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FORTRAN PROGRAM FOR PREDICTING OFF-DESIGN PERFORMANCE OF RADIAL-INFLOW TURBINES

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16. Abstract

The FORTRAN IV program uses a one-dimensional solution of flow conditions through the turbine along the mean streamline. The program inputs needed are the design-point requirements and turbine geometry. The output includes performance and velocity-diagram parameters over a range of speed and pressure ratio. Computed performance is compared with the experimental data from two radial-inflow turbines and with the performance calculated by a previous computer program. The flow equations, program listing, and input and output for a sample problem are given.

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FORTRAN PROGRAM FOR PREDICTING OFF-DESIGN PERFORMANCE OF RADIAL-INFLOW TURBINES

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SUMMARY

A FORTRAN IV program for calculating off-design performance of a radial-inflow turbine is presented. The program uses a one-dimensional solution of flow conditions through the turbine along the mean streamline. The loss model accounts for stator, rotor, incidence, and exit losses. Other program features include consideration of stator and rotor trailing-edge blockage and computation of performance to limiting loading. Overall turbine geometry and design-point values of efficiency, pressure ratio, and mass flow are needed as input information. The output includes performance and velocity-diagram parameters for any number of given speeds over a range of turbine pressure ratio. Included in this report are the engineering equations, the program listing, and the input information and output listing for a sample turbine problem.

The experimental performance of two radial-inflow turbines is compared with the results from the computer program presented herein and with those from a previously used program. The overall computed results from the program of this report show a marked improvement over those from the previously used program and good agreement with experimental data.

INTRODUCTION

A procedure for predicting the off-design performance of a radial-inflow turbine is described in reference 1. This procedure is based on a one-dimensional solution to determine the flow conditions through the turbine along the mean streamline. The FORTRAN IV computer program for this procedure is given in reference 2. This program uses turbine geometry and design-point performance as input and computes the performance and velocity-diagram parameters over a range of speed and pressure ratio. The results from this program, however, did not correlate as well as desired with the experimental results of some subsequently tested turbines.

The basic loss-model assumptions used in this program were reexamined to see if alternative assumptions would yield a better correlation with experimental data. Accordingly, the computer program described in reference 2 was modified. In addition, new features were added to the program to account for trailing-edge blockage and to compute the conditions for pressure ratios at or beyond stator and/or rotor choke. These features give more flexibility to the program and offer a greater range for off-design turbine analysis.

This report presents the modified FORTRAN IV program which computes overall performance for a radial-inflow turbine. The revised loss assumptions and new program features are described. Also included in the report are the engineering equations, the program listing, and a complete description of input and output including a sample turbine problem. The performance of two radial-inflow turbines (refs. 3 and 4) was computed by using the program of this report and that of reference 2. The performance predicted by each program is compared with experimental data for the two turbines.

METHOD OF ANALYSIS

A one-dimensional solution of flow conditions through the turbine along the mean streamline is the basis for this analysis. Two independent variables are assumed for each calculated performance point. A value of rotor-inlet-tip speed U_3 is chosen, and for each speed a range of stator-exit critical-velocity ratios $(V/V_{cr})_1$ is assumed. Symbols are defined in appendix A, and a typical turbine with station nomenclature is shown in figure 1. The equations used in the program are given in appendix B. The computer uses these equations in essentially the order listed.

There are two modes of operation for this program - the design mode and the off-design performance mode. Before the off-design performance mode can be used, two loss determinants, the stator total-pressure ratio p_1'/p_0' and the rotor loss coefficient K, must be known. In the design mode the program automatically determines these loss determinants at the design point by means of a search routine. By repeated iterations the computer finds a pair of values for p_1'/p_0' and K which satisfy the input design values of mass flow rate, efficiency, and pressure ratio. These values of p_1'/p_0' and K are then used in the off-design performance mode. If desired, the values of p_1'/p_0' and K can be determined from the user's own loss procedures and used in the off-design performance mode. The off-design performance mode computes all performance parameters over the entire range of rotor speeds and stator-exit velocity ratios requested.

Turbine Losses

The results from the computer program of reference 2 did not correlate well with the experimental results from the turbine tests of references 3 to 6. The three main losses were (1) a stator loss, (2) an incidence loss, and (3) a rotor loss. It was decided to reexamine and modify the models used to represent these losses to see if a better correlation could be obtained.

Stator loss. - In reference 1 the loss in kinetic energy across the stator is proportional to the average kinetic energy in the blade row and is represented by the equation

$$L_S = \frac{V_{1,id}^2 - V_1^2}{2gJ} = K_S \frac{V_0^2 + V_1^2}{2gJ} \tag{1}$$

The stator loss coefficient K_S is determined from design-point performance and then is assumed to be constant for the off-design calculations.

In order to check this assumption, stator loss coefficients were calculated from unpublished data obtained with the turbines of references 3 to 6. All four of these turbines had static-pressure taps located just inside the stator trailing edge. Therefore, stator performance could be calculated by using these static-pressure data along with the design stator-exit blade angle and the measured values of mass flow rate, stator-exit area, and total temperature. The calculated stator loss coefficients are given as a function of stator-exit critical-velocity ratio in figure 2. As shown, the stator loss coefficient decreases significantly with increasing velocity ratio over the range of data. Thus, the assumption of a constant stator loss coefficient, as made in reference 1, does not seem to be valid.

Another way to express stator loss is as the ratio of stator-exit to turbine-inlet total pressure. Figure 3 shows the variation of stator-exit to turbine-inlet total-pressure ratio with stator-exit velocity ratio as obtained from the data of references 3 to 6. The stator total-pressure ratio for each turbine was fairly constant over the range of velocity ratio tested. Total-pressure-ratio level ranged from about 0.98 to 0.99 for most of the data. This examination and analysis indicated that a constant stator total-pressure ratio would be a better model for the stator loss, and thus it was incorporated into the program.

Incidence loss. - Minimum incidence loss does not occur at zero incidence angle with respect to the rotor blade, but at some optimum flow angle φ (fig. 4). The calculation of the optimum flow angle follows the method of Stanitz (ref. 7). This method was used in reference 2 and is described in appendix B as equations (B8a) to (B8d). The flow angle at the rotor inlet is β_3, and the incidence angle is defined as

$$i_3 = \beta_3 - \varphi \tag{2}$$

In reference 2 the incidence loss is assumed to be the component of relative velocity normal to the angle φ:

$$L_{IN} = \frac{W_3^2 \sin^2 i_3}{2gJ} \tag{3}$$

In the program of this report, different variations in loss with positive and negative incidence were used, and equation (3) was changed to

$$L_{IN} = \frac{W_3^2 \sin^n i_3}{2gJ} \tag{3a}$$

A value of 2 was used for the exponent n for negative incidence. However, for positive incidence, a value of 3 for the exponent n gave a better correlation with experimental data.

Rotor loss. - In reference 1 the viscous loss in the rotor is assumed to be proportional to the average kinetic energy in the blade row as calculated from the equation

$$L_R = \frac{W_{4,id}^2 - W_4^2}{2gJ} = K\left(\frac{W_3^2 + W_4^2}{2gJ}\right) \tag{4}$$

At high pressure ratios the level of rotor inlet velocity W_3 seemed to have an excessive influence on the loss. Using the component of velocity in the direction of the optimum flow angle gave a better correlation with experimental data. In the present program, therefore, the rotor loss was calculated as

$$L_R = \frac{W_{4,id}^2 - W_4^2}{2gJ} = K\left(\frac{W_3^2 \cos^2 i + W_4^2}{2gJ}\right) \tag{4a}$$

The value of K was approximately 0.3 for all the turbines examined in this report.

Trailing-Edge Blockage

In order to account for the effect of stator trailing-edge blockage, the analysis of reference 1 assumes a variable station where the flow from the stator is assumed to occupy the entire cylindrical flow area. Trailing-edge blockage at the rotor exit is not taken into account.

The analysis of this report accounts for trailing-edge blockage at both the stator and rotor exits. The effect of blockage for each blade row is specified in terms of the ratio of the flow area just inside to that just outside the blade trailing edge. Figure 5 shows the blade-row trailing-edge region, specifically the areas used in the blockage calculation. Both angular momentum and continuity are conserved when the conditions at these stations are calculated.

Stator and Rotor Choke

The program of reference 2 did not compute turbine performance at or beyond the stator and rotor choking points. The program of this report allows turbine performance to be computed at the stator and rotor choking points and at pressure ratios beyond choking to rotor blade limiting loading. The stator choke point is where $(V/V_{cr})_1 = 1.0$, which is the point of maximum flow per unit area. For values of $(V/V_{cr})_1$ greater than 1.0, a new stator-exit flow angle α_1 is computed from the area required to pass the choking mass flow rate.

In order to find the rotor choking point, an iteration is required to determine the value of $(V/V_{cr})_1$ that maximizes flow per unit area at the rotor exit. Conditions upstream of the rotor exit are then held fixed. As the velocity ratio $(W/W_{cr})_4$ is increased beyond the choking value, the exit flow angle β_4 is adjusted to pass the choking mass flow. The program is terminated at or close to blade limiting loading, where $(W_x/W_{cr})_4 = 1.0$.

COMPARISON OF COMPUTED AND EXPERIMENTAL RESULTS

This section compares the experimental results obtained with two radial-inflow turbines to the results obtained by the analytical procedures described in reference 2 and this report. The two radial-inflow turbines are those of references 3 and 4. The results of the comparison are presented in terms of mass flow rate and total and static efficiency variations with pressure ratio and speed.

Mass Flow Rate

Calculated and experimental variations of mass flow rate with turbine total- to static-pressure ratio for various speeds are compared in figure 6(a) for the reference 3 turbine and in figure 6(b) for the reference 4 turbine. The data for the reference 4 turbine are unpublished air data, which were used herein because they covered a wider range of pressure ratios than the published argon data. For both turbines, the off-design values of mass flow rate computed by using the program of this report showed a significantly better correlation with the experimental data, especially at higher pressure ratios and lower speeds, than did the values computed by the program of reference 2. The poorest correlation between the computed and experimental values was in the region near choked flow (fig. 6(b)). In this region, the maximum deviation between computed and experimental mass flow rates was reduced from about 9 percent (program of ref. 2) to about $3\frac{1}{2}$ percent by using the program of this report.

Total Efficiency

Calculated and experimental variations of total efficiency with blade-jet speed ratio for a number of speeds are compared in figure 7(a) for the reference 3 turbine and in figure 7(b) for the reference 4 turbine. In figure 7(a) the 90- and 110-percent speed lines are not shown in order to avoid overlapping of data. The off-design values of total efficiency computed by using the program of this report showed a significantly better correlation with the experimental data, especially in the case of the reference 4 turbine, than did the values computed by the program of reference 2. As shown in figure 7(b), the maximum deviation between computed and experimental total efficiencies was reduced from about 10 percent (program of ref. 2) to essentially zero by using the program of this report.

Static Efficiency

Calculated and experimental variations of static efficiency with blade-jet speed ratio for a number of speeds are compared in figure 8(a) for the reference 3 turbine and in figure 8(b) for the reference 4 turbine. Except for blade-jet speed ratios higher than the design value, the efficiencies computed by the program of reference 2 for all speeds were generally about 2 percentage points lower than experimental values for both turbines. The efficiencies computed by the program of this report over the same range of blade-jet speed ratio generally were within 1 percentage point of the experimental values.

The overall improvement in the correlation of calculated values of mass flow rate and efficiency with experimental data indicates that the turbine loss assumptions used in this report provide a better model than those used in reference 2.

FORTRAN PROGRAM

Program Input

The program input consists of two title, or heading, cards followed by the required physical data and option indicators in NAMELIST format. The information contained in columns 1 to 60 of the title cards is printed as two lines of heading on the output listing. The two title cards, even if left blank, must be the first two cards in the data package. Two additional title cards must precede each different case being run in the same data package.

The physical data and option indicators are input in data records having the NAMELIST name IN. All necessary physical data and option indicators must be inputted for the first case in the data package. For succeeding cases in the same data package, only those items being changed need be inputted.

Options. - There are three sets of options that must be specified by the input. All three are specified by the variable MODE as described in the input variable list. The first option is the choice of units, SI or U.S. customary, to be used for input and output. The particular unit to be used for each variable is included in the input variable list.

The second option is the choice of a mode of operation: either the design mode or the off-design performance mode. The design mode is used to automatically determine the stator total-pressure ratio and rotor loss coefficient that yield design flow and efficiency at the design pressure ratio. The input variable ITEST, as described in the input variable list, is used to specify whether total efficiency and total- to total-pressure ratio or static efficiency and total- to static-pressure ratio are used as the design values being matched. The off-design performance mode is used to compute the performance over the desired ranges of speed and pressure ratio.

The third option provides for the choice of long or short output for the off-design performance mode. Long output is always given for the design mode. The long output includes complete velocity-diagram information in terms of critical-velocity ratios and angles, actual and equivalent overall performance parameters, and dimensionless design parameters. The short output includes only certain of the equivalent performance and dimensionless design parameters. The exact output provided is described in the section Description of Output.

Input variables. - The input variables comprising NAMELIST IN are as follows:

AL1	stator-exit blade angle, α_1, deg
A0	area at turbine inlet (scroll inlet), A_0, m^2; ft^2
A1	area upstream of stator exit (circumferential area inside blade trailing edge), A_1, m^2; ft^2
A3	area upstream of rotor inlet (circumferential area outside blade leading edge), A_3, m^2; ft^2
A5	area downstream of rotor exit (annular area outside blade trailing edge), A_5, m^2; ft^2
BL1	blockage factor at stator exit, ratio of area inside blade passage to area outside blade passage (fig. 5)
BL4	blockage factor at rotor exit, ratio of area inside blade passage to area outside blade passage (fig. 5)
B4	rotor-exit blade angle, β_4, deg
DELV	incremental value of stator-exit critical-velocity ratio $(V/V_{cr})_1$
DELY	incremental value of rotor-exit critical-velocity ratio $(W/W_{cr})_4$ used after rotor choke
D2	stator-exit diameter, D_2, cm; in.
D3	rotor-inlet diameter, D_3, cm; in.
ETAD	specified design value of static efficiency η_s or total efficiency η_t (see ITEST)
G	ratio of specific heat at constant pressure to specific heat at constant volume, γ
ITEST	specifies which design values are used for PDSGN and ETAD: if ITEST=1, total- to static-pressure ratio p_0'/p_5 and static efficiency η_s are used if ITEST=2, total- to total-pressure ratio p_0'/p_5' and total efficiency η_t are used
MODE	specifies which program option is used: MODE=0 yields the off-design performance mode in SI units and with long output MODE=1 yields the off-design performance mode in SI units and with short output MODE=2 yields the design mode in SI units

MODE=3 yields the off-design performance mode in U.S. customary units and with long output

MODE=4 yields the off-design performance mode in U.S. customary units and with short output

MODE=5 yields the design mode in U.S. customary units

PD stator total-pressure ratio, p_1'/p_0'

PDSGN specified design total- to total-pressure ratio p_0'/p_5' or total- to static-pressure ratio p_0'/p_5 (see ITEST)

P0 inlet total pressure, p_0', N/m^2; psfa

R gas constant, R, J/(kg)(K); ft-lb/(lb)($^{\circ}$R)

T0 inlet total temperature, T_0', K; $^{\circ}$R

U3 rotor-inlet tip speed, U_3, m/sec; ft/sec

U4U3 ratio of rotor-exit mean speed to rotor-inlet tip speed, U_4/U_3 (Rotor-exit mean speed must correspond to rotor-exit mean velocity diagram. It is recommended that this be at the area-mean radius if no better value is available.)

