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TURBINE MODELING TECHNIQUE TO GENERATE OFF-DESIGN PERFORMANCE DATA FOR BOTH SINGLE AND MULTISTAGE AXIAL-FLOW TURBINES

FINAL REPORT: USER'S MANUAL

by

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GENERAL ELECTRIC COMPANY

Prepared for

National Aeronautics and Space Administration

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16. Abstract
A turbine modeling technique has been developed which will enable the user to obtain consistant and rapid off-design performance from design point input. This technique is applicable to larger axial-flow turbines which may or may not incorporate variable geometry in the first stage stator. A user-specified option will also permit the caluculation of design point cooling flow levels and the corresponding change in turbine efficiency. The modeling technique has been incorporated into a time-sharing computer program in order to facilitate its use. Because this report contains a description of the input output data, values of typical inputs, and example cases, it is suitable as a user's manual.

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1.0 INTRODUCTION

The NASA Lewis Research Center employs a general computer program (Reference 1) for calculating the thermodynamic performance of jet propulsion engines. To calculate off-design engine performance, the user must input component maps. These maps define the characteristics of the various components over their full range of operating conditions.

For advanced propulsion systems these characteristics are not generally known. Furthermore, the typical user of the program is not sufficiently knowledgable and/or cannot afford the time to do an extensive design analysis of the component in question. Instead he usually scales some available map.

The objective of the study is an improved method of representing the turbine component when performing calculations of off-design performance for advanced air-breathing jet engines. This method, which is a computer program called PART, is compatible in both form and format with the cycle program of Reference 1 and the example map representation of Reference 2.

Because this report contains a description of the input-output data, values of typical inputs, and sample cases, it is suitable as a user's manual. A brief description of the engineering analysis used to generate the program is given near the end of the report.

The program uses turbine design point data as input to generate off-design values of turbine flow-function and total-to-total efficiency over a range of pressure ratios and speeds specified by the user. A user-specified option will also permit calculating design point cooling flows and the corresponding change in turbine efficiency. The cooling flow subroutine, developed at the Lewis Research Center, is described in Reference 3.

The Aircraft Engine Group of the General Electric Company has a turbine data base consisting of 25 turbines having design point turbine flow functions ranging from about 14 to 290. The number of stages for each of these turbines together with the approximate design point values of specific work output divided by inlet total temperature (DHQTD) and flow function (TFFD) are summarized in Table I. The last seven turbines shown in the table are variable-geometry turbines. Table II shows the set of first stage nozzle area ratios for each of the seven variable-geometry turbines. Five of these variable geometry turbines were generated by turbine design and off-design computer programs similar, if not identical, to that described in Reference 4. Two of the turbines shown in Table II were generated from air turbine test carried out by the Lewis Research Center. The results of these tests are given in References 5 to 8. The Table II designation of the NASA test turbines have been given a trailing X. The analytical prediction of the performance of these turbines obtained from Reference 9 has been a trailing P.

Table I. Summary of Turbine Design Point Data.

No.	Data Base Name*	No. of Stages	DHQTD	TPFD
1	HPT1-1	1	0.0596	14.6
2	HPT1-2	1	0.0705	16.4
3	HPT1-3	1	0.0335	88.5
4	HPT2-4	2	0.0670	17.3
5	HPT2-5	2	0.0787	32.4
6	HPT3-6	3	0.0810	45.5
7	LPT1-1	1	0.0220	45.0
8	LPT1-2	1	0.0425	45.0
9	LPT2-3	2	0.0571	58.5
10	LPT2-4	2	0.065	60.4
11	LPT4-5	4	0.0665	106.0
12	LPT4-6	4	0.0709	134.4
13	LPT6-7	6	0.0814	104.9
14	PT3-1	3	0.0800	210.0
15	AT3-1	3	0.0590	---
16	AT3-2	3	0.0785	---
17	AT3-3	3	0.0635	43.16
18	AT4-4	4	0.0499	38.85
19	VAT1-1	1	0.044	99.0
20	VAT1-2	1	0.060	60.0
21	VAT1-3	1	0.0238	290.0
22	VAT1-4P	1	0.0328	61.8
23	VAT1-4X	1	0.0328	61.8
24	VAT2-5P	2	0.0636	61.8
25	VAT2-5X	2	0.0636	61.8

*HPT - High Pressure Turbine
LPT - Low Pressure Turbine
AT - Air Turbine Test Rig
VAT - Variable Area Turbine

Table II. Summary of Variable Geometry Turbines Included on Data Base.

Turbine No.	Designation	No. of Stages	First Stage Nozzle Area Ratios %					
1	VAT1-1	1	50.0	62.5	75.0	87.5	100.0	
2	VAT1-2	1	71.0	86.0	100.0	109.0	120.0	
3	VAT1-3	1	76.0	84.0	92.0	100.0	108.0	116.0
4	VAT1-4P	1	70.0	100.0	130.0			
5	VAT1-4X	1	70.0	100.0	130.0			
6	VAT2-5P	2	70.0	100.0	130.0			
7	VAT2-5X	2		100.0				

(OGRAM STRUCTURE

A flow chart of control in the NASA parametric turbine program is shown :er the input has been read and processed, the program carripitch line analysis starting with the last stage of the turbs starts at the exit of the turbine stage (in order to avoicalculates the bucket and nozzle flow angles. This staen used to generate the stage flow and loss characteristics ually based correlations developed during the program. Suce then calculated until the first stage is reached. The firristics are then generated, and the stages stacked for each st stage turbine nozzle area specified. If the turbine is ccocedure given in Reference 3 is used to calculate both thquirements, and the cooled turbine efficiency. Finally,ocessed to obtain a turbine map representation compatible wk of Reference 1.

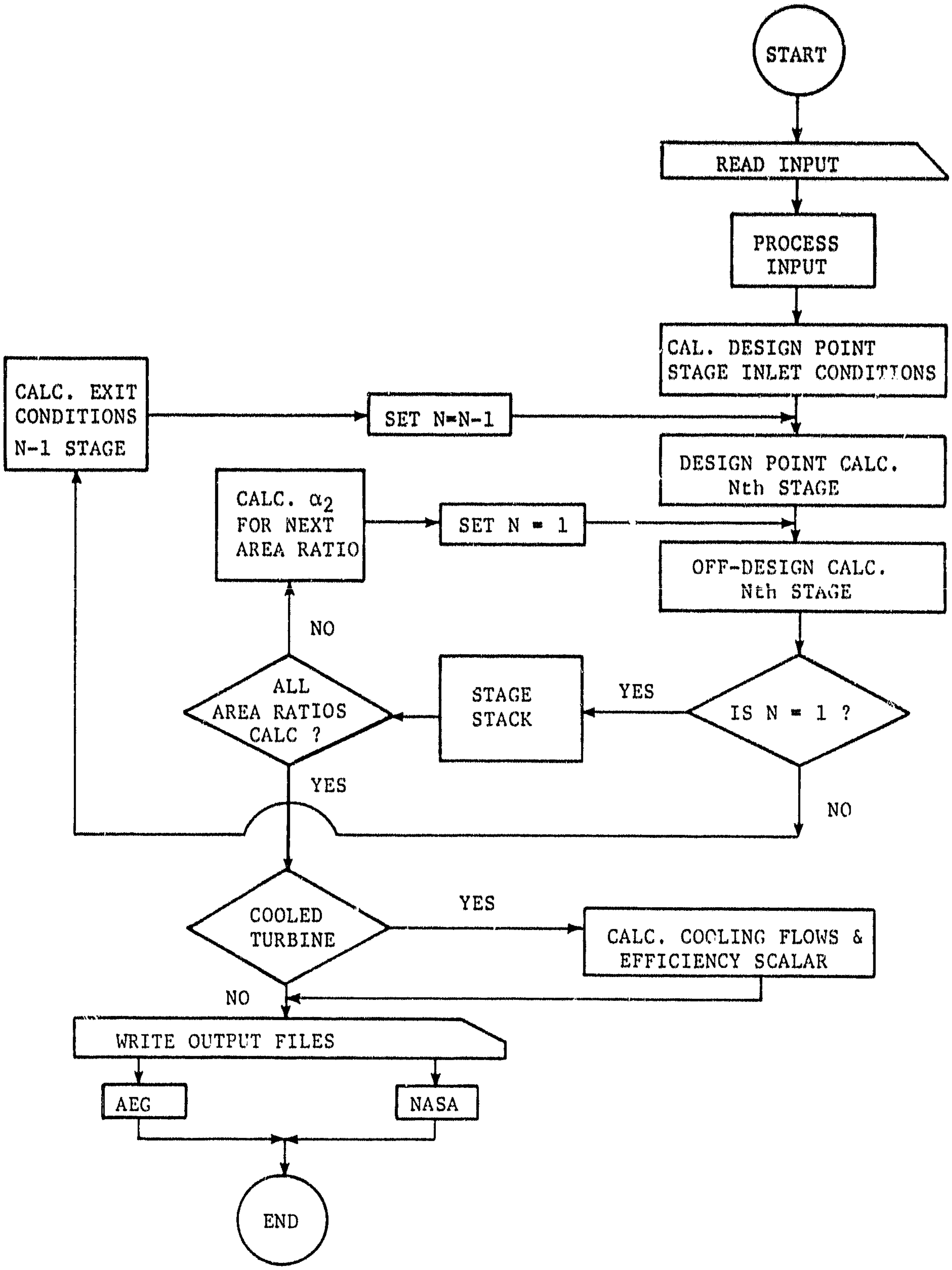

Figure 1. Flow Chart Showing Flow of Control in Parametric Turbine Program.

3.0 PROGRAM INPUTS

All of the PART inputs are of the free-field format (NAMELIST) type, and begin in column two. There is no specified order to the inputs. The program initially lists the contents of the NAMELIST INPUT together with the default settings of all the input variables. The user may then change as many of the inputs as desired. The program then echoes the updated NAMELIST. If none of the inputs are changed, the program will execute the first example case and the user can inspect the output. The input variables together with their default settings are summarized in Table III.

The first six input variables in Table III are used to control the number and values of speed, pressure ratio, and nozzle area ratios (transformed into nozzle angle) to be written on the output files. For example, in the input to the first example case shown in Figure 2, all of the corrected speed and pressure ratio arrays are used by the program, but only the first three positions in the area ratio array. Note that speeds and pressure ratios are entered in increasing value, but that area ratios are entered in decreasing value (this is so that the nozzle angles will be written in increasing order on the output file). Speeds less than 10% should not be used. The input to the second example case shown in Figure 3 illustrates the use of the first six variables to limit the size of the output files.

Some of the design point inputs will be calculated internally by the program, if the user inputs the correct value to trigger the calculation. This subset of inputs together with the required settings are summarized in Table IV. An input value equal to or less than zero will trigger all of the calculations with the exception of exit swirl angle, here a value greater than 90 degrees must be input (180 degrees is recommended).

A minimum set of design point input would consist of NSTG and DHQTD. The values of TFFD and XNRTD could be input as 100.0 and the resulting values of TFFD interpreted as percent. The user could then use the settings in Table IV to trigger program calculations of the remaining design point information. The use of the program to calculate the number of stages will frequently result in a single-stage turbine, since the only upper limit on turbine radius is the limiting value of rim speed. This is not usually sufficiently restrictive to require the use of additional stages.

