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P. 29

NASA Contractor Report 189118

# Users Manual and Modeling Improvements for Axial Turbine Design and Performance Computer Code TD2-2

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March 1992

Prepared for  
Lewis Research Center  
Under Grant NAG3-1165



(NASA-CR-189118) USERS MANUAL AND MODELING  
IMPROVEMENTS FOR AXIAL TURBINE DESIGN AND  
PERFORMANCE COMPUTER CODE TD2-2 Final Report  
(Toledo Univ.) 29 p

N92-27376

Unclas  
0099198

G3/02



# USERS MANUAL AND MODELING IMPROVEMENTS FOR AXIAL TURBINE DESIGN AND PERFORMANCE COMPUTER CODE TD2-2

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## SUMMARY

Computer code TD2 is used to study and select design geometries for axial-flow turbines. Improved modeling was incorporated into this code, which computes design-point gas velocities, gas angles, and efficiency for multistage, multishaft, cooled or uncooled, axial-flow turbines. The code is based on a streamline analysis that can use meridional velocity gradients as a primary design variable. An internal correlation is used to determine blade-row total-pressure-loss coefficients along the streamlines.

The modeling improvements made to code TD2 were related to turbine cooling and to the internal loss correlation. With regard to turbine cooling: (1) an option was added to compute coolant flow rate for each blade row, (2) coolant specific heat was made to be a function of coolant temperature instead of being assumed equal to main-stream specific heat, (3) coolant pressure was input for each of the blade rows instead of being assumed equal to turbine-inlet pressure, and (4) stage efficiency loss due to cooling was added as an optional input and incorporated directly into the blade-row streamline loss calculation. With regard to the internal loss correlation, a Reynolds number dependency was added, and the coefficients were calibrated to produce best agreement between calculated efficiencies and measured efficiencies for a data base of 10 turbines. The resultant average deviation was about 1 point in efficiency.

This report presents the improved modeling and serves as a users manual for the upgraded Fortran code, which is renamed TD2-2. The modified analysis methods and the revised loss correlation are given. Program input and output, which contain some additions to those of the original code, are described. A sample case for a cooled turbine is included.

## INTRODUCTION

One of the first steps in the design of a turbine is the study and selection of stage number, flow path annulus, flow angles and velocities, and the resultant turbine efficiency. A computer code that can be used to accomplish this process for a multistage, multishaft, cooled or uncooled, axial-flow turbine is the TD2 code presented in reference 1. It is based on a streamline analysis that can use meridional velocity gradients as a primary design variable, and it includes an internal correlation, developed in reference 2, for blade-element total-pressure-loss coefficient. The use of meridional velocity gradients rather than tangential velocity gradients for the stators and work gradients for the rotors was an innovative approach that largely eliminated the input specification of gradients having either no solution at all or no acceptable solution.

A recent evaluation of the TD2 code indicated a need for improved modeling, partly to correct deficiencies and partly to enhance capabilities. Modeling deficiencies included the assumption of coolant specific heat being equal to main-stream specific heat, the assumption of coolant inlet pressure being

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equal to main-stream inlet pressure and, most serious of all, failure of the internal loss correlation to provide adequate estimates of efficiencies for turbines whose design characteristics (loading, reaction, Mach number) fall outside the limited range of characteristics of those turbines from which the correlation was developed. Code enhancements deemed desirable included the computation of coolant flow rates and the incorporation of stage-efficiency loss due to cooling directly into the blade-row design calculation.

The improved modeling used for code TD2 is presented herein. This report also serves as a users manual for the upgraded Fortran code, which is renamed TD2-2. Program input and output, which include some additions, are described. A sample case for a cooled turbine is included.

## SYMBOLS

$a_1, \dots, a_8$	coefficients for loss correlation, eq. (12) or (14)
$c_p$	heat capacity, Btu/(lb)(°R)
$f$	fuel-to-air mass ratio
$K$	loss coefficient correction factor for cooling
$n$	number of stages
$P$	power, Btu/sec
$p$	total pressure, lb/ft <sup>2</sup>
$Re$	Reynolds number
$r$	radius, ft
$T$	total temperature, °R
$V$	gas velocity, ft/sec
$w$	mass flow rate, lb/sec
$Y$	total-pressure loss coefficient
$y$	ratio of blade-row cooling flow to stage-inlet mainstream flow
$\beta$	flow angle from axial direction, deg
$\gamma$	specific heat ratio
$\delta$	stage-efficiency specific loss due to cooling
$\eta$	efficiency
$\mu$	viscosity, lb/(sec)(ft)

### Subscripts:

$c$	coolant or cooled
$ex$	stage or turbine exit
$i$	dummy index for blade row number
$id$	ideal
$in$	stage or turbine inlet
$m$	main stream
$mix$	value after coolant and mainstream mixing
$p$	primary (i.e., value at turbine inlet)
$ro$	rotor
$rp$	rotor primary
$st$	stator
$static$	static value
$th$	thermodynamic
$tp$	turbine primary

unc      uncooled  
1        first stator of turbine

Superscripts:

\*        value based on constant heat capacity  
—        average value

## MODELING IMPROVEMENTS

Computer code TD2 computes design-point velocity diagrams and performance for multistage, multishaft, cooled or uncooled, axial-flow turbines. The basic model for the analysis consists of a series of streamlines that trace the path of the flow from known conditions at the inlet to the final calculation station at the exit. With the assumption of axisymmetric flow, the streamlines define a series of annular streamtubes, each containing a fixed fraction of the flow, as represented by the meridional section shown in figure 1. Calculations are made at the indicated design stations, which are located between the blade rows as shown in figure 1.

A recent evaluation of the TD2 analysis indicated a need for modeling improvements related to turbine cooling as well as to the internal loss correlation. These were made partly to correct deficiencies and partly to enhance capabilities.

### Turbine Cooling

The modeling in code TD2 was based on the assumption of coolant specific heat being equal to main-stream specific heat for both coolant and main-stream mixing and turbine (or stage) ideal power. Ideal power was also based on the assumption of coolant inlet pressure equal to turbine inlet pressure. Improved modeling in these areas are addressed herein. Also, options were added to the code to compute coolant flow rate for each blade row and to incorporate an input stage-efficiency loss due to cooling directly into the blade-row streamline calculation. Finally, additional values of turbine total efficiency based on alternative definitions of ideal power were computed and displayed.

Specific heat. — Coolant specific heat was related to temperature by an equation obtained from reference 3 and shown in table I. This is a general equation for the specific heat of air with a given initial humidity  $W$  and containing products of combustion of a hydrocarbon fuel with a hydrogen-to-carbon mass ratio, HOC. The value of HOC used in table I is for a typical jet fuel such as JP-4 or JetA. For the coolant, the fuel-to-air ratio  $f$  is set to zero. An option is provided to also use this equation for the turbine main-stream flow instead of using input values of specific heat at each station. For that usage, a value for  $f$  can be included in the input.

Mixing. — The heat balance for the mixing of coolant and main stream in code TD2 was based on constant specific heat:

$$T_{\text{mix}}^* = \frac{w_m T_m + w_c T_c}{w_m + w_c} \quad (1)$$

For code TD2-2, this has been modified to

$$T_{\text{mix}} = \frac{w_m \bar{c}_{p,m} T_m + w_c \bar{c}_{p,c} T_c}{w_m \bar{c}_{p,m} + w_c \bar{c}_{p,c}} \quad (2)$$

where the  $\bar{c}_p$  are the average specific heat values between the initial temperature of a stream and the mixed temperature.

Where products of combustion are present, the fuel-to-air ratio after mixing of main stream and coolant in each blade row is

$$f_{\text{mix}} = \frac{f_m}{1 + \frac{w_c}{w_m} (1 + f_m)} \quad (3)$$

This fuel-to-air ratio is used for the calculation of specific heat (table I).