VMAX final value of stator-exit critical-velocity ratio $(V/V_{cr})_1$

V1 initial value of stator-exit critical-velocity ratio $(V/V_{cr})_1$

WD design value of mass flow rate, w, kg/sec; lb/sec

XK rotor loss coefficient, K

YMAX final value of rotor-exit critical-velocity ratio $(W/W_{cr})_4$

ZZ number of blades at rotor inlet

Sample input. - Input sheets with the data used in computing the performance for the reference 3 turbine (figs. 6(a), 7(a), and 8(a)) are shown in tables I and II. Selected output obtained with this input is presented and described in the next section. Table I is for the design mode. Table II is for the off-design performance mode for speeds of 100, 110, 90, 70, 50, and 30 percent of design. Each line of the input form shown in tables I and II represents one data card. The first two cards are the mandatory title cards, which can contain any desired message. The next four cards contain the turbine physical data and option indicators. The design-point quantities ETAD, PDSGN, and WD are included for the design mode (table I). The loss coefficients XK and PD determined by the design-mode calculation are included in the off-design-mode (table II) data. Additional data sets may follow the first data set, as they do in table II, and need only include those values that differ from previous case data. As shown in table II, only the speed is changed for the next five cases.

Description of Output

The design-mode output for the input of table I is shown in table III. The top line of output is a program identification title that is automatically printed. The next two lines are the title card messages. The following three lines are the input variable values. The symbolism used to identify the output values is defined in terms of the engineering symbols in the list at the end of this section. Printed next are the computed values of stator total-pressure ratio and rotor loss coefficient followed by the design values of mass flow rate, efficiency, and pressure ratio.

The remainder of the output in table III is divided into two parts. In the section VELOCITIES AND ANGLES, all the absolute and relative critical-velocity ratios and angles at various stations throughout the turbine are listed for the design stator-exit critical-velocity ratio. The section OVERALL PERFORMANCE gives all the performance parameters computed by the program.

Off-design performance mode output is shown in tables IV and V. Table IV shows the long output and presents the first three points obtained by using the input of table II. Table V shows the short output that would be obtained from the first data set of table II if MODE=1. The first six lines in both tables are the same as for the design-mode output. The remainder of the output in table IV gives the velocities, angles, and overall performance in the same format as previously described for the design-mode output. In table V the output is limited to certain of the overall performance parameters useful for defining the overall performance map.

A list of the variable names as used for the output and their corresponding engineering symbols is given in the following table:

Variable name	Engineering symbol	Variable name	Engineering symbol	Variable name	Engineering symbol
ALPHA-1	α_1	ETA-T	η_t	VCR)3	$V_{cr,3}$
ALPHA-2	α_2	GAMMA	γ	V/VCR)3	$(V/V_{cr})_3$
ALPHA-3	α_3	I-3	i_3	VR/VCR)3	$(V_r/V_{cr})_3$
ALPHA-5	α_5	K	K	VU/VCR)3	$(V_u/V_{cr})_3$
A0	A_0	N	N	VCR)5	$V_{cr,5}$
A1	A_1	NS	N_s	V/VCR)5	$(V/V_{cr})_5$
A3	A_3	N/T	$N/\sqrt{T_0'}$	VU/VCR)5	$(V_u/V_{cr})_5$
A5	A_5	NU	ν	VX/VCR)5	$(V_x/V_{cr})_5$
BETA-3	β_3	P	P	W	W
BETA-4	β_4	PD	$(p_1'/p_0')_{des}$	W. F.	WF
BETA-5	β_5	P0,	p_0'	WN/DEL	WN/δ
BL1	B_1	P0, /P5	p_0'/p_5	WT/P	$10\ 000W\sqrt{T_0'}/p_0'$; $144W\sqrt{T_0'}/p_0'$
BL4	B_4	P0, /P5,	p_0'/p_5'	W/WCR)3	$(W/W_{cr})_3$
DEL-H	$\Delta h'$	R	R	WR/WCR)3	$(W_r/W_{cr})_3$
DEL-H/T	$\Delta h'/T_0'$	TOR	Γ	WU/WCR)3	$(W_u/W_{cr})_3$
DESIGN ETA-S	$\eta_{s,des}$	TOR/P	$10^6\Gamma/p_0'$; $144\Gamma/p_0'$	W/WCR)4	$(W/W_{cr})_4$
DESIGN ETA-T	$\eta_{t,des}$	T0,	T_0'	WU/WCR)4	$(W_u/W_{cr})_4$
DESIGN P0, /P5	$(p_0'/p_5)_{des}$	U3	U_3	WX/WCR)4	$(W_x/W_{cr})_4$
DESIGN P0, /P5,	$(p_0'/p_5')_{des}$	U4U3	U_4/U_3	W/WCR)5	$(W/W_{cr})_5$
DESIGN WT-FLOW	W_{des}	V/VCR)0	$(V/V_{cr})_0$	WX/WCR)5	$(W_x/W_{cr})_5$
D3	D_3	V/VCR)1	$(V/V_{cr})_1$	ZZ	ZZ
EQ-DEL-H	$\Delta h_{eq}'$	VR/VCR)1	$(V_r/V_{cr})_1$		
EQ-N	N_{eq}	VU/VCR)1	$(V_u/V_{cr})_1$		
EQ-P0, /P5,	$(p_0'/p_5')_{eq}$	V/VCR)2	$(V/V_{cr})_2$		
EQ-P0, /P5	$(p_0'/p_5)_{eq}$	VR/VCR)2	$(V_r/V_{cr})_2$		
EQ-TOR	Γ_{eq}				
EQ-W	w_{eq}				
ETA-S	η_s				

Messages

If there is no solution for a particular turbine case in the design mode, a message will be printed - "NO SOLUTION FOR THIS CASE - CHECK A1, BL1, AL1 OR B4, BL4." This will happen when the program cannot select values for the loss determinants p_1'/p_0' and K that will satisfy the design input values of mass flow, efficiency, and pressure ratio.

In the off-design performance mode for conditions beyond choking to blade limiting loading, a message will be printed after the last computed performance point - "LAST CASE IS APPROXIMATE LIMITING LOADING CASE."

MAIN PROGRAM

FORTRAN Variables

The FORTRAN variables used in the main program are defined in the following table in terms of the engineering symbols, where available, or by descriptive terminology:

Variable name	Engineering symbol	Variable name	Engineering symbol	Variable name	Engineering symbol
AB	φ	DELHOT	$\Delta h'/T'_0$	FC	cos i_3
ALX	α_1	DELL	incremental value of $(W/W_{cr})_4$	FP	integration variable
AL1	α_1			FS	sin i_3
AL2	α_2	DELTA	δ	F1	integration variable
AL3	α_3	DELV	incremental value of $(V/V_{cr})_1$	G	γ
AL5	α_5			GIV	temporary storage
AX	temporary storage			GR	g
A0	A_0	DELV1	incremental value of $(V/V_{cr})_1$	G1	$\gamma + 1$
A1	A_1			G2	$\gamma - 1$
A3	A_3	DELY	incremental value of $(W/W_{cr})_4$	G3	$(\gamma - 1)/(\gamma + 1)$
A5	A_5			G4	$\gamma/(\gamma + 1)$
BL1	B_1	DHIDS	$\Delta h'_{id,s}$	G5	$\gamma/(\gamma - 1)$
BL4	B_4	DHIDT	$\Delta h'_{id,t}$	HA	$(W_x/W_{cr})_4$
BX	temporary storage	DHTCR	$\Delta h'/\theta_{cr}$		
B3	β_3	D2	D_2	HB	$(W_x/W_{cr})_4$
B4	β_4	D3	D_3	H1	temporary storage
B4X	β_4	ELAM	WF	I	index variable
B5	β_5	EPS	ϵ	IND	integer variable controlling logical sequence in CONTIN
CAPQ	w/ρ_5	EQPRS	$(p'_0/p_5)_{eq}$		
CASE	variable for title message	EQPRT	$(p'_0/p'_5)_{eq}$	IT	index variable
COSAL1	cos α_1	EQTOR	$\Gamma\epsilon/\delta$	ITEST	integer variable controlling proper input in GETK and SEEKPR
COSAL2	cos α_2	ET	temporary storage		
COSAL3	cos α_3	ETAD	$\eta_{s,des}$ or $\eta_{t,des}$		
COSB3	cos β_3	ETAS	η_s	J	index variable
COSB4	cos β_4	ETAT	η_t	K	index variable
CX	temporary storage	EX	temporary storage	L	index variable
DELH	$\Delta h'$	F	integration variable	M	index variable

Variable name	Engineering symbol
MODE	integer variable controlling all program options
NAME	variable for title message
NCOUNT	index variable
P	P
PD	p_1'/p_0'
PDSGN	$(p_0'/p_5)_{des}$ or $(p_0'/p_5')_{des}$
PR	temporary storage (pressure ratio)
PRS	$(p_0'/p_5)_{eq}$
PVCR	$(\rho' V_{cr})_1$
PVK	$(\rho/\rho')_{cr}$
PV1	$(\rho V/\rho' V_{cr})_1$
PV2	$(\rho V/\rho' V_{cr})_2$
PWC3	$(\rho W/\rho'' W_{cr})_3$
PWC4	$(\rho'' W_{cr})_4$
PWVC3	$(\rho'' W_{cr}/\rho' V_{cr})_3$
PW4	$(\rho W/\rho'' W_{cr})_4$
PW4PW3	$(\rho'' W_{cr,4}/\rho'' W_{cr,3})$
P0	p_0'
P3P3	p_3''/p_3'
P4P3ID	$(p_4''/p_3'')_{id}$
P4P4ID	$(p_4''/p_4')_{id}$
P5	p_5'
P5P0	p_5'/p_0'
P5P0G	$(p_5'/p_0')^{(\gamma-1)/\gamma}$
P5P0P	p_5/p_0'
P5P0PG	$(p_5/p_0')^{(\gamma-1)/\gamma}$
P5P5	$(p'/p'')_5$
P5P5P	$(p/p')_5$
Q	temporary storage
QX	$(\rho V/\rho' V_{cr})_0$
Q1	$(T_4'/T_4'')^{1/2}$
R	R
RHO5	ρ_5
RHO5P	ρ_5'
RHO5RT	$(\rho/\rho')_5$
SCAPQ	$(w_1/\rho_5)^{1/2}$
SINAL1	$\sin \alpha_1$
SINAL2	$\sin \alpha_2$
SINAL3	$\sin \alpha_3$
SINB3	$\sin \beta_3$
SINB4	$\sin \beta_4$
SINB5	$\sin \beta_5$
SS	temporary storage
STHETA	$(\theta_{cr})^{1/2}$
T	0.01745329
THETCR	θ_{cr}
TOL	0.00001
TOP	Γ/p_0'
TOR	Γ
T0	T_0
T3T3	$(T''/T')_3$
T4T3	T_4''/T_3''
T4T4	T_4'/T_4''
U3	U_3
U4U3	U_4/U_3
VC5VC0	$(V_{cr,5}/V_{cr,0})^2$
VCR	$V_{cr,0}$
VCR5	$V_{cr,5}$
VK	1.0
VMAX	maximum value of $(V/V_{cr})_1$
VRVC1	$(V_r/V_{cr})_1$
VRVC2	$(V_r/V_{cr})_2$
VRVC3	$(V_r/V_{cr})_3$
VU3T	$V_{u,3,opt}$
VU4VC3	$V_{u,4}/V_{cr,3}$
VUVC1	$(V_u/V_{cr})_1$
VUVC2	$(V_u/V_{cr})_2$
VUVC3	$(V_u/V_{cr})_3$
VUVC5	$(V_u/V_{cr})_5$
VUWC4	$(V_u/W_{cr})_4$
VUWC5	$(V_u/W_{cr})_5$
VX	temporary storage of variable V1VC1
VXVC5	$(V_x/V_{cr})_5$
V0VC0	$(V/V_{cr})_0$
V1	initial value of $(V/V_{cr})_1$
V1VC1	$(V/V_{cr})_1$
V2VC2	$(V/V_{cr})_2$
V3TU3	$(V_u/U)_{3,opt}$
V3VC3	$(V/V_{cr})_3$
V5VC5	$(V/V_{cr})_5$
V5WC5	$(V/W_{cr})_5$
WC4WC3	$W_{cr,4}/W_{cr,3}$
WCR3	$W_{cr,3}$
WCVC3	$(W_{cr}/V_{cr})_3$
WD	w_{des}
WK	w_{cr}
WNODE	$wN\epsilon/\delta$
WRWC3	$(W_r/W_{cr})_3$

Variable name	Engineering symbol	Variable name	Engineering symbol
WTHODE	$w(\theta_{cr})^{1/2}\epsilon/\delta$	XDEL	index variable on estimated velocity in CONTIN
WTOP	$w(T_0)^{1/2}/p_0$	XI3	i_3
WU3T	$W_{u,3,opt}$	XJ	J
WUVC3	$\left(W_u/V_{cr}\right)_3$	XK	K
WUWC3	$\left(W_u/W_{cr}\right)_3$	XN	N
WUWC4	$\left(W_u/W_{cr}\right)_4$	XNOT	$N/(T_0')^{1/2}$
WUWC5	$\left(W_u/W_{cr}\right)_5$	XNOTH	$N/\theta_{cr}^{1/2}$
WXWC4	$\left(W_x/W_{cr}\right)_4$	XNS	N_s
WXWC5	$\left(W_x/W_{cr}\right)_5$	XNU	ν
W1	w	X1	iteration variable for velocity
W3VC3	$\left(W/V_{cr}\right)_3$	Y	integration variable for velocity
W3WC3	$\left(W/W_{cr}\right)_3$	YCAL	temporary storage
W3WC4	$W_3/W_{cr,4}$	YGIV	temporary storage
W4WC4	$\left(W/W_{cr}\right)_4$	YMAX	$\left(W/W_{cr}\right)_{4,max}$
W5WC5	$\left(W/W_{cr}\right)_5$	Z	p_0'/p_5
X	iteration variable for velocity	ZZ	ZZ
		Z1	p_0'/p_5'

