NASA TECHNICAL MEMORANDUM

NASA TM X-2229

NASA TM X-2229

CASE FILE COPY

COMPUTER PROGRAM DESCRIBING TURBINE AERODYNAMIC REQUIREMENTS, APPROXIMATE EXTERNAL BLADE GEOMETRIES, AND COOLANT FLOW REQUIREMENTS FOR A TWO-STAGE AXIAL-FLOW TURBINE

by Keith A. Furgalus, David G. Evans, and Michael R. Vanco

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1971

1. Report No.
NASA TM X-2229

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle COMPUTER PROGRAM DESCRIBING TURBINE AERODYNAMIC REQUIREMENTS, APPROXIMATE EXTERNAL BLADE GEOMETRIES, AND COOLANT FLOW REQUIREMENTS FOR A TWO-STAGE AXIAL-FLOW TURBINE

5. Report Date
April 1971

6. Performing Organization Code

7. Author(s)
Keith A. Furgalus, David G. Evans, and Michael R. Vanco

8. Performing Organization Report No.
E-6014

9. Performing Organization Name and Address
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

10. Work Unit No.
720-03

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A computer code is described which generates aerodynamic and thermodynamic designs for a two-stage cooled or uncooled axial-flow turbine. A free vortex flow model is used to generate hub, mean, and tip velocity diagrams. From these diagrams, inner-stage temperatures and pressures, approximate external blade shapes, external blade surface areas, and turbine blade and wall coolant airflow requirements are computed. Inner-stage temperatures and turbine annulus areas are adjusted to include the effects of the mass flow and energy addition of the blade cooling air.

17. Key Words (Suggested by Author(s))
Turbine design
Turbine cooling
Computer program

18. Distribution Statement
Unclassified - unlimited

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
59

22. Price*
$3.00

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

COMPUTER PROGRAM DESCRIBING TURBINE AERODYNAMIC REQUIREMENTS, APPROXIMATE EXTERNAL BLADE GEOMETRIES, AND COOLANT FLOW REQUIREMENTS FOR A TWO-STAGE AXIAL-FLOW TURBINE

by Keith A. Furgalus, David G. Evans, and Michael R. Vanco

Lewis Research Center

SUMMARY

A computer code was written which enables a turbine designer to simultaneously determine turbine aerodynamic requirements, approximate external blade geometries, and turbine blade and hub and tip wall coolant flow requirements for a two-stage, air-cooled, axial-flow turbine.

Using a free vortex flow model, turbine hub, mean, and tip velocity diagrams are generated, along with preliminary inner-stage gas temperatures and pressures.

Approximate external blade dimensions for each blade row are determined. These are based on design data obtained from a survey of existing high-performance aircraft gas turbine stator and rotor blades. The resultant designs are able to utilize reasonable air cooling schemes, if cooling is required, and at the same time have good aerodynamic performance.

Blade coolant flows are computed by a simplified method based on an assumed blade thermodynamic cooling effectiveness. The heat-sink capacity available from the cooling air is made to balance the heat sink required to cool each blade row. The blade cooling air is adiabatically mixed with the main gas stream. The innerstage temperatures and annulus areas are adjusted accordingly.

Blade hub and tip walls are assumed to be cooled with a tangentially injected air film. The inclusion of this wall coolant in the calculations is optional.

INTRODUCTION

Several computer codes are available for computing turbine velocity diagrams (refs. 1 and 2). Also, several are available which predict turbine blade coolant flow requirements and/or metal temperatures. It was felt that there was a need to integrate some of the previous efforts in these areas into one package that would enable a designer to simultaneously determine turbine aerodynamic requirements, external blade geometries, and coolant flow requirements.

A program was written which meets these objectives for a two-stage, air-cooled, axial-flow turbine. The program was originally developed to generate designs for a turbojet-powered, Mach 3 transport using methane fuel (ref. 3). Based on considerations of turbine efficiency, size, weight, stress, and cooling requirements, it was felt that two-stage turbines were best suited to this application. Hence, the analysis was restricted to two-stage designs. The program can, however, be used in any application where a two-stage design is desired.

A complete discussion of the assumptions, equations, computation procedures, and computer program is presented along with a complete sample problem.

A FORTRAN IV program deck is available from the authors.

ASSUMPTIONS

The following assumptions were made in the analysis:

(1) A two-stage turbine is designed.

(2) A free vortex distribution of the flow from blade hub to tip is assumed in generating the velocity diagrams.

(3) The velocity diagrams are generated assuming a constant turbine mean diameter D_M, a constant main gas stream specific heat $C_{p,g}$, and a constant main gas stream specific heat ratio γ_g. The blade coolant airflows are assumed to contribute one-half of the equivalent specific work output of the turbine main gas stream. One-half of the total blade coolant flow is added at the inlet to the turbine in the calculation of the velocity diagrams only. The other half is assumed to bypass the turbine for this computation.

(4) External blade profiles are determined from design curves obtained from a survey of existing stator and rotor blade profiles from high-performance aircraft gas turbine engines.

(5) Blade coolant airflows are calculated for each row by the simplified method presented in reference 4.

(6) Blade coolant airflows are mixed with the main gas stream at the exit of each blade row. Turbine inner-stage annulus areas and temperatures are adjusted to account for the mass flow and energy addition effects of the blade cooling air.

(7) All flow velocities, flow angles, and blade mean diameters are fixed during the calculations of cooling flow requirements to assure no change in turbine work output.

(8) Hub and tip wall coolant airflows can be computed if desired. The walls are cooled by a tangentially injected air film that is assumed to mix with the main gas stream only at the turbine exit. It is also assumed that the wall cooling airflow does not contribute to the work output of the turbine.

PROGRAM DESCRIPTION

The following description outlines the equations and computation procedures employed by the computer program. It is intended to serve as a user's guide to enable the designer to better understand and more effectively utilize the computer program.

The program is divided into three main sections. The first is the main program (TD), which computes the basic turbine velocity diagrams and preliminary inner-stage thermodynamic data (i.e., main gas stream temperatures and pressures). The second is subroutine SURC, which calculates the approximate external blade profiles and surface areas. The third is subroutine COOL, which computes the required blade coolant airflows, mixes these flows with the main gas stream, and iterates until the correct combinations of blade cooling flows, inner-stage gas temperatures, and blade heights are found. It also computes the required turbine hub and tip wall coolant flows. A description of the calculations involved in each of these programs follows.

Program TD - Velocity Diagram Calculations

As was previously mentioned, this program calculates the velocity diagrams and preliminary inner-stage temperatures and pressures. The velocity diagrams are based on a free vortex distribution of the flow from blade hub to tip between each blade row using the equations for simplified radial equilibrium:

$$V_x = \text{Constant} \tag{1}$$

$$r(V_u) = \text{Constant} \tag{2}$$

(Turbine velocity diagram nomenclature is defined in appendix C and fig. 1(a).) A constant mean diameter D_M, gas specific heat $C_{p,g}$, and gas specific heat ratio γ_g are assumed throughout the turbine. The velocity diagrams are made to satisfy the turbine work and hub reaction values specified in the input data. In order to allow for the additional annulus area required to pass the blade cooling air, one-half of the estimated blade coolant airflow is added to the turbine inlet weight flow to determine the radius at which the hub and tip diagrams are determined in the velocity diagram calculations.

This cooling air is assumed to contribute one-half of the equivalent specific work output of the main gas stream. A detailed description of the calculations for each stage follows.

