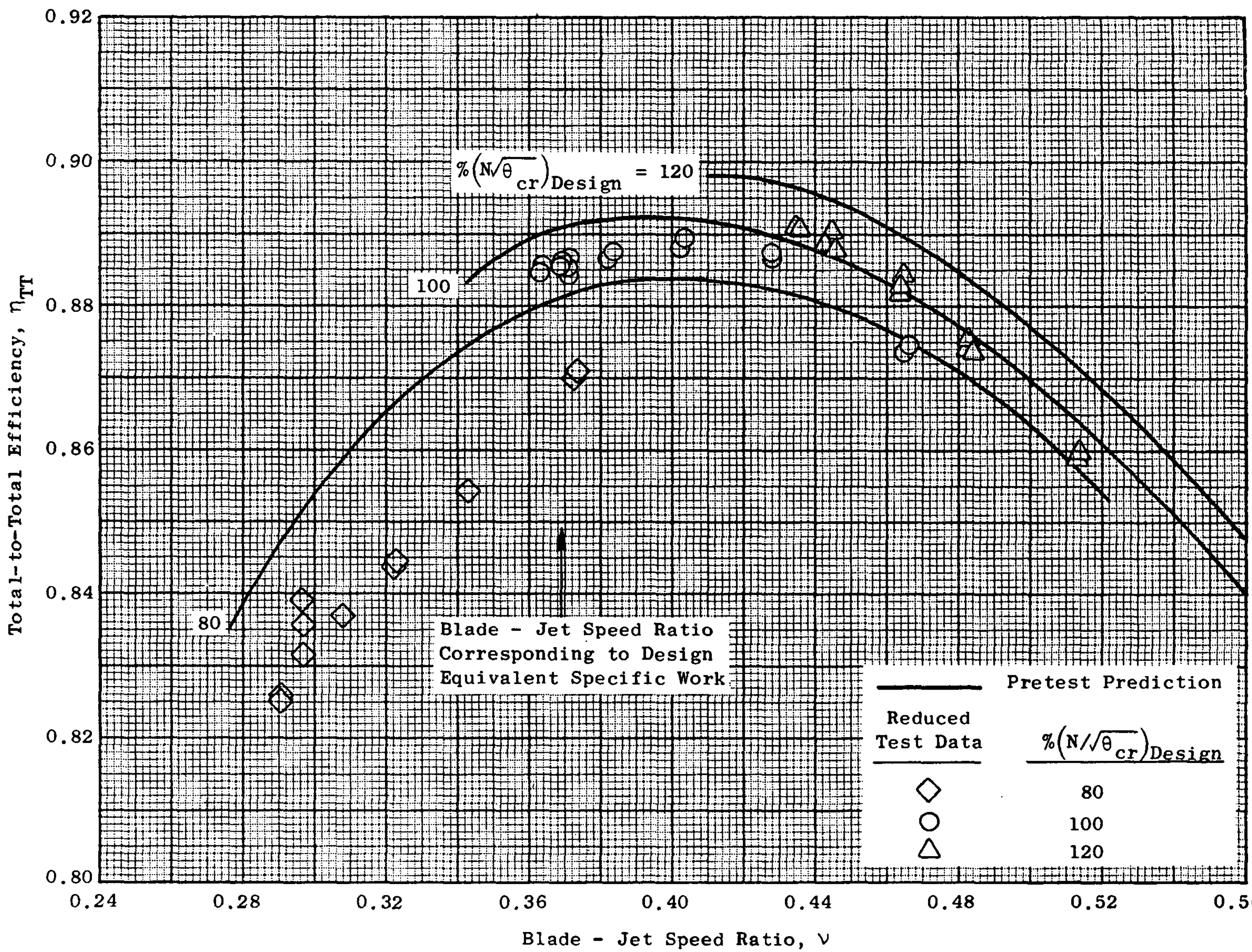


Figure 46. Predicted and Actual Total-to-Total Efficiency Vs. Blade - Jet Speed Ratio, Configuration 1A (PPPPPP).

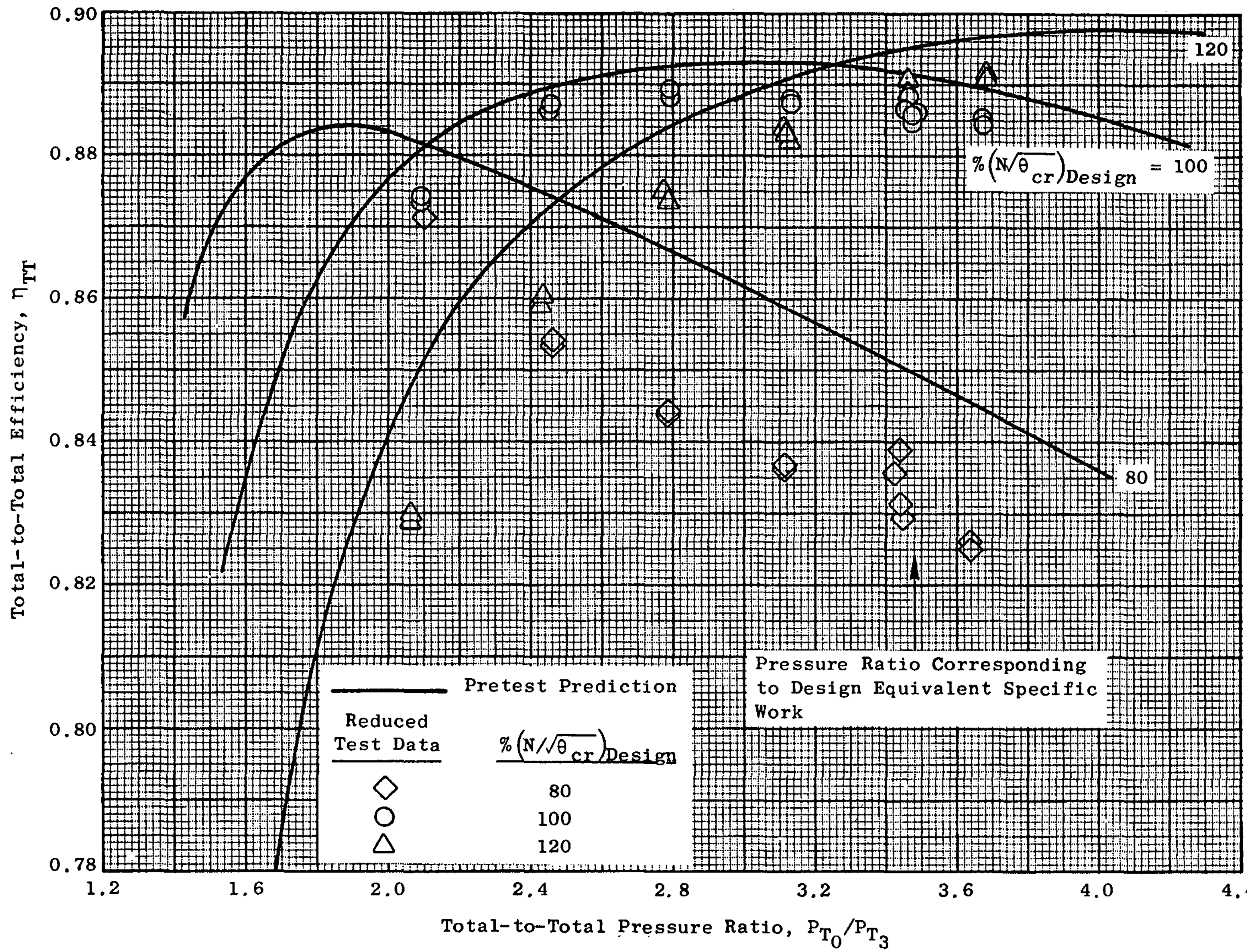


Figure 47. Predicted and Actual Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio, Configuration 1A (PPPPPP).

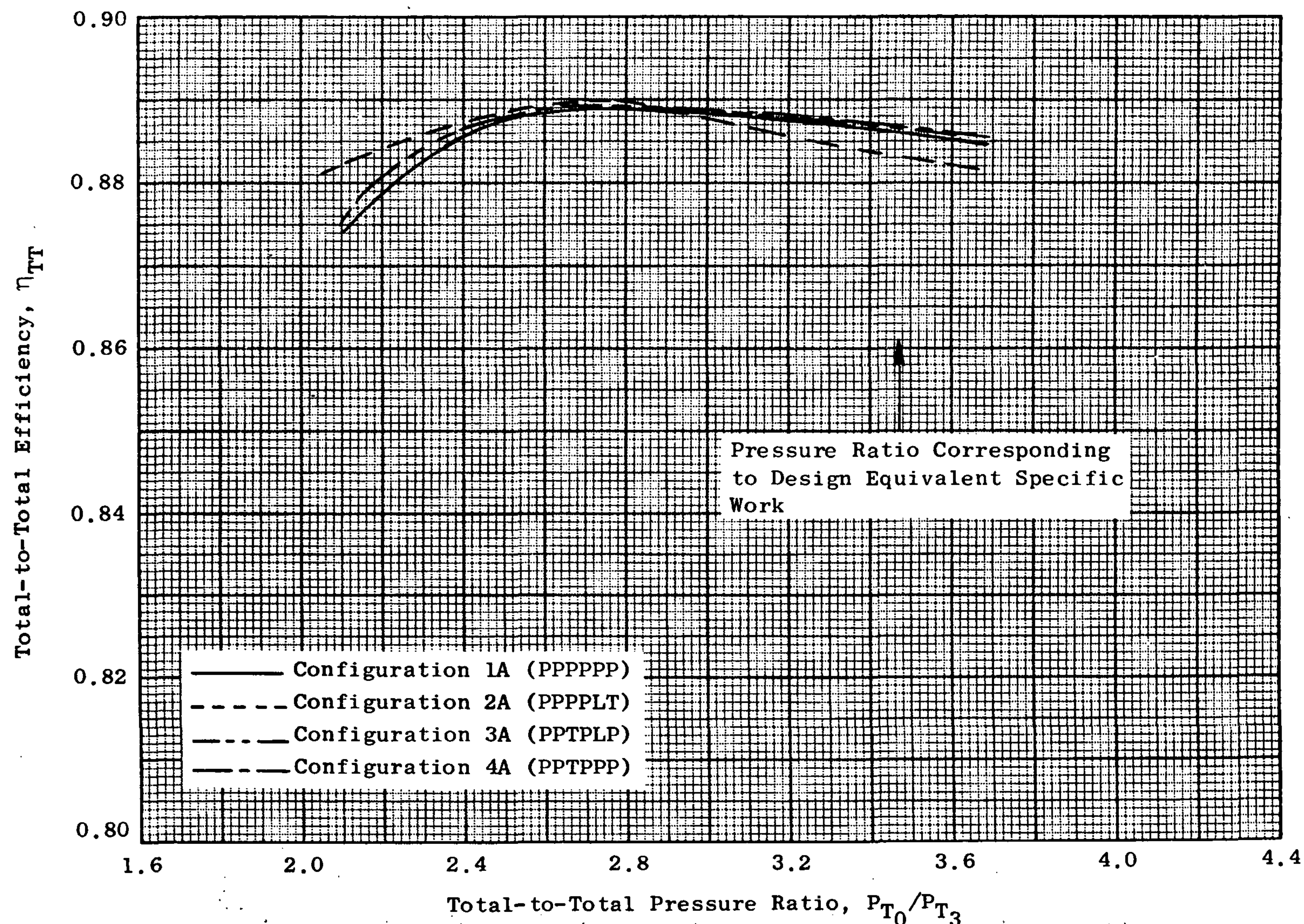


Figure 48. Total-to-Total Efficiency Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed, Three-Stage Turbine Configurations Compared.