Program Listing

```
C       A FORTRAN IV COMPUTER PROGRAM TO PREDICT DESIGN AND OFF
C       DESIGN PERFORMANCE OF A RADIAL INFLOW TURBINE
C
C                INTERNATIONAL SYSTEM OF UNITS
C       MODE=0, IMPLIES OFF-DESIGN PERFORMANCE MODE WITH FULL OUTPUT.
C       MODE=1, IMPLIES OFF-DESIGN PERFORMANCE MODE WITH SHORT OUTPUT.
C       MODE=2, IMPLIES DESIGN MODE TO DETERMINE THE VALUE OF K AND PD.
C
C                U. S. CUSTOMARY UNITS
C       MODE=3, IMPLIES OFF-DESIGN PERFORMANCE MODE WITH FULL OUTPUT.
C       MODE=4, IMPLIES OFF-DESIGN PERFORMANCE MODE WITH SHORT OUTPUT.
C       MODE=5, IMPLIES DESIGN MODE TO DETERMINE THE VALUE OF K AND PD.
C
      DIMENSION NAME(10),CASE(10)
      NAMELIST/IN/ G,PO,TO,AO,A1,A3,A5,D3,AL1,B4,BL1,BL4,PDSGN,ITEST,
     1U3,U4U3,R,V1,DELV,VMAX,XK,WD,ZZ,MODE,PD,ETAD,DELY,YMAX,D2
      SUBR(X,G)=(1.-(G-1.)/(G+1.)*X*X)**(1./(G-1.))*X
    1 READ(5,100) (NAME(I),I=1,10)
      READ(5,100) (CASE(I),I=1,10)
      READ(5,IN)
      WRITE(6,200)NAME,CASE
      WRITE(6,400)G,PO,A1,AL1,B4,PD,R,TO,A3,BL1,BL4,XK,D3,AO,A5,U3,
```

```
     1U4U3,ZZ
      IF(MODE.EQ.1.OR.MODE.EQ.4) WRITE(6,666)
      DELV1= DELV
      ALX=AL1
      B4X=B4
      T=.01745329
      TOL=.00001
      AL1=T*AL1
      B4=T*B4
      COSAL1=COS(AL1)
      SINAL1=SIN(AL1)
      COSB4=COS(B4)
      SINB4=SIN(B4)
      XJ= 778.029
      GR = 32.1741
      IT= 1
      J= 1
      K=1
      L=1
      M=1
      N=1
      VX=0.
      XDEL=.1
      G1=G+1.
      G2=G-1.
      G3=G2/G1
      G4= G/G1
      G5= G/G2
C                 BEGIN STATOR ANALYSIS
C
      IF(MODE.EQ.3.OR.MODE.EQ.4.OR.MODE.EQ.5) GO TO 2
      VCR=SQRT(2.*G4*R*TO)
      PVCR= PO*SQRT(2.*G4/R/TO)
      GO TO 3
    2 VCR= SQRT(2.*G4*GR*R*TO)
      PVCR= PO*SQRT(2.*G4*GR/R/TO)
    3 V1VC1=V1
    9 CONTINUE
      IF(V1VC1.GT.1.) GO TO 15
      NCOUNT=0
      IF(MODE.EQ.0.OR.MODE.EQ.1.OR.MODE.EQ.3.OR.MODE.EQ.4) GO TO 10
      PD=1.0
    4 K=1
      SS=WD/PVCR/A1/COSAL1/PD
      V1VC1=.5
    5 X= V1VC1
      F= SUBR(X,G) -SS
      FP= (F+SS)/X-2.*X*X/G1*(1.-G3*X*X)**(1./G2-1.)
      V1VC1= X-F/FP
      IF(ABS((V1VC1-X)/V1VC1).LT.TOL)  GO TO 10
      GO TO 5
   15 VK=1.
      PVK=SUBR(VK,G)
      WK=COS(ALX*T)*PVK*A1*PVCR*PD
      PV1=SUBR(V1VC1,G)
      COSAL1=WK/(A1*PD*PV1*PVCR)
      AL1=ACOS(COSAL1)
      SINAL1=SIN(AL1)
      GO TO 13
```

```
   10 PV1=SUBR(V1VC1,G)
      W1=PV1*A1*PVCR*COSAL1*PD
      VOVCO=V1VC1/6.
      QX=PV1*A1/A0*COSAL1*PD
   12 X= VOVCO
      F=SUBR(X,G) -QX
      FP= (F+QX)/X-2.*X*X/G1*(1.-G3*X*X)**(1./G2-1.)
      VOVCO= X-F/FP
      IF(ABS((VOVCO-X)/V1VC1).LT.TOL)  GO TO 13
      GO TO 12
   13 VUVC1=V1VC1*SINAL1
      VRVC1=V1VC1*COSAL1
      VUVC2=VUVC1
C                    STATOR EXIT CONDITIONS
C
      Q=PV1*COSAL1 *BL1
      X=V1VC1/3.
   61 F=(1.-G3*(X*X+VUVC2**2))**(1./G2)*X-Q
      F1=(F+Q)/X
      FP=-2.*X*X/G1*F1**(1./G2-1.)+F1
      X1=X-F/FP
      IF(ABS((X1-X)/X1)-TOL) 62.62.63
   63 X=X1
      GO TO 61
   62 VRVC2=X
      V2VC2=SQRT(VRVC2**2+VUVC2**2)
      PV2=SUBR(V2VC2,G)
      COSAL2=VRVC2/V2VC2
      AL2=ACOS(COSAL2)
      SINAL2=SIN(AL2)
C                    FREE STREAM SPACE CONDITIONS
C
      VUVC3=VUVC2*D2/D3
      Q= PV2*COSAL2*D2/D3
      X=VUVC3/5.
   22 F=(1.-G3*(X*X+VUVC3**2))**(1./G2)*X-Q
      F1=(F+Q)/X
      FP=-2.*X*X/G1*F1**(1./G2-1.)+F1
      X1=X-F/FP
      IF(ABS((X1-X)/X1)-TOL) 20,20,21
   21 X=X1
      GO TO 22
   20 V3VC3=SQRT(VUVC3**2+X*X)
      COSAL3=X/V3VC3
      AL3=ACOS(COSAL3)
      SINAL3=SIN(AL3)
      VRVC3=X
C                    ROTOR INLET CONDITIONS
C
      T3T3=(1.0-G3*(2.0*U3*VUVC3/VCR-(U3/VCR)**2))
      WCVC3=SQRT(T3T3)
      WUVC3=VUVC3-U3/VCR
      WUWC3=WUVC3/WCVC3
      W3VC3=SQRT(WUVC3**2+VRVC3**2)
      W3WC3=W3VC3/WCVC3
      WRWC3=SQRT(W3WC3**2-WUWC3**2)
      P3P3=T3T3**(G5)
      PWVC3=T3T3**(G1/2./G2)
      SINB3=WUWC3/W3WC3
```

```
      B3=ASIN(SINB3)
      COSB3=COS(B3)
      V3TU3=1.-1.98/ZZ
      VU3T=V3TU3*U3
      WU3T=VU3T-U3
      AB=ATAN((WU3T/VCR)/VRVC3)
      XI3=B3-AB
      FS =SIN(XI3)
      FC =COS(XI3)
      WCR3=WCVC3*VCR
      T4T3=1.-G3*(U3/WCR3)**2*(1.-U4U3**2)
      WC4WC3=SQRT(T4T3)
      W3WC4=W3WC3/WC4WC3
      PW4PW3=T4T3**(1./G3/2.)
      PWC3=SUBR(W3WC3,G)
      YGIV=PWC3*(A3/A5/BL4 )*(COS B3/COSB4)/PW4PW3
      IF(MODE.EQ.2.OR.MODE.EQ.5) XK=.1
C                     ROTOR ANALYSIS
C
      Y= .3
   31 IND=1
   32 NCOUNT=NCOUNT+1
      CX=W3WC4**2*(XK*FC**2+FS**2)
      IF(B3.GT.AB) CX=W3WC4**2*(XK*FC**2+FS**3)
      AX= XK*Y*Y+CX
      BX= 1.-G3*Y*Y
      EX= (1.-G3*(AX/BX))**G5
      YCAL=SUBR(Y.G)*EX
      IF(IND.GE.6.AND.ABS((YCAL-YGIV)/YCAL).LE.TOL) GO TO 80
      CALL CONTIN(Y.YCAL.IND,M.YGIV.XDEL)
      IF(IND.LT.10) GO TO 32
C        IND=10 INDICATES CHOKED FLOW
      IF(IND.EQ.10) GO TO 33
C        IND=11 INDICATES NO SOLUTION IS FOUND IN 100 ITERATIONS
      IF(IND.EQ.11) WRITE(6,2040)
      IF(NCOUNT.GE.1000) WRITE(6.2050)
   33 V1VC1= V1VC1-DELV
   34 DELV= DELV/2.
      V1VC1= V1VC1+DELV
      N=2
      GO TO 9
   35 IT=2
      GO TO 82
   80 IF(MODE.EQ.2.OR.MODE.EQ.5) GO TO 82
      IF(ABS((V1VC1-VX)/V1VC1).LT.TOL) GO TO 35
      VX=V1VC1
      IF(N.EQ.2) GO TO 34
   82 W4WC4= Y
      PW4= SUBR(Y,G)
      P4P4ID=YGIV/PW4
      PWC4 =PVCR*PD*PWVC3*PW4PW3*P4P4ID
   85 CONTINUE
      WUWC4=W4WC4*SINB4
      WXWC4=W4WC4*COSB4
      HA = WXWC4
      IF(HA.GT.1.) GO TO 56
      Q=PW4*COSB4*BL4
      X=W4WC4/3.
```

```
   70 F=(1.-G3*(X*X+WUWC4**2))**(1./G2)*X-Q
      F1=(F+Q)/X
      FP=-2.*X/G1*F1**(2.-G)*X+F1
      X1=X-F/FP
      IF(ABS((X1-X)/X1)-TOL) 71,71,72
   72 X=X1
      GO TO 70
C                    ROTOR  EXIT CONDITIONS
C
   71 WXWC5=X
      W5WC5=X*X+WUWC4**2
      W5WC5=SQRT(W5WC5)
      SINB5=WUWC4/W5WC5
      VUWC4=1./WCVC3*U4U3*U3/VCR/WC4WC3+WUWC4
      VUWC5=VUWC4
      V5WC5=VUWC5**2+X*X
      V5WC5=SQRT(V5WC5)
      T4T4=1.+G3*(VUWC4**2-WUWC4**2)
      Q1=SQRT(T4T4)
      VXVC5=WXWC5/Q1
      VUVC5=VUWC5/Q1
      V5VC5=V5WC5/Q1
      AL5=1./T*ASIN(VUVC5/V5VC5)
      B5=1./T*ASIN(SINB5)
      WUWC5=WUWC4
      VU4VC3=WUWC4*WC4WC3*WCVC3+U4U3*U3/VCR
      T5T0= 1.-2.*G3/VCR*(U3*VUVC3-U4U3*U3*VU4VC3)
      T5= T0*T5T0
      VCR5 = VCR*SQRT(T5T0)
      P5P5 = T4T4**(G5)
      P4P3ID = T4T3**(G5)
      P5P0 = PD*P3P3*P4P3ID*P4P4ID*P5P5
      P5=P0*P5P0
      P5P5P = (1.-G3*(V5VC5**2))**(G5)
      P5P0P = P5P0*P5P5P
      VC5VC0 = (VCR5/VCR)**2
      P5P0G = P5P0**(G2/G)
      P5P0PG = P5P0P**(G2/G)
      Z = 1./P5P0
      Z1 = 1./P5P0P
      H1=1.-VC5VC0
      ETAS=H1/(1.-P5P0PG)
      ETAT=H1/(1.-P5P0G)
C                    AUTOMATIC DETERMINATION OF XK AND PD
C
      IF(MODE.EQ.0.OR.MODE.EQ.1.OR.MODE.EQ.3.OR.MODE.EQ.4) GO TO 40
      ET= ETAS
      IF(ITEST.EQ.2)  ET= ETAT
      IF(K.EQ.5)  GO TO 30
      CALL GETK(XK.ET.ETAD.K)
      IF((ETAD-ET).GT..1) GO TO 90
      GO TO 31
   30 PR=Z1
      IF(ITEST.EQ.2) PR=Z
      IF(L.EQ.5) GO TO 40
      CALL SEEKPR(PDSGN.PR.PD.L)
      GO TO 4
```

```
C                     EXTRA OUTPUT CALCULATIONS
C
   40 CONTINUE
      IF(MODE.EQ.3.OR.MODE.EQ.4.OR.MODE.EQ.5) GO TO 41
      THETCR=G4*R*T0/48247.36
      STHETA = SQRT(THETCR)
      DELTA=P0/101325.
      XNOTH= 100.*U3/3.14159/D3/STHETA
      XN= XNOTH*STHETA
      DHTCR=H1*48247.36/G3
      DELH=DHTCR*THETCR
      DHIDS = (1.-P5P0PG)*G5*R*T0
      DHIDT = (1.-P5P0G)*G5*R*T0
      EQPRS = 1./(1.-DHIDS/289484.2/THETCR)**3.5
      EQPRT = 1./(1.-DHIDT/289484.2/THETCR)**3.5
      XNU=U3/SQRT(2.*DHIDS)
      WTOP= W1*100.**2*SQRT(T0)/P0
      TOR= DELH*W1*9.549274/XN
      TOP= TOR*1.E+06/P0
      ELAM = DELH/U3**2
      RHO5P = P5P0*P0/VCR5**2*2.*G4
      P = DELH*W1/1000.
      GO TO 43
   41 THETCR=G4*R*T0/16141.4357
      STHETA = SQRT(THETCR)
      DELTA=P0/2116.22
      XNOTH=720.*U3/3.14159/D3/STHETA
      XN= XNOTH*STHETA
      DHTCR=H1*16141.4357/G3/XJ
      DELH=DHTCR*THETCR
      DHIDS = (1.-P5P0PG)*G5*R*T0/XJ
      DHIDT = (1.-P5P0G)*G5*R*T0/XJ
      EQPRS = 1./(1.-DHIDS/124.4808/THETCR)**3.5
      EQPRT = 1./(1.-DHIDT/124.4808/THETCR)**3.5
      XNU=U3/SQRT(2.*GR*XJ*DHIDS)
      WTOP=W1*SQRT(T0)*144./P0
      TOR= DELH*W1/1.12164E-05/XN
      TOP= TOR*144./P0
      ELAM = DELH*GR*XJ/U3**2
      RHO5P = P5P0*P0*2.*GR*G4/VCR5**2
      P = DELH*W1*XJ/550.
   43 PRS= 1./EQPRS
      EPS=(G1/2.)**(G5)*.7395945/G
      WTHODE=W1*STHETA*EPS/DELTA
      EQTOR= TOR*EPS/DELTA
      WNODE=WTHODE*XNOTH
      DELHOT=DELH/T0
      XNOT= XN/SQRT(T0)
      RHO5RT = P5P5P**(1./G)
      RHO5 = RHO5RT*RHO5P
      CAPQ = W1/RHO5
      SCAPQ = SQRT(CAPQ)
      IF(MODE.EQ.3.OR.MODE.EQ.4.OR.MODE.EQ.5) GO TO 42
      XNS=XN*.10472*SCAPQ/(DHIDT**.75)
      GO TO 45
   42 XNS=XN*SCAPQ/((XJ*DHIDT)**.75)
   45 CONTINUE
```

```
C                    COMPLETE WRITE OUT
C
      IF(IT.EQ.3) GO TO 44
      AL1=AL1/T
      AL2=AL2/T
      XI3 = XI3/T
      AL3=AL3/T
      B3=B3/T
      B4=B4/T
   44 CONTINUE
      IF(MODE.EQ.1.OR.MODE.EQ.4) WRITE(6,505) V1VC1,XNS,PRS,XNU,ETAT,
     1ETAS.DHTCR.WTHODE.EQPRS.EQPRT
      IF(MODE.EQ.0.OR.MODE.EQ.3) GO TO 46
      IF(MODE.EQ.1.OR.MODE.EQ.4) GO TO 48
      WRITE(6.509) PD.XK.WD
      IF(ITEST.EQ.1) WRITE(6,525) ETAD,PDSGN
      IF(ITEST.EQ.2) WRITE(6,526) ETAD.PDSGN
   46 CONTINUE
      WRITE(6,500)V1VC1,AL1,V3VC3,W4WC4,W5WC5,VUVC1,AL2,VUVC3,WUWC4,
     1WXWC5.VRVC1.AL3.VRVC3.WXWC4.V5VC5.VOVCO.B3.W3WC3.B4.VUVC5.V2VC2.
     2XI3.WUWC3.B5.VXVC5,VRVC2,VCR,WRWC3,VCR5,AL5
      WRITE(6,501)WTHODE,EQPRS,Z1,WTOP,W1,DHTCR,ETAS,XNU,DELHOT,DELH,
     1XNOTH.ETAT.XNS.XNOT.ELAM.EQTOR.EQPRT.Z.TOP.TOR.XN.P.WNODE.T5.P5
      IF(MODE.EQ.2.OR.MODE.EQ.5) GO TO 51
   48 CONTINUE
      IF(WXWC4.EQ.1.) GO TO 59
      IF(J.EQ.2) GO TO 57
      IF(IT.GE.2) GO TO 55
      AL1=ALX*T
      B4=B4X*T
      V1VC1=V1VC1+DELV
      IF(V1VC1.GT.VMAX) GO TO 51
      GO TO 9
   51 AL1=ALX
      DELV= DELV1
      B4= B4X
      GO TO 1
   55 IT=3
      GIV=YGIV*COS(B4X*T)
      Y= Y+DELY
      IF(Y.GT.YMAX) GO TO 51
   53 W4WC4= Y
      PW4= SUBR(Y.G)
      AX= XK*Y*Y+CX
      BX= 1.-G3*Y*Y
      P4P4ID= (1.-G3*(AX/BX))**G5
      COSB4=GIV/(PW4*P4P4ID)
      B4= ACOS(COSB4)
      B4= -B4
      COSB4= COS(B4)
      SINB4= SIN(B4)
      B4= B4/T
      IF(J.EQ.2) GO TO 58
      GO TO 85
   56 IF(J.EQ.2) GO TO 57
      Y= Y-DELY
      DELL= DELY/5.
      J= 2
   57 Y= Y+DELL
      GO TO 53
```

```
   58 HB= W4WC4*COSB4
      IF(ABS((HB-HA)/HA ).LT..02) GO TO 59
      DELL= DELL/2.
      GO TO 85
   59 WRITE(6,600)
      GO TO 51
   90 WRITE(6.300)
      GO TO 1
      STOP
C                    FORMAT STATEMENTS
C

ERROR MESSAGE NUMBER     1
  100 FORMAT(10A6)
  200 FORMAT(1H1,35X,43HNASA RADIAL  INFLOW TURBINE COMPUTER PROGRAM/
     124X.10A6/24X.10A6 )
  300 FORMAT(/10X,54HNO SOLUTION FOR THIS CASE - CHECK A1,BL1,AL1 OR B4,
     1BL4)
  400 FORMAT(7HK GAMMA.2X.G13.5.7H     PO..2X.G13.5.6H     A1.2X.G13.5.
     12X,7HALPHA-1,2X,G13.5,7H BETA-4,2X,G13.5,5H   PD,2X,G13.5/
     27H       R,2X,G13.5,7H     TO,,2X,G13.5.6H     A3.2X.G13.5.2X.
     37H     BL1.2X.G13.5.7H     BL4.2X.G13.5.5H     K.2X,G13.5   /
     47H      D3,2X,G13.5,7H      A0,2X,G13.5,6H     A5,2X,G13.5,2X,
     57H      U3.2X.G13.5.7H  U4/U3.2X.G13.5.5H   ZZ.2X.G13.5 )
  500 FORMAT(/ 50X,21HVELOCITIES AND ANGLES/
     112H V/VCR)1     ,G13.5,1X,11HALPHA-1     ,G13.5,1X,11HV/VCR)3    ,
     AG13.5.1X.11HW/WCR)4    .G13.5.1X.11HW/WCR)5    .G13.5/
     212H VU/VCR)1    ,G13.5,1X,11HALPHA-2     ,G13.5,1X,11HVU/VCR)3   ,
     AG13.5,1X,11HWU/WCR)4   ,G13.5,1X,11HWX/WCR)5   ,G13.5/
     312H VR/VCR)1    .G13.5.1X.11HALPHA-3     .G13.5.1X.11HVR/VCR)3   .
     AG13.5,1X,11HWX/WCR)4   ,G13.5,1X,11HV/VCR)5    ,G13.5/
     412H V/VCR)0     ,G13.5,1X.11HBETA-3      .G13.5.1X.11HW/WCR)3    .
     AG13.5.1X.11HBETA-4     .G13.5.1X.11HVU/VCR)5   ,G13.5/
     512H V/VCR)2     ,G13.5,1X,11HI-3         ,G13.5,1X,11HWU/WCR)3   ,
     AG13.5.1X.11HBETA-5     .G13.5.1X.11HVX/VCR)5   .G13.5/
     612H VR/VCR)2    ,G13.5,1X,11HVCR)3       ,G13.5,1X,11HWR/WCR)3   ,
     AG13.5,1X,11HVCR)5      ,G13.5,1X,11HALPHA-5    ,G13.5)
  501 FORMAT(50X.19HOVERALL PERFORMANCE/
     112H EQ-W        ,G13.5,1X,11HEQ-PO,/P5  ,G13.5,1X,11HPO,/P5
     BG13.5,1X,11HWT/P        ,G13.5,1X,11HW          ,G13.5/
     212H EQ-DEL-H    .G13.5.1X.11HETA-S      .G13.5.1X.11HNU
     BG13.5,1X,11HDEL-H/T     ,G13.5,1X,11HDEL-H      ,G13.5/
     312H EQ-N        .G13.5.1X.11HETA-T      .G13.5.1X.11HNS
     BG13.5.1X.11HN/T         .G13.5,1X,11HW.F.       ,G13.5/
     412H EQ-TOR      ,G13.5,1X,11HEQ-PO,/P5, ,G13.5,1X,11HPO,/P5,
     BG13.5.1X.11HTOR/P       .G13.5.1X.11HTOR        .G13.5/
     512H N           ,G13.5,1X,11HP          ,G13.5,1X,11HWN/DEL
     BG13.5,1X,11HT5,         ,G13.5,1X,11HP5,        ,G13.5)
  505 FORMAT(10G13.5)
  509 FORMAT( 13X,2HPD,G15.6/14X,1HK,G15.6/1X,14HDESIGN WT-FLOW,G15.6)
  525 FORMAT(3X,12HDESIGN ETA-S ,G15.6/2X,13HDESIGN PO./P5.G15.6)
  526 FORMAT(3X.12HDESIGN ETA-T .G15.6/1X.14HDESIGN PO,/P5,,G15.6)
  600 FORMAT(/10X,41HLAST CASE IS APPROXIMATE LIMITING LOADING)
  666 FORMAT(7HK V1VC1.8X.2HNS.11X.9HEQ-P5/PO..4X.2HNU.11X.4HETAT.9X.
     14HETAS.9X.5HDHTCR,8X,6HWTHODE,7X,9HEQ-PO,/P5,4X,10HEQ-PO,/P5, )
 2040 FORMAT( 10X,44HNO SOLUTION COULD BE FOUND IN 100 ITERATIONS)
 2050 FORMAT(10X.69HITERATION PROCEDURE HAD TO BE RESTARTED TO AVOID NEG
     1ATIVE TEMPERATURE/15X,67HRESTART PROCEDURE WAS ABORTED AFTER 1000
     2TOTAL NUMBER OF ITERATIONS)
      END
```