If the user wishes the program to calculate the value of design point cooling flow, and the corresponding decrease in turbine efficiency, the JCOOL switch in the NAMELIST INPUT should be set to 1. The program will then list the contents of the NAMELIST INPUT1 together with the default settings of all the variables. The user may then change as many of the inputs as desired. Since the default settings of the NAMELIST INPUT are for an uncooled turbine, these inputs (namely, TTIN, PTIN) must be changed in order to successfully calculate cooling flows. The input variables for NAMELIST INPUT1 together with their default settings are summarized in Table V. The input to the second example case shown in Figure 3 illustrates the proper format for a cooled three-stage turbine.

Table III. Default Settings for Variables in Namelist "Input."

Variable Name	Units	Default Values	Description
NSPDS	None	15	Number of Speed Lines Desired
APCNC(I)	None	10% to 150%	The Array of Percent Corrected Speeds (Max of 15)
NPR	None	20	Number of Pressure Ratios Desired
APR(I)	None	1.1 to 4.6	The Array of Pressure Ratios (Max of 20)
NAR	None	3	Number of First Stage Nozzle Area Ratios
ARN	None	1.3, 1.0, 0.7	Array of Nozzle Area Ratios (Max of 6)
NSTG	None	1	Number of Turbine Stages (Max of 6)
JCOOL	None	0	Cooling Flow Switch (0=Uncooled; 1=Cooled)
DHQTD	Btu/lbm °R	0.03278	Specific Work Output Divided by Inlet Temperature
ETATTD	None	0.923	Turbine Total-to-Total Efficiency
TFFD	$\frac{\text{lbm } {}^\circ\text{R}^{1/2}}{\text{sec*psi}}$	62.98	Turbine Inlet Flow Function, i.e., (TFF = $W\sqrt{T_t}/P_t$)
XNRTD	rpm/$^\circ$R$^{1/2}$	193.52	Turbine Corrected Speed (XNRT = $N/\sqrt{T_t}$)
PSID	None	0.8511	Average Turbine pitch line loading, i.e., PSID = $(DHQT/[2(U/\sqrt{T_t})^2/g_oJ]/NSTG$
ANGSWX	Degrees	15.2	Exit Pitch Line Swirl Angle (Positive When Opposite to Direction of Rotation)
XMZXD	None	0.373	Exit Pitch Line Axial Mach Number
TTIN	° R	518.67	Turbine Inlet Total Temperature
PTIN	psia	14.696	Turbine Inlet Total Pressure
FARGD	None	0.0	Turbine Inlet Fuel-Air Ratio

```
EXEC NPT
ENTRY (A) E14262A.F  E15.DATA DELETED
ENTRY (A) E14262A.F LE16.DATA DELETED
NAMELIST      INPUT
 NSPDS =          15,
 APCNC (I)=
     1        10.000000,        20.000000,        30.000000,        40.000000,
     5        50.000000,        60.000000,        70.000000,        80.000000,
     9        90.000000,       100.000000,       110.000000,       120.000000,
    13       130.000000,       140.000000,       150.000000,
 NPR   =          20,
 APR   (I)=
     1         1.100000,         1.200000,         1.400000,         1.600000,
     5         1.700000,         1.800000,         2.000000,         2.200000,
     9         2.400000,         2.600000,         2.800000,         3.000000,
    13         3.200000,         3.400000,         3.600000,         3.800000,
    17         4.000000,         4.200000,         4.400000,         4.600000,
 NAR   =           3,
 ARN   (I)=
     1         1.300000,         1.000000,         0.700000,         0.0      ,
     5         0.0      ,        0.0      ,
 NSTG  =           1,      JCOOL =          0,
 DHQTD =        0.032780,      ETATTD=        0.923000,
 TFFD  =       62.979996,      XNRTD =      193.520004,
 PSID  =        0.851100,      XMZXD =        0.373000,
 ANGSWX=       15.200000,      TTIN  =      518.669922,
 PTIN  =       14.696000,      FARGD =        0.0      ,
END NAMELIST      INPUT

ENTER NAMELIST INPUT ?
 &INPUT  &END
NAMELIST      INPUT
 NSPDS =          15,
 APCNC (I)=
     1        10.000000,        20.000000,        30.000000,        40.000000,
     5        50.000000,        60.000000,        70.000000,        80.000000,
     9        90.000000,       100.000000,       110.000000,       120.000000,
    13       130.000000,       140.000000,       150.000000,
 NPR   =          20,
 APR   (I)=
     1         1.100000,         1.200000,         1.400000,         1.600000,
     5         1.700000,         1.800000,         2.000000,         2.200000,
     9         2.400000,         2.600000,         2.800000,         3.000000,
    13         3.200000,         3.400000,         3.600000,         3.800000,
    17         4.000000,         4.200000,         4.400000,         4.600000,
 NAR   =           3,
 ARN   (I)=
     1         1.300000,         1.000000,         0.700000,         0.0      ,
     5         0.0      ,        0.0      ,
 NSTG  =           1,      JCOOL =          0,
 DHQTD =        0.032780,      ETATTD=        0.923000,
 TFFD  =       62.979996,      XNRTD =      193.520004,
 PSID  =        0.851100,      XMZXD =        0.373000,
 ANGSWX=       15.199997,      TTIN  =      518.669922,
 PTIN  =       14.696000,      FARGD =        0.0      ,
END NAMELIST      INPUT

NASA OUTPUT ON IFC=15,16
READY
```

Figure 2. Input to First Example Case.

```
READY
EXEC NPT
ENTRY (A) E14262A.FILE15.DATA DELETED
ENTRY (A) E14262A.FILE16.DATA DELETED
NAMELIST .   INPUT
 NSPDS =            15,
 APCNC (I)=
     1       10.000000,        20.000000,        30.000000,        40.000000,
     5       50.000000,        60.000000,        70.000000,        80.000000,
     9       90.000000,       100.000000,       110.000000,       120.000000,
    13      130.000000,       140.000000,       150.000000,
 NPR    =           20,
 APR    (I)=
     1        1.100000,         1.200000,         1.400000,         1.600000,
     5        1.700000,         1.800000,         2.000000,         2.200000,
     9        2.400000,         2.600000,         2.800000,         3.000000,
    13        3.200000,         3.400000,         3.600000,         3.800000,
    17        4.000000,         4.200000,         4.400000,         4.600000,
 NAR    =            3,
 ARN    (I)=
     1        1.300000,         1.000000,         0.700000,         0.0      ,
     5        0.0      ,        0.0      ,
 NSTG   =            1,     JCOOL  =            0,
 DHOTD  =     0.032780,      ETATTD=     0.923000,
 TFFD   =    62.979996,      XNRTD  =   193.520004,
 PSID   =     0.851100,      XMZXD  =     0.373000,
 ANGSWX=     15.200000,      TTIN   =   518.669922,
 PTIN   =    14.696000,      FARGD  =     0.0      ,
END NAMELIST      INPUT

ENTER NAMELIST INPUT ?
 &INPUT
 NSPDS=6
 APCNC=20.,40.,60.,80.,100.,120.
 NPR=5
 APR=2.0,2.5,3.0,3.5,3.8
 NAR=1
 ARN=1.0
 NSTG=3
 JCOOL=1
 DHOTD=0.0635
 ETATTD=.886
 TFFD=58.53
 XNRTD=40.10
 PSID=1.5
 XMZXD=0.41
 ANGSWX=2.9
 TTIN=2500.
 PTIN=59.8
 FARGD=0.02
 &END
```

Figure 3. Input to Second Example Case.

```
NAMELIST      INPUT1
 KINDOF=,       86400000,
 TC      =        700.000000,   FARCX =           0.0       ,
 YEAR    =      1980.,          YEARB =       1980.,
 ELIFE   =      0.1000000E+05,
END NAMELIST        INPUT1

ENTER NAMELIST INPUT1 ?
 &INPUT1
 KINDOF=864000
 &END
NAMELIST       INPUT
 NSPDS  =                6,
 APCNC  (I)=
      1         20.000000,          40.000000,          60.000000,          80.000000,
      5        100.000000,         120.000000,          70.000000,          80.000000,
      9         90.000000,         100.000000,         110.000000,         120.000000,
     13        130.000000,         140.000000,         150.000000,
 NPR    =                5,
 APR    (I)=
      1          2.000000,           2.500000,           3.000000,           3.500000,
      5          3.800000,           1.800000,           2.000000,           2.200000,
      9          2.400000,           2.600000,           2.800000,           3.000000,
     13          3.200000,           3.400000,           3.600000,           3.800000,
     17          4.000000,           4.200000,           4.400000,           4.600000,
 NAR    =                1,
 ARN    (I)=
      1          1.000000,           1.000000,           0.700000,           0.0       ,
      5          0.0       ,         0.0       ,
 NSTG   =                3,     JCOOL =             1,
 DHQTD  =         0.063500,       ETATTD=          0.886000,
 TFFD   =        5[illegible].529999,       XNRTD =         40.100006,
 PSID   =         1.500000,       XMZXD =          0.410000,
 ANGSWX=          2.899999,       TTIN  =       2500.00000 ,
 PTIN   =        59.800003,       FARGD =          0.020000,
END NAMELIST         INPUT

NAMELIST       INPUT1
 KINDOF=,          864000,
 TC      =        700.000000,   FARCX =           0.0       ,
 YEAR    =      1980.,          YEARB =       1980.,
 ELIFE   =      0.1000000E+05,
END NAMELIST        INPUT1
PCBLED= 0.06337 PCNCH= 0.02001 EFF4=  0.8835 PRN=  3.315
NASA OUTPUT ON IFC=15,16
READY
```

Figure 3. Input to Second Example Case (Concluded).

Table IV. Variable Settings to Trigger Default Calculation of Some Design Point Input.

Variable Name	Setting	Action Taken
NSTG	0.0	Program Calculates Number of Stages (Not Recommended)
ETATTD	0.0	Program Calculates Design Point Efficiency
PSID	0.0	Design Point Loading Set to 0.9
ANGSWX	180.0	Exit Swirl Angle Calculated From Zero Hub Reaction
XMZXD	0.0	Sets Exit Axial Mach Number to 0.5

Table V. Default Settings for Variables in Namelist "Input 1"

Variable Name	Units	Default Value	Description
KINDOF	None	86400000	An Ordered Combination of Digits Representing the Cooling Configuration of the Turbine
TC	° R	700.0	Total Temperature of the Cooling Flow
FARCX	None	0.0	Fuel-Air Ratio of the Cooling Flow
Year	---	1980	First Year of Service for Stator Vane Material
Year B	---	1980	First Year of Service for Rotor Blade Material
ELIFE	hrs	10,000	Desired Life of Turbine Airfoil

The integer variable KINDOF represents the cooling configuration of the turbine. Each blade row starting with the first stage stator is assigned an integer value characterizing the type of cooling employed as follows:

0	Uncooled
1	Convection cooling
2	Convection with coating
3	Advanced convection
4	Film with convection (75% trailing edge injection)
5	Film with convection (50% trailing edge injection)
6	Film with convection (25% trailing edge injection)
7	Transpiration with convection (25% trailing edge injection)
8	Full coverage film
9	Transpiration

For example, the 86400000 configuration has the first three blade rows cooled and the remaining five rows uncooled (a four-stage turbine). For a detailed description of the cooling flow calculation and the various cooling flow configurations, the reader should consult Reference 3.