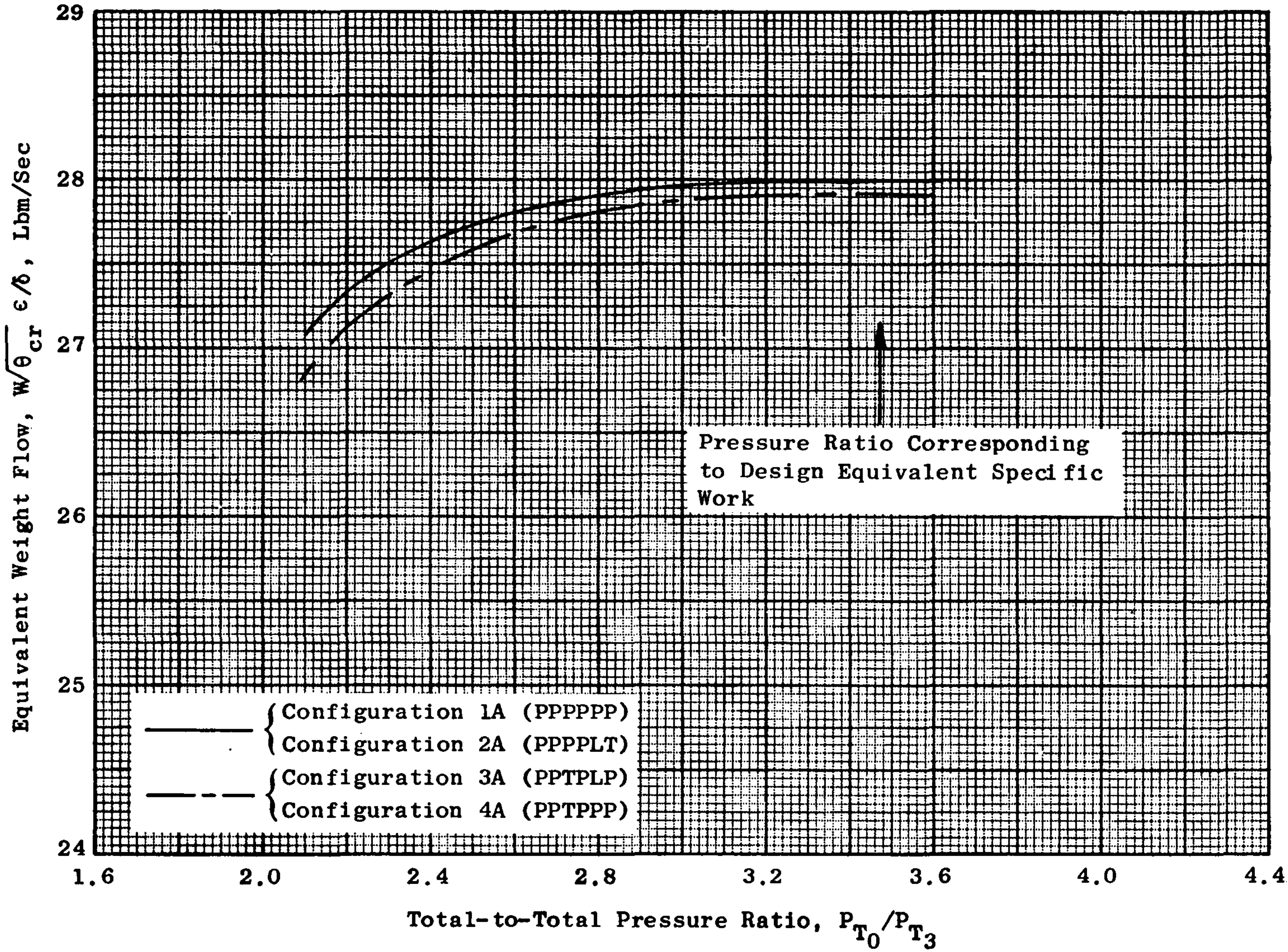


Figure 49. Equivalent Weight Flow Vs. Total-to-Total Pressure Ratio at Design Equivalent Speed, Three-Stage Turbine Configurations Compared.

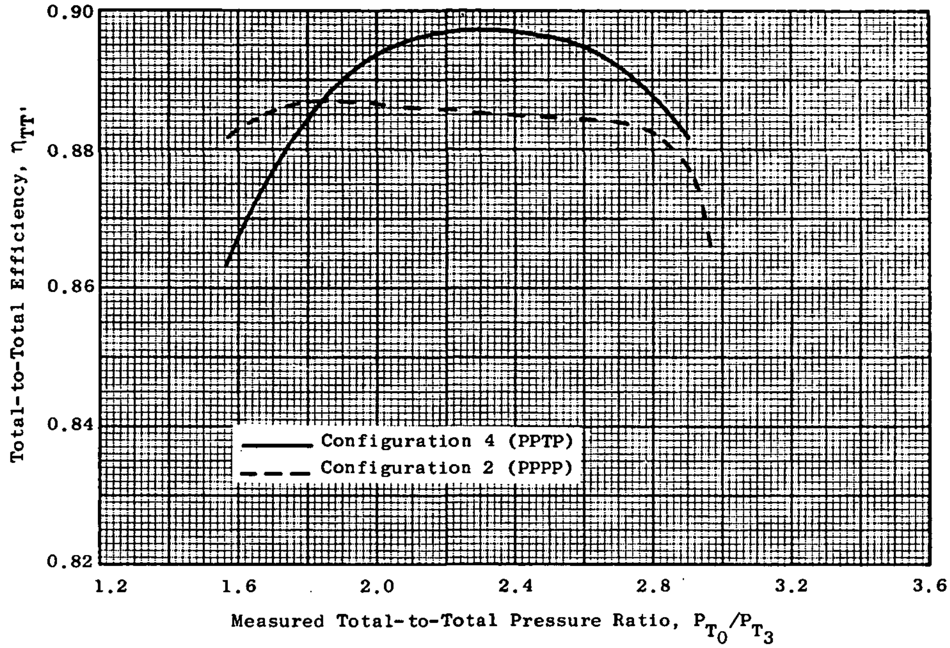


Figure 50a. Total-to-Total Efficiency Based on Measured Temperature Drop and Measured Inlet and Exit Total Pressure Vs. Measured Total-to-Total Pressure Ratio at Design Speed, Configuration 2 (PPPP) and Configuration 4 (PPTP) Compared.

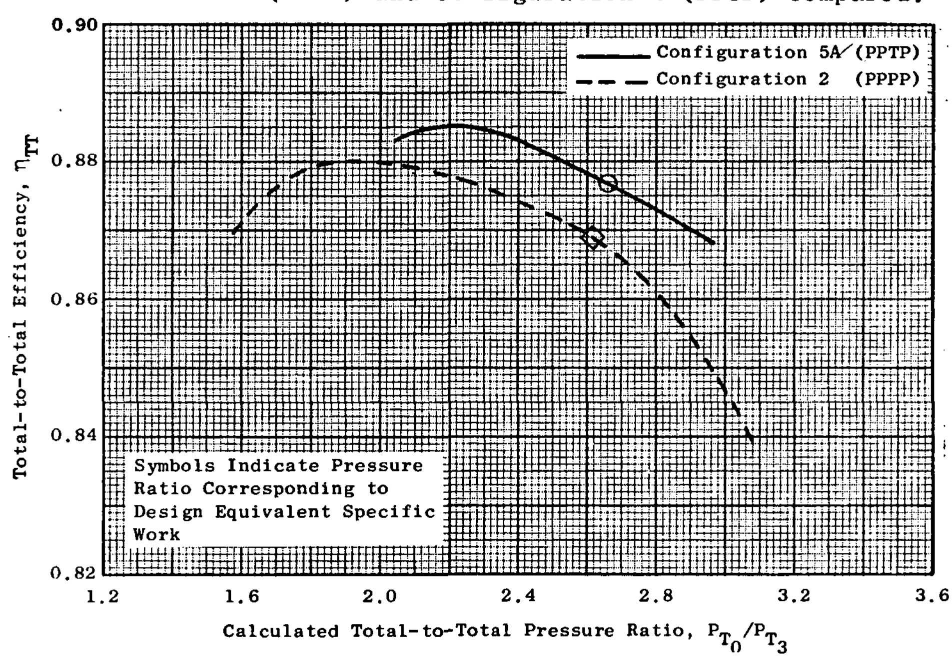


Figure 50b. Total-to-Total Efficiency Based on Measured Torque and Calculated Inlet and Exit Total Pressure Vs. Calculated Total-to-Total Pressure Ratio at Design Equivalent Speed, Configuration 2 (PPPP) and Configuration 5A (PPTP) Compared.

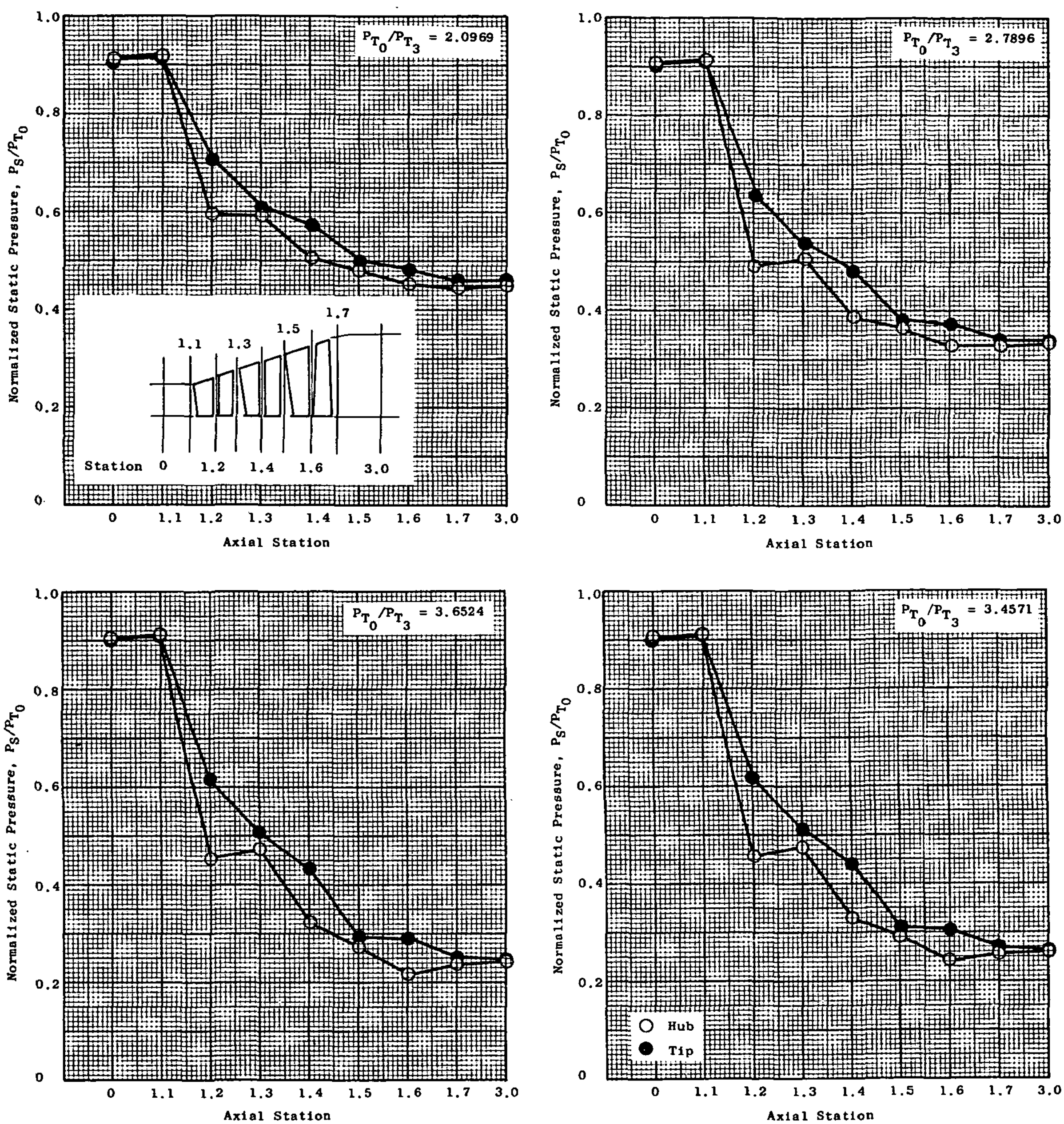


Figure 51. Normalized Static Pressure Vs. Axial Station, Configuration 1A (PPPPPP), at Design Equivalent Speed.