Subroutine GETK (XK, ETA, ETAD, K)

Subroutine GETK varies the value of the loss coefficient K by false positioning until the design value of efficiency is met.

XK rotor loss coefficient, K

ETA computed value of efficiency from main program

ETAD design value of η_t or η_s

K indicator used in method of false positioning

```
      SUBROUTINE GETK(XK,ETA,ETAD,K)
      GO TO (100,101),K
100   XK1= XK
      DIF1= ETA-ETAD
      K=2
      XK= XK+.005
      RETURN
101   XK2= XK
      DIF2 = ETA-ETAD
      IF(DIF2*DIF1) 104,103,102
102   XK1= XK2
      XK= XK+.005
      DIF1= DIF2
      RETURN
103   XK= XK2
      K= 5
      RETURN
104   XK= -(XK2-XK1)/(DIF2-DIF1)*DIF1+XK1
      K=5
      RETURN
      END
```

Subroutine SEEKPR (PDSGN, PR, PD, L)

Subroutine SEEKPR varies the value of the stator total-pressure ratio p_1'/p_0' by false positioning until all design specifications are met.

PDSGN design value of p_0'/p_5' or p_0'/p_5

PR computed value of turbine pressure ratio from main program

PD value of stator total-pressure ratio p_1'/p_0'

L indicator used in method of false positioning

```
      SUBROUTINE SEEKPR(PDSGN,PR,PD,L)
      GO TO (10,11),L
   10 PD1=PD
      DIF1= PR-PDSGN
      L=2
      PD=PD-.005
      RETURN
   11 PD2=PD
      DIF2 = PR-PDSGN
      IF(DIF2*DIF1) 14,13,12
   12 PD1=PD2
      PD=PD-.005
      DIF1= DIF2
      RETURN
   13 PD=PD2
      L= 5
      RETURN
   14 PD= -(PD2-PD1)/(DIF2-DIF1)*DIF1+PD1
      L= 5
      RETURN
      END
```

Subroutine CONTIN (XEST, YCALC, IND, JZ, YGIV, XDEL)

Subroutine CONTIN is a curve-fitting routine which is described in detail in reference 8. It is used to determine the rotor-exit velocity ratio value needed to satisfy continuity at the rotor exit.

XEST value of estimated velocity Y

YCALC mass flow parameter based on estimated velocity

IND index to control next iteration in CONTIN and to indicate when a choked-flow solution has been found

JZ index variable

YGIV input mass flow parameter

XDEL maximum permitted change in estimated velocity Y per iteration

```
      SUBROUTINE CONTIN(XEST,YCALC,IND,JZ,YGIV,XDEL)
C
C--CONTIN CALCULATES AN ESTIMATE OF THE RELATIVE FLOW VELOCITY
C--FOR USE IN THE VELOCITY GRADIENT EQUATION
C
      DIMENSION X(3),Y(3)
      NCALL = NCALL+1
      IF (IND.NE.1.AND.NCALL.GT.100) GO TO 160
      GO TO (10,30,40,50,60,110,150),IND
```

```
C--FIRST CALL
   10 NCALL = 1
      XORIG = XEST
      IF (YCALC.GT.YGIV.AND.JZ.EQ.1) GO TO 20
      IND = 2
      Y(1) = YCALC
      X(1) = 0.
      XEST = XEST+XDEL
      RETURN
   20 IND = 3
      Y(3) = YCALC
      X(3) = 0.
      XEST = XEST-XDEL
      RETURN
C--SECOND CALL
   30 IND = 4
      Y(2) = YCALC
      X(2) = XEST-XORIG
      XEST = XEST+XDEL
      RETURN
   40 IND = 5
      Y(2) = YCALC
      X(2) = XEST-XORIG
      XEST = XEST-XDEL
      RETURN
C--THIRD OR LATER CALL - FIND SUBSONIC OR SUPERSONIC SOLUTION
   50 Y(3) = YCALC
      X(3) = XEST-XORIG
      GO TO 70
   60 Y(1) = YCALC
      X(1) = XEST-XORIG
   70 IF (YGIV.LT.AMIN1(Y(1),Y(2),Y(3))) GO TO (120,130),JZ
   80 IND = 6
      CALL PABC(X,Y,APA,BPB,CPC)
      DISCR = BPB**2-4.*APA*(CPC-YGIV)
      IF (DISCR.LT.0.) GO TO 140
      IF (ABS(400.*APA*(CPC-YGIV)).LE.BPB**2) GO TO 90
      XEST = -BPB-SIGN( SQRT(DISCR).APA)
      IF (JZ.EQ.1.AND.APA.GT.0..AND.Y(3).GT.Y(1)) XEST = -BPB+
     1SQRT(DISCR)
      IF (JZ.EQ.2.AND.APA.LT.0.) XEST = -BPB-SQRT(DISCR)
      XEST = XEST/2./APA
      GO TO 100
   90 IF (JZ.EQ.2.AND.BPB.GT.0.) GO TO 130
      ACB2 = APA/BPB*(CPC-YGIV)/BPB
      IF (ABS(ACB2).LE.1.E-8) ACB2=0.
      XEST = -(CPC-YGIV)/BPB*(1.+ACB2+2.*ACB2**2)
  100 IF (XEST.GT.X(3)) GO TO 130
      IF (XEST.LT.X(1)) GO TO 120
      XEST = XEST+XORIG
      RETURN
C--FOURTH OR LATER CALL - NOT CHOKED
  110 IF(XEST-XORIG.GT.X(3)) GO TO 130
      IF(XEST-XORIG.LT.X(1)) GO TO 120
      Y(2) = YCALC
      X(2) = XEST-XORIG
      GO TO 70
C--THIRD OR LATER CALL - SOLUTION EXISTS,
C--BUT RIGHT OR LEFT SHIFT REQUIRED
  120 IND = 5
```

```
C--LEFT SHIFT
      XEST = X(1)-XDEL+XORIG
      XOSHFT = XEST-XORIG
      XORIG = XEST
      Y(3) = Y(2)
      X(3) = X(2)-XOSHFT
      Y(2) = Y(1)
      X(2) = X(1)-XOSHFT
      RETURN
  130 IND = 4
C--RIGHT SHIFT
      XEST = X(3)+XDEL+XORIG
      XOSHFT = XEST-XORIG
      XORIG = XEST
      Y(1) = Y(2)
      X(1) = X(2)-XOSHFT
      Y(2) = Y(3)
      X(2) = X(3)-XOSHFT
      RETURN
C--THIRD OR LATER CALL - APPEARS TO BE CHOKED
  140 XEST = -BPB/2./APA
      IND = 7
      IF (XEST.LT.X(1)) GO TO 120
      IF(XEST.GT.X(3)) GO TO 130
      XEST = XEST+XORIG
      RETURN
C--FOURTH OR LATER CALL - PROBABLY CHOKED
  150 IF (YCALC.GE.YGIV) GO TO 110
      IND = 10
      RETURN
C--NO SOLUTION FOUND IN 100 ITERATIONS
  160 IND = 11
      RETURN
      END
```

Subroutine PABC (X, Y, A, B, C)

Subroutine PABC calculates the coefficients A, B, and C of the parabola $y = Ax^2 + Bx + C$ passing through three given X, Y points supplied by subroutine CONTIN.

```
      SUBROUTINE PABC(X,Y,A,B,C)
C
C--PABC CALCULATES COEFFICIENTS A.B.C OF THE PARABOLA
C--Y=A*X**2+B*X+C, PASSING THROUGH THE GIVEN X,Y POINTS
C
      DIMENSION X(3),Y(3)
      C1 = X(3)-X(1)
      C2 = (Y(2)-Y(1))/(X(2)-X(1))
      A = (C1*C2-Y(3)+Y(1))/C1/(X(2)-X(3))
      B = C2-(X(1)+X(2))*A
      C = Y(1)-X(1)*B-X(1)**2*A
      RETURN
      END
```

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, June 17, 1975,

505-04.