Second stage. - The design begins at the second-stage rotor exit. The exit total temperature and pressure are calculated from the given input:

$$T'_{2,IV} = T'_{1,I} - \frac{\Delta h_{t,TOT}}{C_{p,g}} \tag{3}$$

$$p'_{2,IV} = p'_{1,I}\left(1 - \frac{\Delta h_{t,TOT}}{C_{p,g}T'_{1,I}\eta_{TOT}}\right)^{\frac{\gamma}{\gamma-1}} \tag{4}$$

Note that $\Delta h_{t,TOT}$ includes the contribution that the blade coolant air makes to the turbine work output. This work contribution is discussed later, in the description of subroutine COOL. The blade exit tip speed is computed from the input values of exit tip radius and turbine rotative speed:

$$U_{T,2,IV} = \frac{\pi N r_{T,2,IV}}{30} \tag{5}$$

Using the specified exit hub-tip radius ratio, the hub radius is computed:

$$r_{H,2,IV} = \left(\frac{r_H}{r_T}\right)_{2,IV} r_{T,2,IV} \tag{6}$$

The mean radius is computed:

$$r_{M,2,IV} = \frac{(r_H + r_T)_{2,IV}}{2} \tag{7}$$

The mean exit whirl is computed:

$$V_{u,M,2,IV} = \left(\frac{V_u}{V_{cr}}\right)_{M,2,IV} \sqrt{\frac{2\gamma R T'_{2,IV}}{\gamma + 1}} \tag{8}$$

where $(V_u/V_{cr})_{M,2,IV}$ is specified in the input data. The whirl at the hub and tip are computed:

$$V_{u,H,2,IV} = \frac{(V_u r)_{M,2,IV}}{r_{H,2,IV}} \tag{9}$$

$$V_{u,T,2,IV} = \frac{(V_u r)_{M,2,IV}}{r_{T,2,IV}} \tag{10}$$

The axial absolute velocity $V_{x,2,IV}$ is computed in subroutine VXR:

$$V_{x,2,IV} = \left[\frac{w_t}{2\pi \int_H^T \rho(r) r dr}\right]_{2,IV} \tag{11}$$

A check is made to determine whether the computed value of $\left(V_x/V_{cr}\right)_{2,IV}$ exceeds the input limiting value VXEL. If it does, the calculations are terminated and an error message is printed out indicating that the exit tip diameter must be changed to yield a solution. If the calculated value is acceptable, the mean and hub blade speeds are computed:

$$U_{M,2,IV} = \frac{\pi N r_{M,2,IV}}{30} \tag{12}$$

$$U_{H,2,IV} = \frac{\pi N r_{H,2,IV}}{30} \tag{13}$$

The exit relative velocity at the hub is then computed:

$$W_{H,2,IV} = \sqrt{V_{x,2,IV}^2 + (V_u - U)_{H,2,IV}^2} \tag{14}$$

The exit relative velocities at the mean and tip radii are computed by substituting the mean and tip values for whirl and blade speed into equation (14). The absolute exit velocities at the hub, mean, and tip are computed:

$$V_{i,2,IV} = \sqrt{(V_{u,i,2,IV})^2 + (V_{x,2,IV})^2} \tag{15}$$

where $i = H, M, T$ and indicates a substitution of the appropriate values for the hub, mean or tip, respectively.

The calculations for the second-stage rotor inlet are now started. The input value of stage reaction is used to compute the relative velocity ratio

$$\left(\frac{W_1}{W_2}\right)^2_{H,IV} = 1 - \mathscr{R}_{H,②} \tag{16}$$

The inlet total temperature and pressure are computed:

$$T'_{1,IV} = T'_{2,IV} + \left(\frac{\tau_{②}\Delta h_{t,TOT}}{C_{p,g}}\right) \tag{17}$$

$$p'_{1,IV} = \left[\frac{p'_{2,IV}}{\left(1 - \frac{\tau_{②}\Delta h_{t,TOT}}{C_{p,g}T'_{1,IV}\eta_{②}}\right)^{\frac{\gamma}{\gamma-1}}}\right]\left(\frac{p'_2}{p'_1}\right)_{III} \tag{18}$$

where

$$\eta_{②} = \frac{\tau_{②}\Delta h_{t,TOT}}{C_{p,g}(T'_{1,IV})\left[1 - \left(\frac{p'_{2,IV}}{p'_{1,III}}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{19}$$

and

$$p'_{1,III} = p'_{1,I}\left(1 - \frac{\tau_{①}\Delta h_{t,TOT}}{C_{p,g}T'_{1,I}\eta_{①}}\right)^{\frac{\gamma}{\gamma-1}} \tag{20}$$

The stator total-pressure ratio $(P_2'/P_1')_{III}$ is specified in the input data. The hub-tip radius ratio at the rotor inlet is not known. However, the required value for $W_{H,1,IV}$ is known from equation (16) since $W_{H,2,IV}$ has already been computed. Hence, the value of rotor inlet radius ratio which yields the required $W_{H,1,IV}$ must be found. Two estimates are made for the inlet radius ratio, denoted in the program as RHRTI1 and RHRTI2. A check is made to determine whether these radius ratios yield values for $(V_x/V_{cr})_{1,IV}$ which exceed the input limiting value VXIL. The calculation is not terminated if they do. Instead, the smaller of the two estimated radius ratios at the inlet is reduced until a solution exists for which $(V_x/V_{cr})_{1,IV} \leq$ VXIL. If no value for radius ratio can be found which satisfies this criterion, the input value of VXIL is internally increased, and the calculations are restarted at the turbine exit. Having two suitable inlet radius ratio estimates, a curve of $W_{H,1,IV}$ against $(r_H/r_T)_{1,IV}$ is generated by subroutine MAXIM. The curve is generated by computing $W_{H,1,IV}$ from

$$W_{H,1,IV} = \sqrt{(V_u - U)^2_{H,1,IV} + V^2_{x,1,IV}} \tag{21}$$

where using values for inlet hub-tip radius ratio between RHRTI1 and RHRTI2 and letting $r_{M,1,IV} = r_{M,2,IV}$, the hub whirl and blade speed are computed:

$$V_{u,H,1,IV} = \frac{\tau_{2} \Delta h_{t,TOT} + \frac{\pi N}{30} (V_u r)_{M,2,IV}}{\frac{\pi N}{30} r_{H,1,IV}} \tag{22}$$

$$U_{H,1,IV} = r_{H,1,IV} \frac{\pi N}{30} \tag{23}$$

The inlet axial absolute velocity is computed in subroutine VXR as before:

$$V_{x,1,IV} = \left[\frac{w_t}{2\pi \int_H^T \rho(r) r dr} \right]_{1,IV} \tag{24}$$

Subroutine MAXIM then proceeds to find the minimum value of $W_{H,1,IV}$ and its corresponding radius ratio. This newly computed radius ratio is used as the new minimum radius ratio, replacing the previously estimated minimum. If these limiting inlet radius ratios, RHRTI1 and RHRTI2, yield values for $W_{H,1,IV}$ which bracket the desired value computed from equation (16), subroutine ROOT proceeds to find the value of radius ratio between RHRTI1 and RHRTI2 which yields the desired value for $W_{H,1,IV}$. If a solution is not possible with the previously computed radius ratio limits, the exit tip radius is changed and the calculations restarted. Having found the correct inlet radius ratio, the following velocities are computed at the rotor inlet:

$$U_{i,1,IV} = \frac{\pi N}{30} (r_i)_{1,IV} \tag{25}$$

$$V_{u,i,1,IV} = -\frac{\tau_{②}\Delta h_{t,TOT} + \frac{\pi N}{30} (V_u r)_{M,2,IV}}{\frac{\pi N}{30} r_{i,1,IV}} \tag{26}$$

$$W_{i,1,IV} = \sqrt{V_{x,1,IV}^2 + (V_u - U)_{i,1,IV}^2} \tag{27}$$

$$V_{i,1,IV} = \sqrt{(V_{u,i,1,IV})^2 + (V_{x,1,IV})^2} \tag{28}$$

First stage. - The calculations are now continued for the first-stage rotor. The rotor inlet and exit total pressures and temperatures are computed:

$$p'_{2,II} = \frac{p'_{1,IV}}{\left(\frac{p'_2}{p'_1}\right)_{III}} \tag{29}$$

$$T'_{2,II} = T'_{1,IV} \tag{30}$$

$$T'_{1,II} = T'_{2,II} + \frac{\tau_{①}\Delta h_{t,TOT}}{C_{p,g}} \tag{31}$$

$$p'_{1,II} = \frac{p'_{2,II}}{\left(1 - \frac{\tau_{①}\Delta h_{t,TOT}}{C_{p,g}T'_{1,II}\eta_{①}}\right)^{\frac{\gamma}{\gamma-1}}\left(\frac{p'_2}{p'_1}\right)_I} \qquad (32)$$