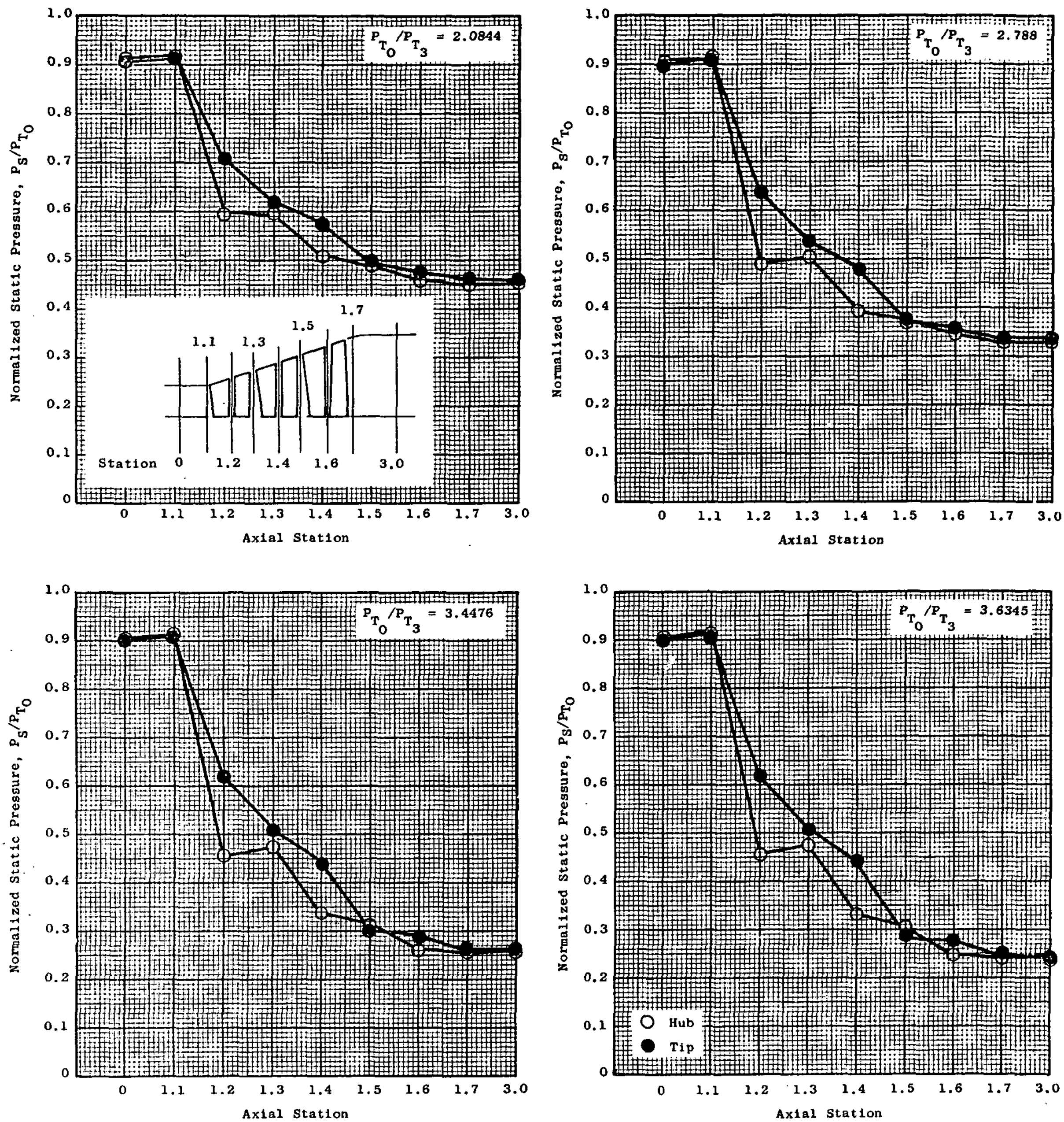


Figure 52. Normalized Static Pressure Vs. Axial Station, Configuration 2A (PPPPLT), at Design Equivalent Speed.

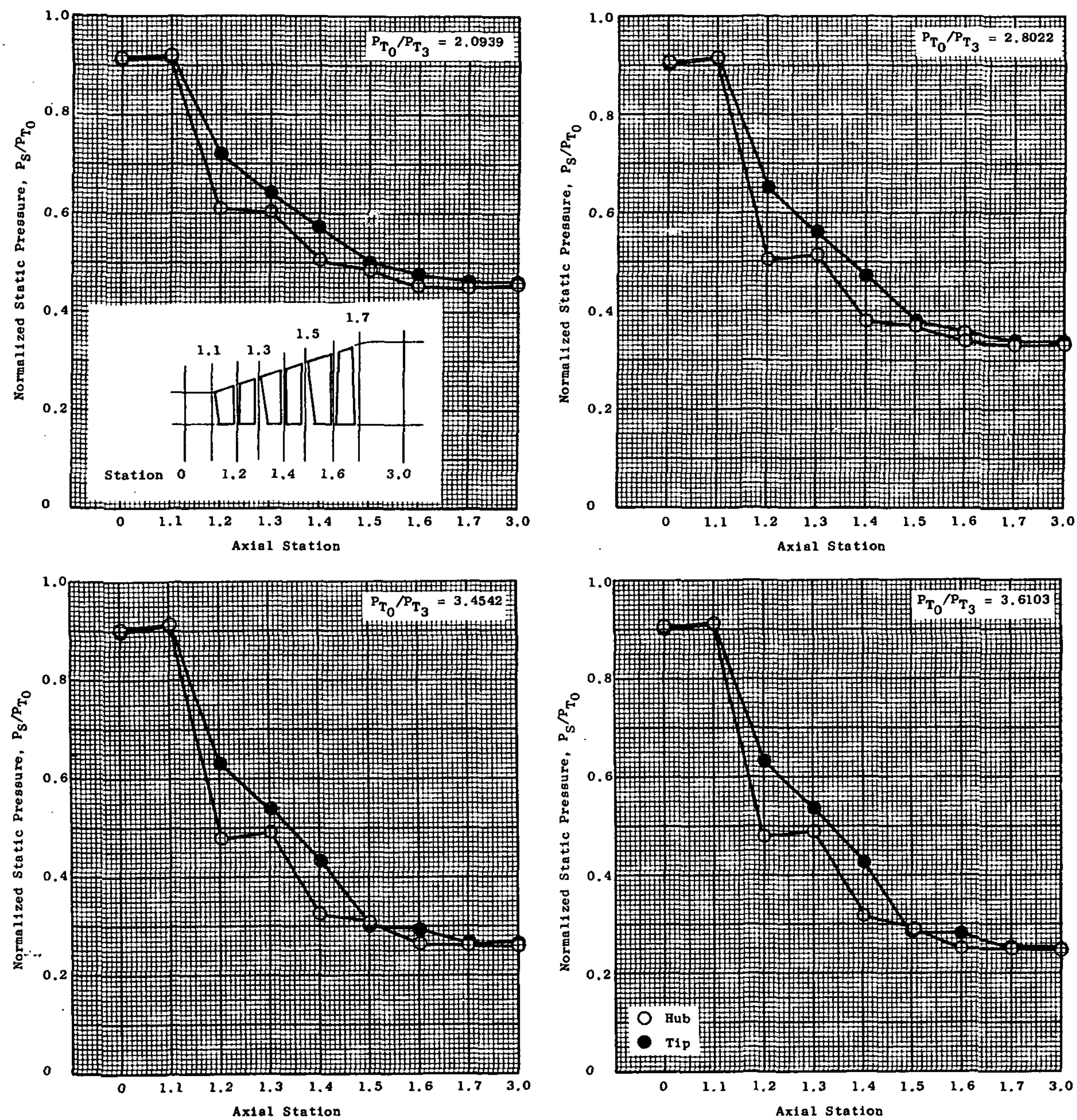


Figure 53. Normalized Static Pressure Vs. Axial Station, Configuration 3A (PPTPLP), at Design Equivalent Speed.