APPENDIX A

SYMBOLS

A	area, m^2; ft^2
B	blockage factor
C_1	dimensional constant, 200; $720/\pi$
C_2	dimensional constant, 1; $360/\pi$
C_3	dimensional constant, 1000; 550
D	diameter, cm; in.
g	conversion constant, 1; 32.1741 ft/sec^2
$\Delta h'$	specific turbine work, J/kg; Btu/lb
$\Delta h'_{id,s}$	ideal turbine work based on inlet-total- to exit-static-pressure ratio, J/kg; Btu/lb
$\Delta h'_{id,t}$	ideal turbine work based on inlet-total- to exit-total-pressure ratio, J/kg; Btu/lb
i	incidence angle, deg
J	mechanical equivalent of heat, 1; 778.029 ft-lb/Btu
K	rotor loss coefficient, dimensionless
K_S	stator loss coefficient, dimensionless (ref. 1)
L	kinetic energy loss, J/kg; Btu/lb
N	turbine speed, rad/sec; rpm
N_s	specific speed, dimensionless; rpm $(ft^{3/4})/sec^{1/2}$
n	incidence loss exponent
P	power, kW; hp
p	pressure, N/m^2; psfa
R	gas constant, J/(kg)(K); (ft-lb)/(lb)($^{\circ}$R)
T	absolute temperature, K; $^{\circ}$R
U	blade speed, m/sec; ft/sec
V	absolute velocity of gas, m/sec; ft/sec
W	gas velocity relative to rotor, m/sec; ft/sec

WF work factor, eq. (B38)

w mass flow rate, kg/sec; lb/sec

ZZ number of rotor blades at rotor inlet

α absolute gas angle (angle between absolute velocity vector and meridional plane, positive when tangential velocity component is in direction of wheel velocity), deg

β relative gas angle (angle between velocity vector relative to wheel and meridional plane, same sign convention as for α), deg

Γ torque, N-m; in.-lb

γ ratio of specific heat at constant pressure to specific heat at constant volume

δ ratio of turbine inlet total pressure to U.S. standard atmospheric pressure, eq. (B22)

ϵ function of γ used in relating parameters to those using air inlet conditions at U.S. standard sea-level conditions, eq. (B23)

η_s efficiency based on ratio of inlet total to exit static pressure

η_t efficiency based on ratio of inlet total to exit total pressure

θ_{cr} squared ratio of critical velocity at turbine inlet to critical velocity at U.S. standard atmospheric temperature, eq. (B21)

ν blade-jet speed ratio, eq. (B37)

ρ gas density, kg/m^3; lb/ft^3

φ optimum rotor flow angle, deg

Subscripts:

cr condition corresponding to $V/V_{cr} = 1$

des design

eq air equivalent (U.S. standard sea level) values

id ideal

IN incidence

max maximum

opt optimum

R rotor

r radial component

S stator

u tangential component, positive when in direction of wheel velocity

x meridional component, component in plane containing axis of rotation

0 station at turbine inlet

1 station immediately upstream of stator exit

2 station immediately downstream of stator exit

3 station immediately upstream of rotor inlet

4 station immediately upstream of rotor exit

5 station immediately downstream of rotor exit

Superscripts:

' absolute total state

'' total state relative to rotor

* U.S. standard sea-level air conditions (temperature, 288.15 K (518.67° R); pressure, 101 325 N/m^2 (2116.22 psfa), specific-heat ratio, 1.4; gas constant, 287.04 J/(kg)(K) (53.35 (ft-lb)/(lb)(°R))

APPENDIX B

EQUATIONS USED IN PROGRAM

The analytical procedure involves a step-by-step solution of the flow conditions through the turbine along a mean line. Thus, at the rotor exit, the flow conditions and velocity diagrams are those at the mean radius, which could be a flow mean or an area mean. The two independent variables that are fixed for any given calculation point are the rotor-inlet-tip speed ratio $(U/V_{cr})_3$ and the stator-exit critical-velocity ratio $(V/V_{cr})_1$. The analytical procedure and the equations used are outlined in the following paragraphs.

Stator Analysis

The total temperature is assumed to be constant for the first four stations. Thus,

$$V_{cr,0} = V_{cr,1} = V_{cr,2} = V_{cr,3}$$

The mass flow per unit area is expressed as

$$\frac{\rho V}{\rho' V_{cr}} = \frac{V}{V_{cr}}\left[1 - \frac{\gamma - 1}{\gamma + 1}\left(\frac{V}{V_{cr}}\right)^2\right]^{1/(\gamma-1)} \tag{B1}$$

For an input value of p_1'/p_0' and the assumed value of $(V/V_{cr})_1$, the continuity relation at station 0 is

$$\left(\frac{\rho V}{\rho' V_{cr}}\right)_0 = \frac{p_1'}{p_0'}\left(\frac{\rho V}{\rho' V_{cr}}\right)_1 \frac{A_1}{A_0} \cos \alpha_1 \tag{B2}$$

Equation (B1) is substituted into equation (B2), which can then be solved iteratively for $(V/V_{cr})_0$.

The mass flow rate is then computed as

$$w = \frac{p_1'}{p_0'}\left(\frac{\rho V}{\rho' V_{cr}}\right)_1 \left(\rho' V_{cr}\right)_0 A_1 \cos \alpha_1 \tag{B3}$$

where $\left(\rho' V_{cr}\right)_0$ is evaluated from the known inlet conditions of p_0' and T_0' by using

$$\rho' = \frac{p'}{RT'}$$

and

$$V_{cr} = \sqrt{\frac{2\gamma}{\gamma + 1} gRT'}$$

For values of V/V_{cr} greater than 1.0, the choking value of mass flow rate is used to calculate a new stator-exit flow angle:

$$\cos \alpha_1 = \frac{w_{cr}}{\frac{p_1'}{p_0'}\left(\frac{\rho V}{\rho' V_{cr}}\right)_1 \left(\rho' V_{cr}\right)_0 A_1} \tag{B4a}$$

At station 1 the geometry of the velocity diagram gives

$$\left(\frac{V_u}{V_{cr}}\right)_1 = \left(\frac{V}{V_{cr}}\right)_1 \sin \alpha_1 \tag{B4b}$$

$$\left(\frac{V_r}{V_{cr}}\right)_1 = \left(\frac{V}{V_{cr}}\right)_1 \cos \alpha_1 \tag{B4c}$$

Station 2 conditions are determined by assuming that $\left(\rho' V_{cr}\right)_1 = \left(\rho' V_{cr}\right)_2$ and since $D_2 = D_1$, $\left(V_u/V_{cr}\right)_1 = \left(V_u/V_{cr}\right)_2$. The continuity relation between stations 1 and 2 is written as

$$\left(\frac{\rho V}{\rho' V_{cr}}\right)_1 B_1 \cos \alpha_1 = \left(\frac{\rho V}{\rho' V_{cr}}\right)_2 \cos \alpha_2 \tag{B5a}$$

where

$$B_1 = \frac{A_1}{A_2} \tag{B5b}$$

and

$$\left(\frac{\rho V}{\rho' V_{cr}}\right)_2 \cos \alpha_2 = \left\{1 - \frac{\gamma - 1}{\gamma + 1}\left[\left(\frac{V_r}{V_{cr}}\right)^2 + \left(\frac{V_u}{V_{cr}}\right)^2\right]_2\right\}^{1/(\gamma-1)} \left(\frac{V_r}{V_{cr}}\right)_2 \tag{B5c}$$

The geometry of the velocity diagram gives

$$\left(\frac{V}{V_{cr}}\right)_2 = \left[\left(\frac{V_r}{V_{cr}}\right)_2^2 + \left(\frac{V_u}{V_{cr}}\right)_2^2\right]^{1/2} \tag{B5d}$$

and

$$\alpha_2 = \cos^{-1} \frac{\left(\frac{V_r}{V_{cr}}\right)_2}{\left(\frac{V}{V_{cr}}\right)_2} \tag{B5e}$$

Equations (B5a) to (B5e) are solved iteratively to determine $\left(V_r/V_{cr}\right)_2$, $\left(V/V_{cr}\right)_2$, and α_2.

The conditions at station 3 are determined by assuming that

$$\left(\rho' V_{cr}\right)_2 = \left(\rho' V_{cr}\right)_3$$

and

$$\left(\frac{V_u}{V_{cr}}\right)_3 = \left(\frac{V_u}{V_{cr}}\right)_2 \frac{D_2}{D_3} \tag{B6a}$$

The continuity relation between stations 2 and 3 is given as

$$\left(\frac{\rho V}{\rho' V_{cr}}\right)_2 \frac{D_2}{D_3} \cos \alpha_2 = \left(\frac{\rho V}{\rho' V_{cr}}\right)_3 \cos \alpha_3 \tag{B6b}$$

where

$$\left(\frac{\rho V}{\rho' V_{cr}}\right)_3 \cos \alpha_3 = \left\{1 - \frac{\gamma - 1}{\gamma + 1}\left[\left(\frac{V_r}{V_{cr}}\right)^2 + \left(\frac{V_u}{V_{cr}}\right)^2\right]_3\right\}^{1/(\gamma-1)} \left(\frac{V_r}{V_{cr}}\right)_3 \tag{B6c}$$

From the geometry of the velocity diagrams,

$$\left(\frac{V}{V_{cr}}\right)_3 = \left[\left(\frac{V_r}{V_{cr}}\right)_3^2 + \left(\frac{V_u}{V_{cr}}\right)_3^2\right]^{1/2} \tag{B6d}$$

and

$$\alpha_3 = \cos^{-1} \frac{\left(\frac{V_r}{V_{cr}}\right)_3}{\left(\frac{V}{V_{cr}}\right)_3} \tag{B6e}$$

Equations (B6a) to (B6e) are solved iteratively to determine $(V_r/V_{cr})_3$, $(V/V_{cr})_3$, and α_3.

The relations between relative and absolute parameters at the rotor inlet are given by the following four equations:

$$\left(\frac{T''}{T'}\right)_3 = \left\{1 - \frac{\gamma - 1}{\gamma + 1}\left[\frac{2U_3V_{u,3}}{V_{cr,3}^2} - \left(\frac{U}{V_{cr}}\right)_3^2\right]\right\} \tag{B7a}$$

$$\frac{p_3''}{p_3'} = \left(\frac{T''}{T'}\right)_3^{\gamma/(\gamma-1)} \tag{B7b}$$

$$\left(\frac{W_{cr}}{V_{cr}}\right)_3 = \left(\frac{T''}{T'}\right)_3^{1/2} \tag{B7c}$$

$$\left(\frac{\rho''W_{cr}}{\rho'V_{cr}}\right)_3 = \left(\frac{T''}{T'}\right)_3^{(\gamma+1)/2(\gamma-1)} \tag{B7d}$$

The velocity-diagram geometry gives

$$\left(\frac{W_u}{W_{cr}}\right)_3 = \left[\left(\frac{V_u}{V_{cr}}\right)_3 - \left(\frac{U}{V_{cr}}\right)_3\right]\left(\frac{V_{cr}}{W_{cr}}\right)_3 \tag{B7e}$$

$$\left(\frac{W}{W_{cr}}\right)_3 = \left[\left(\frac{W_u}{V_{cr}}\right)_3^2 + \left(\frac{V_r}{V_{cr}}\right)_3^2\right]^{1/2}\left(\frac{V_{cr}}{W_{cr}}\right)_3 \tag{B7f}$$

$$\left(\frac{W_r}{W_{cr}}\right)_3 = \left[\left(\frac{W}{W_{cr}}\right)_3^2 - \left(\frac{W_u}{W_{cr}}\right)_3^2\right]^{1/2} \tag{B7g}$$

$$\beta_3 = \sin^{-1} \frac{\left(\frac{W_u}{W_{cr}}\right)_3}{\left(\frac{W}{W_{cr}}\right)_3} \tag{B7h}$$

The optimum rotor-inlet flow angle φ is calculated as follows:

$$\frac{V_{u,3,opt}}{U_3} = 1 - \frac{1.98}{ZZ} \tag{B8a}$$

$$V_{u,3,opt} = U_3 \left(\frac{V_{u,3,opt}}{U_3}\right) \tag{B8b}$$

$$W_{u,3,opt} = V_{u,3,opt} - U_3 \tag{B8c}$$

$$\varphi = \tan^{-1} \frac{\left(\frac{W_{u,3,opt}}{V_{cr,3}}\right)}{\left(\frac{V_r}{V_{cr}}\right)_3} \tag{B8d}$$

The rotor incidence angle is

$$i_3 = \beta_3 - \varphi \tag{B9}$$

Since the rotor mean radius decreases from inlet to exit, there is a relative total-temperature drop expressible by the following equation:

$$\frac{T_4''}{T_3''} = 1 - \frac{\gamma - 1}{\gamma + 1}\left(\frac{U}{W_{cr}}\right)_3^2 \left[1 - \left(\frac{U_4}{U_3}\right)^2\right] \tag{B10a}$$

This allows the following rotor-exit parameters to be calculated:

$$\frac{p''_{4,id}}{p''_3} = \left(\frac{T''_4}{T''_3}\right)^{\gamma/(\gamma-1)} \tag{B10b}$$

$$\frac{W_{cr,4}}{W_{cr,3}} = \left(\frac{T''_4}{T''_3}\right)^{1/2} \tag{B10c}$$

$$\frac{\left(\rho''W_{cr}\right)_{4,id}}{\left(\rho''W_{cr}\right)_3} = \left(\frac{T''_4}{T''_3}\right)^{(\gamma+1)/2(\gamma-1)} \tag{B10d}$$

The rotor-exit conditions are calculated by using the continuity equation between stations 3 and 4

$$\left(\rho A W_r\right)_3 = \left(\rho A W_x\right)_4$$

which is written as

$$\left(\frac{\rho W}{\rho''W_{cr}}\right)_4 = \frac{\left(\frac{\rho W}{\rho''W_{cr}}\right)_3 \frac{A_3}{A_4} \frac{\cos\beta_3}{\cos\beta_4}}{\frac{p''_4}{p''_{4,id}} \frac{\left(\rho''W_{cr}\right)_{4,id}}{\left(\rho''W_{cr}\right)_3}} \tag{B11}$$

where $A_4 = B_4A_5$.