The first-stage velocity calculations are similar to those for the second stage. The major difference in the calculations for the first stage is that the mean exit whirl has not been specified as it was for the second stage. Two practical design limits between which a solution should exist are chosen:

$$V_{u,M,2,II} = (0.1\ V_{cr})_{M,2,II} \qquad (33)$$

and

$$V_{u,M,2,II} = (-0.4\ V_{cr})_{M,2,II} \qquad (34)$$

The annulus area at the first-stage exit is initially assumed equal to the area at the inlet to the second-stage rotor times the area ratio across the second-stage rotor. The first-stage rotor exit radii are then computed:

$$r_{T,2,II} = r_{T,1,IV}\sqrt{AR_{IV}} \qquad (35)$$

$$r_{M,2,II} = r_{M,1,IV} \qquad (36)$$

$$r_{H,2,II} = 2r_{M,2,II} - r_{T,2,II} \qquad (37)$$

Using the first assumed value for mean exit whirl (i.e., $0.1\ V_{cr,M,2,II}$), exit blade speeds and whirls are computed at the hub, mean, and tip by the same procedure employed for the second stage. The axial absolute velocity ratio $(V_x/V_{cr})_{2,II}$ is computed as before in subroutine VXR. If the computed value exceeds the input limiting value VXEI, the area ratio is increased until an acceptable value for the axial velocity ratio is found. The exit hub relative velocity is then calculated from

$$W_{H,2,II} = \sqrt{(V_{x,2,II})^2 + (V_u - U)^2_{H,2,II}} \qquad (38)$$

The calculation proceeds to the inlet where the hub, mean, and tip radii are computed:

$$r_{T,1,II} = r_{T,2,II} \sqrt{AR_{II}} \tag{39}$$

$$r_{M,1,II} = r_{M,2,II} \tag{40}$$

$$r_{H,1,II} = 2r_{M,1,II} - r_{T,1,II} \tag{41}$$

The blade hub, mean, and tip inlet blade speeds and whirls are computed exactly as before. The axial velocity ratio $(V_x/V_{cr})_{1,II}$ is computed in subroutine VXR and checked against its input limit VXII. Again, the area ratio is increased, if necessary, to yield an acceptable axial velocity ratio. The inlet hub relative velocity $W_{H,1,II}$ is then computed as before. With known values for $W_{H,1,II}$ and $W_{H,2,II}$, the stage hub reaction can be computed:

$$\mathscr{R}_{①} = 1 - \left(\frac{W_1}{W_2}\right)^2_{H,II} \tag{42}$$

The calculations are repeated for the second assumed mean exit whirl (i.e., $-0.4\,V_{cr,M,2,II}$). These calculations yield a second value for the stage hub reaction. If these two calculated values for hub reaction bracket the desired value supplied in the input data, a series of calculations similar to those in subroutine ROOT finds the value of mean exit whirl between the two assumed design limits which yields the desired stage hub reaction. If the two initially assumed values for mean exit whirl do not yield a solution, the calculations are terminated with an error message indicating that in the mean exit whirl iteration there is no solution and that the hub-tip radius ratio or whirl limits must be changed.

Subprogram SURC - External Blade Geometry Calculations

A method was developed to determine the approximate external blade configurations required for each blade row in the turbine. The method consisted of surveying existing government and industrial high-performance aircraft gas turbine stator and rotor blade profiles. From the survey, a series of working curves were made which relate the required design parameters. These curves were then used to obtain the dimensional characteristics of blading required by interpreting the curves at the mean radius values of blade gas entering and leaving angles β_1 and β_2. (Nomenclature is defined in appendix C and fig. 1(b).) These design curves are supplied as an integral part of the program.

As noted, the starting point in the calculation is that of determining the blade entering and leaving angles β_1 and β_2 at the mean radius from the data generated in program TD. With these angles, an initial blade camber angle φ_Z is found by interpolation from figure 2, which is based on data from references 3 and 5. This interpolation is performed using a four-point bivariate technique (subroutine BVTL).

The value for the stator aerodynamic loading coefficient ψ is interpolated from figure 3. The loading coefficient for the rotors is set equal to 1. From the survey, it was found that the blade camber angle was influenced by the aerodynamic loading coefficient and by the particular row for which the blading was designed. The effect is shown in figure 4, which relates ψ to a correction $\Delta\varphi$ for each of the four blade rows. The final value for the blade camber angle for each blade row is then computed from

$$\varphi = \varphi_Z + \Delta\varphi \tag{43}$$

Using these values for camber angle along with a $\Delta\beta$ defined as

$$\Delta\beta = \beta_1 - \beta_2 \tag{44}$$

values for blade camber length to axial chord length ratio $(C_L/C_x)_Z$ are found for each row from figure 5; the data being taken from references 3 and 5. Blade chord lengths are determined by dividing the blade heights found in program TD by their aspect ratios, which were found, from the survey, to equal 2, 3, 3, and 5, respectively, for the four blade rows. In cases where these values of aspect ratio result in an axial chord length of less than 1 inch (2.54 cm) for any of the blade rows, the aspect ratios for all rows are reduced and the chord lengths recomputed for all the rows until the minimum value of axial chord length for any row is greater than 1 inch (2.54 cm). This is done to assure that the cross-sectional area of the various blade profiles will be large enough to accommodate internal cooling air passages.

Note that $(C_L/C_x)_Z$ for the stators is corrected as a function of blade thickness ratio t_{max}/C_L, as indicated in figure 6. A value for blade thickness ratio of 0.16 was assumed for blading developed in this program. No corrections are applied to the rotor blades.

It was also noted that the surveyed blading had airfoil perimeter lengths approximately 2.03 times their mean camber lengths at blade thickness ratios of 0.16. Thus, a single blade external surface area $A_{S,b}$ is computed for each blade in a row:

$$A_{S,b} = 2.03\ (C_L)\ (\overline{BH}) \tag{45}$$

The number of blades in each row is found by dividing the mean radial circumference (a constant throughout the turbine) by the blade pitch for that row, where the pitch is computed from

$$P = \frac{\psi(C_X)}{2\ \sin^2 \beta_2\ (\cot \beta_2 - \cot \beta_1)} \tag{46}$$

With this information and the velocity diagram angles and blade heights generated in TD, approximate external blade profiles are described. The resultant external blade surface areas are used as the starting point in the iteration to determine blade coolant airflow requirements (if cooling is required), as described in the next section.

Subprogram COOL - Turbine Blade and Wall Coolant Flow Calculations

The coolant airflow required to cool both the turbine blades and the hub and tip walls is computed next.

Rather than becoming concerned with the complexities associated with individual blade cooling configurations and determinations of cooling airflow requirements based on local metal temperature levels and heat-transfer coefficients, the simplified method described in reference 4 is employed. The method consists of making a heat balance between the heat sink required to cool each blade row to the heat sink available in the cooling air. The method requires knowledge of the average main gas stream conditions in each row, the average blade midspan metal temperatures, the cooling air supply temperature, and the thermal cooling effectiveness of the blade cooling design.

To start the coolant calculations, a base design is needed. This design is obtained from the previously computed velocity diagrams and blade external surface areas. All flow velocities and angles, and the turbine mean diameter computed in the base case are fixed during the coolant flow calculations to assure no change in turbine work output.

The calculations for the base turbine assume that one-half of the initially estimated blade coolant flow is added to the burner discharge flow and that this flow remains constant throughout the turbine and does not affect the turbine inlet temperature. The other half of the coolant flow bypasses the turbine. In subsequent cooling iterations, the total coolant flow from each blade row is mixed with the main gas stream at the exit of that blade row, and the turbine inner-stage weight flows and temperatures are adjusted accordingly.