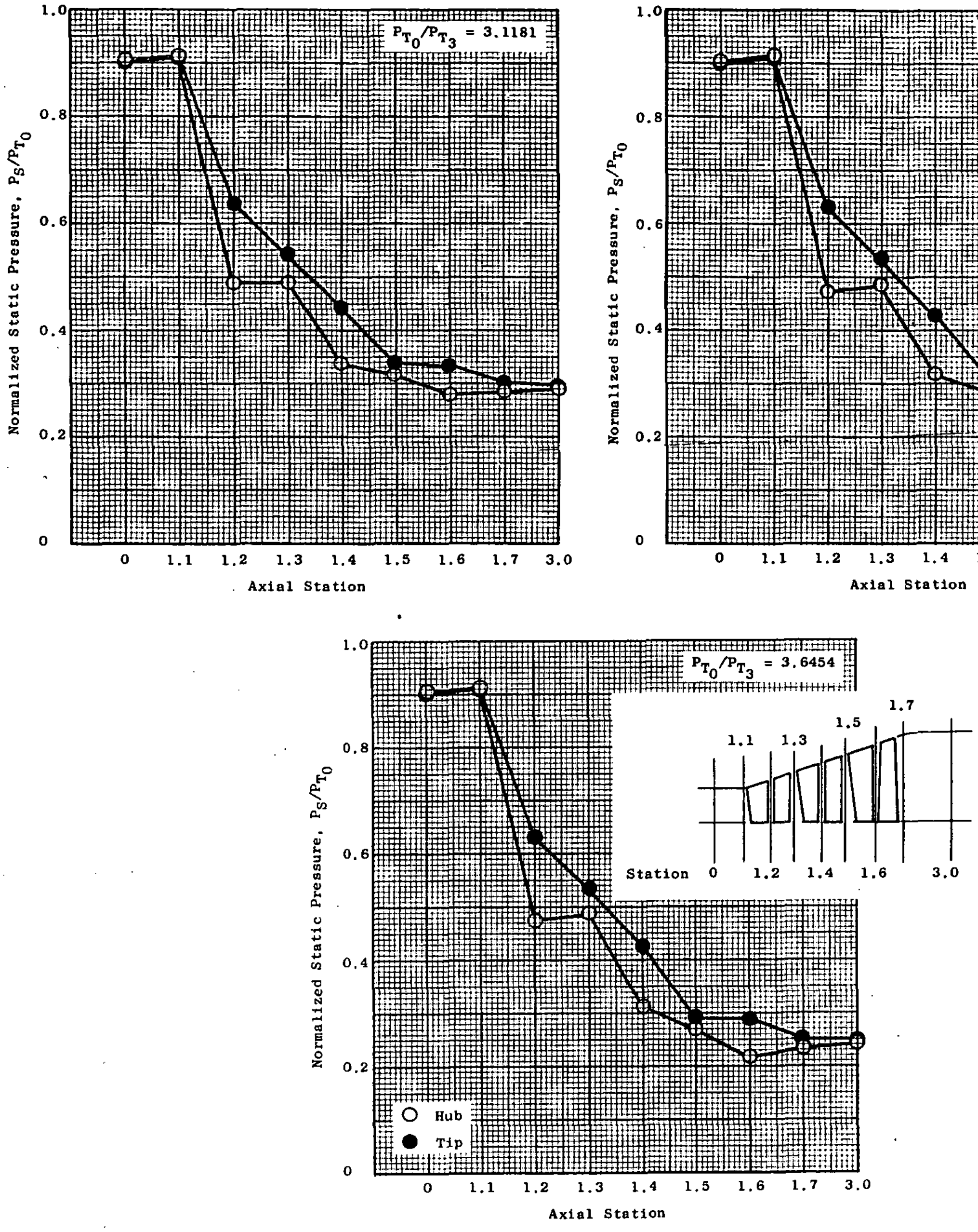


Figure 54. Normalized Static Pressure Vs. Axial Station, Configuration 4A (PPTPPP), at Design Equivalent Speed.

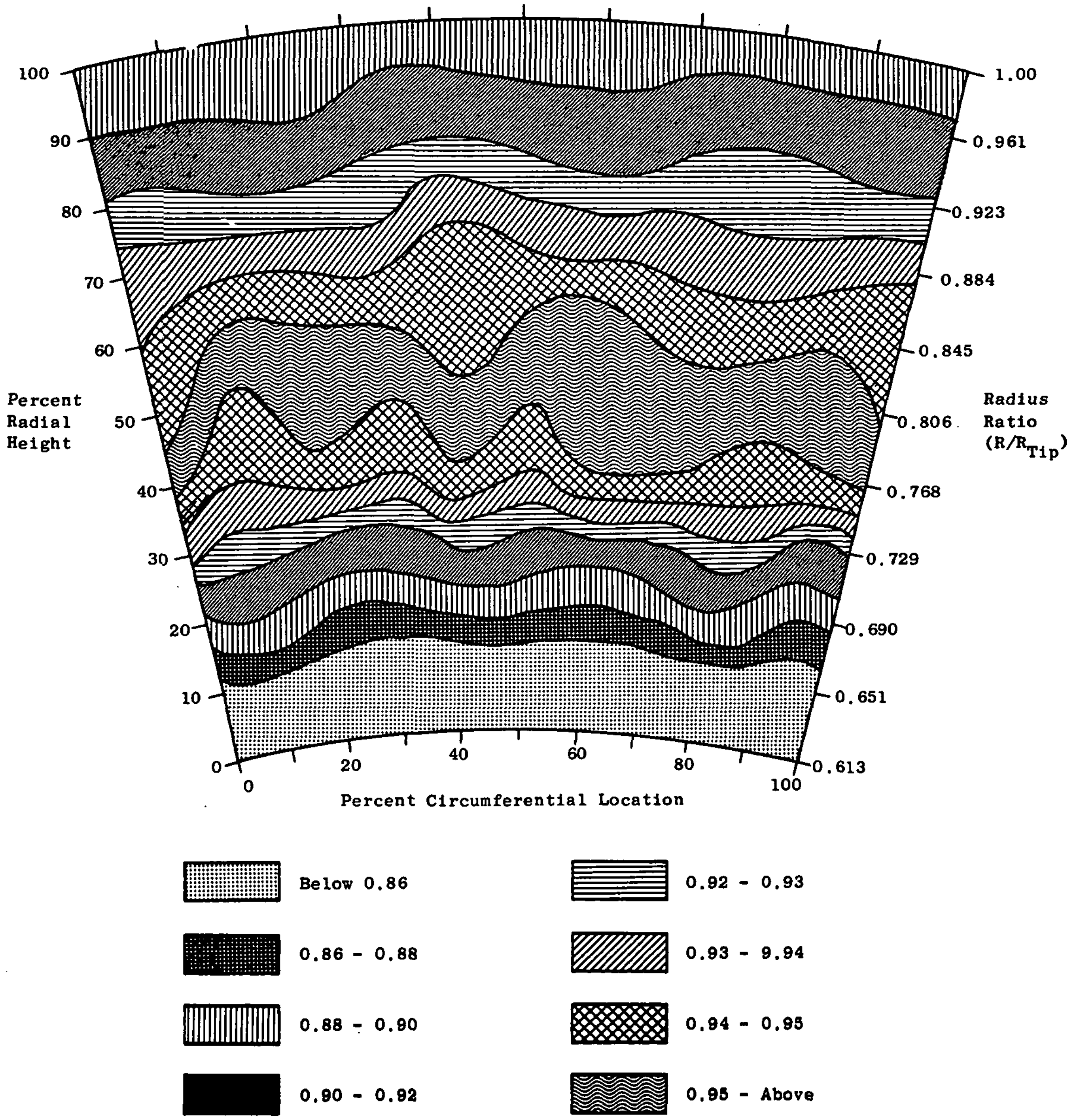


Figure 55. Turbine Efficiency Contour Plot, Configuration 1A (PPPPPP).

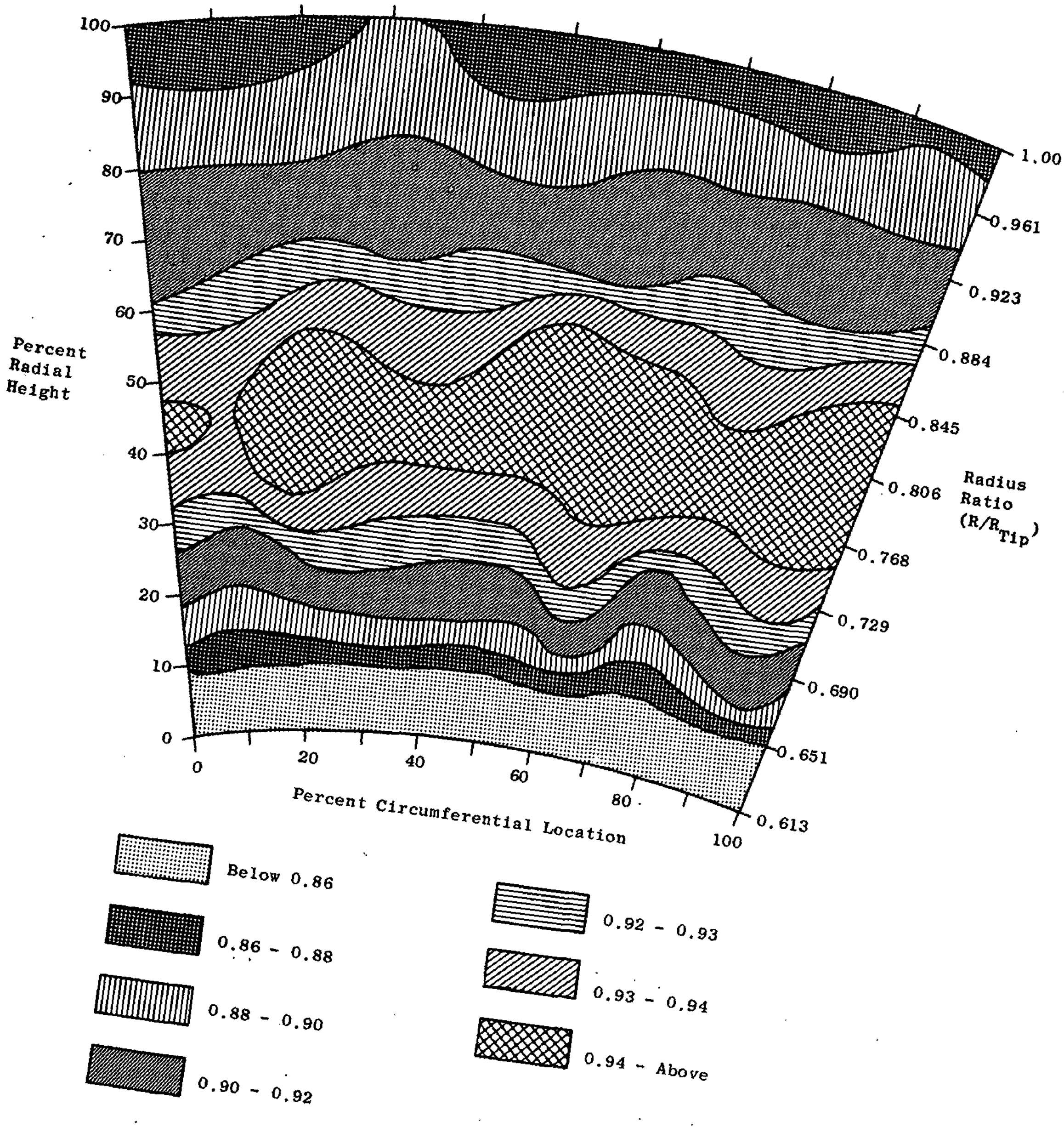


Figure 56. Turbine Efficiency Contour Plot, Configuration 2A (PPPPLT).