Everything on the right side of equation (B11) is known except $p''_4/p''_{4,id}$, which is the relative total pressure recovery for the rotor. It can be expressed as follows:

$$\frac{p''_4}{p''_{4,id}} = \left\{1 - \frac{\frac{\gamma-1}{\gamma+1}\left[K\left(\frac{W}{W_{cr}}\right)_4^2 + \left(\frac{W_3}{W_{cr,4}}\right)^2\left(K\cos^2 i_3 + \sin^n i_3\right)\right]}{1 - \frac{\gamma-1}{\gamma+1}\left(\frac{W}{W_{cr}}\right)_4^2}\right\}^{\gamma/(\gamma-1)} \tag{B12}$$

Equation (B1) is substituted, in terms of relative quantities, into equation (B11). And the values of $\left(W/W_{cr}\right)_4$ and $p''_4/p''_{4,id}$ are determined by an iteration procedure with equations (B11) and (B12). After the rotor choke point, conditions upstream of the rotor exit are held fixed. As the velocity ratio $\left(W/W_{cr}\right)_4$ is increased beyond the choking value, the exit flow angle β_4 is adjusted by the following equation:

$$\cos\beta_4 = \frac{\left(\frac{\rho W}{\rho''W_{cr}}\right)_3 \frac{A_3}{A_4}\cos\beta_3}{\frac{p''_4}{p''_{4,id}}\frac{\left(\rho''W_{cr}\right)_{4,id}}{\left(\rho''W_{cr}\right)_3}\left(\frac{\rho W}{\rho''W_{cr}}\right)_4} \tag{B13a}$$

The velocity-diagram geometry gives

$$\left(\frac{W_u}{W_{cr}}\right)_4 = \left(\frac{W}{W_{cr}}\right)_4 \sin\beta_4 \tag{B13b}$$

$$\left(\frac{W_x}{W_{cr}}\right)_4 = \left(\frac{W}{W_{cr}}\right)_4 \cos\beta_4 \tag{B13c}$$

Station 5 conditions are determined by assuming that $\left(\rho''W_{cr}\right)_4 = \left(\rho''W_{cr}\right)_5$ and $\left(W_u/W_{cr}\right)_4 = \left(W_u/W_{cr}\right)_5$. The continuity relation between stations 4 and 5 is given as

$$\left(\frac{\rho W}{\rho''W_{cr}}\right)_4 B_4\cos\beta_4 = \left(\frac{\rho W}{\rho''W_{cr}}\right)_5 \cos\beta_5 \tag{B14a}$$

where

$$B_4 = \frac{A_4}{A_5} \tag{B14b}$$

and

$$\left(\frac{\rho W}{\rho'' W_{cr}}\right)_5 \cos \beta_5 = \left\{1 - \frac{\gamma - 1}{\gamma + 1}\left[\left(\frac{W_x}{W_{cr}}\right)_5^2 + \left(\frac{W_u}{W_{cr}}\right)_4^2\right]_2\right\}^{1/(\gamma-1)} \left(\frac{W_x}{W_{cr}}\right)_5 \tag{B14c}$$

The geometry of the velocity diagram gives

$$\left(\frac{W}{W_{cr}}\right)_5 = \left[\left(\frac{W_u}{W_{cr}}\right)_4^2 + \left(\frac{W_x}{W_{cr}}\right)_5^2\right]^{1/2} \tag{B14d}$$

$$\beta_5 = \sin^{-1} \frac{\left(\frac{W_u}{W_{cr}}\right)_5}{\left(\frac{W}{W_{cr}}\right)_5} \tag{B14e}$$

Equations (B14a) to (B14e) are solved iteratively to determine the values of $\left(W_x/W_{cr}\right)_5$, $\left(W/W_{cr}\right)_5$, and β_5.

The relations between absolute and relative parameters at the rotor exit are given by

$$\left(\frac{T'}{T''}\right)_4 = \left(\frac{T'}{T''}\right)_5 = 1 - \frac{\gamma - 1}{\gamma + 1}\left(\frac{W_u}{W_{cr}}\right)_4^2 + \frac{\gamma - 1}{\gamma + 1}\left(\frac{V_u}{W_{cr}}\right)_4^2 \tag{B15a}$$

where

$$\left(\frac{V_u}{W_{cr}}\right)_4 = \left(\frac{W_u}{W_{cr}}\right)_4 + \left(\frac{U_4}{V_{cr,3}}\right)\left(\frac{V_{cr}}{W_{cr}}\right)_3\left(\frac{W_{cr,3}}{W_{cr,4}}\right) \tag{B15b}$$

$$\left(\frac{p'}{p''}\right)_5 = \left(\frac{T'}{T''}\right)_5^{\gamma/(\gamma-1)} \tag{B15c}$$

and

$$\left(\frac{V_{cr}}{W_{cr}}\right)_5 = \left(\frac{T'}{T''}\right)_5^{1/2} \tag{B15d}$$

With the assumption that $(V_u/W_{cr})_4 = (V_u/W_{cr})_5$ and $(W_x/W_{cr})_5 = (V_x/W_{cr})_5$, the geometry of the velocity diagram gives

$$\left(\frac{V_x}{V_{cr}}\right)_5 = \left(\frac{W_x}{W_{cr}}\right)_5 \left(\frac{W_{cr}}{V_{cr}}\right)_5 \tag{B16a}$$

$$\left(\frac{V_u}{V_{cr}}\right)_5 = \left(\frac{V_u}{W_{cr}}\right)_4 \left(\frac{W_{cr}}{V_{cr}}\right)_5 \tag{B16b}$$

$$\left(\frac{V}{V_{cr}}\right)_5 = \left[\left(\frac{V_x}{V_{cr}}\right)_5^2 + \left(\frac{V_u}{V_{cr}}\right)_5^2\right]^{1/2} \tag{B16c}$$

$$\alpha_5 = \sin^{-1} \frac{\left(\frac{V_u}{V_{cr}}\right)_5}{\left(\frac{V}{V_{cr}}\right)_5} \tag{B16d}$$

Overall Turbine Performance

The turbine overall total-temperature ratio is given by

$$\frac{T_5'}{T_0'} = 1 - 2\left(\frac{\gamma - 1}{\gamma + 1}\right)\left(\frac{U_3 V_{u,3}}{V_{cr,3}^2} - \frac{U_4 V_{u,4}}{V_{cr,3}^2}\right) \tag{B17a}$$

where

$$\frac{V_{u,4}}{V_{cr,3}} = \left(\frac{W_u}{W_{cr}}\right)_4 \left(\frac{W_{cr,4}}{W_{cr,3}}\right)\left(\frac{W_{cr}}{V_{cr}}\right)_3 + \left(\frac{U_4}{V_{cr,3}}\right) \tag{B17b}$$

and the critical velocity at the turbine exit is

$$V_{cr,5} = \left(\frac{T_5'}{T_0'}\right)^{1/2} V_{cr,0} \tag{B17c}$$

The overall turbine total- to total-pressure ratio is given by the equation

$$\frac{p_5'}{p_0'} = \left(\frac{p_1'}{p_0'}\right)\left(\frac{p''}{p'}\right)_3 \left(\frac{p_{4,id}''}{p_3''}\right)\left(\frac{p_4''}{p_{4,id}''}\right)\left(\frac{p'}{p''}\right)_5 \tag{B18}$$

The total- to static-pressure ratio at the turbine exit is obtained from

$$\left(\frac{p}{p'}\right)_5 = \left[1 - \frac{\gamma - 1}{\gamma + 1}\left(\frac{V}{V_{cr}}\right)_5^2\right]^{\gamma/(\gamma-1)} \tag{B19a}$$

The overall turbine total- to static-pressure ratio is then

$$\frac{p_5}{p_0'} = \left(\frac{p_5'}{p_0'}\right)\left(\frac{p}{p'}\right)_5 \tag{B19b}$$

The turbine total and static efficiencies are obtained from

$$\eta_t = \frac{1 - \dfrac{T_5'}{T_0'}}{1 - \left(\dfrac{p_5'}{p_0'}\right)^{(\gamma-1)/\gamma}} \tag{B20a}$$

$$\eta_s = \frac{1 - \frac{T'_5}{T'_0}}{1 - \left(\frac{p_5}{p'_0}\right)^{(\gamma-1)/\gamma}} \tag{B20b}$$

The following equations define the additional performance parameters which appear in the output listing:

$$\theta_{cr} = \frac{\frac{\gamma}{\gamma + 1} RT'_0}{\left(\frac{\gamma}{\gamma + 1} RT'\right)^*} \tag{B21}$$

$$\delta = \frac{p'_0}{p'^*} \tag{B22}$$

$$\epsilon = \frac{0.7395945}{\gamma} \left(\frac{\gamma + 1}{2}\right)^{\gamma/(\gamma-1)} \tag{B23}$$

$$N_{eq} = \frac{C_1 U_3}{D_3(\theta_{cr})^{1/2}} \tag{B24}$$

$$\Delta h'_{eq} = \left(\frac{\gamma}{\gamma - 1}\right)\frac{R}{J} \frac{T'_0}{\theta_{cr}} \left(1 - \frac{T'_5}{T'_0}\right) \tag{B25}$$

$$w_{eq} = \frac{w(\theta_{cr})^{1/2}\epsilon}{\delta} \tag{B26}$$

$$\Gamma_{eq} = \frac{C_2 Jw\ \Delta h'}{N} \frac{\epsilon}{\delta} \tag{B27}$$

$$(wN)_{eq} = \frac{wN\epsilon}{\delta} \tag{B28}$$

$$\Delta h'_{id,s} = \left[1 - \left(\frac{p_5}{p'_0}\right)^{(\gamma-1)/\gamma}\right] \frac{\gamma}{\gamma - 1} \frac{RT'_0}{J} \tag{B29}$$

$$\Delta h'_{id,t} = \left[1 - \left(\frac{p'_5}{p'_0}\right)^{(\gamma-1)/\gamma}\right] \frac{\gamma}{\gamma - 1} \frac{RT'_0}{J} \tag{B30}$$

$$\left(\frac{p'_0}{p_5}\right)_{eq} = \left[1 - \left(\frac{\gamma - 1}{\gamma RT'}\right)^* \frac{J\ \Delta h'_{id,s}}{\theta_{cr}}\right]^{-\gamma/(\gamma-1)} \tag{B31}$$

$$\left(\frac{p'_0}{p'_5}\right)_{eq} = \left[1 - \left(\frac{\gamma - 1}{\gamma RT'}\right)^* \frac{J\ \Delta h'_{id,t}}{\theta_{cr}}\right]^{-\gamma/(\gamma-1)} \tag{B32}$$

$$\left(\frac{p_5}{p'_0}\right)_{eq} = \frac{1}{\left(\frac{p'_0}{p_5}\right)_{eq}} \tag{B33}$$

$$\Delta h' = \Delta h'_{eq}\ \theta_{cr} \tag{B34}$$

$$N = N_{eq}(\theta_{cr})^{1/2} \tag{B35}$$

$$\Gamma = \Gamma_{eq} \frac{\delta}{\epsilon} \tag{B36}$$

$$\nu = \frac{U_3}{(2gJ\ \Delta h'_{id,s})^{1/2}} \tag{B37}$$

$$WF = \frac{gJ\ \Delta h'}{U_3^2} \tag{B38}$$

$$P = \frac{\Delta h'\ wJ}{C_3} \tag{B39}$$

$$\frac{\mathrm{WT}}{\mathrm{P}} = \frac{w(T_0')^{1/2}}{p_0'} \tag{B40}$$

$$\frac{\mathrm{DEL\text{-}H}}{\mathrm{T}} = \frac{\Delta h'}{T_0'} \tag{B41}$$

$$\frac{\mathrm{N}}{\mathrm{T}} = \frac{N}{(T_0')^{1/2}} \tag{B42}$$

$$\frac{\mathrm{TOR}}{\mathrm{P}} = \frac{\Gamma}{p_0'} \tag{B43}$$

$$T_5' = T_0'\left(\frac{T_5'}{T_0'}\right) \tag{B44}$$

$$p_5' = p_0'\left(\frac{p_5'}{p_0'}\right) \tag{B45}$$

$$\rho_5' = \frac{p_5'}{RT_5'} \tag{B46}$$

$$\rho_5 = \rho_5'\left(\frac{p}{p'}\right)_5^{1/\gamma} \tag{B47}$$

$$N_s = \frac{N\left(\frac{w}{\rho_5}\right)^{1/2}}{(J\ \Delta h_{id,t}')^{0.75}} \tag{B48}$$

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TABLE I. - SAMPLE INPUT FOR DESIGN MODE

```
      12.62-CM DIA TURBINE
      100 PERCENT SPEED
$IN P0=172368.9,T0=1144.44,A0=.0120176,A1=.0038008,A3=.0039789,A5=.0044543,
AL1=72.47,B4=-56.86,U3=237.9524,U4U3=.567765,R=99.1976,G=1.6667,
BL1=.95168,BL4=.93718,ZZ=22,,V1=.30,DELV=.05,VMAX=.80,DELY=.05,YMAX=1.40,
D3=12.6238,D2=12.9997,MODE=2,ETAD=.913,PDSGN=1.74,ITEST=2,WD=.33879 $
```

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TABLE II. - SAMPLE INPUT FOR OFF-DESIGN PERFORMANCE MODE

STATEMENT NUMBER | CONT | FORTRAN STATEMENT | IDENTIFICATION

```
      12.62-CM DIA TURBINE
      100 PERCENT SPEED
 $IN P0=172368.9,T0=1144.44,A0=.0120176,A1=.0038008,A3=.0039789,A5=.0044543,
 AL1=72.47,B4=-56.86,U3=237.9524,U4U3=.567765,R=99.1976,G=1.6667,
 BL1=.95168,BL4=.93718,ZZ=22.,V1=.30,DELV=.05,VMAX=.80,DELY=.05,YMAX=1.40,
 D3=12.6238,D2=12.9997,MODE=0,XK=.28699,PD=.98783 $
      12.62-CM DIA TURBINE
      110 PERCENT SPEED
 $IN U3=261.7476 $
      12.62-CM DIA TURBINE
       90 PERCENT SPEED
 $IN U3=214.1572 $
      12.62-CM DIA TURBINE
       70 PERCENT SPEED
 $IN U3=166.5667 $
      12.62-CM DIA TURBINE
       50 PERCENT SPEED
 $IN U3=118.9762 $
      12.62-CM DIA TURBINE
       30 PERCENT SPEED
 $IN U3=71.3857 $
```