**Ideal power.** — Turbine ideal power is used to define a turbine efficiency. In code TD2, turbine ideal power was based on coolant specific heat and inlet pressure assumed equal to turbine-inlet specific heat and inlet pressure, respectively.

$$P_{\text{id}}^* = \bar{c}_{p,p} (w_p T_p + w_c T_c) \left[ 1 - \left( \frac{P_{\text{ex}}}{P_{\text{in,p}}} \right)^{(\gamma-1)/\gamma} \right] \quad (4)$$

To account for the differences between turbine-inlet and coolant values of specific heat and inlet pressure, the turbine ideal power in code TD2-2 is calculated as

$$P_{\text{id,th}} = w_p \bar{c}_{p,p} T_p \left[ 1 - \left( \frac{P_{\text{ex}}}{P_{\text{in,p}}} \right)^{(\gamma-1)/\gamma} \right] + \sum_{i=1}^{2n} w_{c,i} \bar{c}_{p,c,i} T_{c,i} \left[ 1 - \left( \frac{P_{\text{ex}}}{P_{c,i}} \right)^{(\gamma-1)/\gamma} \right] \quad (5)$$

The above definition of ideal power includes all the coolant flows and yields a turbine efficiency called thermodynamic efficiency. There are alternative definitions of ideal power that differ in the amount of coolant included. For rotor primary efficiency, ideal power is defined

$$P_{\text{id,rp}} = w_p \bar{c}_{p,p} T_p \left[ 1 - \left( \frac{P_{\text{ex}}}{P_{\text{in,p}}} \right)^{(\gamma-1)/\gamma} \right] + w_{c,1} \bar{c}_{p,c,1} T_{c,1} \left[ 1 - \left( \frac{P_{\text{ex}}}{P_{c,1}} \right)^{(\gamma-1)/\gamma} \right] \quad (6)$$

while, for turbine primary efficiency,

$$P_{id,tp} = w_p \bar{c}_{p,p} T_p \left[ 1 - \left( \frac{P_{ex}}{P_{in,p}} \right)^{(\gamma-1)/\gamma} \right] \quad (7)$$

The calculation and presentation of these primary efficiencies have been added to code TD2-2.

**Coolant flow rate.** — The algorithm of reference 4 can be optionally used to compute a coolant flow rate for each blade row. This is the same algorithm that is used in the NNEP cycle code (ref. 5). When using this option, additional input specifying vane and blade metal temperatures and cooling configuration are required.

**Cooling loss.** — Reference 4 uses assigned values of stage-efficiency specific loss, which is defined as

$$\delta = \frac{\Delta\eta}{\eta_{unc} y} \quad (8)$$

for stator and rotor to determine stage-efficiency loss due to cooling.

$$\frac{\eta_c}{\eta_{unc}} = 1 - y_{st} \delta_{st} - y_{ro} \delta_{ro} \quad (9)$$

To incorporate this loss into the TD2-2 design calculation requires determination of a corresponding increase in blade-row total-pressure loss coefficient  $Y$ . This is done by defining a loss-coefficient correction factor  $K$  such that

$$Y_{st,c} = (1 + y_{st} K) Y_{st,unc} \quad (10a)$$

and

$$Y_{ro,c} = (1 + 2y_{ro} K) Y_{ro,unc} \quad (10b)$$

Code TD2-2 first finds the uncooled solution and then estimates the value of  $K$  needed to produce the required value of  $\eta_c/\eta_{unc}$ .

#### Loss Correlation

Losses in code TD2 are determined by means of blade-row total-pressure loss coefficients

$$Y = \frac{P_{in} - P_{ex}}{P_{ex} - P_{ex,static}} \quad (11)$$

that can be either directly input or calculated internally. The internal correlation developed in reference 2 for code TD2 is for  $V_{in}/V_{ex} \geq a_3$

$$Y = \frac{|\tan \beta_{in} - \tan \beta_{ex}|}{a_4 + a_5 \cos \beta_{ex}} \left[ a_1 + a_2 \left( \frac{V_{in}}{V_{ex}} - a_3 \right) \right] \quad (12a)$$

and for  $V_{in}/V_{ex} < a_3$

$$Y = \frac{|\tan \beta_{in} - \tan \beta_{ex}|}{a_4 + a_5 \cos \beta_{ex}} \left[ a_6 + a_7 \left( \frac{V_{in}}{V_{ex}} \right)^{a_8} \right] \quad (12b)$$

with recommended coefficient values of

$a_1 = 0.055$	$a_5 = 0.8$
$a_2 = 0.15$	$a_6 = 0.03$
$a_3 = 0.6$	$a_7 = 0.157255$
$a_4 = 0.6$	$a_8 = 3.6$

This analytical correlation came from the experimentally based stage-efficiency correlation of reference 6 along with the following assumptions:

- (1) Rotor and stator loss coefficients were equal when their relative design requirements are identical.
- (2) Stage reaction at the mean line was 50 percent.
- (3) Axial velocity was constant through the stage.
- (4) Stator exit Mach number was 0.8.

Most of the stages used for the experimental correlation had a work factor of between 1 and 2, and none was higher than 2.4.

The aforementioned analytical correlation was evaluated in this study using 10 turbines (refs. 7 to 16) that were designed for airbreathing engine applications and were performance tested in component facilities. These turbines represent the output of several different design systems and cover a wide range of design characteristics. Six of the turbines were designed and tested by NASA, two were designed and tested by General Electric Co. (G.E.), and two were designed by Pratt & Whitney (P&W), one being tested by P&W and the other by NASA. The characteristics of these turbines are presented in table II. The number of stages varies from 1 to 5, stage work factor from 1.2 to 4.7, average stator angle from 51 to 80°, mean diameter (except for one) from 47 to 69 cm (18 to 27 in.), and exit radius ratio from 0.50 to 0.86. All the listed total efficiencies except for two were as measured. In those two cases, corrections were made to account for the effects of a large discrepancy in flow rate from design intent (ref. 8) and larger than normal tip clearance and trailing-edge thicknesses (ref. 12).

These turbines were modeled as closely as possible for the subject computer program, and design performance was computed. For the three turbines with the highest work factors, turbine efficiency was grossly underpredicted (by 10 to 15 points). It was noted that these three turbines had, by far, the lowest blade-row reactions  $(1 - V_{in}/V_{ex})$ , which is a factor in the loss correlation equations (12a) and (12b). Further, the efficiency of the one turbine with very high reaction was being overpredicted by several points. It was apparent that the velocity ratio  $V_{in}/V_{ex}$  dependency was too severe. In fact, the best comparisons were obtained by removing the velocity ratio dependency.



Further adjustments were made by multiplying each loss coefficient by an overall Reynolds number correction

$$f(\text{Re}) = \left( \frac{w}{2 \times 10^6 \mu r} \right)^{-0.2} \quad (13)$$

and fine-tuning the coefficients ( $a_4$  and  $a_5$ ) of the exit-angle dependency. Calibration of the proportional constant  $a_1 = a_6$  to best fit the experimental data then completed the revision of the internal loss correlation.

Except for the Reynolds number correction, equations (12a) and (12b) can be used to represent the modified correlation. Therefore, to retain consistency with the original computer code and to maintain some generality that would allow for future modifications, the general format of the original loss correlation was retained in the computer code. The loss correlation for code TD2-2 is, therefore, expressed as, for  $V_{\text{in}}/V_{\text{ex}} \geq a_3$ ,

$$Y = \frac{|\tan \beta_{\text{in}} - \tan \beta_{\text{ex}}|}{a_4 + a_5 \cos \beta_{\text{ex}}} \left[ a_1 + a_2 \left( \frac{V_{\text{in}}}{V_{\text{ex}}} - a_3 \right) \right] \left( \frac{w}{2 \times 10^6 \mu r} \right)^{-0.2} \quad (14a)$$

and, for  $V_{\text{in}}/V_{\text{ex}} < a_3$ ,

$$Y = \frac{|\tan \beta_{\text{in}} - \tan \beta_{\text{ex}}|}{a_4 + a_5 \cos \beta_{\text{ex}}} \left[ a_6 + a_7 \left( \frac{V_{\text{in}}}{V_{\text{ex}}} \right)^{a_8} \right] \left( \frac{w}{2 \times 10^6 \mu r} \right)^{-0.2} \quad (14b)$$

and the recommended coefficient values are

$$\begin{aligned} a_1 &= a_6 = 0.057 \\ a_2 &= a_7 = 0.0 \\ a_3 &= a_8 = 0.0 \text{ (actually, these can be arbitrary)} \\ a_4 &= 1.0 \\ a_5 &= 1.5 \end{aligned}$$

These coefficient values have been programmed into TD2-2 but they can be overwritten by input.