Using the results of the base case turbine velocity diagram and blade surface area computations, a calculation is performed to determine individual blade coolant requirements. The blade gas-side heat transfer coefficient is computed:

$$\bar{h}_g = 0.037 \left(\frac{\overline{\rho_g V_g} \, C_{L,M}}{\mu_g} \right)^{0.8} \frac{(Pr^{0.33} k)_g}{C_{L,M}} \tag{47}$$

where the velocity $\bar{V}_g$ is the velocity relative to the row. The value $\overline{\rho_g V_g}$ is the average between the row inlet and exit. The transport properties are based on the average total relative temperature of the gas entering the blade row. The required heat sink is computed for each blade row:

$$Q_R = \bar{h}_g A_{S,b,TOT} (\bar{T}''_g - \bar{T}_{BM}) \tag{48}$$

Note that the average midspan blade metal temperature $\bar{T}_{BM}$ has been specified in the input data.

To obtain the heat sink available from the coolant Q_A, we use

$$Q_A = \left[(w\bar{C}_p) (T''_2 - T''_1) \right]_{y,b} \tag{49}$$

Modifying this to include the thermal cooling effectiveness of the blade cooling configuration,

$$\eta_b = \frac{(T''_2 - T''_1)_{y,b}}{\bar{T}_{BM} - T''_{1,y,b}} \tag{50}$$

we get

$$Q_A = \eta_b (w\bar{C}_p)_{y,b} (\bar{T}_{BM} - T''_{1,y,b}) \tag{51}$$

Since $Q_A = Q_R$ for each blade row,

$$\frac{w_{y,b}}{w_E} = \frac{\overline{h}_g A_{S,b,TOT} (\overline{T}''_g - \overline{T}_{BM})}{w_E (\overline{C}_p)_{y,b} (\eta_b) (\overline{T}_{BM} - T''_{1,y,b})} \tag{52}$$

If any blade row in the turbine does not require cooling, the program will calculate zero cooling for that row.

This procedure assumes no circumferential gas temperature differences. In practice, the first- and second-stage stators are exposed to these gradients. This temperature variation is accounted for by multiplying the required coolant flow determined in equation (52) by the ratio

$$\frac{T''_{g,max} - \overline{T}_{BM}}{\overline{T}''_g - \overline{T}_{BM}} \tag{53}$$

where $T''_{g,max}$ is the maximum circumferential hot-spot gas temperature. For the first-stage stators

$$T''_{g,max,I} = \overline{T}''_g + PF\left[\overline{T}''_g - (T_{y,1} + \Delta T_y)\right] \tag{54}$$

where $T_{y,1}$, ΔT_y, and PF are specified input data, and are respectively the temperature of the coolant air entering the turbine, the difference between this temperature and the compressor discharge temperature, and the combustor pattern factor. For the second-stage stators, the maximum hot-spot gas temperature is determined by assuming that one-half of the increase in gas temperature in the first-stage stator due to the effect of pattern factor is attenuated across the first stage before entering the second stage so that

$$T''_{g,max,III} = \overline{T}''_{g,III} + \frac{(\overline{T}''_{g,max} - \overline{T}''_g)_{1,I}}{2} \tag{55}$$

The coolant flows computed by this method provide for cooling of the stator location exposed to the circumferential hot-spot gas temperature. The remaining stators are overcooled.

After having computed the individual blade row coolant flows, the turbine flow is recomputed at each location in the turbine taking into account the addition at each location of the blade coolant flow of each blade row upstream. The coolant flows are adiabatically mixed with the main gas stream at each blade row exit:

$$T''_{g,2} = \frac{(w_t T''_g)_1 + (wT'')_{y,b}}{w_{t,2}} \tag{56}$$

These newly computed temperatures are then used to compute new values for $\overline{\rho_g V_g}$ across each row. The revised blade surface areas are then computed:

$$A_{S,b,TOT,n+1} = A_{S,b,TOT,n} \frac{(w_{t,n+1})}{(w_{t,n})} \frac{(\overline{\rho V})_n}{(\overline{\rho V})_{n+1}} \tag{57}$$

(For the rotors, V is replaced by W.) These steps are repeated until successive iterations yield repeating combinations of blade cooling airflow ratios, inner-stage gas temperatures, and required external blade surface areas for each row.

The wall hub-tip cooling airflow ratio $w_{y,w}/w_E$ is computed next. This calculation is optional (see input instructions). The cooling method employed is that of film cooling air injected tangentially to the hub and tip walls upstream of each blade row. The following correlation is used to predict wall coolant flow ratios:

$$\frac{w_{y,w}}{w_E} = \frac{\dfrac{1.914}{w_E}\left(\dfrac{C_{p,g}}{C_{p,y}}\right)\mu_g^{0.2}\left(\overline{\rho_g V_g} C_L\right)^{0.8} D_M}{\dfrac{1.9\ Pr^{0.67}}{\Lambda} - 1} \tag{58}$$

where

$$\Lambda = \frac{1600 - (\overline{T}''_g - 150)}{T'_y - (\overline{T}''_g - 150)} \tag{59}$$

The development of this equation is presented in reference 3. It is assumed that the wall cooling air remains as a cool boundary layer along the walls. As a result, the wall cooling air is assumed not to reduce the inner-stage main gas stream temperatures or to produce any work in subsequent turbine stages. The wall coolant is assumed to mix with the main gas stream only at the turbine exit. A final adjustment of blade height in each row is required to accommodate the hub and tip wall coolant airflows. Assuming that the injection velocity of the wall coolant is one-half of the absolute axial velocity of the main gas stream at the exit to each row and that the coolant static pressure is equal to the main gas stream static pressure at the exit of each row, the blade height adjustment due to wall coolant flow is computed:

$$\frac{(\Delta BH)_{y,w}}{(BH)_{g+y,b}} = \frac{\left(\dfrac{w}{\rho V_x}\right)_{y,w}}{A_{a,(g+y,b)}} \tag{60}$$

This additional length of blading is assumed to be cooled by the wall cooling air. Therefore, an increase in blade cooling airflow is not needed.

The preceding calculations yield a complete design based on the initially assumed values of coolant flow ratios for the blades and walls. If the final calculated values for these coolant flow ratios do not equal the initially assumed values which are provided as input data, the program must be recycled. Since the turbine specific enthalpy change is given

$$\Delta h_t = \frac{\Delta h_c}{\left[\left(1 - \dfrac{w_{y,TOT}}{w_E}\right)(1 + f/a)\right]\left\{1 + \dfrac{1}{2}\left[\dfrac{\dfrac{w_{y,b}}{w_E}}{\left(1 - \dfrac{w_{y,TOT}}{w_E}\right)(1 + f/a)}\right]\dfrac{T'_{y,1}}{T'_{t,1}}\right\}} \tag{61}$$

a change in coolant flow ratio affects the turbine work output (assuming that the compressor enthalpy change or turbine shaft work stays constant). Since the velocity diagrams are computed using the input assumed coolant airflow ratios, the velocities used in the program are not correct if the assumed and calculated coolant flow ratios do not agree. Thus the program must be recycled using the newly calculated values as input until the calculations predict the same coolant flow ratios as were assumed in the input. A correct overall solution is then assured. All the iterations leading to a correct solution are printed out by the program.

Utility Subprograms

Several utility subroutines are used by TD, SURC, and COOL. These are briefly described below.

Subroutine ROOT. - Working between two end points a and b, this subroutine finds the value of X which yields the desired value of Y for an arbitrary function $Y = f(X)$ where $a \leq X \leq b$. It is used in the program to find the radius ratio which yields the desired hub inlet relative velocity for the rotors.