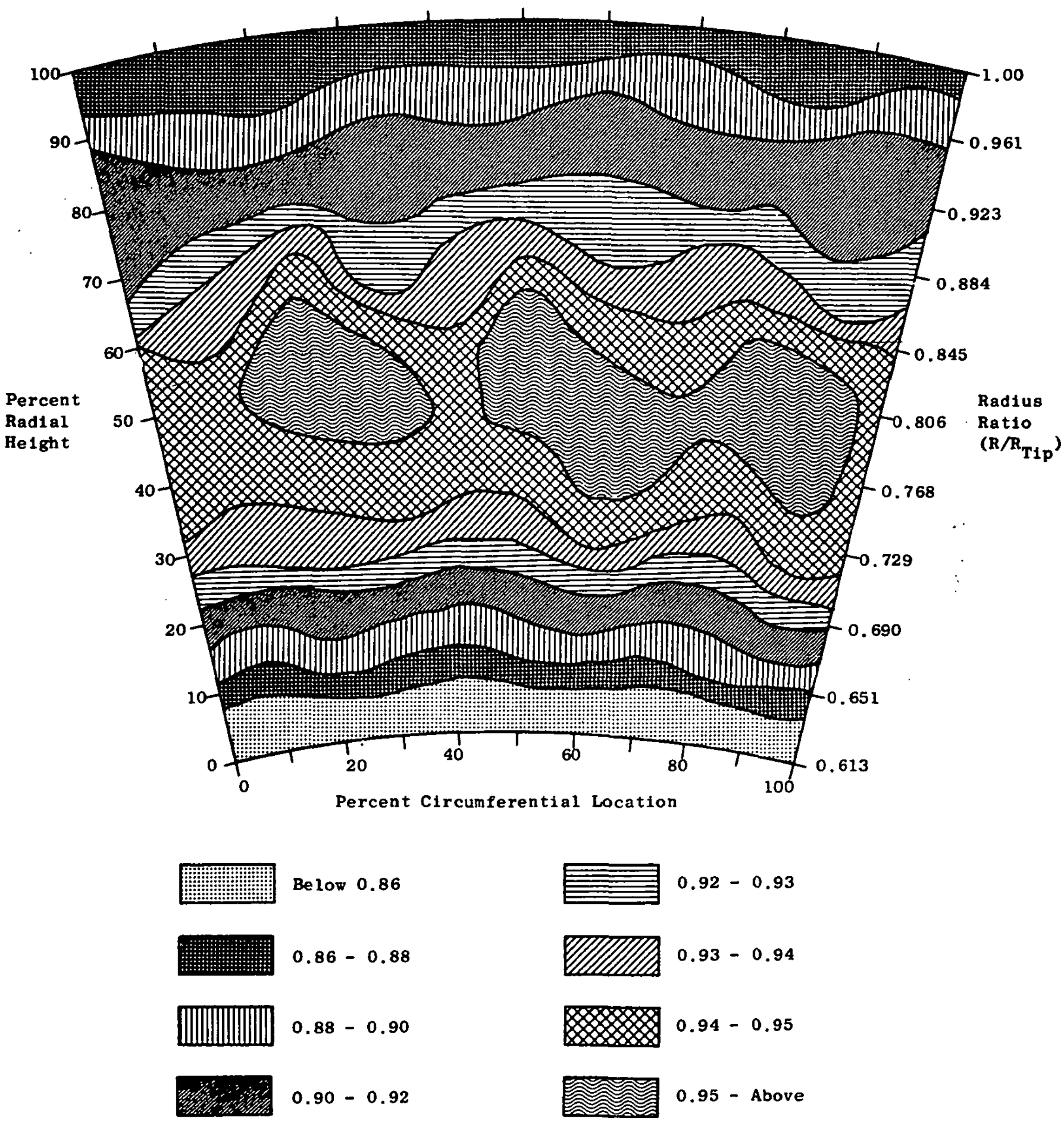


Figure 57. Turbine Efficiency Contour Plot, Configuration 3A (PPTPLP).

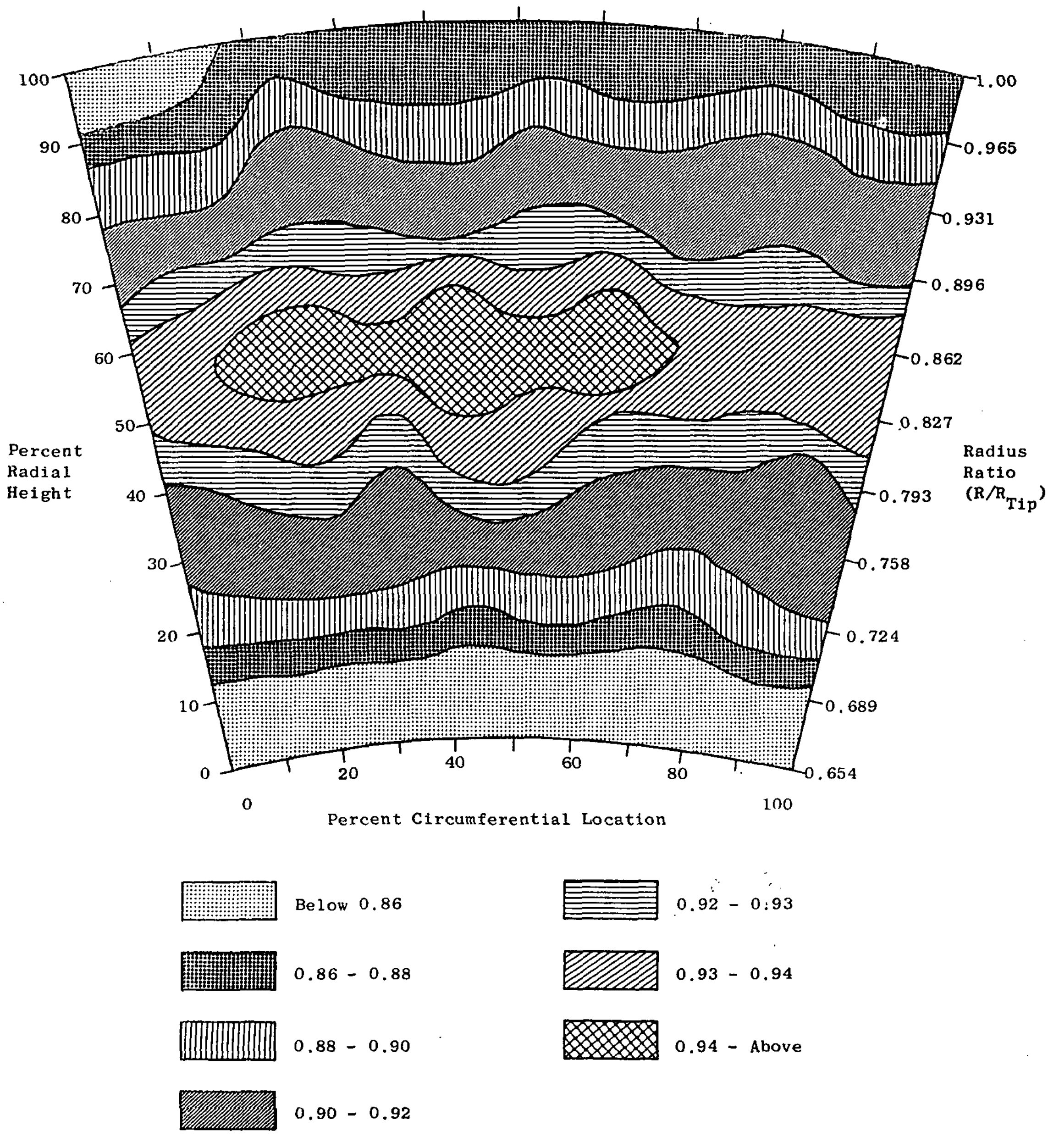


Figure 58. Turbine Efficiency Contour Plot, Configuration 5A (PPTP).

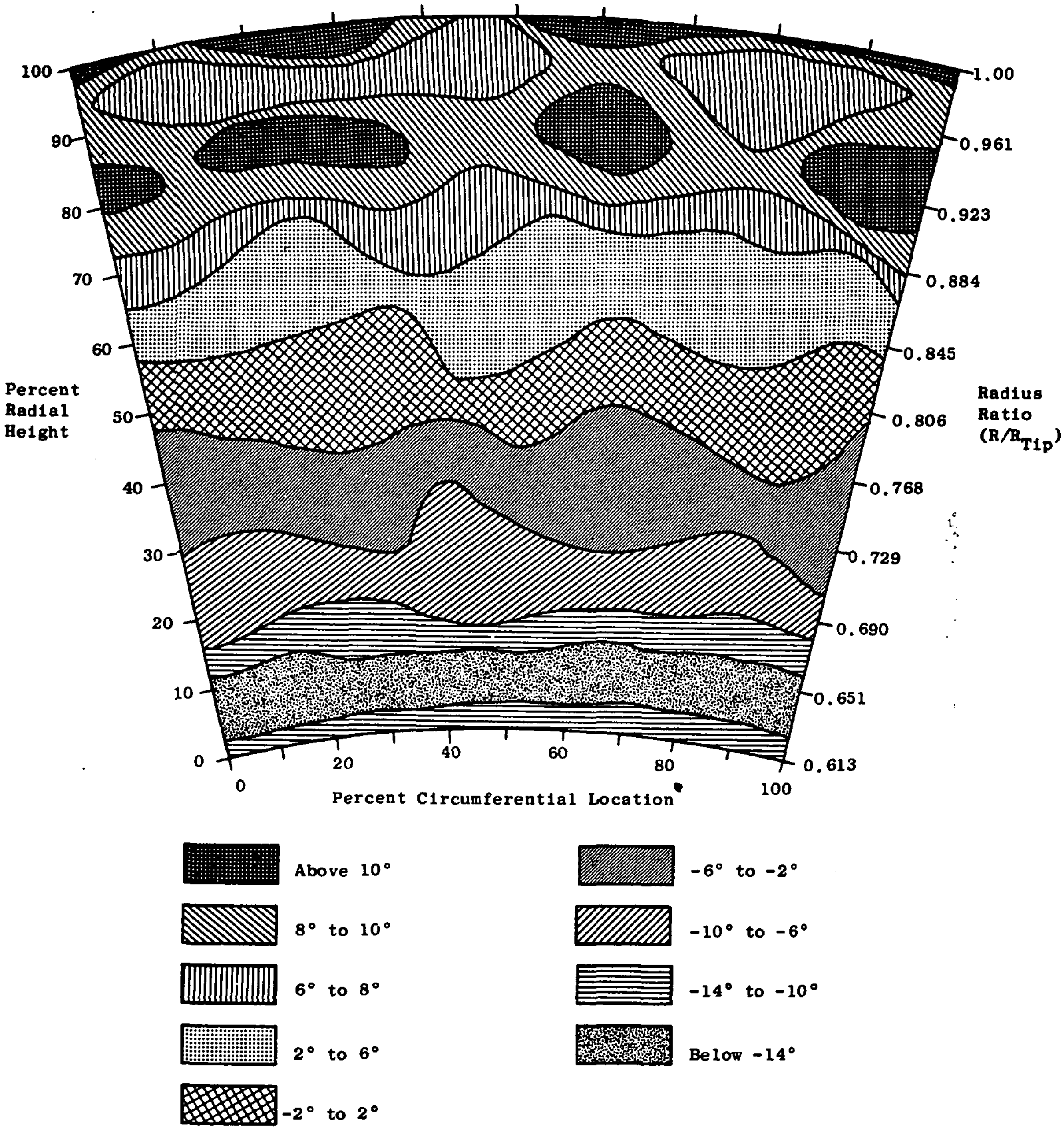


Figure 59. Turbine Exit Swirl Contour Plot, Configuration 1A (PPPPPP).