4.0 PROGRAM OUTPUTS

The basic output from the program consists of two tables. These tables show the turbine efficiency and turbine flow function variations for each of the first stage nozzle area ratios, pressure ratios, and percent corrected speeds specified in the input. The input values of area ratio are converted to first stage nozzle angles before being printed out. The output tables for the first example case are shown on pages 18 through 25. The table structure is compatible with NASA cycle deck requirements given in Reference 2 (pages 23 and 24).

The output tables can be visualized as three dimensional, composed of a series of planes with each plane assigned a value of nozzle angle, BETA. Then in each BETA plane, the dependent variable (ordinate axis) is a function of pressure ratio, PR, and corrected speed, rpm. The dependent variables are respectively turbine corrected flow, W, and total-to-total efficienty, ETA.

For example, in the output table on page 28, the six lines of the dependent variable correspond to the six values of corrected speed, respectively. And the five values of the dependent variable in each line corresponds to the five values of pressure ratio above each column, respectively.

In addition to these two tables, there is a terminal listing summarizing the results of the cooling flow calculation, if this option was used. The value of the total cooling flow, PCBLED, is printed out together with the cooling flow for the first stage nozzle alone, PCNCH. The new cooled turbine efficiency value, EFF4, is given together with the new value of the total-to-total pressure ratio across the turbine, PRN. An example of this printout is shown on page 27 in the second example case. With the flows, shaft work, and turbine pressure ratio known, the user can calculate the new cooled turbine efficiency, ETATTD, using the bookkeeping procedure compatible with the cycle deck representation to be employed. A cycle deck efficiency scalar could then be used or, if desired, the program could be rerun on the uncooled branch using the new design point efficiency value as an input.

5.0 PROGRAM DIAGNOSTICS

The PART computer program contains error printouts to aid the user in trouble shooting his input. A listing of the error messages and their meanings are given below.

1. LIMITING VALUE OF UHUB=1600.0, CALCULATED VALUE OF UHUB=

This warning message is printed out only if the calculated rim speed exceeds the recommended value (this is a disk stress warning).

2. LIMITING VALUE OF ANS=42.0E9, CALCULATED VALUE OF ANS=

This warning message is printed out if the product of the exit annulus area and the rpm squared exceeds the recommended value (this is a centrifugal stress limit on the rotor blading).

3. QIRE CTR ERROR--(CALLING LINE=,I5,)

There are six iterations in the program. Each iteration is balanced using the Method of False Position. This method is contained in the subroutine QIREXX. A maximum of 25 passes is allowed for any single iteration to balance. If the iteration does not balance within the specified tolerance, the error message will appear with the number of the offending iteration in the I5 Format field.

Normally, the occurrence of such an error will not cause a problem. However, in the case of QIRE loop number five which calculates the turbine efficiency for the specified input values of pressure ratio and corrected speed, an additional message indicating the convergence error is printed out. This message has the form:

DHQT= ,ERR= ,PQP=

where the blanks contain the current values of specific enthalpy change divided by inlet total temperature, the convergence error in pressure ratio, and the pressure ratio at which the error occurred.

The user should inspect the error to see if the degree of convergence is satisfactory, if not, it may be necessary to restrict the range of input speeds and/or pressure ratios requested. The individual QIRE loops together with the calling routines and type of iteration are as follows:

QIRE LOOP	CALLING ROUTINES	COMMENTS
1	INLETX	Calculates individual stage efficiencies from the input value of overall turbine efficiency (NSTG>1)
2	VELRAT	Obtains the axial velocity ratio across the rotor.
3	CHOKEX	Solves for the value of nozzle Mach number when the rotor chokes.
4	ROTCKX	Solves for exit annulus choke location given the location of rotor choke.
5	PRTEFF	Calculates efficiency for input values of speed and pressure ratio.
6	FSTACK	Solves for the "polytropic" exponent for a multistage turbine.

6.0 EXAMPLE CASES

Two example cases are given in order to illustrate the use of the program. The first case utilizes the default settings to generate the output for a single-stage, uncooled, variable-geometry turbine. The second case is a four-stage, fixed-geometry turbine having cooling in the first three blade rows.

A complete record of the two terminal sessions including a listing of the output tables is given on the following pages. The program inputs and outputs for these two cases have been discussed previously in Sections 3.0 and 4.0.

```
EXEC NPT
ENTRY (A) E14262A.FILE15.DATA DELETED
ENTRY (A) E14262A.FILE16.DATA DELETED
NAMELIST      INPUT
 NSPDS =          15,
 APCNC (I)=
     1        10.000000,        20.000000,        30.000000,        40.000000,
     5        50.000000,        60.000000,        70.000000,        80.000000,
     9        90.000000,       100.000000,       110.000000,       120.000000,
    13       130.000000,       140.000000,       150.000000,
 NPR    =         20,
 APR    (I)=
     1         1.100000,         1.200000,         1.400000,         1.600000,
     5         1.700000,         1.800000,         2.000000,         2.200000,
     9         2.400000,         2.600000,         2.800000,         3.000000,
    13         3.200000,         3.400000,         3.600000,         3.800000,
    17         4.000000,         4.200000,         4.400000,         4.600000,
 NAR    =          3,
 ARN    (I)=
     1         1.300000,         1.000000,         0.700000,         0.0      ,
     5         0.0      ,        0.0      ,
 NSTG   =          1,    JCOOL  =          0,
 DHQTD  =   0.032780,      ETATTD=          0.923000,
 TFFD   =  62.979996,      XNRTD  =       193.520004,
 PSID   =   0.851100,      XMZXD  =         0.373000,
 ANGSWX=   15.200000,      TTIN   =       518.669922,
 PTIN   =  14.696000,      FARGD  =         0.0      ,
END NAMELIST      INPUT

ENTER NAMELIST INPUT ?
 &INPUT  &END
NAMELIST      INPUT
 NSPDS =          15,
 APCNC (I)=
     1        10.000000,        20.000000,        30.000000,        40.000000,
     5        50.000000,        60.000000,        70.000000,        80.000000,
     9        90.000000,       100.000000,       110.000000,       120.000000,
    13       130.000000,       140.000000,       150.000000,
 NPR    =         20,
 APR    (I)=
     1         1.100000,         1.200000,         1.400000,         1.600000,
     5         1.700000,         1.800000,         2.000000,         2.200000,
     9         2.400000,         2.600000,         2.800000,         3.000000,
    13         3.200000,         3.400000,         3.600000,         3.800000,
    17         4.000000,         4.200000,         4.400000,         4.600000,
 NAR    =          3,
 ARN    (I)=
     1         1.300000,         1.000000,         0.700000,         0.0      ,
     5         0.0      ,        0.0      ,
 NSTG   =          1,    JCOOL  =          0,
 DHQTD  =   0.032780,      ETATTD=          0.923000,
 TFFD   =  62.979996,      XNRTD  =       193.520004,
 PSID   =   0.851100,      XMZXD  =         0.373000,
 ANGSWX=   15.199997,      TTIN   =       518.669922,
 PTIN   =  14.696000,      FARGD  =         0.0      ,
END NAMELIST      INPUT

NASA OUTPUT ON IFC=15,16
READY
```

```
LIST FILE16.DATA
 FILE16.DATA
270         TURBINE FLOW FUNCTION VS. PR, RPM, AND BETA
BETA  3          61.       68.       75.
RPM  15          10.       20.       30.       40.       50.       60.       70.
RPM  15          80.       90.      100.      110.      120.      130.      140.
RPM  15         150.
PR   20          1.1       1.2       1.4       1.6       1.7       1.8       2.0
PR   20          2.2       2.4       2.6       2.8       3.0       3.2       3.4
PR   20          3.6       3.8       4.0       4.2       4.4       4.6
TFF  20       60.008    77.054    83.416    83.416    83.416    83.416    83.416
TFF  20       83.416    83.416    83.416    83.416    83.416    83.416    83.416
TFF  20       83.416    83.416    83.416    83.416    83.416    83.416
TFF  20       49.625    68.579    80.750    81.116    81.116    81.116    81.116
TFF  20       81.116    81.116    81.116    81.116    81.116    81.116    81.116
TFF  20       81.116    81.116    81.116    81.116    81.116    81.116
TFF  20       42.691    61.244    76.854    79.254    79.254    79.254    79.254
TFF  20       79.254    79.254    79.254    79.254    79.254    79.254    79.254
TFF  20       79.254    79.254    79.254    79.254    79.254    79.254
TFF  20       38.499    55.562    72.533    77.523    77.742    77.742    77.742
TFF  20       77.742    77.742    77.742    77.742    77.742    77.742    77.742
TFF  20       77.742    77.742    77.742    77.742    77.742    77.742
TFF  20       36.122    51.438    68.468    75.081    76.255    76.517    76.517
TFF  20       76.517    76.517    76.517    76.517    76.517    76.517    76.517
TFF  20       76.517    76.517    76.517    76.517    76.517    76.517
TFF  20       35.005    48.625    65.008    72.409    74.236    75.186    75.549
TFF  20       75.549    75.549    75.549    75.549    75.549    75.549    75.549
TFF  20       75.549    75.549    75.549    75.549    75.549    75.549
TFF  20       34.695    46.813    62.208    69.877    72.068    73.403    74.600
TFF  20       74.769    74.769    74.769    74.769    74.769    74.769    74.769
TFF  20       74.769    74.769    74.769    74.769    74.769    74.769
TFF  20       34.975    45.797    60.111    67.722    70.064    71.616    73.329
TFF  20       74.053    74.192    74.192    74.192    74.192    74.192    74.192
TFF  20       74.192    74.192    74.192    74.192    74.192    74.192
TFF  20       35.676    45.385    58.633    66.003    68.386    70.031    72.027
TFF  20       73.105    73.614    73.777    73.780    73.780    73.780    73.780
TFF  20       73.780    73.780    73.780    73.780    73.780    73.780
TFF  20       36.649    45.438    57.666    64.725    67.093    68.762    70.891
TFF  20       72.169    72.904    73.305    73.485    73.519    73.519    73.519
TFF  20       73.519    73.519    73.519    73.519    73.519    73.519
```