The efficiencies computed by code TD2-2 using this revised correlation are compared with the measured efficiencies in figure 2. The average deviation between the calculated and measured efficiencies for the 10 turbines is about 1 point. The maximum deviation, which occurred for two of the turbines, was about 2 points on the high side (i.e., high prediction). Interestingly enough, there are reasons to explain the overprediction for these two turbines. One of these turbines was the only "small" turbine in the data base, having a diameter one-half, or less, of any of the others, and the loss correlation does not account for size effects associated with clearances and surface roughness. The second turbine had flow angles that were at least  $10^\circ$  less than those of any of the other turbines, and the decrease in loss with reduced angle very possibly does not continue into that region in the manner specified by the correlation.

## DESCRIPTION OF INPUT AND OUTPUT

This section presents a detailed description of program input, normal output, and error messages. Included in the input and output sections is a sample case for a cooled turbine.

## Input

**General input.** — The major part of this section is taken directly from reference 1. The physical input data used by program TD2-2 can be divided into three categories: input options, general design requirements, and spool design requirements and analysis variables. Input data in the first two categories are specified once for each turbine as a unit. Input data in the last category are specified for each spool of the turbine, if there is more than one spool, or for each set of analysis variables to be considered. New variables added to the code or additional allowable values for a variable are indicated by an asterisk to the left of the variable name or value.

The information required to prepare the input data for a typical case is furnished below. Each input item is described, as is the form in which the input items are written. The units of each input item is included in its description. Sample input for a cooled two-stage turbine is presented in table III.

The first group of input items read by program TD2-2 consists of a description of the case and the general input options. These items which appear in the following table, are read into the program using format statements. The case description given on the first line is read as an alphanumeric field; any combination of numbers, capital letters, punctuation, or blanks may be used. The general input options are read as integer fields.

Line	Location	Fortran symbol	Description
1	1-72	COMENT	A statement describing the case to be considered. This may <u>not</u> be omitted but may be left blank.
2	12	ISPEC	Indicator: ISPEC = 0 if values of total-pressure-loss coefficients as a function of radius are specified at each blade row exit. ISPEC = 1 if streamline values of total-pressure-loss coefficient are calculated from the internal correlation <u>without</u> an additional loss factor at each blade row exit. ISPEC = 2 if streamline values of total-pressure-loss coefficient are calculated from the internal correlation <u>with</u> an additional loss factor at each blade row exit.
	30	ICOOL	Indicator: ICOOL = 0 if this is an uncooled turbine. ICOOL = 1 if only a coolant mass flow schedule is specified in the input data. ICOOL = 2 if only coolant mass flow and total-temperature schedules are specified in the input data. * ICOOL = 3 if coolant mass-flow, total-temperature, and total-pressure schedules are specified in the input data. * ICOOL = 4 if a stage-efficiency specific-loss schedule is specified along with the coolant mass flow, total temperature, and total-pressure schedules. * ICOOL = 5 same as ICOOL=4 except that coolant mass flow is calculated (per ref. 4) rather than specified. (NOTE: if ICOOL = 4 or 5, see "Special cases" subheading at end of this Input section.)

Line	Location	Fortran symbol	Description
36		IMIX	Indicator: IMIX = 0 if a mixing schedule is <u>not</u> specified in the input data. IMIX = 1 if a mixing schedule is specified in the input data.
42		ISTRAC	Indicator: ISTRAC = 0 if the streamline angles of inclination and curvatures are calculated internally at each design station. ISTRAC = 1 if values of streamline angle of inclination and curvature as a function of radius are specified at each design station.
48		IDLETE	Indicator: IDLETE = 0 if only the converged results of the iteration loop on streamline position are to be printed at each design station. IDLETE = 1 if the results of each pass through the iteration loop on streamline position are to be printed at each design station.
54		IEXTRA	Indicator: IEXTRA = 0 if the results of the passes through the iteration loop on meridional velocity at the mean streamline are <u>not</u> to be printed. IEXTRA = 1 if the results of the passes through the iteration loop on meridional velocity at the mean streamline are to be printed when the results of a pass through iteration loop on streamline position are to be printed.

The remaining input items are read into program TD2-2 using NAMELIST statements. The namelist NAM1 is used to read the input items which include the general design requirements. The items in NAM1 are as follows:

Fortran symbol	Description
NSPOOL	Number of spools of the turbine being considered. 1, 2, or 3 spools are allowed.
NAV	Number of sets of analysis variables. Any number is allowed if NSPOOL = 1. But only one set of analysis variables is allowed if NSPOOL > 1 and NAV need not be specified. If ICOOL > 3, NAV must = 2.
NLINES	Number of streamlines to be used in the calculations (including the hub and casing streamlines). Any odd number from 3 to 17 is allowed.
GASC	Gas constant of the working fluid, ft·lbf/lbm·°R.

Fortran symbol	Description
FLWM	Mass flow rate at the inlet of the turbine, lbm/sec.
*FAR	Fuel-to-air ratio of inlet flow (default value = 0.0).
NLT	Number of radii at which the inlet conditions of the turbine are specified; any number from 1 to 17 is allowed.
(RLT(J), J=1,NLT)	Radial coordinates at which the inlet conditions of the turbine are specified, in. The values of RLT must be monotonically increasing.
(TOLT(J), J=1,NLT)	Values of the absolute total temperature at the inlet of the turbine corresponding to the radial coordinates RLT, °R.
(POLT(J), J=1,NLT)	Values of the absolute total pressure at the inlet of the turbine corresponding to the radial coordinates RLT, psi.
(BETLT(J), J=1,NLT)	Values of the absolute flow angle at the inlet of the turbine corresponding to the radial coordinates RLT, deg.

The namelist NAM2 is used to read the input items for a spool, including the spool design requirements and the spool analysis variables. Each spool of the turbine, or each set of analysis variables, is specified in separate namelist groups. The items in NAM2 are as follows:

Fortran symbol	Description
RPM	Rotative speed of the spool, rpm.
HP	Power output of the spool, hp.
NSTG	Number of stages on the spool. Any number from 1 to 8 is allowed.
(FHP(I), I=1,NSTG)	Power output of each stage of the spool, expressed as a fraction of the total power output of the spool.
*(CP(I), I=1,NDSTAT)	Specific heat at constant pressure of the working fluid at each design station of the spool (where NDSTAT = 2*NSTG + 1), Btu/lbm·°R. (If CP(1) is omitted or set = 0.0, specific heat for air with inlet fuel-to-air ratio FAR is computed internally.)
*VISC	Viscosity of the working fluid at spool inlet, lbm/ft·sec.

Fortran symbol	Description
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If ISTRAC = 0, the following three items must be included.

(XSTAT(I),  
I=1,NSTAT)      Axial coordinate of each station of the spool (where NSTAT = 2\*NSTG + 3), in.

(RANN(I,1),  
I=1,NSTAT)      Radial coordinate of the hub at each station of the spool, in.

(RANN(I,2),  
I=1,NSTAT)      Radial coordinate of the casing at each station of the spool, in.

If ISTRAC = 1, the following six items must be included.

(RANN(I,1),  
I=1,NDSTAT)      Radial coordinate of the hub at each design station of the spool, in.

(RANN(I,2),  
I=1,NDSTAT)      Radial coordinate of the casing at each design station of the spool, in.

NSTRAC      Number of radii at which streamline angles of inclination and curvatures are specified at each design station of the spool. Any number from 1 to 17 is allowed.

((RSTRAC(J,I),  
J=1,NSTRAC),  
I=1,NDSTAT)      Radial coordinates at which streamline angles of inclination and curvatures are specified at each design station of the spool, in. The values of RSTRAC at each design station must be monotonically increasing.

((ASTR(J,I),  
J=1,NSTRAC),  
I=1,NDSTAT)      Values of the streamline angle of inclination of each design station of the spool corresponding to the radial coordinates RSTRAC, deg.

((CSTR(J,I),  
J=1,NSTRAC),  
I=1,NDSTAT)      Values of the streamline curvature at each design station of the spool corresponding to the radial coordinates RSTRAC, in.<sup>-1</sup>.