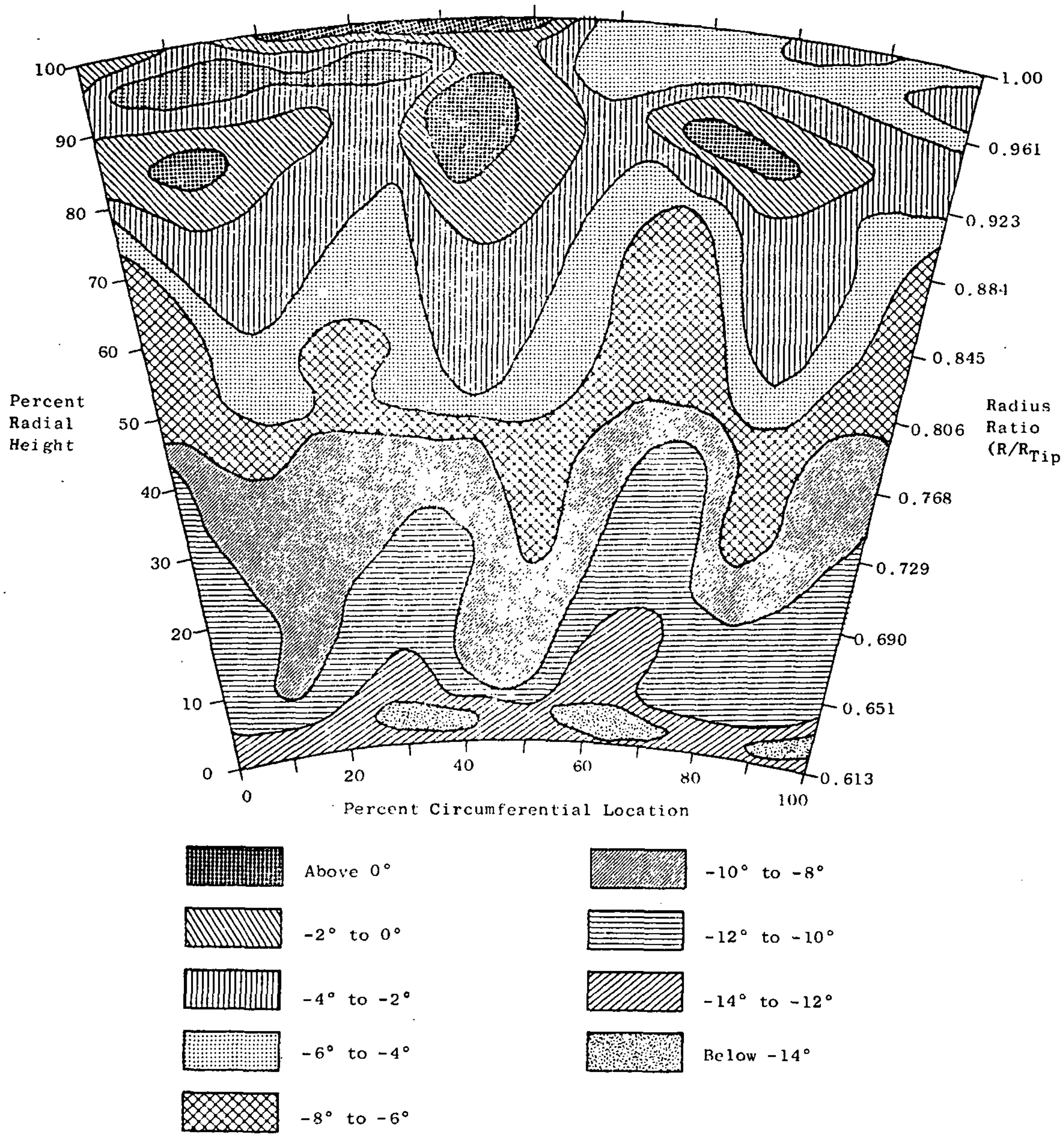


Figure 60. Turbine Exit Swirl Contour Plot, Configuration 2A (PPPPLT).

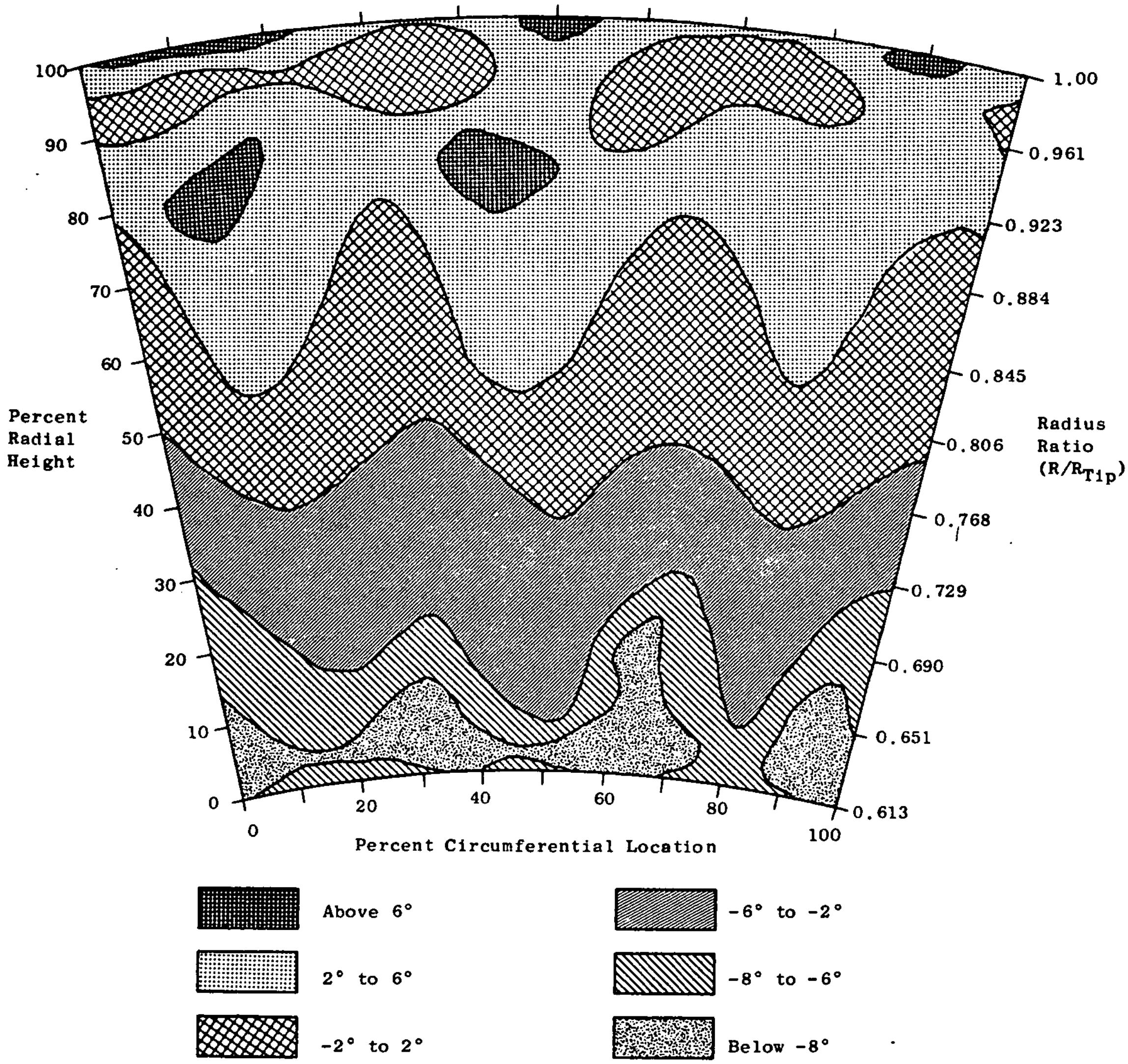


Figure 61. Turbine Exit Swirl Contour Plot, Configuration 3A (PPTPLP).

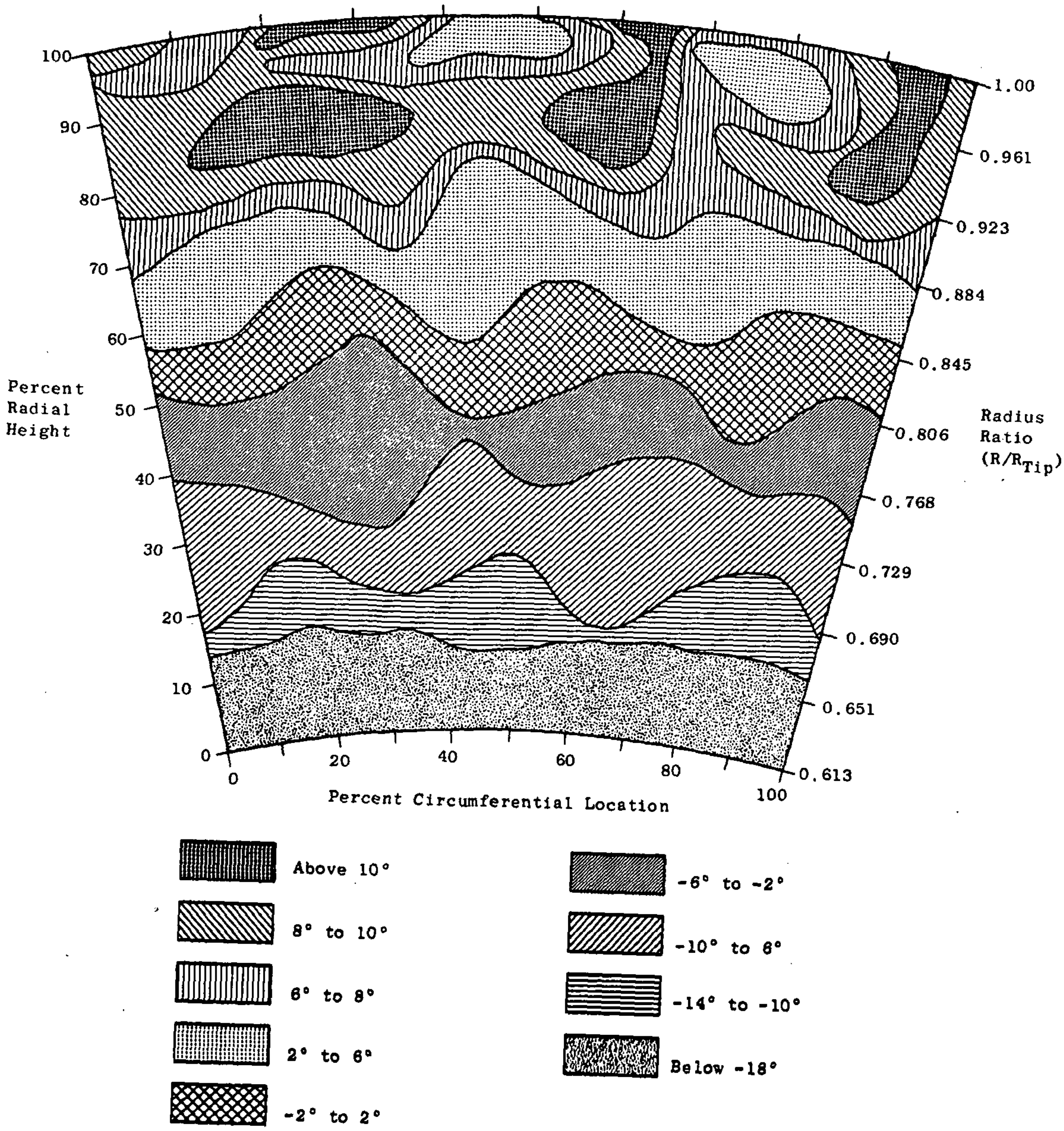


Figure 62. Turbine Exit Swirl Contour Plot, Configuration 4A (PPTPPP).