TFF	20	37.926	45.867	57.145	63.862	66.184	67.841	70.010
TFF	20	71.389	72.254	72.799	73.129	73.310	73.386	73.395
TFF	20	73.395	73.395	73.395	73.395	73.395	73.395	
TFF	20	39.414	46.599	57.008	63.371	65.605	67.241	69.410
TFF	20	70.828	71.760	72.390	72.810	73.085	73.257	73.354
TFF	20	73.395	73.399	73.399	73.399	73.399	73.399	
TFF	20	41.036	47.583	57.198	63.212	65.339	66.952	69.089
TFF	20	70.503	71.464	72.136	72.608	72.941	73.172	73.329
TFF	20	73.430	73.489	73.515	73.519	73.519	73.519	
TFF	20	43.158	48.761	57.666	63.342	65.355	66.941	69.027
TFF	20	70.412	71.376	72.062	72.560	72.924	73.191	73.384
TFF	20	73.523	73.619	73.684	73.723	73.742	73.746	
TFF	20	45.983	50.124	58.372	63.725	65.623	67.177	69.200
TFF	20	70.540	71.489	72.172	72.677	73.055	73.339	73.553
TFF	20	73.714	73.833	73.921	73.983	74.026	74.053	
RPM	15	10.	20.	30.	40.	50.	60.	70.
RPM	15	80.	90.	100.	110.	120.	130.	140.
RPM	15	150.						
PR	20	1.1	1.2	1.4	1.6	1.7	1.8	2.0
PR	20	2.2	2.4	2.6	2.8	3.0	3.2	3.4
PR	20	3.6	3.8	4.0	4.2	4.4	4.6	
TFF	20	46.480	59.664	66.410	66.425	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	
TFF	20	41.219	55.715	65.685	66.425	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	
TFF	20	37.658	52.205	64.253	66.425	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	
TFF	20	35.530	49.433	62.524	66.265	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	
TFF	20	34.505	47.424	60.828	65.675	66.367	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	
TFF	20	34.276	46.112	59.322	64.859	65.995	66.411	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	66.425
TFF	20	66.425	66.425	66.425	66.425	66.425	66.425	
TFF	20	34.598	45.361	58.066	63.959	65.396	66.151	66.385

TFF	20	66.385	66.385	66.385	66.385	66.385	66.385	66.385
TFF	20	66.385	66.385	66.385	66.385	66.385	66.385	
TFF	20	35.099	44.798	56.747	62.709	64.327	65.312	65.918
TFF	20	65.918	65.918	65.918	65.918	65.918	65.918	65.918
TFF	20	65.918	65.918	65.918	65.918	65.918	65.918	
TFF	20	35.850	44.578	55.691	61.547	63.251	64.357	65.322
TFF	20	65.399	65.399	65.399	65.399	65.399	65.399	65.399
TFF	20	65.399	65.399	65.399	65.399	65.399	65.399	
TFF	20	36.810	44.671	54.941	60.580	62.303	63.465	64.655
TFF	20	64.917	64.917	64.917	64.917	64.917	64.917	64.917
TFF	20	64.917	64.917	64.917	64.917	64.917	64.917	
TFF	20	37.955	45.050	54.509	59.869	61.565	62.741	64.059
TFF	20	64.503	64.534	64.534	64.534	64.534	64.534	64.534
TFF	20	64.534	64.534	64.534	64.534	64.534	64.534	
TFF	20	39.189	45.633	54.325	59.371	61.010	62.172	63.543
TFF	20	64.100	64.216	64.216	64.216	64.216	64.216	64.216
TFF	20	64.216	64.216	64.216	64.216	64.216	64.216	
TFF	20	40.583	46.409	54.384	59.102	60.664	61.794	63.168
TFF	20	63.787	63.993	63.999	63.999	63.999	63.999	63.999
TFF	20	63.999	63.999	63.999	63.999	63.999	63.999	
TFF	20	42.067	47.331	54.639	59.026	60.500	61.586	62.925
TFF	20	63.570	63.829	63.862	63.862	63.862	63.862	63.862
TFF	20	63.862	63.862	63.862	63.862	63.862	63.862	
TFF	20	43.600	48.371	55.059	59.119	60.497	61.532	62.810
TFF	20	63.454	63.737	63.798	63.798	63.798	63.798	63.798
TFF	20	63.798	63.798	63.798	63.798	63.798	63.798	
RPM	15	10.	20.	30.	40.	50.	60.	70.
RPM	15	80.	90.	100.	110.	120.	130.	140.
RPM	15	150.						
PR	20	1.1	1.2	1.4	1.6	1.7	1.8	2.0
PR	20	2.2	2.4	2.6	2.8	3.0	3.2	3.4
PR	20	3.6	3.8	4.0	4.2	4.4	4.6	
TFF	20	31.467	40.472	46.178	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	28.788	38.332	45.472	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	27.087	36.576	44.591	46.479	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498

TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	26.212	35.272	43.705	46.282	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	25.970	34.423	42.915	45.962	46.432	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	26.207	33.985	42.281	45.607	46.262	46.492	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	26.790	33.880	41.827	45.277	46.056	46.425	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	27.619	34.055	41.551	45.003	45.856	46.321	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	28.621	34.446	41.438	44.809	45.692	46.213	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	29.741	35.004	41.471	44.698	45.579	46.127	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	30.938	35.685	41.625	44.666	45.521	46.071	46.494
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	32.179	36.455	41.878	44.706	45.516	46.048	46.486
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	33.439	37.284	42.207	44.806	45.559	46.058	46.482
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	34.699	38.148	42.593	44.953	45.639	46.095	46.483
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	
TFF	20	35.923	39.027	43.016	45.135	45.749	46.154	46.489
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	46.498
TFF	20	46.498	46.498	46.498	46.498	46.498	46.498	