(FLWCN(I),  
I=1,NBR)      Mass flow of the coolant added in each blade row of the spool (where NBR = 2\*NSTG), expressed as a fraction of the inlet mass flow of the turbine; this item should be omitted if ICOOL = 0.

(TOC(I),  
I=1,NBR)      Absolute total temperature of the coolant added in each blade row of the spool, °R. This item should be included if ICOOL > 1.

Fortran symbol	Description
*POC(I), I=1,NBR)	Absolute total pressure of the coolant added in each blade row of the spool, psi. This item should be included if ICOOL > 2.
*DELE(I) I=1,NBR)	Stage-efficiency specific loss for each blade row of the spool. This item should be included if ICOOL > 3.
If ICOOL = 5, the following three items must be included:	
*FACTOR	Coolant flow weighting factor (ref. 4).
*TMVANE	Allowable metal temperature for stator vanes, °R.
*TMBLADE	Allowable metal temperature for rotor blades, °R.
((XMIX(J,I), J=1,NLINES), I=1,NBR)	Streamline values of the mixing coefficient for each blade row of the spool. This item should be omitted if IMIX = 0.
NXT	Number of radii at which the exit conditions of each blade row of the spool are specified. Any number from 1 to 17 is allowed.
(IWRL(I), I=1,NSTG)	Indicator: IWRL(I)=0 if values of the derivative of meridional velocity with respect to radius, (in reciprocal seconds), are specified as a function of radius at a stator exit of the spool. IWRL(I)=1 if values of flow angle (in degrees), are specified as a function of radius at a stator exit of the spool and the subsonic solution is desired. IWRL(I)=2 if values of flow angle, (in degrees), are specified as a function of radius at a stator exit of the spool and the supersonic solution is desired.
((RNXT(J,I), J=1,NXT), I=1,NSTG)	Radial coordinates at which the exit conditions of each stator of the spool are specified, in. The values of RNXT at each stator exit must be monotonically increasing.
The following two items should be given for each stage for which IWRL(I)=0:	
(VUM(I), I=1,NSTG)	Values of whirl velocity at the mean streamline, ft/sec.
((DVMDR(J,2*I-1), J=1,NXT), I=1,NSTG)	Values of the derivative of meridional velocity with respect to radius at a stator exit of the spool corresponding to the radial coordinates RNXT, sec <sup>-1</sup> .

Fortran symbol	Description
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The following item should be given for each stage for which  $IWRL(I) = 1$  or  $2$ :

((WRL(J,I),  
J=1,NXT),  
I=1,NSTG)                      Values of flow angle, deg, at a stator exit of the spool corresponding to the radial coordinates RNXT.

(IPOF(I),  
I=1,NSTG)                      Indicator:  
IPOF(I)=0 if a uniform power output distribution is desired at a stage exit of the spool.  
IPOF(I)=1 if a gradient of meridional velocity will be specified at a stage exit of the spool.

If IPOF(I) = 1, the following item must be included:

((DVMDR(J,2\*I),  
J=1,NXT),  
I=1,NSTG)                      Values of the derivative of meridional velocity with respect to radius, at a stage exit of the spool corresponding to the radial coordinates RSXT,  $\text{sec}^{-1}$ .

If IPOF(I) = 1 or ISPEC = 0 or 2, the following item must be included:

((RSXT(J,I),  
J=1,NXT),  
I=1,NSTG)                      Radial coordinates at which the exit conditions of each stage of the spool are specified. The values of RSXT at each stage exit must be monotonically increasing.

If ISPEC = 0 or 2, the following two items must be included:

((YOSS(J,2\*I-1),  
J=1,NXT),  
I=1,NSTG)                      Values of the loss coefficient (if ISPEC=0) or an additional loss factor (if ISPEC=2) at each stator exit of the spool corresponding to the radial coordinates RNXT.

((YOSS(J,2\*I),  
J=1,NXT),  
I=1,NSTG)                      Values of the loss coefficient (if ISPEC=0) or an additional loss factor (if ISPEC=2) at each stage exit of the spool corresponding to the radial coordinates RSXT.

If ISPEC = 1 or 2 and the default values (see eqs. (14a) and (14b)) are not acceptable, the following item must be included:

\*(YCON(I),  
I=1,9)                      Value of the nine constants which define the internal loss correlation (see eqs. (14a) and (14b)) for default values).

This completes the input data description for a single spool, one spool of a multispool design, or one set of analysis variables. For each new case, the complete input specification from "line 1," the comment card, will be required. For additional spools or sets of analysis variables, the input specification returns to the beginning of the NAM2 namelist. When more than one set of analysis variables is used, any quantity that is not explicitly reset will remain unchanged from the value previously specified.

**Special cases.** — There are two special cases requiring a specific combination of inputs in order to achieve the desired outcome. One is a turbine with an exit guide vane, and the other is a cooled turbine for which a stage-efficiency specific loss due to cooling is incorporated into the design calculation.

For a turbine with  $n$  stages plus an exit guide vane (EGV), often referred to as an  $n + 1/2$  stage turbine, the following variables must be set as shown, and the reasons for doing so are indicated.

$NSTG = n + 1$	Provides for the additional blade row
$FHP(n + 1) = 0.0$	Sets average power output of $(n + 1)^{th}$ stage equal to zero
$IPOF(n + 1) = 0$	Results in power extraction for each streamline in $(n + 1)^{th}$ rotor to be equal to the average value of zero
$ISPEC = 0$ or $2$	Allows external specification of loss or loss modifier
$YOSS(J, 2n + 2) = 0.0$	Sets loss in $(n + 1)^{th}$ rotor equal to zero

The internal loss model is not specifically for a diffusing blade row (i.e., the EGV). If so desired, the EGV loss can be externally set or modified through the input value of  $YOSS(J, 2n + 1)$ .

To incorporate a stage-efficiency specific loss due to cooling into the design calculation requires a procedure for modifying the blade-row loss coefficients. This is accomplished by having the code execute a design without the additional cooling losses, internally estimating a loss-coefficient correction factor based on mean-streamline flow properties, and then reexecuting the design with the modified loss coefficients. The input variables must be set as follows:

$ISPEC = 2$	Allows use of the loss-coefficient correction factor
$NAV = 2$	Allows design calculations to be executed twice
$ICOOL = 4$ or $5$	Activates the loss-coefficient correction factor estimation procedure
$YOSS(J, I) = 1.0$	Sets loss-coefficient correction factor to unity for the initial calculation
Namelist NAM2	Left blank for second case

While not exactly duplicating the input values for stage-efficiency specific loss, this simplified procedure does appear to capture better than 90 percent of the cooling loss. This should be acceptable since the specific-loss values are usually rather approximate. Should greater accuracy be desired, additional computer runs can be made using the results from the previous run to determine better values for the additional loss factors.

**Sample input.** — The sample input presented in table III is for a two-stage cooled turbine and includes stage-efficiency specific loss. The alphanumeric case description is followed by the line of input option indicators. As required for this case, an additional loss factor is needed ( $ISPEC = 2$ ), and the stage-efficiency specific loss is to be included ( $ICOOL = 4$ ). The four zeros specify no mixing, internal calculation of streamline slopes and curvatures, and no debug output.



Namelist NAM1, which is used only once, includes the turbine-inlet conditions and, for this case, indicates that two cases are to be computed ( $NAV = 2$ ). The specification of three streamlines ( $NLINES = 3$ ) is made to reduce the amount of sample output. Normally, a value of 9 or 11 would be used to provide greater detail.

Namelist NAM2 must appear once for each spool or each case. Spool speed, power, flow-path geometry, and design specifications are included. For this case, stator exit angle is specified ( $IWRL = 1$ ) at each of three radii ( $NXT = 3$ ), as is rotor exit meridional velocity gradient ( $IPOF = 1$ ). Included for the coolant are flows, temperatures, pressures, and specific losses. An additional loss factor of unity is specified for the first case, and this is modified by the internally computed multiplier for the second case. As seen, NAM2 is blank for the second case. The output corresponding to this input is presented in the next section.

### Output

The program output consists of title headings, the input variables, and the computed results. This section presents normal output. Error message output is described in the next section.

Table IV presents the output that corresponds to the sample input shown in table III. The output for both cases (without and with the additional loss factor for cooling) are normally printed. For brevity herein, however, only the final result (i.e., the second case) is shown since the output format for each case is identical.