Subroutine RHRT2. - This subroutine calculates the axial absolute velocities at the mean radius and compares them to the limiting values prescribed in the input data. It reduces the hub-tip radius ratios in an effort to reduce the axial velocities if the calculated values exceed the specified limits. In the case of the second-stage rotor inlet, the subroutine will increase the input limit VXIL if necessary, and return to the beginning of the calculations.

Subroutine DENR. - The axial velocities V_x at the mean radius are computed based on compressible flow.

Subroutine VXR. - This subroutine calculates densities at the hub, mean, and tip and then integrates to find the axial velocities.

Subroutine MAXIM. - This subroutine is used to find the minimum value on a curve of relative hub velocity against radius ratio.

Subroutine BVTL. - This is an interpolation subroutine used to interpolate values when the desired value actually lies on a surface (i.e., a family of curves are presented from which the desired value must be chosen as a function of two other coordinates). The procedure is described in reference 6 under the subject heading "Four Point Bivariate Interpolation." An error message - "Bivariate Interp Error VI = XXX.X, V2 = XXX.X" indicates that the coordinates presented to the subroutine are out of range of the data provided for the particular set of curves. The subroutine does not extrapolate data.

Subroutine LINT. - This is a standard linear interpolation routine used whenever data are required from a curve which is described by $y = f(x)$.

DESCRIPTION OF REQUIRED INPUT DATA

The following instructions provide a detailed description of the required program input data. The "Line" designation refers to one data card. The "Location" specifies the card columns in which the input variable must be entered. The "Type of Number" refers to either integer or fixed point numbers. An integer may consist of more than one digit but must be oriented to the right in its field. A decimal point must not appear in the field. A fixed point number may appear anywhere in its field. A decimal point should appear in the field if the number is not right adjusted. All the data cards must be in the deck. If an uncooled turbine is being considered, the data cards must still contain cooling input data; the program will predict zero coolant flow based on the input data.

An approximate initial input value for DHT can be computed by equation (61) using the estimated cooling flow ratios and a known compressor enthalpy change or turbine shaft work requirement.

If wall cooling is to be ignored (i.e., NWC = 1), the values entered for Y and YB should be equal.

Line	Location	Type of number	FORTRAN symbol	Description
1	1-3	I	NCASE	Identification number for the case
2	1-12	FP	TCI	Temperature of the coolant air as it enters the blades and hub and tip walls, ^{o}R
2	13-18	FP	CORRF	A value of 1.0 must be entered
2	19-24	FP	CORRFW	A value of 1.0 must be entered
3	1-12	FP	FAR	Primary burner fuel-air ratio
3	13-24	FP	Y	Initially estimated value of the total (blades plus wall) coolant airflow ratio $w_{y,TOT}/w_E$
3	25-36	FP	YB	Initially estimated value for the blade coolant flow ratio $w_{y,b}/w_E$
4	1-6	FP	TTO	Turbine total inlet temperature, ^{o}R
4	7-12	FP	PTO	Turbine total inlet pressure, lbf/ft^2 abs
4	13-18	FP	RPM	Turbine rotational speed, rpm
4	19-24	FP	DRTE	Exit tip radius increment, in. (A value of 0.1 is usually sufficient.)
4	25-30	FP	WO	Turbine inlet gas weight flow, lbm/sec
4	31-36	FP	DHT	Turbine enthalpy drop, including the contribution from the blade cooling air (see eq. (61)), Btu/lbm
4	37-42	FP	RTE	Assumed tip radius at the second-stage exit, in.
4	43-48	FP	RHRTE	Assumed hub-tip radius ratio at exit of last stage
4	49-50	I	NWC	NWC = 1, if only blade coolant flows are to be calculated; NWC = 2, if both blade and wall coolant flows are to be calculated

Line	Location	Type of number	FORTRAN symbol	Description
5	1-6	FP	WS(1)	Work fraction for first stage
5	7-12	FP	WS(2)	Work fraction for second stage
6	1-6	FP	GAMMA	Main gas stream specific heat ratio γ_g
6	7-12	FP	R	Main gas stream gas constant, ft-lbf/(lbm)(^{O}R)
6	13-18	FP	PC	Stator total-pressure ratio (p_2'/p_1')
7	1-6	FP	ETAT	Overall turbine total efficiency
7	7-12	FP	ETA(1)	Total efficiency of first stage
8	1-6	FP	R(1)	Hub reaction for first-stage rotor $\left[1 - \left(\frac{w_1}{w_2}\right)^2\right]_{H,1}$
8	7-12	FP	R(2)	Hub reaction for second-stage rotor $\left[1 - \left(\frac{w_1}{w_2}\right)^2\right]_{H,2}$
9	1-6	FP	VUMCR	Mean exit whirl of last-stage rotor $(V_u/V_{cr})_{M,2,IV}$
10	1-6	FP	VXEL	Limiting value on axial velocity ratio V_x/V_{cr} at exit of second-stage rotor
10	7-12	FP	VXEI	Limiting value on axial velocity ratio V_x/V_{cr} at exit of first-stage rotor
10	13-18	FP	VXII	Limiting value on axial velocity ratio V_x/V_{cr} at inlet to first-stage rotor
10	19-24	FP	VXIL	Limiting value on axial velocity ratio V_x/V_{cr} at inlet to second-stage rotor
11	1-12	FP	FARC	Value for FARC must be set equal to value for FAR specified in line 3
11	13-24	FP	PF	Combustor pattern factor $(T''_{g,max} - \overline{T}''_g)/(\overline{T}''_g - T'_{c,2})$
11	25-36	FP	DTY	Decrease (+DTY value) or increase (-DTY value) in temperature of cooling air between compressor bleed and inlet of blade or wall coolant passage
12	1-3	I	NPTD	Number of temperatures at which gas stream fluid properties are entered

Line	Location	Type of number	FORTRAN symbol	Description
13	1-12	FP	TPR	First temperature at which fluid properties will be entered, ^{o}R
13	13-24	FP	PRN	Value of Prandtl number at first temperature entered
13	25-36	FP	VIS	Value of viscosity at first temperature entered, lbm/(sec)(ft)
13	37-48	FP	CON	Value of thermal conductivity at first temperature entered, Btu/(sec)(ft)(^{o}R)

The remaining values of temperature, Prandtl number, viscosity, and thermal conductivity are entered on (NPTD-1) cards according to the format just described.

13+NPTD	1-12	FP	TMS	Average stator midspan metal temperature, ^{o}R
14+NPTD	1-12	FP	TMR	Average rotor midspan metal temperature, ^{o}R
15+NPTD	1-12	FP	THERME	Turbine blade thermal cooling effectiveness (This value is used for all four blade rows.)
16+NPTD	1-12	FP	CPC	Average specific heat for cooling air, Btu/(lbm)(^{o}R)
17+NPTD	1-12	FP	TWALLA	Average blade hub and tip wall metal temperature, ^{o}R

DESCRIPTION OF COMPUTER OUTPUT DATA

Several sets of computer output are presented in appendix A. Each set contains three sections - "velocity diagrams," "initial surface area calculations," and "coolant calculations." Each set is the result of one iteration to converge to a correctly matched solution, as described previously. This allows the designer to examine intermediate results to observe trends in the iteration. The format in all the sets is identical. Hence, only one set will be described.

In the velocity diagrams and coolant calculations sections, a subsection titled "input data" is printed out. This is a recapitulation of data read and/or used by routines TD and COOL. The FORTRAN symbols and units are the same as those used in the input instructions. The units used in the printout are defined in table I. The velocity diagrams section of the printout is the result of the computations in program TD. The inlet and exit designations refer to the rotor inlet and exit. Since total and total relative data are presented, the stator data is also available. The actual velocity diagrams are described under the headings RADE, BAE, VAE, etc. The first line of data under these headings is data at the turbine tip radius. The second and third lines are for the mean and hub data, respectively. (The heading nomenclature is related to the velocity diagrams in fig. 7.) The numbers printed directly under the velocity ratios are the actual velocities at that location (i.e., the numerator in the velocity ratio). Note that when the individual blade row cooling air is mixed with the main gas stream later in subroutine COOL, different inner-stage temperatures and hence, different critical velocities result. Thus, the velocity ratios printed out here will change. The actual velocities, however, do not change. The critical velocities computed after the addition of the blade cooling air are printed out in the coolant calculations section. Thus, using the actual velocities and the revised critical velocities, corrected velocity ratios can be computed.