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TABLE III. - OUTPUT FOR DESIGN MODE

```
                         NASA RADIAL INFLOW TURBINE COMPUTER PROGRAM
                         12.62-CM DIA TURBINE
                         100 PERCENT SPEED

 GAMMA    1.66670      P0,     0.17237E+06   A1   0.38008E-02  ALPHA-1   72.4700     BETA-4   -56.8600        PD   500000000000
     R    99.1976      T0,     1144.44       A3   0.39789E-02      BL1   0.95168        BL4   0.93718          K   500000000000
    D3    12.6238       A0     0.12018E-01   A5   0.44543E-02       U3   237.952      U4/U3   0.56776         ZZ    22.0000
          PD     0.987836
           K     0.286840
DESIGN WT-FLOW   0.338790
  DESIGN ETA-T   0.913000
DESIGN P0./P5.   1.740000

                                              VELOCITIES AND ANGLES
V/VCR)1       0.60480       ALPHA-1      72.4700    V/VCR)3      0.62055       W/WCR)4       0.42154     W/WCR)5      0.41351
VU/VCR)1      0.57671       ALPHA-2      73.2895    VU/VCR)3     0.59389       WU/WCR)4     -0.35297     WX/WCR)5     0.21541
VR/VCR)1      0.18217       ALPHA-3      73.1421    VR/VCR)3     0.17996       WX/WCR)4      0.23045     V/VCR)5      0.22205
V/VCR)0       0.49333E-01   BETA-3      -11.8554    W/WCR)3      0.19253       BETA-4      -56.8600      VU/VCR)5     0.37859E-01
V/VCR)2       0.60214       I-3          5.67598    WU/WCR)3    -0.39554E-01   BETA-5      -58.6058      VX/VCR)5     0.21880
VR/VCR)2      0.17314       VCR)3        376.707    WR/WCR)3     0.18842       VCR)5        340.824      ALPHA-5      9.81656
                                              OVERALL PERFORMANCE
EQ-W          0.22000       EQ-P0,/P5    1.68890    P0,/P5       1.79477       WT/P          0.66492     W            0.33879
EQ-DEL-H      35013.4       ETA-S        0.86975    NU           0.69152       DEL-H/T       44.9930     DEL-H        51491.8
EQ-N          494.764       ETA-T        0.91298    NS           0.97688E-02   N/T           17.7359     W.F.         0.90941
EQ-TOR        148.673       EQ-P0,/P5,   1.64445    P0,/P5,      1.73997       TOR/P         1610.76     TOR          277.644
N             599.999       P            17.4449    WN/DEL       108.849       T5,           936.801     P5,          99064.4
```

TABLE IV. - LONG OUTPUT FOR OFF-DESIGN PERFORMANCE MODE

NASA RADIAL INFLOW TURBINE COMPUTER PROGRAM
12.62-CM DIA TURBINE
100 PERCENT SPEED

GAMMA	1.66670	PO.	0.17237E+06	A1	0.38008E-02	ALPHA-1	72.4700	BETA-4	-56.8600	PD	0.98784
R	99.1976	TO,	1144.44	A3	0.39789E-02	BL1	0.95168	BL4	0.93718	K	0.28684
D3	12.6238	AO	0.12018E-01	A5	0.44543E-02	U3	237.952	U4/U3	0.56776	ZZ	22.0000

VELOCITIES AND ANGLES

V/VCR)1	0.30000	ALPHA-1	72.4700	V/VCR)3	0.30765	W/WCR)4	0.18127	W/WCR)5	0.17792
VU/VCR)1	0.28607	ALPHA-2	73.2733	VU/VCR)3	0.29459	WU/WCR)4	-0.15179	WX/WCR)5	0.92832E-01
VR/VCR)1	0.90362E-01	ALPHA-3	73.2404	VR/VCR)3	0.88714E-01	WX/WCR)4	0.99100E-01	V/VCR)5	0.23649
V/VCR)0	0.27291E-01	BETA-3	-75.2549	W/WCR)3	0.34739	BETA-4	-56.8600	VU/VCR)5	0.21762
V/VCR)2	0.29871	I-3	-42.6024	WU/WCR)3	-0.33595	BETA-5	-58.5503	VX/VCR)5	0.92548E-01
VR/VCR)2	0.85970E-01	VCR)3	376.707	WR/WCR)3	0.88418E-01	VCR)5	366.180	ALPHA-5	66.9618

OVERALL PERFORMANCE

EQ-W	0.12178	EQ-PO,/P5	1.25303	PO,/P5	1.27858	WT/P	0.36807	W	0.18754
EQ-DEL-H	10634.9	ETA-S	0.58860	NU	1.03221	DEL-H/T	13.6661	DEL-H	15640.0
EQ-N	494.764	ETA-T	0.68226	NS	0.12937E-01	N/T	17.7359	W.F.	0.27622
EQ-TOR	24.9971	EQ-PO,/P5,	1.21377	PO,/P5,	1.23436	TOR/P	270.823	TOR	46.6815
N	599.999	P	2.93309	WN/DEL	60.2536	T5.	1081.37	P5.	0.13964E+06

VELOCITIES AND ANGLES

V/VCR)1	0.35000	ALPHA-1	72.4700	V/VCR)3	0.35895	W/WCR)4	0.21500	W/WCR)5	0.21102
VU/VCR)1	0.33375	ALPHA-2	73.2751	VU/VCR)3	0.34368	WU/WCR)4	-0.18003	WX/WCR)5	0.11009
VR/VCR)1	0.10542	ALPHA-3	73.2298	VR/VCR)3	0.10357	WX/WCR)4	0.11754	V/VCR)5	0.22218
V/VCR)0	0.31446E-01	BETA-3	-70.2194	W/WCR)3	0.30739	BETA-4	-56.8600	VU/VCR)5	0.19303
V/VCR)2	0.34849	I-3	-41.4568	WU/WCR)3	-0.28926	BETA-5	-58.5551	VX/VCR)5	0.11002
VR/VCR)2	0.10029	VCR)3	376.707	WR/WCR)3	0.10403	VCR)5	362.253	ALPHA-5	60.3183

OVERALL PERFORMANCE

EQ-W	0.14031	EQ-PO,/P5	1.29942	PO,/P5	1.33130	WT/P	0.42407	W	0.21607
EQ-DEL-H	14524.7	ETA-S	0.69588	NU	0.96036	DEL-H/T	18.6645	DEL-H	21360.4
EQ-N	494.764	ETA-T	0.77581	NS	0.12228E-01	N/T	17.7359	W.F.	0.37725
EQ-TOR	39.3343	EQ-PO,/P5,	1.26365	PO./P5.	1.29061	TOR/P	426.155	TOR	73.4559
N	599.999	P	4.61538	WN/DEL	69.4213	T5,	1058.30	P5,	0.13356E+06

VELOCITIES AND ANGLES

V/VCR)1	0.40000	ALPHA-1	72.4700	V/VCR)3	0.41026	W/WCR)4	0.25008	W/WCR)5	0.24544
VU/VCR)1	0.38142	ALPHA-2	73.2772	VU/VCR)3	0.39278	WU/WCR)4	-0.20941	WX/WCR)5	0.12802
VR/VCR)1	0.12048	ALPHA-3	73.2172	VR/VCR)3	0.11846	WX/WCR)4	0.13672	V/VCR)5	0.21080
V/VCR)0	0.35422E-01	BETA-3	-63.6238	W/WCR)3	0.26994	BETA-4	-56.8600	VU/VCR)5	0.16728
V/VCR)2	0.39827	I-3	-37.9869	WU/WCR)3	-0.24184	BETA-5	-58.5610	VX/VCR)5	0.12827
VR/VCR)2	0.11460	VCR)3	376.707	WR/WCR)3	0.11993	VCR)5	358.262	ALPHA-5	52.5177

OVERALL PERFORMANCE

EQ-W	0.15804	EQ-PO,/P5	1.35205	PO./P5	1.39174	WT/P	0.47763	W	0.24337
EQ-DEL-H	18435.5	ETA-S	0.77129	NU	0.89744	DEL-H/T	23.6900	DEL-H	27111.8
EQ-N	494.764	ETA-T	0.83787	NS	0.11633E-01	N/T	17.7359	W.F.	0.47883
EQ-TOR	56.2318	EQ-PO./P5.	1.31874	PO./P5.	1.35341	TOR/P	609.226	TOR	105.012
N	599.999	P	6.59807	WN/DEL	78.1904	T5,	1035.11	P5,	0.12736E+06

TABLE V. - SHORT OUTPUT FOR OFF-DESIGN PERFORMANCE MODE

NASA RADIAL INFLOW TURBINE COMPUTER PROGRAM
12.62-CM DIA TURBINE
100 PERCENT SPEED

GAMMA	1.66670	PO.	0.17237E+06	A1	0.38008E-02	ALPHA-1	72.4700	BETA-4	-56.8600	PD	0.98784
R	99.1976	TO,	1144.44	A3	0.39789E-02	BL1	0.95168	BL4	0.93718	K	0.28684
D3	12.6238	AO	0.12018E-01	A5	0.44543E-02	U3	237.952	U4/U3	0.56776	ZZ	22.0000

V1VC1	NS	EQ-P5/PO,	NU	ETAT	ETAS	DHTCR	WTHODE	EQ-PO,/P5	EQ-PO,/P5,
0.30000	0.12937E-01	0.79806	1.03221	0.68226	0.58860	10634.9	0.12178	1.25303	1.21377
0.35000	0.12228E-01	0.76957	0.96036	0.77581	0.69588	14524.7	0.14031	1.29942	1.26365
0.40000	0.11633E-01	0.73962	0.89744	0.83787	0.77129	18435.5	0.15804	1.35205	1.31874
0.45000	0.11106E-01	0.70763	0.84072	0.87750	0.82169	22379.6	0.17485	1.41317	1.38098
0.50000	0.10630E-01	0.67325	0.78877	0.90064	0.85235	26373.0	0.19064	1.48533	1.45245
0.55000	0.10196E-01	0.63616	0.74065	0.91145	0.86735	30438.1	0.20532	1.57192	1.53575
0.60000	0.98037E-02	0.59608	0.69565	0.91311	0.86996	34606.9	0.21878	1.67762	1.63416
0.65000	0.94640E-02	0.55348	0.65396	0.90984	0.86434	38907.1	0.23093	1.80673	1.74969
0.70000	0.91646E-02	0.50642	0.61352	0.90078	0.84947	43444.3	0.24169	1.97464	1.89244
0.75000	0.89057E-02	0.45030	0.57117	0.88408	0.82184	48495.8	0.25097	2.22075	2.08615
0.79767	0.87530E-02	0.34555	0.50395	0.84101	0.74373	56375.0	0.25838	2.89392	2.51398
0.79767	0.87904E-02	0.32379	0.49136	0.82970	0.72255	57612.4	0.25838	3.08840	2.61149
0.79767	0.88588E-02	0.30207	0.47914	0.81733	0.70049	58739.5	0.25838	3.31047	2.71498
0.79767	0.89605E-02	0.28066	0.46737	0.80367	0.67765	59721.8	0.25838	3.56308	2.82441
0.79767	0.90976E-02	0.25990	0.45619	0.78839	0.65409	60504.8	0.25838	3.84761	2.93913
0.79767	0.92695E-02	0.24037	0.44584	0.77092	0.62985	61000.7	0.25838	4.16021	3.05727
0.79767	0.94658E-02	0.22317	0.43681	0.75035	0.60520	61060.3	0.25838	4.48087	3.17450
0.79767	0.96420E-02	0.21093	0.43043	0.72494	0.58139	60411.1	0.25838	4.74084	3.28122
0.79767	0.96773E-02	0.20992	0.42990	0.69101	0.56152	58490.2	0.25838	4.76379	3.35536
0.79767	0.96545E-02	0.21189	0.43093	0.68254	0.55811	57857.0	0.25838	4.71935	3.36237

LAST CASE IS APPROXIMATE LIMITING LOADING

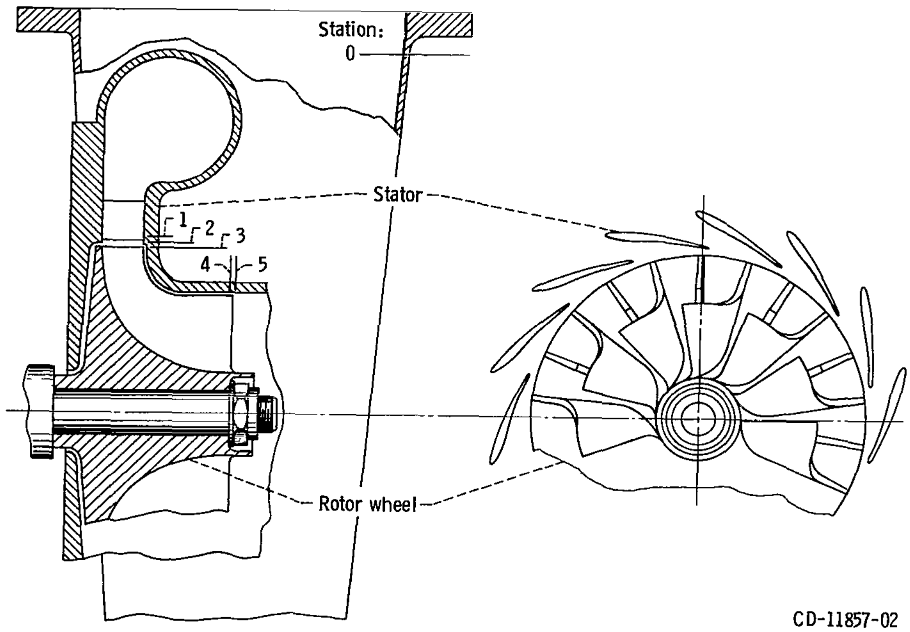


Figure 1. - Turbine stator and rotor.

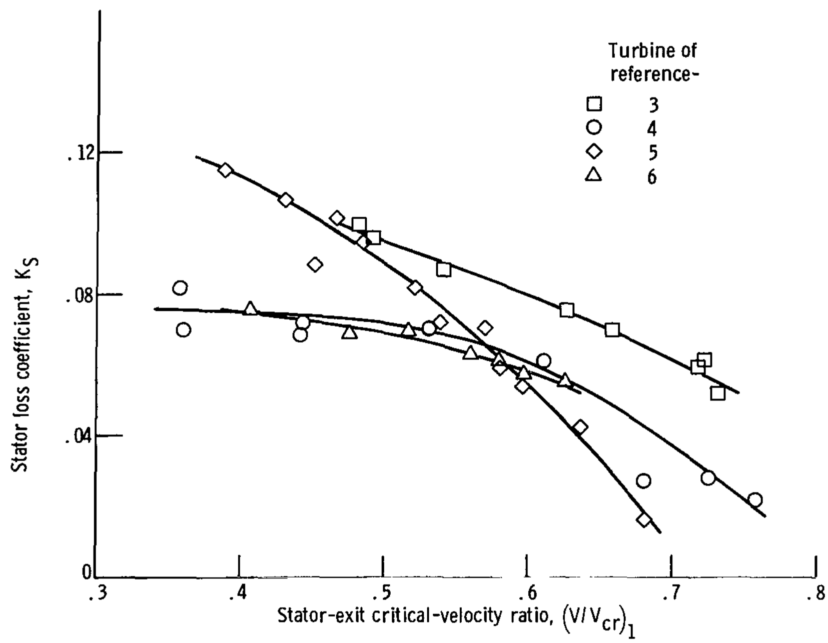


Figure 2. - Variation of stator loss coefficient with stator-exit critical-velocity ratio for design speed.