The output begins with the program title followed by the input case title. Next comes the echo of the input data, first the general input and then the spool input. The final input is the internal loss correlation with the coefficient values appropriately inserted. All output items are fully described to the extent that the output is completely self-explanatory. Note that for this case, the internally computed additional loss factors have replaced the initial input values of unity as shown under the blade-row exit conditions.

The results of the design calculation are then printed for each streamline at every calculation station (i.e., first stator inlet followed by each stator and stage exit). At each stage exit, stage performance is tabulated at each streamline and then mass-averaged for overall stage performance. Finally, at the spool exit, stage performance is tabulated and overall spool performance is presented. Work factor, which is the dimensionless ratio of work to blade speed squared, has been added to both the stage and spool performance summaries. The mass-average and meanline designations refer to the particular value of blade speed used to define work factor. For a cooled turbine, two additional values of total efficiency, based on the ideal power definitions of equations (6) and (7), have been included in the spool performance summary.

### Error Messages

This section, with minor modification, is the same as in reference 1.

In addition to the normal output, various messages may appear in the output. These messages occur when difficulty has been encountered in the calculation. Each of the four messages is considered in turn. All are outputs from the main program. In all cases, some output data will be provided with the message. This output can be used as a basis for the modification of the input specifications.

**1. CALCULATION ABANDONED ON PASS \_\_\_\_\_ BECAUSE OF INSTABILITY IN MEANLINE MERIDIONAL VELOCITY ITERATION DUE TO CHOKED CONDITIONS.**

As the program attempts to find a meanline meridional velocity that will satisfy the specified mass flow requirement, the variation of mass flow with meanline velocity is assessed. If the slope of the flow versus velocity characteristic changes sign more than four times, the calculations are aborted. Normally, the reason for these sign changes is that the specified mass flow exceeds the choked value. After the message, conditions from the final pass through the continuity loop are printed. There are four possible remedies, listed here in order of decreasing importance.

- (a) Increase the available flow area, by modifying either
  - (1) the annulus dimensions or
  - (2) the average flow angle.
- (b) Increase the design station total pressure by improving the efficiency level of the row or reducing rotor work output.
- (c) Reduce the specified inlet mass flow and/or the coolant flows entering upstream of the choked row.
- (d) Reduce the total temperature.

**2. ITERATION FOR THE MERIDIONAL VELOCITY AT THE MEAN STREAMLINE HAS NOT CONVERGED WHEN ILOOP=\_\_\_\_\_.**

If the mass flow has not converged to the required value within the preset tolerance after 35 iterations, the results from the 35th loop are printed, and the case is aborted. The convergence procedure is such that if any design station has not converged within 35 loops, the probability of the design being aerodynamically acceptable is remote.

**3. EQUATIONS ARE SINGULAR WHEN VMM=\_\_\_\_, ILOOP=\_\_\_\_, AND ILLOOP=\_\_\_\_\_.**

This message indicates that radial equilibrium could not be established at some radial position within the annulus because the four simultaneous equations which must be solved for the gradients of the principal unknowns are not independent. Appearance of this message is highly improbable, since such an interdependence is a numerical coincidence. Results from the loop in which the error was detected are printed, and the remainder of the case is aborted.

**4. ITERATION FOR STREAMLINE POSITIONS, PRESSURE-LOSS COEFFICIENTS, OR STAGE WORK OUTPUT HAS NOT CONVERGED.**

The number of loops on streamline position, streamline values of total-pressure-loss coefficient, and streamline values of total temperature drop is limited to 25. If any of these quantities has not converged to within the preset tolerance by this pass, the results are printed. The program is, however, allowed to proceed to the next design station if one exists. For designs in which the meridional velocity distributions are not extreme, it is extremely unlikely that these quantities will fail to converge. It is possible that the streamline position iteration may fail to converge when the secondary option of constant work output at a rotor exit is chosen. When this occurs, the case should be rerun employing the primary option of specifying radial gradients of meridional velocity. The error message is also provided to guard

against the possibility that one or more of these quantities is oscillating about the converged value but just outside the tolerance.

## SUMMARY OF RESULTS

Turbine design computer code TD2 computes design-point gas velocities, gas angles, and efficiency for multistage, multishaft, cooled or uncooled, axial-flow turbines. It is based on a streamline analysis that can use meridional velocity gradients as a primary design variable. An internal correlation for blade-row total-pressure-loss coefficients along the streamlines is incorporated into the code.

A recent evaluation of the code indicated a need for modeling improvements, partly to correct deficiencies and partly to enhance capabilities. Turbine modeling improvements were made in the areas of cooled turbines and the internal loss correlation.

With regard to cooled turbines, the following modifications were made:

1. An option was added to internally compute coolant flow rate for each blade row.
2. Coolant specific heat was made to be an internally computed function of coolant temperature rather than assumed equal to main-stream specific heat. This was done to improve the accuracy of the heat balance for mixing of coolant and main-stream, as well as the accuracy of the computed values of turbine ideal power.
3. Coolant pressure was made to be an input for each coolant stream rather than assumed equal to turbine inlet pressure. This improved the accuracy of the turbine ideal power.
4. Stage-efficiency specific loss was added as an input option so that cooling loss could be incorporated directly into the blade-row streamline loss coefficient.
5. Two additional values of cooled turbine total efficiency based on alternative definitions of ideal power were computed and added to the output.

With regard to the internal loss correlation, a Reynolds number dependency was added to the loss model, and the correlation coefficients were calibrated for best agreement between calculated and measured efficiencies for a data base of 10 turbines. This calibration, which resulted in the deletion of blade-row velocity ratio as a separate term in the loss correlation, produced an average deviation of less than 1 point between calculated and measured values.

This report serves as a users manual for the upgraded code, which is renamed TD2-2. Program input and output are described and a sample case for a cooled turbine is included.

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TABLE I. — EQUATION FOR SPECIFIC HEAT OF AIR

```

W=0.0
HOC=0.16002
A = .24062
B = -.017724E-3
C = .038056E-6
D = -.012662E-9
E = .0013012E-12
AO2 = .20334
BO2 = .02968E-3
CO2 = .0089971E-6
DO2 = -.0058842E-9
EO2 = .00076764E-12
ACO2 = .11097
BCO2 = .21110E-3
CCO2 = -.088140E-6
DCO2 = .018003E-9
ECO2 = -.0014317E-12
AH2O = .44266
BH2O = -.033155E-3
CH2O = .087761E-6
DH2O = -.024552E-9
EH2O = .0021734E-12
A1 = -2.6644*(1.0+2.9787*HOC)
A2 = 3.6644
A3 = 8.9365*HOC
CPAIR= (1.0/(1.0+F+W))*(A+B*T+C*T**2+D*T**3+E*T**4+(F/(1.0+HOC))
&*(A1*(AO2+BO2*T+CO2*T**2+DO2*T**3+EO2*T**4)+A2*(ACO2+BCO2*T+CCO2*
&T**2+DCO2*T**3+ECO2*T**4)))+(A3*F/(1.0+HOC)+W)
&*(AH2O+BH2O*T+CH2O*T**2+DH2O*T**3+EH2O*T**4))
    
```

TABLE II.—TURBINES USED FOR EVALUATION

Stages	Average stage work factor	Average stator angle	Exit mean diameter, cm (in.)	Exit radius ratio	Measured efficiency	References
1	1.7	67.0	66.0 (26.0)	0.73	0.923	9
2	1.7	64.5	66.0 (26.0)	.63	.932	10
1	1.2	63.4	20.3 (8.0)	.68	.917	11
1	1.9	73.1	47.0 (18.5)	.85	.914	12
3.5	4.0	51.4	49.8 (19.6)	.50	.880	8
4.5	4.7	66.6	49.8 (19.6)	.57	.855	13
1	1.7	75.0	46.7 (18.4)	.86	.895	14
1	1.6	79.6	56.4 (22.2)	.85	.901	15
2	1.3	71.6	69.3 (27.3)	.82	.884	7
5	2.6	61.0	63.5 (25.0)	.62	.920	16