The data presented in the initial surface area calculations section are the results from subroutine SURC. Blade geometry symbols are defined in figure 1(b). The values for blade surface areas are those for the base case which are later updated.

The data presented in the coolant calculations section are the results from subroutine COOL. The word "initial" in the descriptions refers to the base case in which one-half of the assumed blade coolant flow is added at the turbine inlet and the other half bypasses the turbine (i.e., the assumption used to generate the velocity diagrams). The word "revised" refers to values computed after the blade cooling air from each row has been mixed with the main gas stream. Note that for total relative temperatures at the rotor inlet or exit, the values presented are at the mean radius. All coolant flow ratios are obtained by ratioing the cooling air weight flow to the engine inlet weight flow. If wall cooling is included (i.e., NWC = 2), the blade heights and turbine exit temperature printed out have been corrected to include the effects of wall cooling airflows.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 3, 1970,
720-03.

APPENDIX A

SAMPLE PROBLEM

Sample Problem Input Data

144								
1204.		1.0	1.0					
.023		.076		.043				
2660.	18734.	6825.	.10	316.7	141.9	22.	.641	2
.56	.44							
1.301	53.98	.97						
.90	.89							
.18	.14							
-.039								
.80	.80	.35	.55					
.023		.15		400.				
12								
1460.		.71		.000024		.0000095		
1660.		.709		.000026		.00001075		
1860.		.708		.000028		.000011750		
2060.		.706		.000030		.00001275		
2260.		.705		.000032		.00001375		
2460.		.704		.000034		.00001475		
2660.		.703		.0000355		.000016		
2860.		.702		.000037		.000017		
3060.		.700		.000039		.000018		
3260.		.695		.0000405		.00001925		
3460.		.693		.000042		.0000205		
3660.		.686		.0000435		.000022		
2180.								
2080.								
.70								
.267								
2060.								

Insert (1)