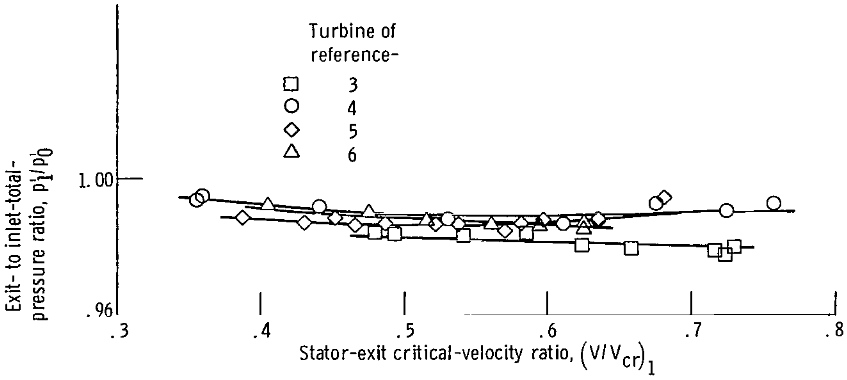


Figure 3. - Variation of stator total-pressure ratio with stator-exit critical-velocity ratio for design speed.

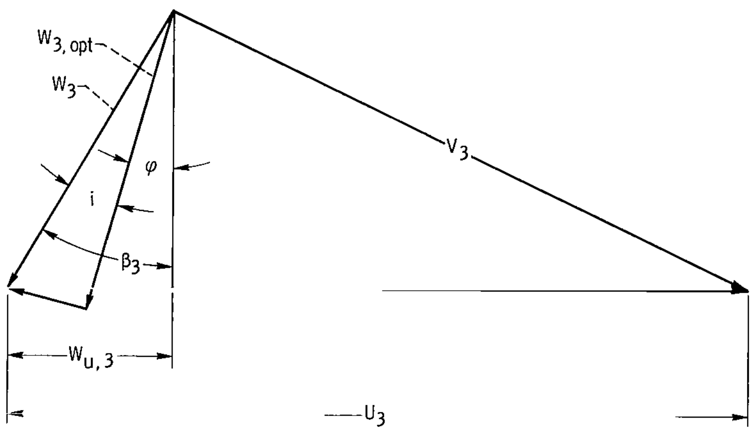


Figure 4. - Rotor blade incidence nomenclature.

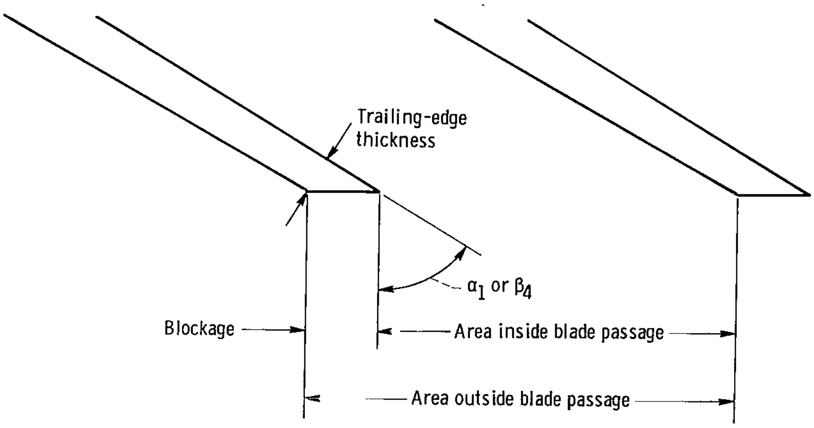
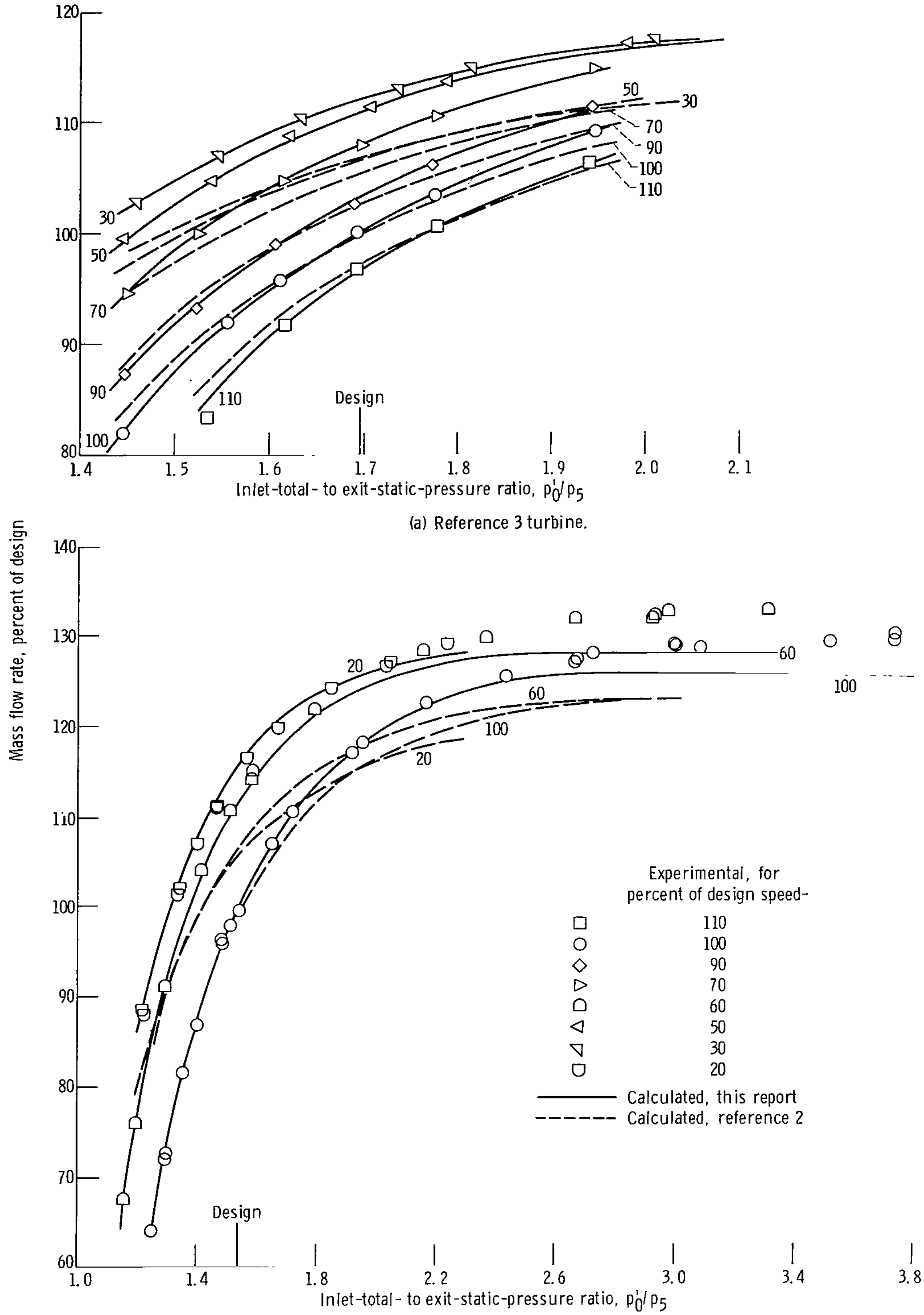


Figure 5. - Trailing-edge blockage for a typical blade row.



(a) Reference 3 turbine.

(b) Reference 4 turbine.

Figure 6. - Comparison of calculated and experimental mass flow rates.

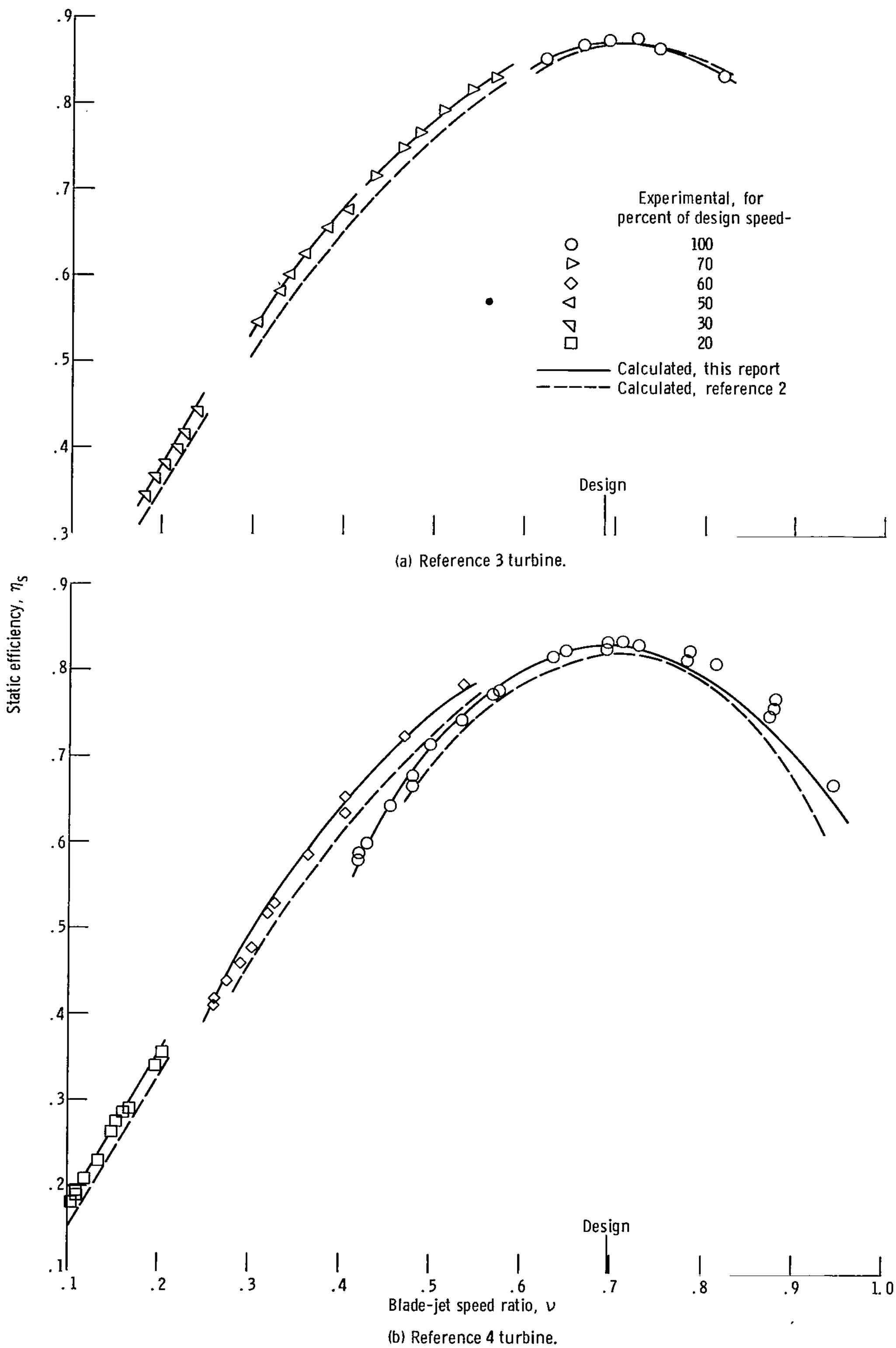
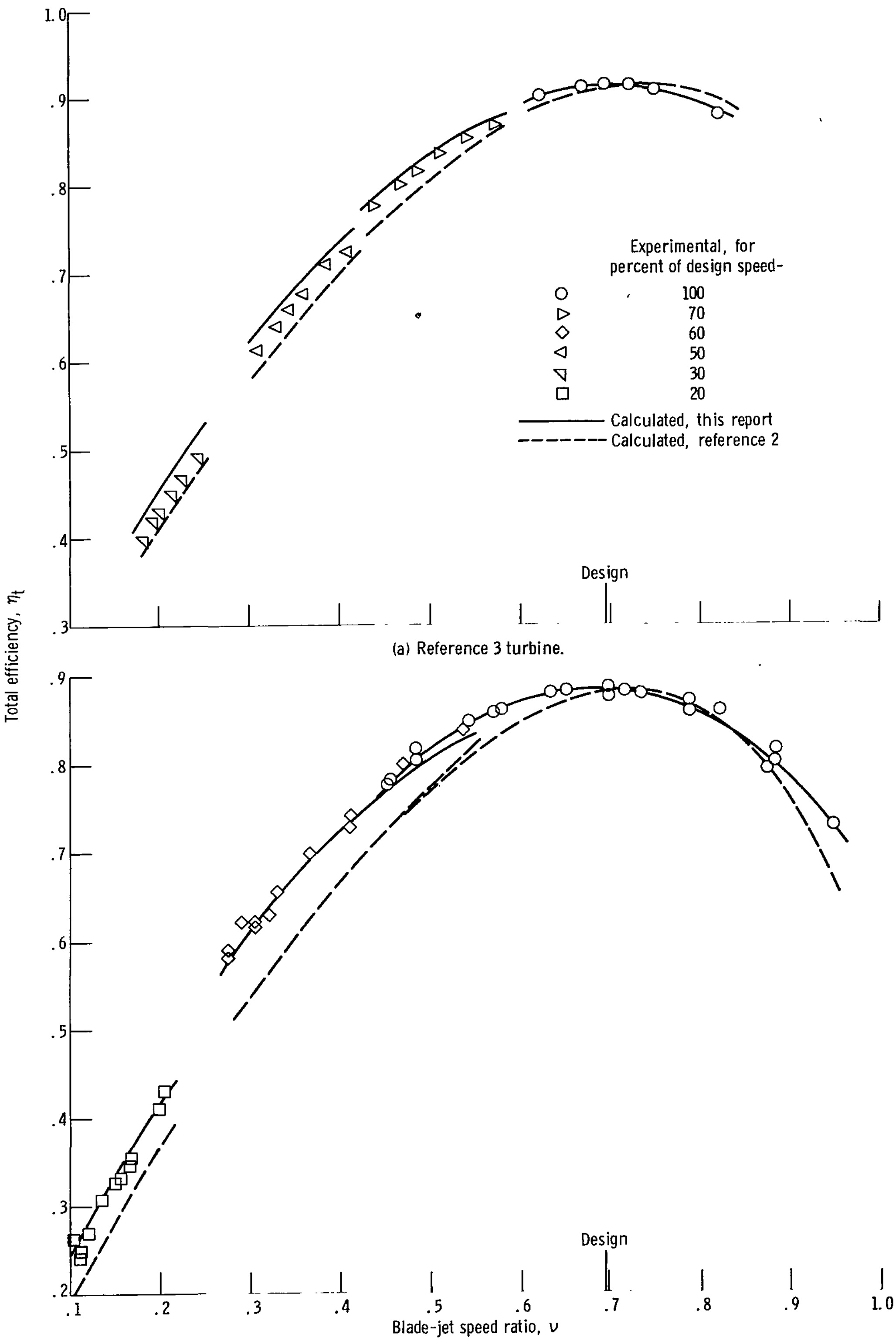


Figure 8. - Comparison of calculated and experimental static efficiencies.



(b) Reference 4 turbine.

Figure 7. - Comparison of calculated and experimental total efficiencies.

NASA-Langley, 1975 E-8368

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