TABLE III. — SAMPLE INPUT

SAMPLE CASE FOR A TWO-STAGE COOLED TURBINE  
<sup>2</sup> <sup>4</sup> <sup>0</sup> <sup>0</sup> <sup>0</sup> <sup>0</sup>  
&NAM1 NSPOOL=1,NAV=2,NLINES=3,GASC=53.37,FLWM=23.3,NLT=1,RLT=13.6,  
TOLT=1291.,POLT=50.,BETLT=0.0,  
&END  
&NAM2 RPM=8284.,HP=3663.,NSTG=2,FHP=.57,.43,  
XSTAT=-1.,0.0,1.4,3.,6.,7.8,9.,VISC=2.69E-5,  
RANN(1,1)=2\*12.6,12.8,12.73,12.29,2\*12.25,  
RANN(1,2)=2\*14.75,14.44,14.44,15.04,2\*15.04,NXT=3,IWRL=2\*1,  
RNXT(1,1)=12.8,13.6,14.4,RNXT(1,2)=12.29,13.635,14.98,  
WRL(1,1)=73.1,74.2,75.4,WRL(1,2)=3\*69.,IPOF=2\*1,  
RSXT(1,1)=12.73,13.57,14.41,RSXT(1,2)=12.25,13.625,15.,  
DVMDR(1,2)=3\*0.0,DVMDR(1,4)=3\*0.0,  
FLWCN=.0941,.0700,.0245,0.0,TOC=616.,622.,2\*640.,  
POC=50.6,50.3,2\*23.7,DELE=.35,.70,.35,.70,  
YOSS=3\*1.00,YOSS(1,2)=3\*1.00,YOSS(1,3)=3\*1.00,YOSS(1,4)=3\*1.00,  
&END  
&NAM2 &END

# TABLE IV.—SAMPLE OUTLET

\*\*PROGRAM TD2-2 - AERODYNAMIC CALCULATIONS FOR THE DESIGN OF AXIAL TURBINES\*\*

SAMPLE CASE FOR A TWO-STAGE COOLED TURBINE

\*\*\* GENERAL INPUT DATA \*\*\*

NUMBER OF SPOOLS = 1  
 NUMBER OF SETS OF ANALYSIS VARIABLES = 2  
 NUMBER OF STREAMLINES = 3  
  
 GAS CONSTANT = 53.37000 LBF FT/LBM DEG R  
 INLET MASS FLOW = 23.30000 LBM/SEC

\* TABULAR INLET SPECIFICATIONS \*

RADIAL COORDINATE (IN)	TOTAL TEMPERATURE (DEG R)	TOTAL PRESSURE (PSI)	ABSOLUTE FLOW ANGLE (DEG)
13.6000	1291.00	50.0000	0.000

\*\*\* SPOOL INPUT DATA \*\*\*

\*\* DESIGN REQUIREMENTS \*\*

ROTATIVE SPEED = 8284.0 RPM  
 POWER OUTPUT = 3663.00 HP

\*\* SET 2 OF ANALYSIS VARIABLES \*\*

NUMBER OF STAGES = 2

\* POWER-OUTPUT SPLIT \*

STAGE NUMBER	FRACTION OF SPOOL POWER OUTPUT
1	0.57000
2	0.43000

\* ANNULUS SPECIFICATION \*

STATION NUMBER	AXIAL POSITION (IN)	HUB RADIUS (IN)	CASING RADIUS (IN)
1	-1.0000	12.6000	14.7500
2	0.0000	12.6000	14.7500
3	1.4000	12.8000	14.4400
4	3.0000	12.7300	14.4400
5	6.0000	12.2900	15.0400
6	7.8000	12.2500	15.0400
7	9.0000	12.2500	15.0400

TABLE IV.—Continued.

\* COOLANT SCHEDULE \*

BLADE ROW NUMBER	FRACTION OF INLET MASS FLOW	TOTAL TEMPERATURE (DEG R)	TOTAL PRESSURE (PSIA)	SPECIFIC LOSS FRACTION
1	0.09410	616.00	50.60	0.3500
2	0.07000	622.00	50.30	0.7000
3	0.02450	640.00	23.70	0.3500
4	0.00000	640.00	23.70	0.7000

\* BLADE-ROW EXIT CONDITIONS \*

STATOR 1

RADIAL POSITION (IN)	WHIRL ANGLE (DEG)	ADDITIONAL LOSS FACTOR
12.8000	73.0999	1.5153
13.6000	74.1999	1.5153
14.4000	75.4000	1.5153

ROTOR 1

RADIAL POSITION (IN)	MERIDIONAL VELOCITY GRADIENT (PER SEC)	ADDITIONAL LOSS FACTOR
12.7300	0.00	1.7007
13.5700	0.00	1.7007
14.4100	0.00	1.7007

STATOR 2

RADIAL POSITION (IN)	WHIRL ANGLE (DEG)	ADDITIONAL LOSS FACTOR
12.2900	69.0000	1.1206
13.6350	69.0000	1.1206
14.9800	69.0000	1.1206

ROTOR 2

RADIAL POSITION (IN)	MERIDIONAL VELOCITY GRADIENT (PER SEC)	ADDITIONAL LOSS FACTOR
12.2500	0.00	1.0000
13.6250	0.00	1.0000
15.0000	0.00	1.0000

\* BASIC INTERNAL LOSS CORRELATION \*

$$Y = \frac{\tan(\text{INLET ANGLE}) + \tan(\text{EXIT ANGLE})}{1.00000000 + 1.50000000 * \cos(\text{EXIT ANGLE})} * \text{TIMES} * \begin{cases} (0.05700000 + 0.00000000 * (V \text{ RATIO}) * 0.00) & \text{IF } (V \text{ RATIO}) \text{ .LT. } 0.00000000 \\ (0.05700000 + 0.00000000 * ((V \text{ RATIO}) - 0.000)) & \text{IF } (V \text{ RATIO}) \text{ .GE. } 0.00000000 \end{cases}$$

THE PRESSURE-LOSS COEFFICIENT COMPUTED IN THIS MANNER MAY NOT EXCEED A LIMIT OF 2.00000000



TABLE IV.—Continued.

\*\*\* OUTPUT OF SPOOL DESIGN ANALYSIS (SET 2 OF ANALYSIS VARIABLES) \*\*\*

\*\* STATOR INLET 1 \*\*

STREAMLINE NUMBER	RADIAL POSITION (IN)	MASS-FLOW FUNCTION (LBM/SEC)	MERIDIONAL VELOCITY (FPS)	AXIAL VELOCITY (FPS)	WHIRL VELOCITY (FPS)	ABSOLUTE VELOCITY (FPS)	ABSOLUTE MACH NUMBER	ABSOLUTE TOTAL PRESSURE (PSI)	ABSOLUTE TOTAL TEMPERATURE (DEG R)	ABSOLUTE FLOW ANGLE (DEG)
1	12.6000	0.00000	173.737	173.295	0.000	173.737	0.10004	50.0000	1291.00	0.000
2	13.6938	11.64999	183.571	183.530	0.000	183.571	0.10571	50.0000	1291.00	0.000
3	14.7500	23.30002	160.224	159.251	0.000	160.224	0.09225	50.0000	1291.00	0.000

STREAMLINE NUMBER	STATIC PRESSURE (PSI)	STATIC TEMPERATURE (DEG R)	STREAMLINE SLOPE ANGLE (DEG)	STREAMLINE CURVATURE (PER IN)
1	49.6604	1288.66	4.086	0.14178
2	49.6210	1288.39	-1.207	-0.04096
3	49.7110	1289.01	-6.318	-0.21742

\*\* STATOR 1 MIXED AND/OR COOLED QUANTITIES \*\*

STREAMLINE NUMBER	ABSOLUTE TOTAL PRESSURE (PSI)	ABSOLUTE TOTAL TEMPERATURE (DEG R)
1	50.0000	1234.81
2	50.0000	1234.81
3	50.0000	1234.81

\*\* STATOR EXIT - ROTOR INLET 1 \*\*

STREAMLINE NUMBER	RADIAL POSITION (IN)	MASS-FLOW FUNCTION (LBM/SEC)	MERIDIONAL VELOCITY (FPS)	AXIAL VELOCITY (FPS)	WHIRL VELOCITY (FPS)	ABSOLUTE VELOCITY (FPS)	ABSOLUTE MACH NUMBER	ABSOLUTE TOTAL PRESSURE (PSI)	ABSOLUTE TOTAL TEMPERATURE (DEG R)	ABSOLUTE FLOW ANGLE (DEG)
1	12.8000	0.00000	432.094	431.564	1428.437	1484.703	0.94089	45.4117	1234.81	73.100
2	13.6093	12.74582	380.550	380.386	1345.437	1398.219	0.87813	45.4381	1234.81	74.213
3	14.4400	25.49174	334.966	332.931	1283.649	1326.633	0.82742	45.3503	1234.81	75.440