Sample Problem Output

```
                    CASE=144
VELOCITY DIAGRAMS ********************
INPUT DATA**
TCI=1204.000              CORRF=   1.000            CORRFW=   1.000            FAR=   0.023
Y=  0.076                 YB=  0.0430               TTO=2660.000              PTO=18734.00
RPM=6825.000              DRTE=   0.100             WO= 316.700               DHT= 141.900
RTE=  22.000              RHRTE=   0.641            N=  2                     NR=  2
NVUM=  1                  NRTE=  1                  WS(1)=   0.560            WS(2)=   0.440
GAMMA=   1.301            CP=   0.300               R=  53.980                PC=   0.970
ETAT=   0.900             ETA(1)=   0.890           RE(1)=   0.180            RE(2)=   0.140
VUMVCR=  -0.039           VXEL=   0.800             VXEI=   0.800             VXII=   0.350
VXIL=   0.550

 LAST STAGE N= 2   WORK SPLIT= 0.440   EFFICIENCY= 0.901   REACTION= 0.140
INLET STATIC PRESSURE AT HUB,MEAN,TIP=  6790.849  7788.621  8381.295
INLET TOTAL PRESSURE=   10878.877
INLET TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP=  8274.052  8718.276  9284.179
INLET STATIC TEMPERATURE AT HUB,MEAN,TIP=  2147.631  2216.838  2254.774
INLET TOTAL TEMPERATURE=    2395.024
INLET TOTAL RELATIVE TEMPERATURE AT HUB,MEAN,TIP=  2248.066  2275.432  2308.782
INLET DENSITY AT HUB,MEAN,TIP=     0.059     0.065     0.069
EXIT STATIC PRESSURE AT HUB,MEAN,TIP=  6435.645  6439.276  6441.135
EXIT TOTAL PRESSURE=    7232.178
EXIT TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP=  8107.205  8585.955  9212.368
EXIT STATIC TEMPERATURE AT HUB,MEAN,TIP=  2128.581  2128.858  2129.0 1
EXIT TOTAL TEMPERATURE=    2186.829
EXIT TOTAL RELATIVE TEMPERATURE AT HUB,MEAN,TIP=  2245.385  2275.389  2312.764
EXIT DENSITY AT HUB,MEAN,TIP=     0.056     0.056     0.056

  RADE     BAE      VAE      VEVCR     UEVCR     WEWCR     RADI      BAI       VAI      VIVCR     UIVCR      WIWCR  VXI   VXE
 22.000  -55.980   -4.082   0.4496    0.6323    0.7794    21.609    -8.972    52.201   0.6691    0.5935     0.4229 0.410 0.448
                            931.7126 1310.3090 1660.8926                                1450.9888 1287.0454  900.412
 18.051  -51.205   -4.971   0.4502    0.5198    0.7016    18.051    18.499    57.060   0.7541    0.4957     0.4437 0.410 0.448
                            932.8574 1075.1085 1483.1238                                1635.4931 1075.1085  937.8549
 14.102  -45.432   -6.352   0.4512    0.4053    0.6306    14.493    43.586    62.517   0.8886    0.3980     0.5844 0.410 0.448
                            935.0899  839.9081 1324.1620                                1927.1086  863.1671 1227.8766

 FIRST STAGE N= 1   WORK SPLIT= 0.560   EFFICIENCY= 0.890   REACTION= 0.180
INLET STATIC PRESSURE AT HUB,MEAN,TIP= 11119.911 12617.624 13629.692
INLET TOTAL PRESSURE=   18171.978
INLET TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP= 13476.945 14001.377 14633.638
INLET STATIC TEMPERATURE AT HUB,MEAN,TIP=  2374.282  2444.716  2488.748
INLET TOTAL TEMPERATURE=    2660.000
INLET TOTAL RELATIVE TEMPERATURE AT HUB,MEAN,TIP=  2482.267  2504.288  2530.010
INLET DENSITY AT HUB,MEAN,TIP=     0.097     0.096     0.101
EXIT STATIC PRESSURE AT HUB,MEAN,TIP= 10291.566 10321.834 10339.600
EXIT TOTAL PRESSURE=   11215.337
EXIT TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP= 13029.800 13600.248 14305.593
EXIT STATIC TEMPERATURE AT HUB,MEAN,TIP=  2347.864  2349.460  2350.395
EXIT TOTAL TEMPERATURE=    2395.024
EXIT TOTAL RELATIVE TEMPERATURE AT HUB,MEAN,TIP=  2479.576  2504.279  2533.747
EXIT DENSITY AT HUB,MEAN,TIP=     0.081     0.081     0.081

  RADE     BAE      VAE      VEVCR     UEVCR     WEWCR     RADI      BAI       VAI      VIVCR     UIVCR      WIWCR  VXI   VXE
 21.226  -61.336  -13.531   0.3774    0.5829    0.7438    20.849    12.095    61.318   0.7015    0.5433     0.3531 0.337 0.367
                            818.5040 1264.2037 1659.0319                                1603.3556 1241.7630  787.0192
 18.051  -58.533  -15.800   0.3814    0.4957    0.6875    18.051    35.534    64.656   0.7866    0.4704     0.4264 0.337 0.367
                            827.0335 1075.1085 1524.4901                                1797.7037 1075.1085  945.6542
 14.876  -55.532  -18.951   0.3880    0.4086    0.6372    15.253    52.813    68.187   0.9062    0.3975     0.5767 0.337 0.367
                            841.3916  886.0133 1406.1247                                2071.0062  908.4540 1273.1968


INITIAL SURFACE AREA CALCULATIONS ********************

BLADE ENTERING ANGLE,BETA 1,FOR ROWS 1,2,3,4=       90.000      125.534      105.800      108.499
BLADE LEAVING ANGLE,BETA 2,FOR ROWS 1,2,3,4=      25.344      31.467      32.940      38.795
BLADE CAMBER ANGLE,PHI,FOR ROWS 1,2,3,4=      40.421      27.341      33.469      24.425
BLADE CAMBER LENGTH TO CHORD LENGTH RATIO FOR ROWS 1,2,3,4=        1.493        1.320        1.328        1.212
AXIAL CHORDS FOR ROWS 1,2,3,4=       2.798       1.991       2.244       1.501
SINGLE BLADE AREAS FOR ROWS 1,2,3,4=      47.447      31.859      40.749      27.728
PITCH FOR ROWS 1,2,3,4=       2.560       1.546       1.931       1.205
MEAN RADIAL CIRCUMFERENCE=      113.418
NUMBER OF BLADES IN ROWS 1,2,3,4=       44.        73.        59.        94.
TOTAL BLADE SURFACE AREAS IN ROWS 1,2,3,4=     2102.041     2337.120     2393.205     2609.172
```

```
COOLANT CALCULATION ********************

INPUT DATA**
PTD=   0.                    FARC=   0.023              PF=   0.150                DTY= 400.000
NPTD= 12
TPR=1460.000                 PRN=   0.710               VIS=0.240E-04              CON=0.950E-05
TPR=1660.000                 PRN=   0.709               VIS=0.260E-04              CON=0.108E-04
TPR=1860.000                 PRN=   0.708               VIS=0.280E-04              CON=0.117E-04
TPR=2060.000                 PRN=   0.706               VIS=0.300E-04              CON=0.127E-04
TPR=2260.000                 PRN=   0.705               VIS=0.320E-04              CON=0.137E-04
TPR=2460.000                 PRN=   0.704               VIS=0.340E-04              CON=0.147E-04
TPR=2660.000                 PRN=   0.703               VIS=0.355E-04              CON=0.160E-04
TPR=2860.000                 PRN=   0.702               VIS=0.370E-04              CON=0.170E-04
TPR=3060.000                 PRN=   0.700               VIS=0.390E-04              CON=0.180E-04
TPR=3260.000                 PRN=   0.695               VIS=0.405E-04              CON=0.192E-04
TPR=3460.000                 PRN=   0.693               VIS=0.420E-04              CON=0.205E-04
TPR=3660.000                 PRN=   0.686               VIS=0.435E-04              CON=0.220E-04
NTS=  1                      TMS=2180.000               NTR=  1                    TMR=2080.000
THERME=    0.700             CPC=   0.267               TWALLA=2060.000

INITIAL TOTAL BLADE SURFACE AREAS FOR ROWS 1,2,3,4=    2102.041    2337.120    2393.205    2609.172
COOLANT INLET TEMPERATURE=      1204.000
ASSUMED BLADE THERMAL COOLING EFFECTIVENESS=   0.700
INITIAL TOTAL EXIT TEMPERATURE RELATIVE TO ROWS 1,2,3,4=     2660.000    2504.279    2395.024    2275.389
INITIAL TOTAL INLET TEMPERATURE RELATIVE TO ROWS 1,2,3,4=     2660.000    2504.288    2395.024    2275.432
REVISED TOTAL INLET TEMPERATURE RELATIVE TO ROWS 1,2,3,4=     2660.000    2479.326    2354.005    2227.523
REVISED TOTAL EXIT TEMPERATURE RELATIVE TO ROWS 1,2,3,4=     2635.038    2463.259    2347.116    2223.450
REVISED TOTAL BLADE SURFACE AREAS FOR ROWS 1,2,3,4=    2050.533    2307.184    2385.141    2606.835
ASSUMED METAL TEMPERATURE FOR ROW( 1)=     2180.000          BLADE COOLANT FLOW RATIO=     0.016565
ASSUMED METAL TEMPERATURE FOR ROW( 2)=     2080.000          BLADE COOLANT FLOW RATIO=     0.012328
ASSUMED METAL TEMPERATURE FOR ROW( 3)=     2180.000          BLADE COOLANT FLOW RATIO=     0.005897
ASSUMED METAL TEMPERATURE FOR ROW( 4)=     2080.000          BLADE COOLANT FLOW RATIO=     0.003933
ASSUMED WALL METAL TEMPERATURE= 2060.000000
WALL COOLANT FLOW RATIO FOR ROW( 1)=     0.015231
WALL COOLANT FLOW RATIO FOR ROW( 2)=     0.005888
WALL COOLANT FLOW RATIO FOR ROW( 3)=     0.003047
WALL COOLANT FLOW RATIO FOR ROW( 4)=     0.000223
TURBINE WEIGHT FLOW AT EXIT OF ROWS 1,2,3,4=  328.818485  334.921719  337.918358  339.310982
AVERAGE BLADE HEIGHTS FOR ROWS 1,2,3,4 WITH BLADE AND WALL COOLANT=        5.546        6.039        6.904        7.726
REVISED VXI AND VXE FOR FIRST AND SECOND STAGE ROTORS=       0.338        0.370        0.414        0.454
TURBINE EXIT TOTAL TEMPERATURE WITH BLADE AND WALL COOLANT=      2112.457
AVERAGE H.T. COEFFICIENTS FOR ROWS 1,2,3,4=    0.111E+00    0.106E+00    0.859E-01    0.808E-01