EOT
READY

```
LIST FILE15.DATA
 FILE15.DATA
269            TURBINE EFFICIENCY VS. PR, RPM, AND BETA
BETA  3           61.         68.         75.
RPM  15           10.         20.         30.         40.         50.         60.         70.
RPM  15           80.         90.        100.        110.        120.        130.        140.
RPM  15          150.
PR   20           1.1         1.2         1.4         1.6         1.7         1.8         2.0
PR   20           2.2         2.4         2.6         2.8         3.0         3.2         3.4
PR   20           3.6         3.8         4.0         4.2         4.4         4.6
EFF  20         0.507       0.402       0.318       0.279       0.266       0.256       0.240
EFF  20         0.228       0.219       0.212       0.207       0.202       0.198       0.194
EFF  20         0.191       0.188       0.186       0.183       0.181       0.179
EFF  20         0.761       0.651       0.546       0.492       0.474       0.459       0.435
EFF  20         0.418       0.404       0.394       0.385       0.377       0.371       0.365
EFF  20         0.361       0.356       0.352       0.349       0.346       0.343
EFF  20         0.873       0.796       0.702       0.648       0.629       0.612       0.587
EFF  20         0.568       0.553       0.540       0.530       0.520       0.512       0.504
EFF  20         0.497       0.492       0.486       0.481       0.477       0.473
EFF  20         0.908       0.875       0.805       0.756       0.738       0.722       0.697
EFF  20         0.676       0.656       0.640       0.627       0.615       0.605       0.596
EFF  20         0.588       0.581       0.574       0.568       0.563       0.558
EFF  20         0.898       0.910       0.869       0.827       0.811       0.797       0.769
EFF  20         0.743       0.721       0.704       0.688       0.675       0.664       0.654
EFF  20         0.645       0.636       0.629       0.622       0.616       0.611
EFF  20         0.858       0.917       0.905       0.872       0.858       0.844       0.812
EFF  20         0.785       0.762       0.743       0.727       0.713       0.700       0.689
EFF  20         0.680       0.671       0.663       0.656       0.649       0.643
EFF  20         0.796       0.902       0.921       0.897       0.887       0.871       0.838
EFF  20         0.810       0.787       0.767       0.750       0.736       0.723       0.712
EFF  20         0.701       0.692       0.684       0.676       0.669       0.663
EFF  20         0.715       0.873       0.922       0.909       0.900       0.885       0.852
EFF  20         0.825       0.802       0.782       0.765       0.750       0.737       0.725
EFF  20         0.715       0.705       0.697       0.689       0.682       0.675
EFF  20         0.619       0.831       0.913       0.910       0.904       0.890       0.859
EFF  20         0.832       0.809       0.789       0.772       0.758       0.744       0.733
EFF  20         0.722       0.713       0.704       0.696       0.689       0.682
EFF  20         0.504       0.778       0.893       0.903       0.900       0.889       0.859
EFF  20         0.834       0.811       0.792       0.775       0.761       0.748       0.736
EFF  20         0.726       0.716       0.708       0.700       0.692       0.686
EFF  20         0.381       0.716       0.866       0.889       0.891       0.882       0.855
EFF  20         0.831       0.810       0.791       0.775       0.761       0.748       0.737
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EFF	20	0.726	0.717	0.709	0.701	0.693	0.687	
EFF	20	0.249	0.646	0.833	0.870	0.876	0.871	0.847
EFF	20	0.826	0.805	0.788	0.772	0.758	0.746	0.735
EFF	20	0.725	0.716	0.707	0.700	0.693	0.686	
EFF	20	0.101	0.569	0.794	0.847	0.856	0.855	0.837
EFF	20	0.817	0.798	0.782	0.767	0.754	0.742	0.731
EFF	20	0.721	0.713	0.704	0.697	0.690	0.684	
EFF	20	0.0	0.483	0.750	0.819	0.832	0.837	0.823
EFF	20	0.806	0.789	0.774	0.760	0.747	0.736	0.726
EFF	20	0.717	0.708	0.700	0.693	0.686	0.680	
EFF	20	0.0	0.391	0.701	0.787	0.805	0.815	0.808
EFF	20	0.793	0.778	0.764	0.751	0.740	0.729	0.719
EFF	20	0.710	0.702	0.695	0.688	0.681	0.675	
RPM	15	10.	20.	30.	40.	50.	60.	70.
RPM	15	80.	90.	100.	110.	120.	130.	140.
RPM	15	150.						
PR	20	1.1	1.2	1.4	1.6	1.7	1.8	2.0
PR	20	2.2	2.4	2.6	2.8	3.0	3.2	3.4
PR	20	3.6	3.8	4.0	4.2	4.4	4.6	
EFF	20	0.441	0.343	0.268	0.234	0.223	0.214	0.200
EFF	20	0.1'	0.182	0.176	0.171	0.167	0.163	0.160
EFF	20	0.157	0.155	0.153	0.151	0.149	0.147	
EFF	20	0.694	0.577	0.473	0.421	0.403	0.389	0.367
EFF	20	0.351	0.339	0.328	0.320	0.313	0.307	0.302
EFF	20	0.298	0.294	0.290	0.287	0.284	0.281	
EFF	20	0.830	0.730	0.625	0.568	0.548	0.531	0.506
EFF	20	0.487	0.472	0.460	0.450	0.441	0.434	0.428
EFF	20	0.422	0.418	0.413	0.409	0.406	0.403	
EFF	20	0.893	0.827	0.735	0.680	0.661	0.644	0.618
EFF	20	0.599	0.583	0.571	0.560	0.551	0.543	0.536
EFF	20	0.530	0.525	0.519	0.515	0.510	0.506	
EFF	20	0.912	0.883	0.813	0.765	0.747	0.732	0.708
EFF	20	0.689	0.673	0.660	0.649	0.638	0.629	0.620
EFF	20	0.613	0.607	0.601	0.596	0.591	0.586	
EFF	20	0.901	0.911	0.866	0.827	0.812	0.799	0.777
EFF	20	0.757	0.741	0.726	0.713	0.702	0.692	0.684
EFF	20	0.676	0.669	0.662	0.656	0.650	0.645	
EFF	20	0.867	0.919	0.900	0.871	0.859	0.848	0.826
EFF	20	0.808	0.790	0.775	0.761	0.750	0.740	0.730

EFF	2Ø	Ø.721	Ø.713	Ø.7Ø6	Ø.699	Ø.693	Ø.687	
EFF	2Ø	Ø.817	Ø.911	Ø.918	Ø.9ØØ	Ø.891	Ø.883	Ø.862
EFF	2Ø	Ø.844	Ø.825	Ø.81Ø	Ø.797	Ø.785	Ø.773	Ø.762
EFF	2Ø	Ø.753	Ø.745	Ø.737	Ø.73Ø	Ø.724	Ø.718	
EFF	2Ø	Ø.752	Ø.89Ø	Ø.925	Ø.918	Ø.913	Ø.9Ø6	Ø.887
EFF	2Ø	Ø.868	Ø.85Ø	Ø.835	Ø.822	Ø.8Ø8	Ø.796	Ø.786
EFF	2Ø	Ø.776	Ø.767	Ø.76Ø	Ø.753	Ø.746	Ø.74Ø	
EFF	2Ø	Ø.675	Ø.86Ø	Ø.923	Ø.927	Ø.924	Ø.919	Ø.9Ø3
EFF	2Ø	Ø.884	Ø.867	Ø.852	Ø.838	Ø.825	Ø.813	Ø.8Ø2
EFF	2Ø	Ø.792	Ø.784	Ø.776	Ø.768	Ø.762	Ø.756	
EFF	2Ø	Ø.587	Ø.821	Ø.912	Ø.927	Ø.929	Ø.925	Ø.912
EFF	2Ø	Ø.894	Ø.878	Ø.864	Ø.849	Ø.836	Ø.824	Ø.813
EFF	2Ø	Ø.8Ø3	Ø.795	Ø.787	Ø.779	Ø.773	Ø.766	
EFF	2Ø	Ø.484	Ø.774	Ø.896	Ø.922	Ø.927	Ø.925	Ø.915
EFF	2Ø	Ø.899	Ø.884	Ø.87Ø	Ø.855	Ø.842	Ø.83Ø	Ø.82Ø
EFF	2Ø	Ø.81Ø	Ø.8Ø2	Ø.794	Ø.786	Ø.78Ø	Ø.773	
EFF	2Ø	Ø.376	Ø.72Ø	Ø.873	Ø.911	Ø.919	Ø.921	Ø.914
EFF	2Ø	Ø.899	Ø.885	Ø.873	Ø.858	Ø.845	Ø.834	Ø.824
EFF	2Ø	Ø.814	Ø.8Ø6	Ø.798	Ø.791	Ø.784	Ø.778	
EFF	2Ø	Ø.262	Ø.66Ø	Ø.845	Ø.895	Ø.9Ø7	Ø.912	Ø.9Ø9
EFF	2Ø	Ø.897	Ø.884	Ø.872	Ø.858	Ø.846	Ø.835	Ø.825
EFF	2Ø	Ø.815	Ø.8Ø7	Ø.799	Ø.792	Ø.786	Ø.78Ø	
EFF	2Ø	Ø.136	Ø.595	Ø.813	Ø.876	Ø.892	Ø.9ØØ	Ø.9ØØ
EFF	2Ø	Ø.891	Ø.879	Ø.869	Ø.856	Ø.844	Ø.833	Ø.824
EFF	2Ø	Ø.815	Ø.8Ø7	Ø.799	Ø.792	Ø.786	Ø.78Ø	
RPM	15	1Ø.	2Ø.	3Ø.	4Ø.	5Ø.	6Ø.	7Ø.
RPM	15	8Ø.	9Ø.	1ØØ.	11Ø.	12Ø.	13Ø.	14Ø.
RPM	15	15Ø.						
PR	2Ø	1.1	1.2	1.4	1.6	1.7	1.8	2.Ø
PR	2Ø	2.2	2.4	2.6	2.8	3.Ø	3.2	3.4
PR	2Ø	3.6	3.8	4.Ø	4.2	4.4	4.6	
EFF	2Ø	Ø.372	Ø.286	Ø.222	Ø.193	Ø.183	Ø.176	Ø.164
EFF	2Ø	Ø.156	Ø.149	Ø.144	Ø.14Ø	Ø.136	Ø.133	Ø.131
EFF	2Ø	Ø.128	Ø.126	Ø.125	Ø.123	Ø.122	Ø.12Ø	
EFF	2Ø	Ø.6Ø2	Ø.491	Ø.397	Ø.351	Ø.336	Ø.323	Ø.3Ø4
EFF	2Ø	Ø.29Ø	Ø.279	Ø.27Ø	Ø.263	Ø.257	Ø.251	Ø.247
EFF	2Ø	Ø.243	Ø.24Ø	Ø.236	Ø.234	Ø.231	Ø.229	
EFF	2Ø	Ø.739	Ø.635	Ø.532	Ø.479	Ø.46Ø	Ø.445	Ø.422
EFF	2Ø	Ø.4Ø4	Ø.39Ø	Ø.379	Ø.37Ø	Ø.362	Ø.356	Ø.35Ø
EFF	2Ø	Ø.345	Ø.34Ø	Ø.336	Ø.332	Ø.329	Ø.326	

EFF	20	0.816	0.732	0.635	0.581	0.561	0.545	0.520
EFF	20	0.501	0.486	0.473	0.463	0.454	0.447	0.440
EFF	20	0.434	0.429	0.425	0.421	0.417	0.413	
EFF	20	0.853	0.797	0.713	0.662	0.643	0.627	0.601
EFF	20	0.582	0.566	0.554	0.543	0.534	0.526	0.519
EFF	20	0.513	0.508	0.503	0.499	0.495	0.491	
EFF	20	0.865	0.837	0.771	0.725	0.707	0.692	0.668
EFF	20	0.649	0.634	0.622	0.612	0.603	0.595	0.588
EFF	20	0.582	0.577	0.572	0.568	0.564	0.560	
EFF	20	0.858	0.859	0.812	0.774	0.758	0.744	0.722
EFF	20	0.705	0.691	0.679	0.669	0.661	0.654	0.647
EFF	20	0.642	0.636	0.632	0.628	0.624	0.621	
EFF	20	0.836	0.868	0.841	0.810	0.797	0.785	0.766
EFF	20	0.751	0.738	0.727	0.718	0.710	0.703	0.697
EFF	20	0.692	0.688	0.684	0.680	0.677	0.674	
EFF	20	0.804	0.866	0.860	0.837	0.826	0.817	0.801
EFF	20	0.787	0.776	0.766	0.758	0.751	0.745	0.740
EFF	20	0.736	0.731	0.728	0.724	0.721	0.717	
EFF	20	0.761	0.856	0.870	0.856	0.848	0.840	0.828
EFF	20	0.816	0.807	0.798	0.791	0.785	0.780	0.775
EFF	20	0.771	0.768	0.765	0.758	0.753	0.747	
EFF	20	0.711	0.839	0.874	0.868	0.863	0.858	0.848
EFF	20	0.839	0.831	0.824	0.818	0.813	0.808	0.804
EFF	20	0.801	0.796	0.789	0.782	0.777	0.771	
EFF	20	0.653	0.816	0.872	0.874	0.872	0.869	0.863
EFF	20	0.856	0.849	0.844	0.839	0.835	0.831	0.828
EFF	20	0.823	0.815	0.808	0.801	0.795	0.789	
EFF	20	0.588	0.787	0.865	0.876	0.877	0.876	0.873
EFF	20	0.868	0.863	0.859	0.855	0.852	0.849	0.846
EFF	20	0.837	0.829	0.822	0.815	0.809	0.803	
EFF	20	0.517	0.754	0.854	0.874	0.877	0.879	0.879
EFF	20	0.876	0.873	0.870	0.867	0.865	0.862	0.857
EFF	20	0.848	0.840	0.832	0.826	0.819	0.813	
EFF	20	0.434	0.717	0.839	0.868	0.874	0.878	0.881
EFF	20	0.881	0.879	0.877	0.876	0.874	0.872	0.865
EFF	20	0.856	0.848	0.840	0.833	0.827	0.821	

EOT
READY

```
READY
EXEC NPT
ENTRY (A) E14262A.FILE15.DATA DELETED
ENTRY (A) E14262A.FILE16.DATA DELETED
NAMELIST .   INPUT
 NSPDS =            15,
 APCNC (I)=
      1         10.000000,        20.000000,        30.000000,        40.000000,
      5         50.000000,        60.000000,        70.000000,        80.000000,
      9         90.000000,       100.000000,       110.000000,       120.000000,
     13        130.000000,       140.000000,       150.000000,
 NPR   =            20,
 APR    (I)=
      1          1.100000,         1.200000,         1.400000,         1.600000,
      5          1.700000,         1.800000,         2.000000,         2.200000,
      9          2.400000,         2.600000,         2.800000,         3.000000,
     13          3.200000,         3.400000,         3.600000,         3.800000,
     17          4.000000,         4.200000,         4.400000,         4.600000,
 NAR   =             3,
 ARN    (I)=
      1          1.300000,         1.000000,         0.700000,         0.0      ,
      5          0.0      ,        0.0      ,
 NSTG   =             1,   JCOOL  =             0,
 DHQTD =       0.032780,     ETATTD=       0.923000,
 TFFD   =     62.979996,     XNRTD  =    193.520004,
 PSID   =      0.851100,     XMZXD  =      0.373000,
 ANGSWX=      15.200000,     TTIN   =    518.669922,
 PTIN   =     14.696000,     FARGD  =       0.0      ,
END NAMELIST      INPUT

ENTER NAMELIST INPUT ?
 &INPUT
 NSPDS=6
 APCNC=20.,40.,60.,80.,100.,120.
 NPR=5
 APR=2.0,2.5,3.0,3.5,3.8
 NAR=1
 ARN=1.0
 NSTG=3
 JCOOL=1
 DHQTD=0.0635
 ETATTD=.886
 TFFD=58.53
 XNRTD=40.10
 PSID=1.5
 XMZXD=0.41
 ANGSWX=2.9
 TTIN=2500.
 PTIN=59.8
 FARGD=0.02
 &END
```

```
NAMELIST      INPUT1
 KINDOF=,      86400000,
 TC     =       700.000000,    FARCX  =          0.0       ,
 YEAR   =     1980.,           YEARB  =      1980.,
 ELIFE  =     0.1000000E+05,
END NAMELIST      INPUT1

ENTER NAMELIST INPUT1 ?
 &INPUT1
 KINDOF=864000
 &END
NAMELIST      INPUT
 NSPDS  =              6,
 APCNC  (I)=
      1         20.000000,        40.000000,        60.000000,        80.000000,
      5        100.000000,       120.000000,        70.000000,        80.000000,
      9         90.000000,       100.000000,       110.000000,       120.000000,
     13        130.000000,       140.000000,       150.000000,
 NPR    =              5,
 APR    (I)=
      1          2.000000,         2.500000,         3.000000,         3.500000,
      5          3.800000,         1.800000,         2.000000,         2.200000,
      9          2.400000,         2.600000,         2.800000,         3.000000,
     13          3.200000,         3.400000,         3.600000,         3.800000,
     17          4.000000,         4.200000,         4.400000,         4.600000,
 NAR    =              1,
 ARN    (I)=
      1          1.000000,         1.000000,         0.700000,         0.0      ,
      5          0.0      ,        0.0      ,
 NSTG   =              3,    JCOOL  =          1,
 DHQTD  =        0.063500,      ETATTD=        0.886000,
 TFFD   =       58.529999,      XNRTD  =      40.100006,
 PSID   =        1.500000,      XMZXD  =       0.410000,
 ANGSWX=         2.899999,      TTIN   =    2500.00000 ,
 PTIN   =       59.800003,      FARGD  =       0.020000,
END NAMELIST      INPUT