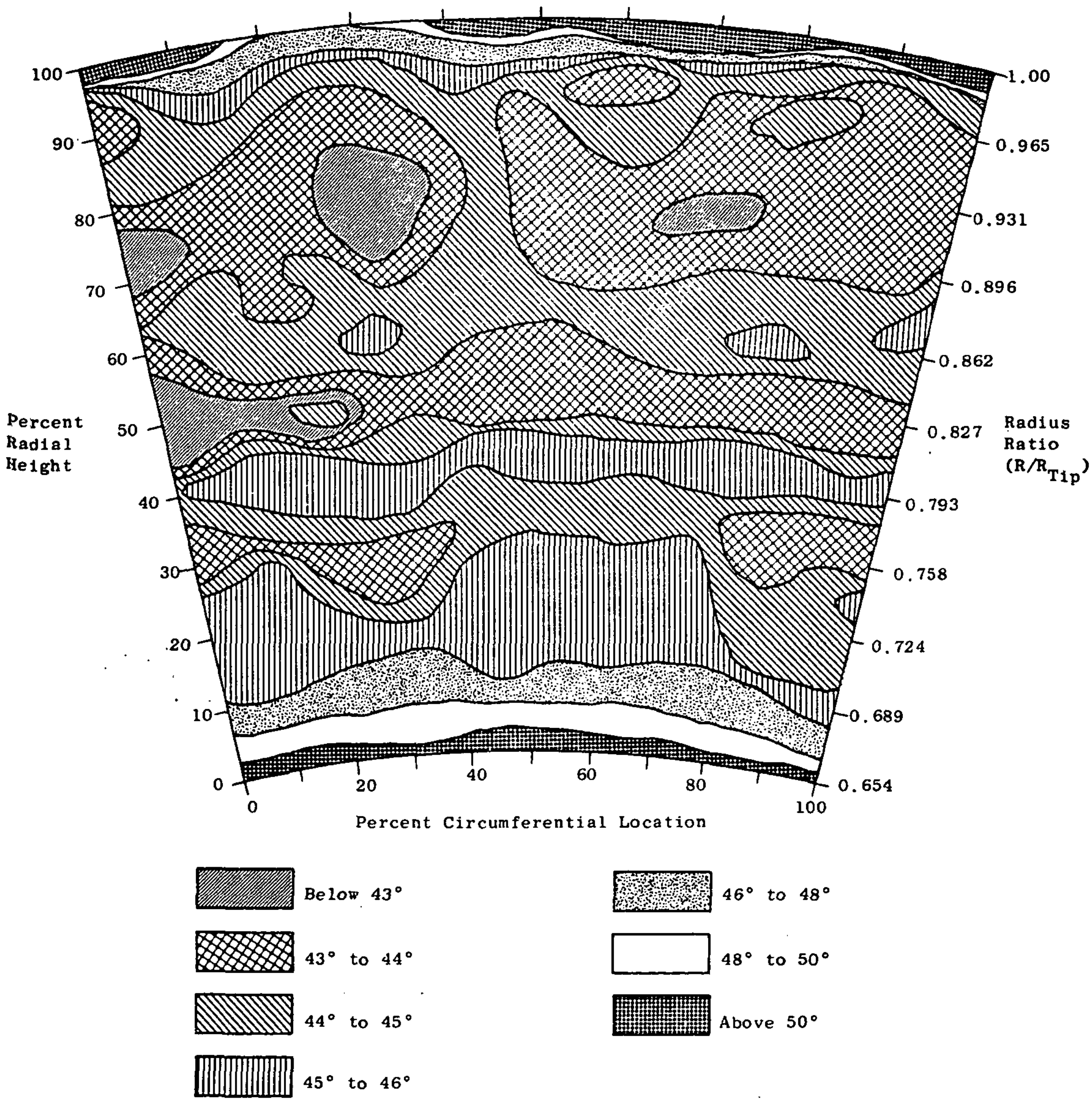


Figure 63. Turbine Exit Swirl Contour Plot, Configuration 5A (PPTP).

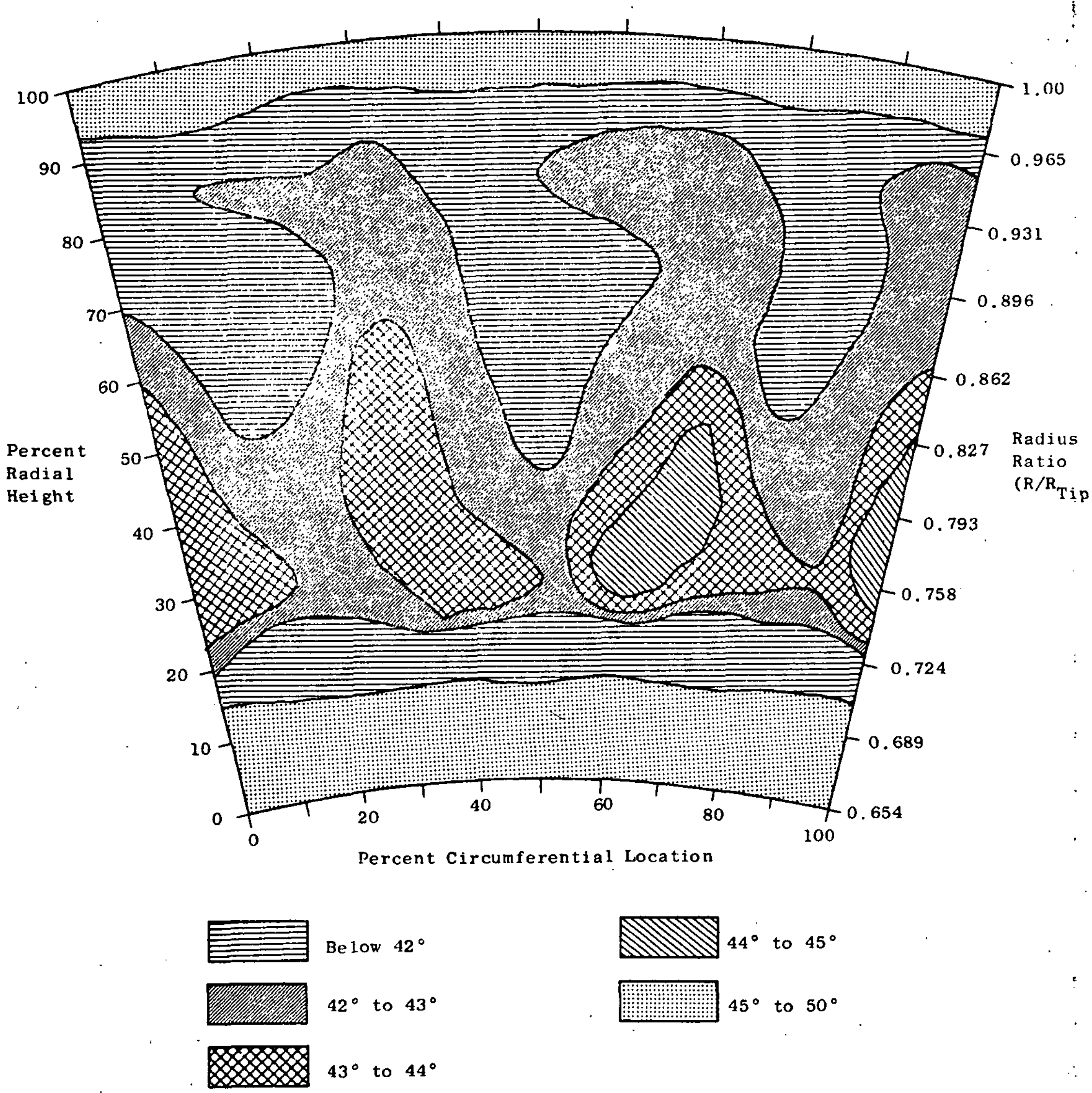


Figure 64. Turbine Exit Swirl Contour Plot, Configuration 2 (PPPP).

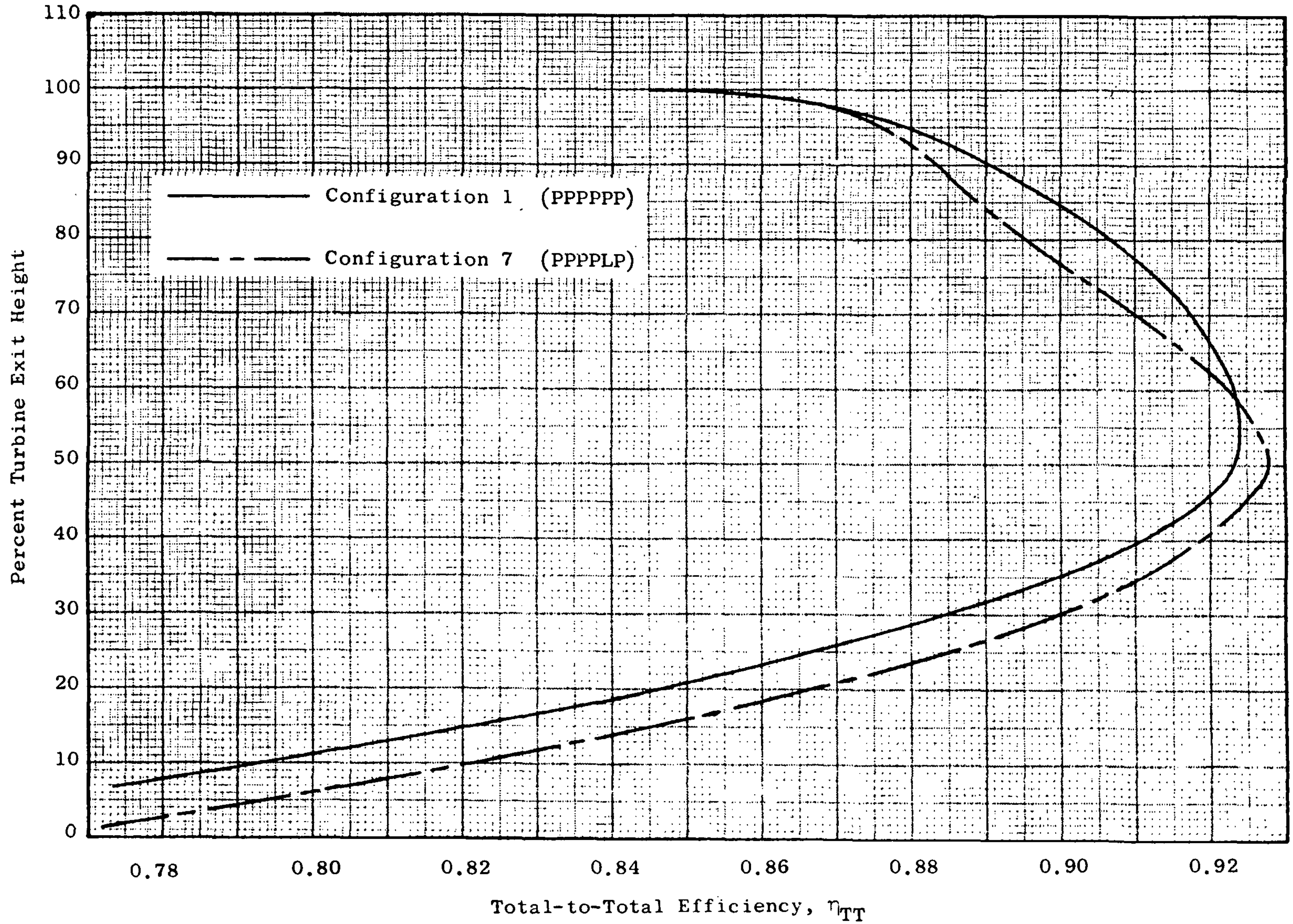


Figure 65. Radial Efficiency Profile, Configuration 7 (PPPPLP) Compared with Configuration 1 (PPPPPP).