STREAMLINE NUMBER	STATIC PRESSURE (PSI)	STATIC TEMPERATURE (DEG R)	STREAMLINE SLOPE ANGLE (DEG)	STREAMLINE CURVATURE (PER IN)	BLADE VELOCITY (FPS)	RELATIVE VELOCITY (FPS)	RELATIVE MACH NUMBER	RELATIVE TOTAL PRESSURE (PSI)	RELATIVE TOTAL TEMPERATURE (DEG R)	RELATIVE FLOW ANGLE (DEG)
1	25.9522	1063.82	2.837	-0.13281	925.331	657.141	0.41644	29.1550	1097.32	48.923
2	27.7842	1083.16	-1.680	0.00936	983.834	524.952	0.32969	29.8989	1104.54	43.550
3	29.2128	1098.29	-6.318	0.15530	1043.888	411.931	0.25692	30.5487	1111.46	35.760

\*\* ROTOR 1 MIXED AND/OR COOLED QUANTITIES \*\*

STREAMLINE NUMBER	ABSOLUTE TOTAL PRESSURE (PSI)	ABSOLUTE TOTAL TEMPERATURE (DEG R)	RELATIVE TOTAL PRESSURE (PSI)	RELATIVE TOTAL TEMPERATURE (DEG R)
1	45.4117	1199.06	28.7484	1061.57
2	45.4381	1199.06	29.5063	1068.79
3	45.3503	1199.06	30.1711	1075.70

TABLE IV.—Continued.

\*\* STAGE EXIT 1 \*\*

STREAMLINE NUMBER	RADIAL POSITION (IN)	MASS-FLOW FUNCTION (LBM/SEC)	MERIDIONAL VELOCITY (FPS)	AXIAL VELOCITY (FPS)	WHIRL VELOCITY (FPS)	ABSOLUTE VELOCITY (FPS)	ABSOLUTE MACH NUMBER	ABSOLUTE TOTAL PRESSURE (PSI)	ABSOLUTE TOTAL TEMPERATURE (DEG R)	ABSOLUTE FLOW ANGLE (DEG)
1	12.7300	0.00000	502.419	500.157	-50.600	505.025	0.33314	20.6327	985.53	-6.602
2	13.6102	13.56179	502.419	502.412	-36.300	503.729	0.33367	20.6635	985.81	-4.133
3	14.4400	27.12306	502.419	499.926	-27.957	503.175	0.33355	20.4611	984.35	-3.155

STREAMLINE NUMBER	STATIC PRESSURE (PSI)	STATIC TEMPERATURE (DEG R)	STREAMLINE SLOPE ANGLE (DEG)	STREAMLINE CURVATURE (PER IN)	BLADE VELOCITY (FPS)	RELATIVE VELOCITY (FPS)	RELATIVE MACH NUMBER	RELATIVE TOTAL PRESSURE (PSI)	RELATIVE TOTAL TEMPERATURE (DEG R)	RELATIVE FLOW ANGLE (DEG)
1	19.1154	965.23	-5.439	-0.06346	920.270	1100.277	0.72900	27.0760	1061.26	-62.935
2	19.1565	965.68	0.300	0.03260	983.903	1137.207	0.75330	27.7501	1068.26	-63.781
3	18.9699	964.27	5.711	0.12315	1043.000	1183.393	0.78446	28.3069	1075.35	-64.987

\*\* STAGE 1 PERFORMANCE \*\*

STREAMLINE NUMBER	STATOR REACTION	ROTOR REACTION	STATOR PRESSURE LOSS COEFFICIENT	ROTOR PRESSURE LOSS COEFFICIENT	STATOR BLADE ROW EFFICIENCY	ROTOR BLADE ROW EFFICIENCY	ROTOR ISENTROPIC EFFICIENCY	STAGE ISENTROPIC EFFICIENCY	STAGE WORK (BTU/LB)
1	0.11702	0.59725	0.23577	0.21040	0.86405	0.87139	0.90329	0.77968	54.37
2	0.13129	0.46162	0.25840	0.20447	0.84776	0.87772	0.90304	0.77982	54.30
3	0.12078	0.34809	0.28812	0.19980	0.82896	0.88132	0.90110	0.77748	54.67

\* MASS-AVERAGED QUANTITIES \*

STATOR BLADE-ROW EFFICIENCY = 0.84713  
 ROTOR BLADE-ROW EFFICIENCY = 0.87704  
 STAGE WORK = 54.407 BTU PER LBM  
 STAGE TOTAL EFFICIENCY = 0.84233  
 STAGE STATIC EFFICIENCY = 0.78360  
 MASS AVERAGE STAGE WORK FACTOR = 1.40795  
 MEANLINE STAGE WORK FACTOR = 1.40870  
 STAGE BLADE- TO JET-SPEED RATIO = 0.50735

\*\* STATOR 2 MIXED AND/OR COOLED QUANTITIES \*\*

STREAMLINE NUMBER	ABSOLUTE TOTAL PRESSURE (PSI)	ABSOLUTE TOTAL TEMPERATURE (DEG R)
1	20.6327	978.52
2	20.6635	978.79
3	20.4611	977.37

TABLE IV.—Continued.

\*\* STATOR EXIT - ROTOR INLET 2 \*\*

STREAMLINE NUMBER	RADIAL POSITION (IN)	MASS-FLOW FUNCTION (LBM/SEC)	MERIDIONAL VELOCITY (FPS)	AXIAL VELOCITY (FPS)	WHIRL VELOCITY (FPS)	ABSOLUTE VELOCITY (FPS)	ABSOLUTE MACH NUMBER	ABSOLUTE TOTAL PRESSURE (PSI)	ABSOLUTE TOTAL TEMPERATURE (DEG R)	ABSOLUTE FLOW ANGLE (DEG)
1	12.2900	0.00000	516.113	514.282	1339.748	1435.722	1.03411	19.3746	978.52	69.000
2	13.7286	13.84809	472.672	472.638	1231.260	1318.870	0.93504	19.3707	978.79	69.000
3	15.0400	27.69641	432.299	430.154	1120.586	1201.081	0.84039	19.5312	977.36	69.000

STREAMLINE NUMBER	STATIC PRESSURE (PSI)	STATIC TEMPERATURE (DEG R)	STREAMLINE SLOPE ANGLE (DEG)	STREAMLINE CURVATURE (PER IN)	BLADE VELOCITY (FPS)	RELATIVE VELOCITY (FPS)	RELATIVE MACH NUMBER	RELATIVE TOTAL PRESSURE (PSI)	RELATIVE TOTAL TEMPERATURE (DEG R)	RELATIVE FLOW ANGLE (DEG)
1	9.8945	813.01	-4.827	0.06840	888.461	685.589	0.49301	11.6643	850.75	41.267
2	11.1977	839.13	0.686	-0.02465	992.463	529.568	0.37545	12.3264	861.65	26.805
3	12.3610	861.53	5.711	-0.10947	1087.263	433.582	0.30337	13.1645	876.63	4.430

\*\* ROTOR 2 MIXED AND/OR COOLED QUANTITIES \*\*

STREAMLINE NUMBER	ABSOLUTE TOTAL PRESSURE (PSI)	ABSOLUTE TOTAL TEMPERATURE (DEG R)	RELATIVE TOTAL PRESSURE (PSI)	RELATIVE TOTAL TEMPERATURE (DEG R)
1	19.3746	978.52	11.6644	850.75
2	19.3707	978.79	12.3264	861.65
3	19.5312	977.36	13.1646	876.63