NAMELIST      INPUT1
 KINDOF=,        864000,
 TC     =       700.000000,    FARCX  =          0.0       ,
 YEAR   =     1980.,           YEARB  =      1780.,
 ELIFE  =     0.1000000E+05,
END NAMELIST      INPUT1
PCBLED= 0.06337 PCNCH= 0.02001 EFF4=  0.8835 PRN=  3.315
NASA OUTPUT ON IFC=15,16
READY
```

```
LIST FILE15.DATA
 FILE15.DATA
269          TURBINE EFFICIENCY VS. PR, RPM, AND BETA
BETA  1            71.
RPM   6            20.       40.       60.       80.      100.      120.
PR    5            2.0       2.5       3.0       3.5       3.8
EFF   5          0.483     0.446     0.423     0.407     0.399
EFF   5          0.717     0.687     0.664     0.647     0.639
EFF   5          0.825     0.809     0.793     0.779     0.772
EFF   5          0.868     0.866     0.858     0.850     0.843
EFF   5          0.877     0.888     0.887     0.883     0.878
EFF   5          0.864     0.889     0.895     0.895     0.892
EOT
READY
```

```
LIST FILE16.DATA
 FILE16.DATA
270        TURBINE FLOW FUNCTION VS. PR, RPM, AND BETA
BETA  1         71.
RPM   6         20.       40.       60.       80.      100.      120.
PR    5         2.0       2.5       3.0       3.5       3.8
TFF   5      59.669    59.669    59.669    59.669    59.669
TFF   5      59.669    59.669    59.669    59.669    59.669
TFF   5      59.500    59.500    59.500    59.500    59.500
TFF   5      58.202    59.208    59.208    59.208    59.208
TFF   5      56.082    57.959    58.458    58.535    58.535
TFF   5      54.125    56.067    56.813    57.131    57.230
EOT
READY
```

7.0 ANALYTICAL BACKGROUND

The following section has been written in order to give the user a general idea of the type of turbine representation used in the program and the approach used in the derivation of the equations. Details of the derivations together with sample calculations may be found in the Monthly Progress Reports (e.g., References 10, 11, and 12).

7.1 TURBINE MAP REPRESENTATION

Typically, cycle deck entry to a turbine map is through corrected speed, N/SQRT(T), and actual energy, DH/T, with turbine flow function, W*SQRT(T)/P, and total-to-total efficiency being output. Total-to-total pressure ratio is sometimes used instead of actual energy as the second map entry.

The discussion of the turbine map representation can be conveniently subdivided into two parts: the flow and the efficiency.

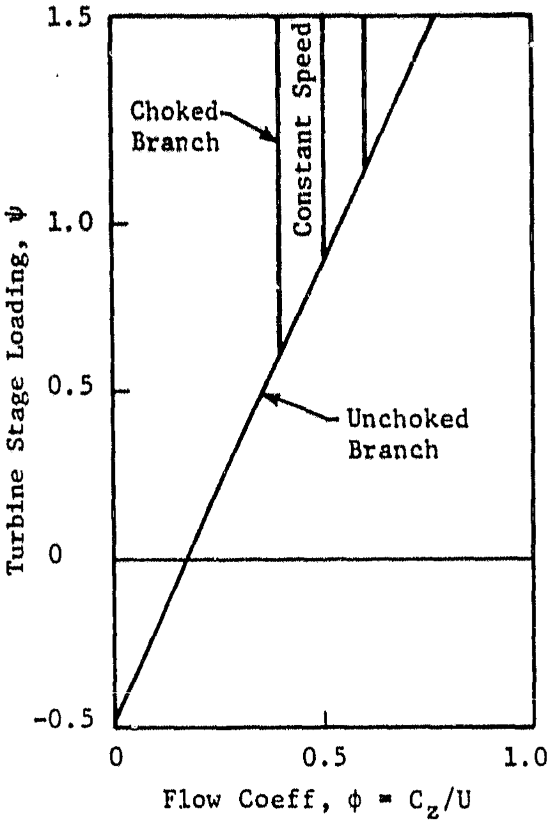
The flow model is illustrated by the three sketches shown in Figure 4. The two curves on the top in the figure are used to generate the flow representation on the bottom. Sketch 4-1 shows the turbine stage characteristic (i.e., a plot of turbine loading against flow coefficient). Sketch 4-2 shows the dependence of the maximum value of the turbine flow function on corrected speed. With the corrected speed and DH/T known, the stage loading can be calculated, and the flow coefficient obtained from Sketch 4-1. Once the flow is choked (i.e., the choked branch of the stage characteristic), the flow coefficient remains constant for that speed. Sketch 4-2 is next used to obtain the maximum value of the turbine flow function at the corrected speed of interest. The value of the turbine flow function is then calculated. The equations used are as follows:

$$U/A_t = (2\pi R/60)\ (N/\sqrt{rR_g g_o T}$$

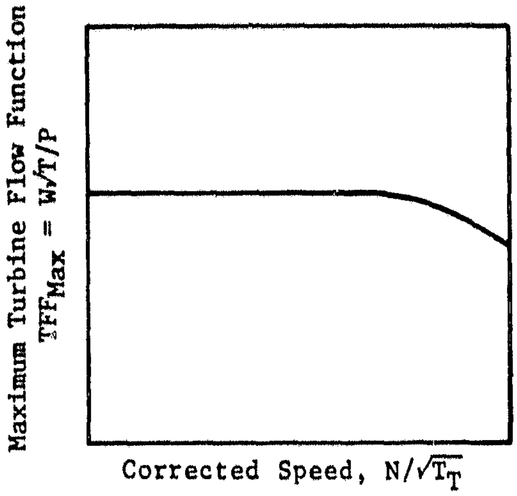
$$\psi \;\;= (DH/T)/[2(U/\sqrt{T})^2/g_o J]$$

$$C/A_t = (\phi/\text{Cos}\ \alpha_2)/(U/A_t)$$

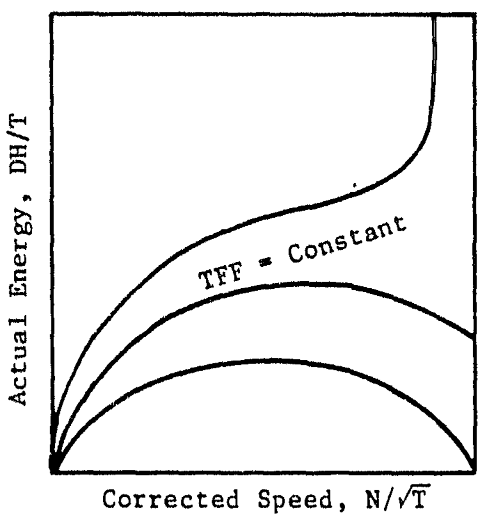
$$TFF = (TFF)_{max} \frac{C/A_t\left(1 - \frac{r-1}{2}\left(\frac{C}{A_t}\right)^2\right)^{\frac{1}{r-1}}}{\left(\frac{2}{r+1}\right)^{\frac{r+1}{2(r-1)}}}$$



4-1 Stage Characteristic



4-2 Maximum Flow Function



4-3 Flow Function Contours

Figure 4. Turbine Flow Representation.

where

DH/T = turbine stage specific enthalpy drop divided by inlet total temperature, Btu/lbm R

N/SQRT(T) = cor ected speed, RPM/SQRT(R)

R = pitch line radius, ft

C = velocity, ft/sec

A_t = speed of sound at inlet total temperature, ft/sec

TFF = inlet turbine flow function, lbm/sec*SQRT(R)/psia

Cos(α_2) = nozzle exit angle

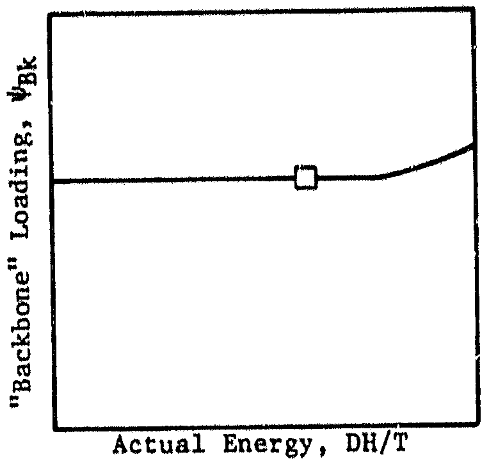
The value of Cos(α_2) is obtained from the design point information as is the value of the pitch line radius.

The efficiency model is illustrated by the five sketches shown in Figure 5. The first three curves in the figure are used to generate the last two sketches. The "backbone" of the turbine map shown in Sketch 5-4 is the locus of the peak efficiency at each value of DH/T. This locus is obtained from Sketch 5-1, which shows turbine pitch line loading along the map "backbone" as a function of DH/T. The "backbone" efficiencies are obtained from Sketch 5-2. This sketch gives the "backbone" loss (defined as the difference between the ideal and actual values of DH/T) as a funciton of DH/T. With the "backbone" loading and efficiencies known at each DH/T, Sketch 5-3 is used to evaluate the "off-backbone" loss and to obtain the efficiency at any value of corrected speed. When the turbine "off-backbone" loss is plotted with the coordinates shown in Sketch 5-3, the resulting curves are nearly linear at any given DH/T. These five curves, three univariate and two bivariate, are sufficient to define the turbine map. Note that as shown on Sketch 5-5, the design point does not generally fall on the "backbone" but is seperated from it by a "stand-off" distance which is calculated from design point information.

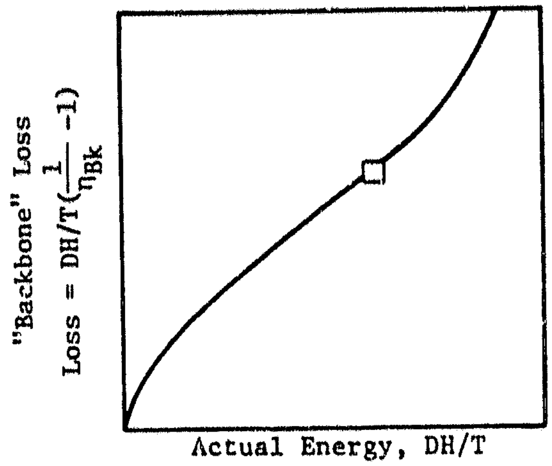
The analytical basis for the five correlating curves is discussed in the following sections.