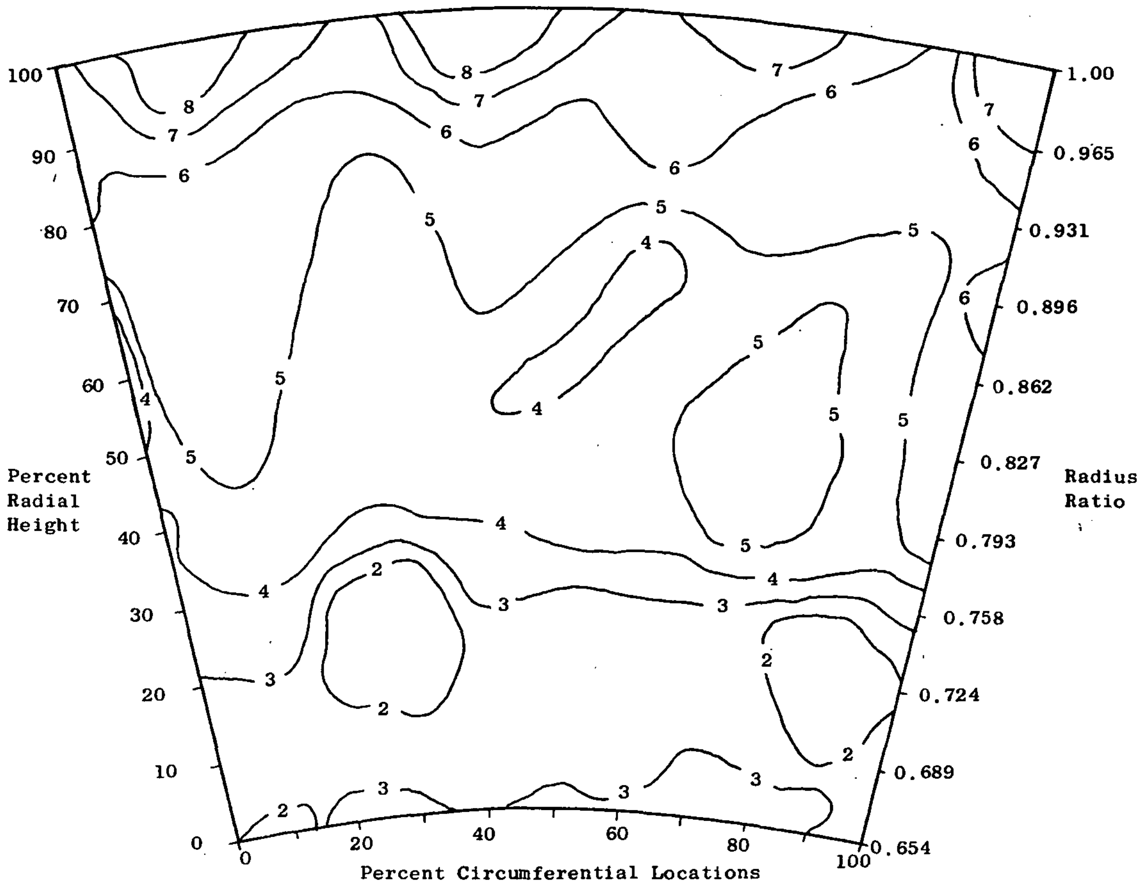


Figure 66. Stage Three Incidence Angle Contour Plot, Typical for Two-Stage Tandem Turbine (PPTP).

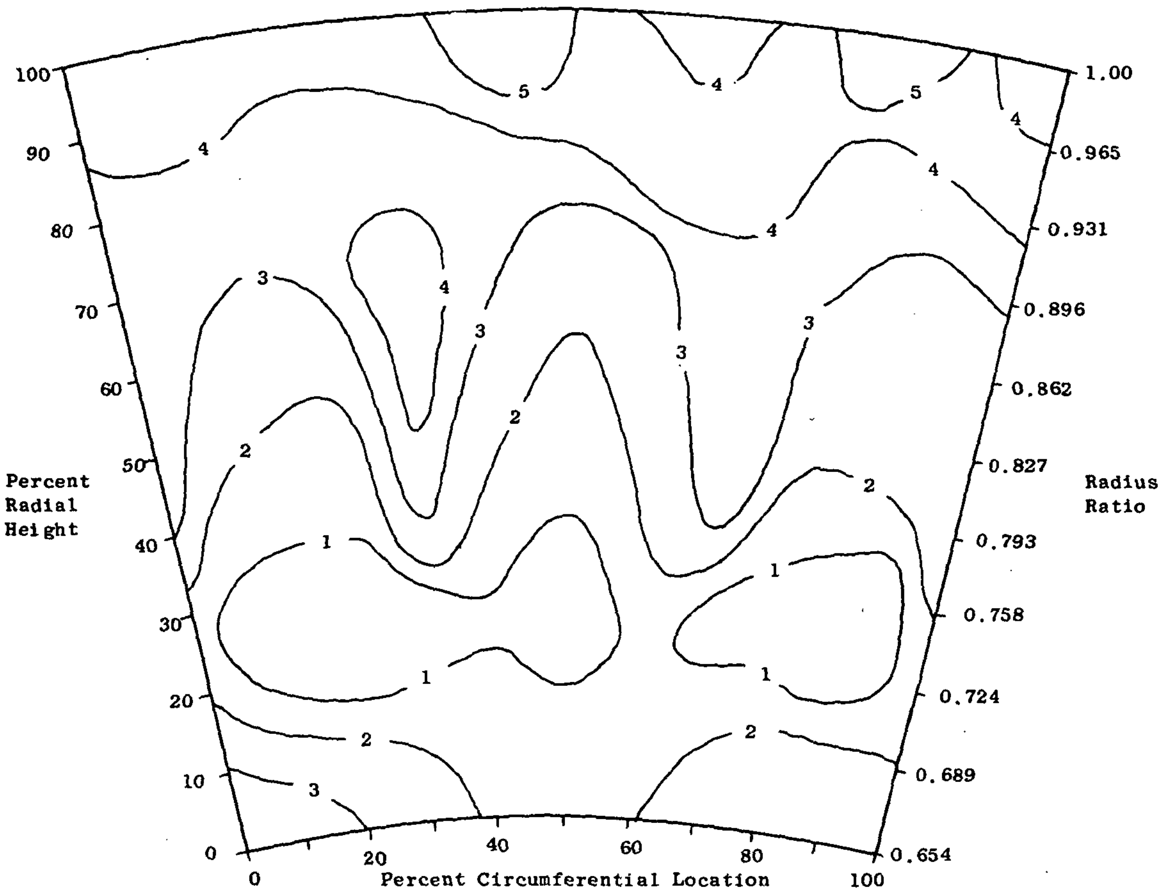


Figure 67. Stage Three Incidence Angle Contour Plot, Typical for Two-Stage Plain Turbine (PPPP).

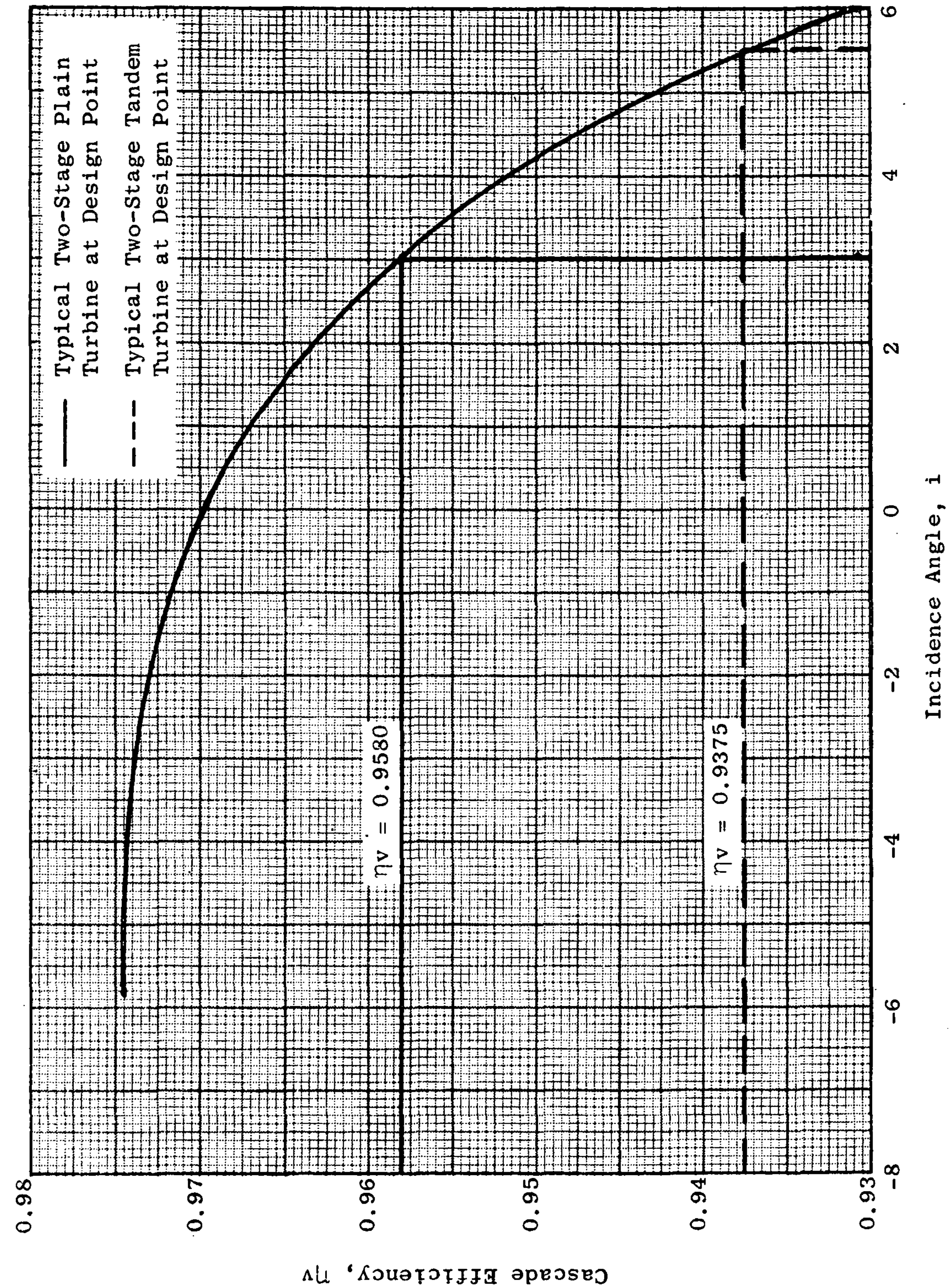


Figure 68. Cascade Efficiency Vs. Incidence Angle, Typical for a Plain Stator.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1974—635-044/31

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

SPECIAL FOURTH-CLASS RATE
BOOK

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
451

U.S.MAIL

POSTMASTER: If Undeliverable (Section 15
Postal Manual) Do Not Retu

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546