\*\* STAGE EXIT 2 \*\*

STREAMLINE NUMBER	RADIAL POSITION (IN)	MASS-FLOW FUNCTION (LBM/SEC)	MERIDIONAL VELOCITY (FPS)	AXIAL VELOCITY (FPS)	WHIRL VELOCITY (FPS)	ABSOLUTE VELOCITY (FPS)	ABSOLUTE MACH NUMBER	ABSOLUTE TOTAL PRESSURE (PSI)	ABSOLUTE TOTAL TEMPERATURE (DEG R)	ABSOLUTE FLOW ANGLE (DEG)
1	12.2500	0.00000	555.615	555.581	214.520	595.593	0.43459	9.9560	817.33	21.113
2	13.7173	13.84607	555.615	555.607	212.847	594.989	0.43464	9.9496	815.46	20.961
3	15.0400	27.69229	555.615	555.615	196.048	589.188	0.43044	9.9407	814.79	19.435

STREAMLINE NUMBER	STATIC PRESSURE (PSI)	STATIC TEMPERATURE (DEG R)	STREAMLINE SLOPE ANGLE (DEG)	STREAMLINE CURVATURE (PER IN)	BLADE VELOCITY (FPS)	RELATIVE VELOCITY (FPS)	RELATIVE MACH NUMBER	RELATIVE TOTAL PRESSURE (PSI)	RELATIVE TOTAL TEMPERATURE (DEG R)	RELATIVE FLOW ANGLE (DEG)
1	8.7540	788.49	-0.637	0.01851	885.570	871.209	0.63570	11.4659	850.19	-50.377
2	8.7481	786.69	-0.302	0.00878	991.643	956.677	0.69886	12.0917	861.08	-54.495
3	8.7616	786.58	0.000	0.00000	1087.263	1050.225	0.76725	12.8977	876.23	-58.059

TABLE IV.—Concluded.

\*\*\* STAGE 2 PERFORMANCE \*\*\*

STREAMLINE NUMBER	STATOR REACTION	ROTOR REACTION	STATOR PRESSURE LOSS COEFFICIENT	ROTOR PRESSURE LOSS COEFFICIENT	STATOR BLADE ROW EFFICIENCY	ROTOR BLADE ROW EFFICIENCY	ROTOR ISENTROPIC EFFICIENCY	STAGE ISENTROPIC EFFICIENCY	STAGE WORK (BTU/LB)
1	0.35231	0.78694	0.13271	0.07128	0.92720	0.95563	0.97672	0.89303	39.85
2	0.38194	0.55355	0.13052	0.06816	0.92314	0.95831	0.97514	0.90224	40.38
3	0.41893	0.41285	0.12968	0.06270	0.91864	0.96156	0.97350	0.90944	40.19

\* MASS-AVERAGED QUANTITIES \*

STATOR BLADE-ROW EFFICIENCY =	0.92303
ROTOR BLADE-ROW EFFICIENCY =	0.95845
STAGE WORK =	40.198 BTU PER LBM
STAGE TOTAL EFFICIENCY =	0.90648
STAGE STATIC EFFICIENCY =	0.78439
MASS AVERAGE STAGE WORK FACTOR =	1.02749
MEANLINE STAGE WORK FACTOR =	1.03282
STAGE BLADE- TO JET-SPEED RATIO =	0.61602

\*\*\* SPOOL PERFORMANCE SUMMARY (MASS-AVERAGED QUANTITIES) \*\*\*

STAGE NUMBER	STATOR BLADE-ROW EFFICIENCY	ROTOR BLADE-ROW EFFICIENCY	STAGE WORK (BTU/LBM)	STAGE TOTAL EFFICIENCY	STAGE STATIC EFFICIENCY	STAGE BLADE- TO JET-SPEED RATIO
1	0.84713	0.87704	54.407	0.84233	0.78360	0.58735
2	0.92303	0.95845	40.198	0.90648	0.78439	0.61602

SPOOL WORK =	94.606 BTU PER LBM
SPOOL POWER =	3662.99 HP
SPOOL TOTAL- TO TOTAL-PRESSURE RATIO =	5.02564
SPOOL TOTAL- TO STATIC-PRESSURE RATIO =	5.71235
SPOOL TOTAL EFFICIENCY =	0.88957
SPOOL STATIC EFFICIENCY =	0.83785
MASS AVERAGE SPOOL WORK FACTOR =	1.21782
MEANLINE SPOOL WORK FACTOR =	1.21820
SPOOL BLADE- TO JET-SPEED RATIO =	0.39783
SPOOL PRIMARY TOTAL EFFICIENCY =	0.96080
ROTOR PRIMARY TOTAL EFFICIENCY =	0.92258

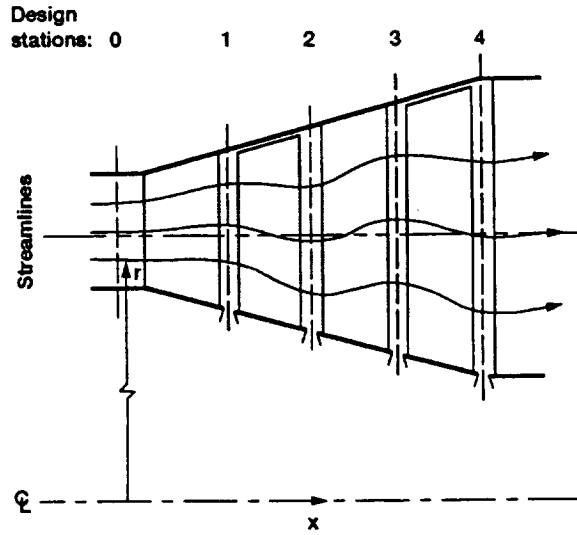


Figure 1.—Meridional section of a two-stage turbine to illustrate axisymmetric streamline flow.

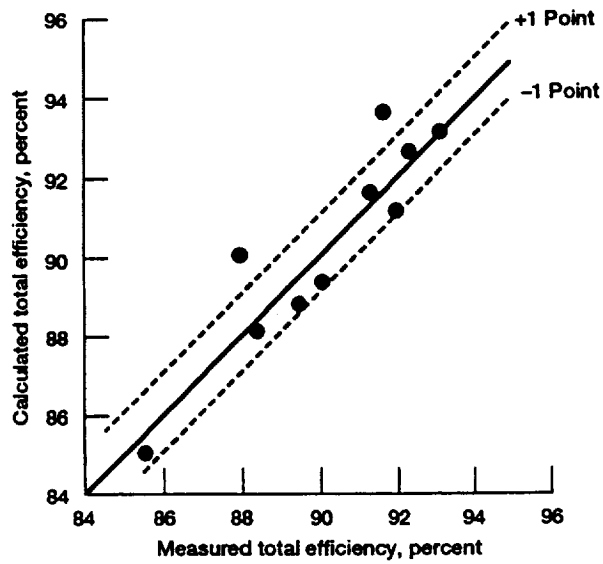


Figure 2.—Comparison of calculated and measured total efficiencies.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE March 1992	3. REPORT TYPE AND DATES COVERED Final Contractor Report		
4. TITLE AND SUBTITLE Users Manual and Modeling Improvements for Axial Turbine Design and Performance Computer Code TD2-2			5. FUNDING NUMBERS  WU-505-69-50 G-NAG3-1165	
6. AUTHOR(S)  Arthur J. Glassman				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  University of Toledo Toledo, Ohio 43606			8. PERFORMING ORGANIZATION REPORT NUMBER  E-6828	
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)  National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191			10. SPONSORING/MONITORING AGENCY REPORT NUMBER  NASA CR-189118	
11. SUPPLEMENTARY NOTES Project Manager, Daniel C. Mikkelson, Aeropropulsion Analysis Office, NASA Lewis Research Center, (216) 433-7011. Arthur J. Glassman, University of Toledo, Toledo, Ohio 43606 and NASA Resident Research Associate at Lewis Research Center (work funded by NASA Grant NAG3-1165).				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Unclassified - Unlimited Subject Category 02			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  Computer code TD2 computes design-point velocity diagrams and performance for multistage, multishaft, cooled or uncooled, axial-flow turbines. This streamline analysis code was recently modified to upgrade modeling related to turbine cooling and to the internal loss correlation. These modifications are presented in this report along with descriptions of the code's expanded input and output. This report serves as the user's manual for the upgraded code, which is named TD2-2.				
14. SUBJECT TERMS  Axial-flow turbine; Turbine design code			15. NUMBER OF PAGES 28	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	