7.2 TURBINE FLOW MODEL

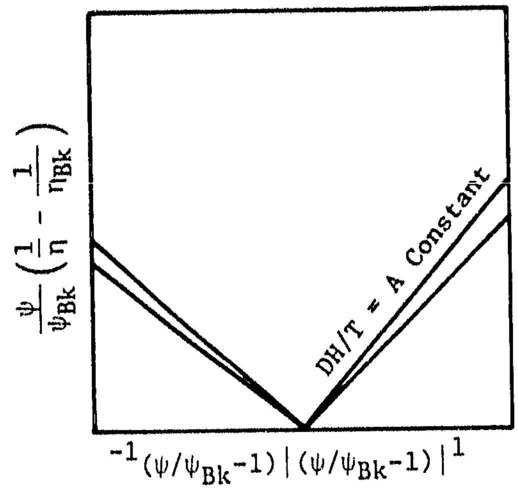
The turbine stage characteristic serves as the basis for modeling the turbine flow. An analytical expression for the stage characteristic of a constant-pitch, axial-flow turbine can be obtained by using the continuity, energy, and angular momentum equations, together with a number of relationships from the pitch line vector diagram. In deriving this equation, it is assumed that the pitch line flow angles at nozzle and bucket exit are invariant, and that the axial velocity ratio across the bucket is constant.



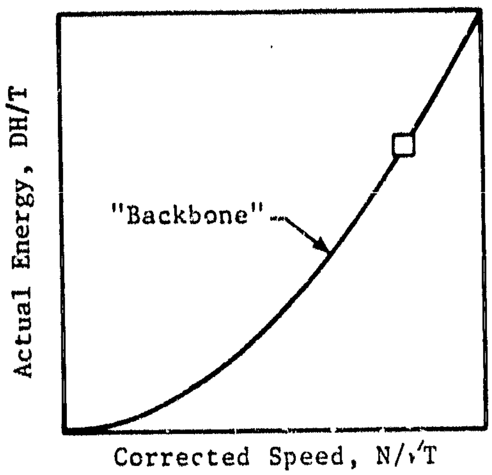
5-1 Backbone Loading



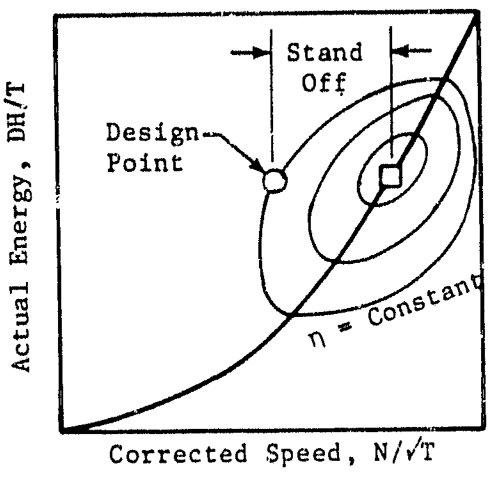
5-2 Backbone Loss



5-3 Loss Function



5-4 Backbone Locus



5-5 Efficiency Contours

Figure 5. Turbine Efficiency Representation.

This later assumption is reasonable for incompressible or low Mach number ($M<0.25$) flows. It should be emphasized, however, that the final correlations have no such restrictions.

The stage characteristic for a single-stage turbine with the above assumptions can be written in the form

$$\psi = \phi\left(\tan \alpha_2 + \frac{C_{z3}}{C_{z2}} \tan \beta_3\right) - 1/2 \tag{1}$$

where

ψ = $DH/(2U^2/g_oJ)$, Turbine stage Loading

ϕ = C_z/U, Flow coefficient

α_2 = Nozzle exit flow angle

β_3 = Bucket exit flow angle.

Selecting a reference point and assuming that

$$\tan \alpha_2 + \frac{C_{z3}}{C_{z2}} \tan \beta_3 = \text{a constant},$$

this equation may be written as

$$\frac{\psi}{\psi_R} = \frac{\phi}{\phi_R} + \frac{1}{2\psi_R}\left(\frac{\phi}{\phi_R} - 1\right) \tag{2}$$

For unchoked flow, the reference point (indicated by the subscript R) was selected at the design point on the turbine map. For choked flow, the reference point was selected at the critical point (subscript CRIT) on the turbine map. The critical point is located at the value of DH/T at the reference speed (e.g., 100%) where nozzle choking first occurs. For a variable-geometry turbine, the angle α_2 is calculated from the input value of nozzle area ratio.

The equation used for the normalized flow coefficient is

$$\frac{\phi}{\phi_R} = \frac{C_z/A_t}{(C_z/A_t)_R} \frac{(N/\sqrt{T})_R}{N/\sqrt{T}} = \frac{C/A_t}{(C/A_t)_R} \frac{(N/\sqrt{T}_R}{N/\sqrt{T}} \tag{3}$$

The velocity ratio, C/A_t, for a point at a selected speed is determined by calculating a pseudoarea at which the Mach number is assumed to be unity (i.e., at the maximum turbine flow function for that speed). This pseudoarea is assumed to be constant for that speed. The Mach number (velocity ratio) at any point on the speed line is then calculated from the usual flow function equations. By definition, the pseudoarea varies with speed in direct proportion to the maximum turbine flow function variation with speed. This method of calculating the flow coefficient was found to give better results than that obtained using the first stage nozzle throat area for all speeds. For the case in which the first stage nozzle is choked, the two procedures are identical.

Typically, the calculated and measured values of velocity ratio are within about 6%, with the larger errors occurring at the higher Mach numbers. The predicted value of the normalized flow coefficient intercept (at DH/T=0) are within about 5% of experimentally derived values. These errors combine to yield flow errors on the order of 5% for nominal area maps (i.e., nozzle area ratios equal to 1). Slightly higher values may occur for other stator settings.

A typical comparison between measured and calculated values of the turbine flow function is shown in Figure 6. This figure is for test turbine number 25 in Table I. The maximum error shown on this figure is about 2.4% and occurs at the lower end of the test data. This type of plot was used in obtaining the error estimates given above.

7.3 TURBINE LOSS MODEL

There are four key steps in the development of the equations governing the turbine off-design loss model. These steps are

1. The development of an equation giving the turbine total-to-total efficiency at a general point in terms of nozzle and bucket efficiencies coupled with a semiempirical loss term due to the departure of the rotor incidence angle from the optimum.

2. The transformation of the semiempirical incidence angle loss law so as to eliminate the explicit occurrence of the incidence angle by introducing the stage loading.

3. The differentiation of the resulting efficiency expression in order to obtain the locus of peak efficiencies. This peak efficiency ridge then becomes the "backbone" of the map.

4. The substitution of the peak efficiency relationships back into the general efficiency equation in order to obtain an expression for the "off-backbone" loss.

The development of the efficiency expression proceeds from the (h,s) diagram for adiabatic flow through a two-dimensional turbine stage as shown in the following sketch.

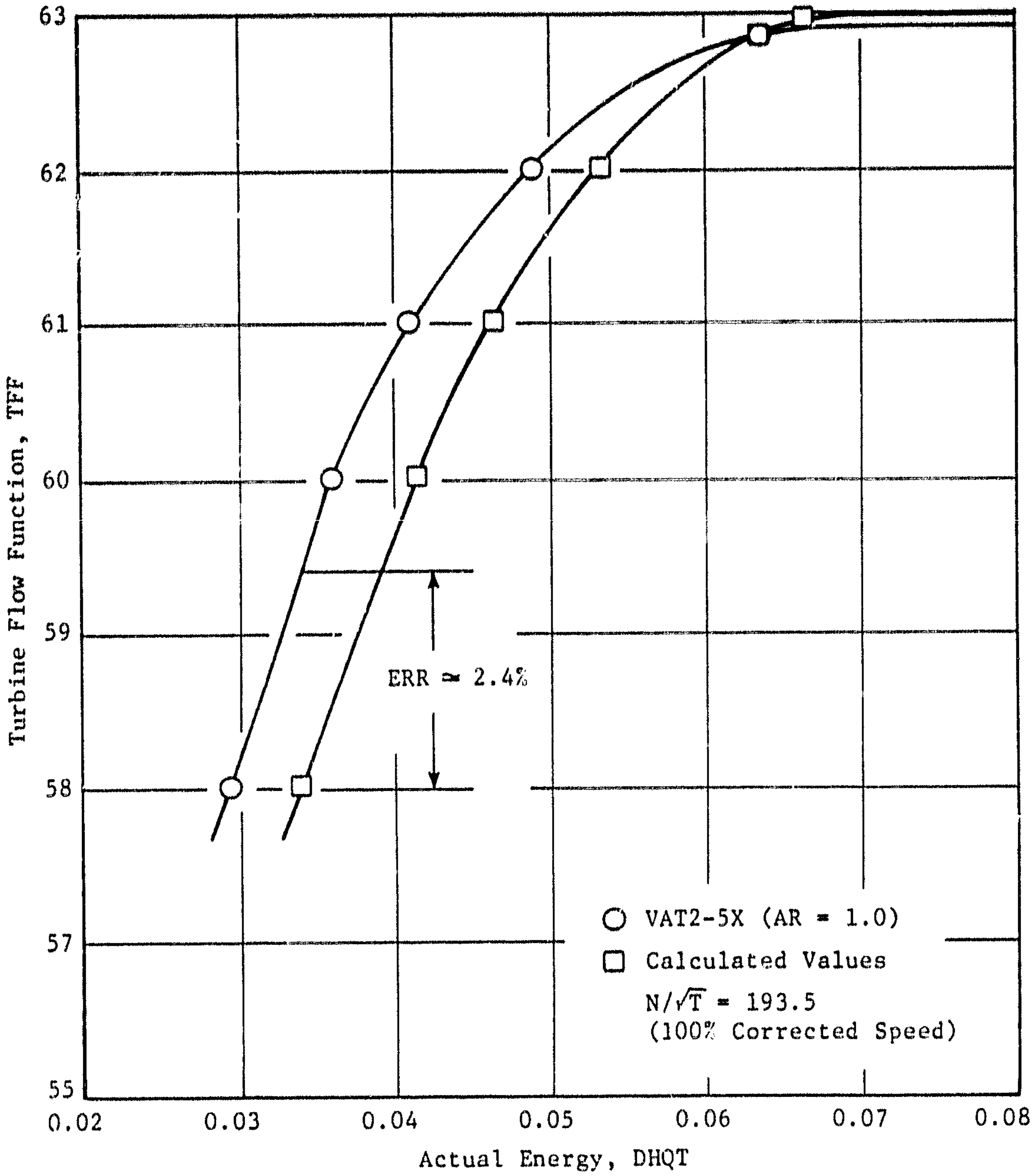
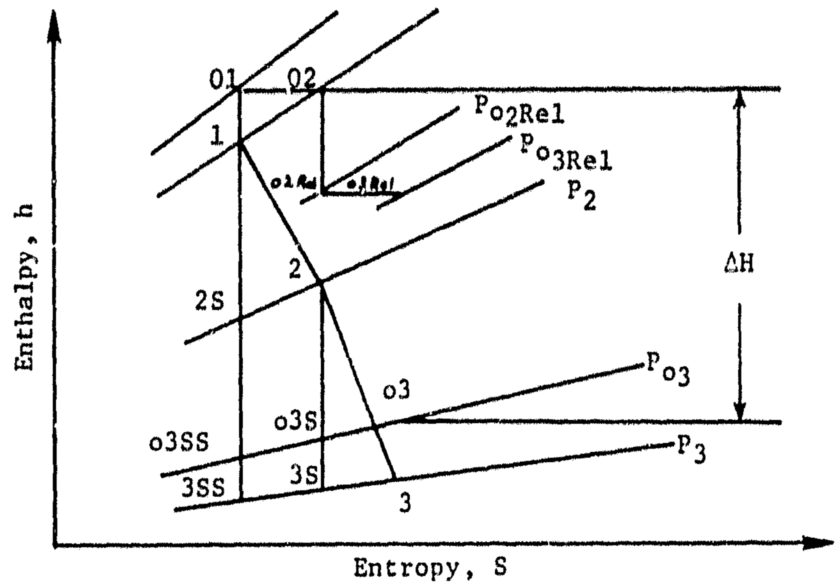


Figure 6. Comparison of Measured and Calculated Values of Inlet Turbine Flow Function.



Enthalpy-Entropy Diagram for a Turbine Stage

Using the station numbers shown in the above sketch, the definition of turbine total-to-total efficiency may be written in the form:

$$\eta_{TT} = \frac{\Delta H}{\Delta H + \frac{T_{o3}}{T_3}(h_3 - h_{3s}) + \frac{T_{o3s}}{T_2}(h_2 - h_{2s})} \qquad (4)$$

By definition, the nozzle efficiency is equal to the ratio of the actual nozzle exit kinetic energy to the ideal nozzle exit kinetic energy. A similar definition in terms of relative velocities holds for the bucket efficiency. For off-design calculations at any incidence angle (i), an additional loss term must be included, i.e.,

$$h_3 - h_{3s} = \left(1 - \frac{1}{\eta_B}\right)\frac{W_3^{\,2}}{2g_oJ} + \left(1 - \mathrm{Cos}^2(i)\right)\frac{W_2^{\,2}}{2g_oJ} \qquad (5)$$

where

η_N = nozzle efficiency
η_B = bucket efficiency
W_2 = bucket inlet relative velocity
W_3 = bucket exit relative velocity

The semiempirical incidence angle loss law is based on the assumption that the kinetic energy of the component of velocity normal to the optimum incidence angle is lost. This is a fairly standard assumption (see, for example, Reference 4). Powers other than 2 are frequently used on the cosine.

Before introducing the incidence angle loss term into the efficiency expression, it was transformed into the following expression

$$\left(1 - \text{Cos}^2(i)\right) \frac{W_2^{\,2}}{2g_oJ} = \frac{U^2}{2g_oJ} \text{Cos}^2\ \beta_{2op} \left(\frac{\phi_2}{\phi_{2op}} - 1\right)^2 \tag{6}$$

The stage characteristic was then used to substitute for flow coefficient in terms of stage loading. The substitution of this results into the expression for efficiency yielded, after simplifying, the following results.

$$\psi \left(\frac{1}{\eta_{TT}} - 1\right) = A\ (2\psi + 1)^2 + B\ (\psi - \psi_{op})^2 \tag{7}$$

where

$$A = \frac{1}{4}\ \frac{\left[\frac{T_{o3}}{T_3}\left(\frac{1}{\eta_\beta} - 1\right)\left(\frac{C_{z3}}{C_{z2}}\right)^2 \frac{1}{\text{Cos}^2\beta_3} + \frac{T_{o3_S}}{T_2}\left(\frac{1}{\eta_N} - 1\right)\frac{1}{\text{Cos}^2\alpha_2}\right]}{\left[\tan\ \alpha_2 + \frac{C_{z3}}{C_{z2}}\tan\ \beta_3\right]^2} \tag{8}$$

$$B = \frac{T_{03}}{T_{02}}\ \frac{\text{Cos}^2\ \beta_{2op}}{(2\psi_{op} + 1)^2} \tag{9}$$

The temperature ratios in Equations 8 and 9 are of order one as i[illegible] the bucket axial velocity ratio. If these ratios together with the blad[illegible]w efficiencies and exit flow angles are assumed to remain constant then Equation 7 can be differentiated, and the peak efficiency point located.

$$\psi_{pk} = \sqrt{\frac{A+B\ \psi_{op}^{\,2}}{A+B}} \tag{10}$$

$$\frac{1}{\eta_{pk}} - 1 = \frac{A\ (2\ \psi_{pk} + 1)^2 + B\ (\psi_{pk} - \psi_{op})^2}{\psi_{pk}} \tag{11}$$

Note that if the nozzle and bucket efficiencies equal unity in Equation (9), then A = 0.0. Then there is no loss other than incidence and $\psi_{pk} = \psi_{op}$ as expected.

By substituting Equations 10 and 11 into Equation 7, the following expression for "off-backbone" loss can be obtained.

$$\frac{\psi}{\psi_{pk}}\left(\frac{1}{\eta} - \frac{1}{\eta_{pk}}\right) = \psi_{pk}\ (4A + B)\left(\frac{\psi}{\psi_{pk}} - 1\right)^2 \tag{12}$$

Equations 10, 11, and 12 give the location of the peak efficiency, the magnitude of the peak efficiency, and the variation in efficiency as we move away from the peak.

These equations represent the stage loss characteristic of a turbine. The design point information is used to obtain the initial values of A and B as well as the values of the blade row efficiencies and metal angles. The loss equations are then applied at incremental values of DHQT starting at zero to obtain the turbine efficiencies. Approximate relationships are used for temperature and velocity ratios to obtain new values of A and B for each DHQT.

Typically, the calculated values of the loss slopes and those obtained from air turbine test data are within about 5% for corrected speeds within plus or minus 20% of the design point value. The values of the "backbone efficiencies" generated by the above equations do not include either Reynold's Number effects or the severe rotor exit losses encountered near exit annulus choke. In order to account for these effects, the loss along the peak efficiency ridge was empirically modified using the results of the NASA air turbine tests. Although relatively good correlation existed between the different test turbines at low values of DHQT, the drop in efficiency in the neighborhood of exit annulus choke was so severe that correlation was difficult. For this reason, variations in efficiency on the order of 5% can be obtained in this region.

A comparison between measured and calculated values of the turbine total-to-total efficiency is shown in Figure 7. This figure is for test turbine number 25 in Table I. The maximum error shown on this figure is about 0.8%. This type of plot was used in obtaining the error estimates given above.

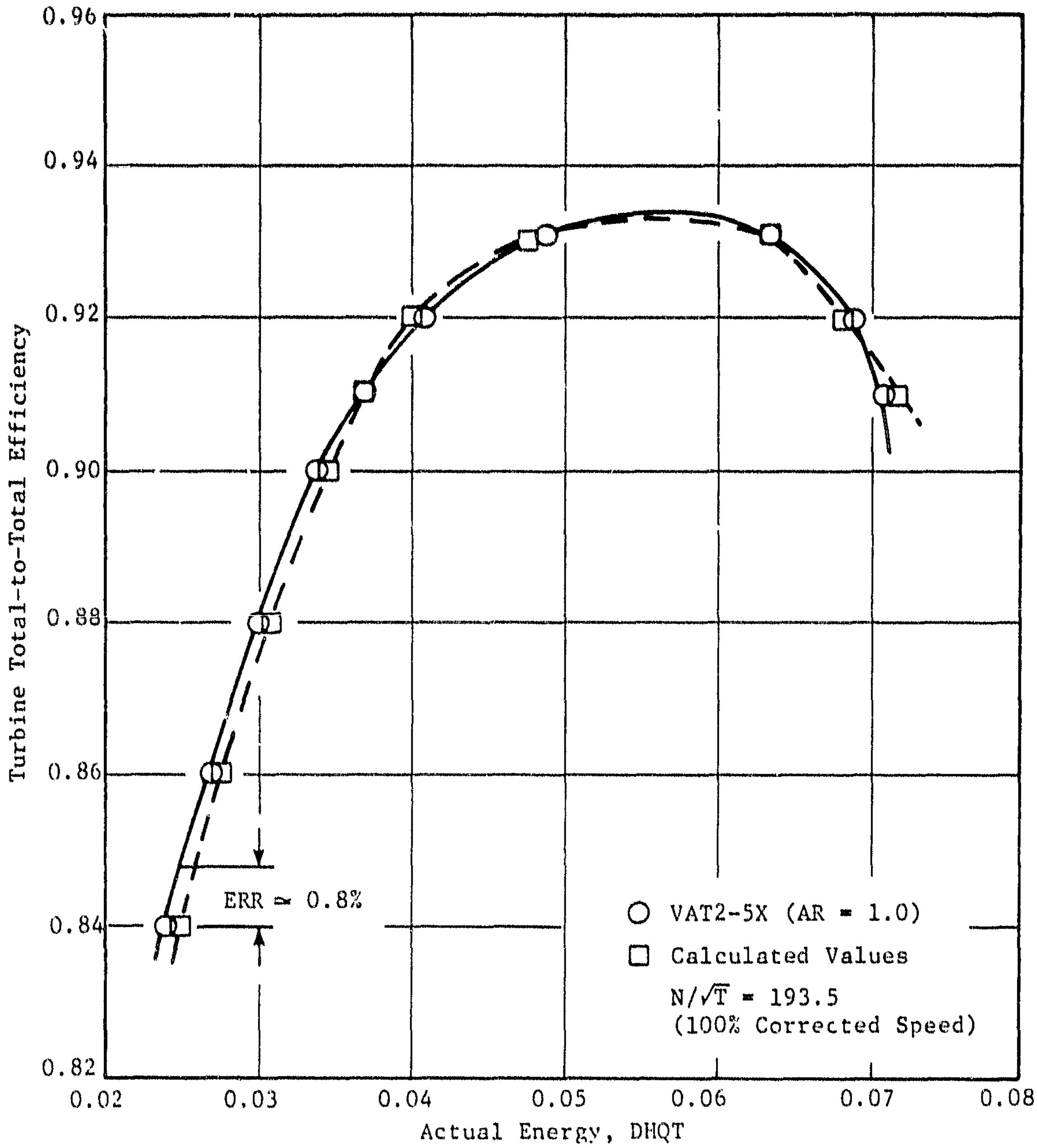


Figure 7. Comparison of Measured and Calculated Values of Total-to-Total Efficiency.

LIST OF SYMBOLS

A, a	Constants
B, b	Constants
C	Velocity, fps
Cp	Constant Pressure Specific Heat, Btu/lbm°R
go	Dimensional Constant, 32.17 ft lbm/lbf sec^2
h	Enthalpy, Btu/lbm
i	Incidence Angle ($i = \beta_2 - \beta_{2op}$), degrees
J	Mechanical Equivalent of Heat, 778.16 ft. lbf/Btu
N	Speed, rpm
P	Pressure, psia
Rg	Gas Constant, 53. 35 ft lbf/lbm°R
S	Entropy, Btu/lbm°R
T	Absolute Temperature, ° R
U	Wheel Speed, fps
W	Relative Velocity, fps
α	Angle of Absolute Velocity With Axial, degrees
β	Angle of Relative Velocity Vector With Axial, degrees
ΔH	Drop in Total Enthalpy, Btu/lbm
r	Ratio of Specific Heats
λ	Enthalpy Loss Coefficient
ρ	Fluid Density, lbm/ft^3
θ	Ratio or Total Temperature to Standard Temperature
ψ	Turbine Stage Loading [$\psi = \Delta H/(2U^2/g_oJ)$]
ϕ	Flow Coefficient ($\phi = C_z/U$)
η	Efficiency

Subscripts

1	Nozzle Inlet
2	Rotor Inlet
3	Rotor Exit
B	Bucket
d	Design Point Value
N	Nozzle
O	Stagnation
op	Optimum
pk	Peak
TT	Total-to-Total
S	Isentropic
z	Axial

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