CRITICAL ABSOLUTE VELOCITIES AT EXITS OF ROWS 1,2,3,4=     2275.795     2151.015     2147.865     2048.452
CRITICAL RELATIVE VELOCITIES AT EXITS OF ROWS 1,2,3,4=     2207.530     2200.365     2092.429     2090.515

                    ********************

                    CASE=144
VELOCITY DIAGRAMS ********************
INPUT DATA**
TCI=1204.000                 CORRF=    1.000            CORRFW=    1.000           FAR=   0.023
Y=  0.0631                   YB=  0.0387                TTO=2660.000               PTO=18734.00
RPM=6825.000                 DRTE=    0.100             WO= 321.117                DHT= 140.108
RTE=  22.000                 RHRTE=    0.641            N=  2                      NR=  2
NVUM=  1                     NRTE=  1                   WS(1)=    0.560            WS(2)=    0.440
GAMMA=    1.301              CP=   0.300                R=  53.980                 PC=    0.970
ETAT=   0.900                ETA(1)=    0.890           RE(1)=    0.180            RE(2)=    0.140
VUMVCR=  -0.039              VXEL=   0.800              VXEI=   0.800              VXII=    0.350
VXIL=   0.550

 LAST STAGE N= 2   WORK SPLIT= 0.440   EFFICIENCY= 0.901   REACTION= 0.140
INLET STATIC PRESSURE AT HUB,MEAN,TIP=  6890.863  7817.989  8378.736
INLET TOTAL PRESSURE=    10953.929
INLET TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP=  8391.906  8825.383  9372.423
INLET STATIC TEMPERATURE AT HUB,MEAN,TIP=  2154.489  2218.339  2254.177
INLET TOTAL TEMPERATURE=     2398.371
INLET TOTAL RELATIVE TEMPERATURE AT HUB,MEAN,TIP=  2254.996  2281.426  2313.391
INLET DENSITY AT HUB,MEAN,TIP=      0.059      0.065      0.069
EXIT STATIC PRESSURE AT HUB,MEAN,TIP=  6523.945  6527.625  6529.510
EXIT TOTAL PRESSURE=     7329.942
EXIT TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP=  8214.524  8698.293  9331.188
EXIT STATIC TEMPERATURE AT HUB,MEAN,TIP=  2134.497  2134.775  2134.918
EXIT TOTAL TEMPERATURE=     2192.805
EXIT TOTAL RELATIVE TEMPERATURF AT HUB,MEAN,TIP=  2251.377  2281.381  2318.756
EXIT DENSITY AT HUB,MEAN,TIP=      0.057      0.057      0.057

  RADE      BAE       VAE      VEVCR     UEVCR     WEWCR      RADI      BAI       VAI      VIVCR     UIVCR     WIWCR   VXI    VXE
 22.000   -55.969   -4.085    0.4492    0.6314    0.7785    21.473    -8.575    50.684    0.6779    0.5893    0.4423  .430  0.448
                            932.1907 1310.3090 1661.2326                                1471.2487 1278.9481  942.8137
 18.051   -51.193   -4.975    0.4498    0.5181    0.7009    18.051    16.666    55.456    0.7575    0.4954    0.4598 0.430  0.448
                            933.3380 1075.1085 1483.5035                                1643.9457 1075.1085  973.1559
 14.102   -45.422   -6.358    0.4509    0.4048    0.6300    14.629    40.625    60.843    0.8817    0.4015    0.5837 0.430  0.448
                            935.5755  839.9081 1324.5949                                1913.3829  871.2689 1228.3160
```

```
 FIRST STAGE N= 1   WORK SPLIT= 0.560   EFFICIENCY= 0.890   REACTION= 0.180
INLET STATIC PRESSURE AT HUB,MEAN,TIP= 10994.290 12534.069 13571.334
INLET TOTAL PRESSURE=   18171.979
INLET TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP= 13418.820 13947.383 14586.089
INLET STATIC TEMPERATURE AT HUB,MEAN,TIP=  2368.049  2440.961  2486.279
INLET TOTAL TEMPERATURE=      2660.000
INLET TOTAL RELATIVE TEMPERATURE AT HUB,MEAN,TIP=  2479.786  2502.051  2528.105
INLET DENSITY AT HUB,MEAN,TIP=      0.086      0.095      0.101
EXIT STATIC PRESSURE AT HUB,MEAN,TIP= 10207.071 10225.395 10236.647
EXIT TOTAL PRESSURE=   11292.710
EXIT TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP= 13032.690 13559.028 14198.323
EXIT STATIC TEMPERATURE AT HUB,MEAN,TIP=  2342.935  2343.908  2344.504
EXIT TOTAL TEMPERATURE=     2398.371
EXIT TOTAL RELATIVE TEMPERATURE AT HUB,MEAN,TIP=  2479.221  2502.035  2528.847
EXIT DENSITY AT HUB,MEAN,TIP=      0.081      0.081      0.081

   RADF      BAE       VAE       VEVCR     UEVCR     WEWCR      RADI       BAI        VAI       VIVCR     UIVCR      WIWCR  VXI   VXE
  20.960   -57.868   -10.273    0.4144    0.5752    0.7465    20.883     12.694     61.401    0.7066    0.5442    0.3556 0.338 0.408
                              899.2326 1248.3378 1663.5103                                 1614.8746 1243.7761  792.39.5
  18.051   -54.951   -11.884    0.4166    0.4954    0.6951    18.051     36.174     64.768    0.7934    0.47 4    0.4320 0.338 0.408
                              904.1979 1075.1085 1540.6920                                 1813.3143 1075.1085  957.6276
  15.142   -51.787   -14.083    0.4203    0.4156    0.6483    15.219     53.354     68.331    0.9160    0.3966    0.5869 0.338 0.408
                              912.2343  901.8792 1430.3347                                 2093.4732  906.44.9 1295.1251



INITIAL SURFACE AREA CALCULATIONS ********************

BLADE ENTERING ANGLE,BETA 1,FOR ROWS 1,2,3,4=       90.000       126.174      101.884      106.666
BLADE LEAVING ANGLE,BETA 2,FOR ROWS 1,2,3,4=        25.232       35.049       34.544       38.807
BLADE CAMBER ANGLE,PHI,FOR ROWS 1,2,3,4=        40.297       23.337       34.848       25.207
BLADE CAMBER LENGTH TO CHORD LENGTH RATIO FOR ROWS 1,2,3,4=        1.489        1.268        1.329        1.213
AXIAL CHORDS FOR ROWS 1,2,3,4=        2.832        1.913        2.110        1.474
SINGLE BLADE AREAS FOR ROWS 1,2,3,4=        48.491       28.271       36.055       26.756
PITCH FOR ROWS 1,2,3,4=        2.587        1.336        1.927        1.210
MEAN RADIAL CIRCUMFERENCE=      113.418
NUMBER OF BLADES IN ROWS 1,2,3,4=          44.          85.          59.          94.
TOTAL BLADE SURFACE AREAS IN ROWS 1,2,3,4=     2125.663     2399.469     2122.615     2507.059



COOLANT CALCULATION ********************

INPUT DATA**
PTD=    0.                    FARC=    0.023                 PF=    0.150                 DTY= 400.000
NPTD= 12
TPR=1460.000                  PRN=    0.710                  VIS=0.240E-04                CON=0.950E-05
TPR=1660.000                  PRN=    0.709                  VIS=0.260E-04                CON=0.108E-04
TPR=1860.000                  PRN=    0.708                  VIS=0.280E-04                CON=0.117E-04
TPR=2060.000                  PRN=    0.706                  VIS=0.300E-04                CON=0.127E-04
TPR=2260.000                  PRN=    0.705                  VIS=0.320E-04                CON=0.137E-04
TPR=2460.000                  PRN=    0.704                  VIS=0.340E-04                CON=0.147E-04
TPR=2660.000                  PRN=    0.703                  VIS=0.355E-04                CON=0.160E-04
TPR=2860.000                  PRN=    0.702                  VIS=0.370E-04                CON=0.170E-04
TPR=3060.000                  PRN=    0.700                  VIS=0.390E-04                CON=0.180E-04
TPR=3260.000                  PRN=    0.695                  VIS=0.405E-04                CON=0.192E-04
TPR=3460.000                  PRN=    0.693                  VIS=0.420E-04                CON=0.205E-04
TPR=3660.000                  PRN=    0.686                  VIS=0.435E-04                CON=0.220E-04
NTS=  1                       TMS=2180.000                   NTR=  1                      TMR=2080.000
THERME=    0.700              CPC=    0.267                  TWALLA=2060.000

INITIAL TOTAL BLADE SURFACE AREAS FOR ROWS 1,2,3,4=     2125.663     2399.469     2122.615     2507.059
COOLANT INLET TEMPERATURE=      1204.000
ASSUMED BLADE THERMAL COOLING EFFECTIVENESS=    0.700
INITIAL TOTAL EXIT TEMPERATURE RELATIVE TO ROWS 1,2,3,4=     2660.000     2502.035     2398.371     2281.381
INITIAL TOTAL INLET TEMPERATURE RELATIVE TO ROWS 1,2,3,4=     2660.000     2502.051     2398.371     2281.426
REVISED TOTAL INLET TEMPERATURE RELATIVE TO ROWS 1,2,3,4=     2660.000     2477.096     2356.921     2233.581
REVISED TOTAL EXIT TEMPERATURE RELATIVE TO ROWS 1,2,3,4=     2635.045     2460.591     2350.526     2229.434
REVISED TOTAL BLADE SURFACE AREAS FOR ROWS 1,2,3,4=     2068.574     2363.058     2111.156     2498.749
ASSUMED METAL TEMPERATURE FOR ROW( 1)=      2180.000            BLADE COOLANT FLOW RATIO=      0.016708
ASSUMED METAL TEMPERATURE FOR ROW( 2)=      2080.000            BLADE COOLANT FLOW RATIO=      0.012804
ASSUMED METAL TEMPERATURE FOR ROW( 3)=      2180.000            BLADE COOLANT FLOW RATIO=      0.005509
ASSUMED METAL TEMPERATURE FOR ROW( 4)=      2080.000            BLADE COOLANT FLOW RATIO=      0.004016
ASSUMED WALL METAL TEMPERATURE= 2060.000000
WALL COOLANT FLOW RATIO FOR ROW( 1)=      0.015377
WALL COOLANT FLOW RATIO FOR ROW( 2)=      0.005504
WALL COOLANT FLOW RATIO FOR ROW( 3)=      0.003049
WALL COOLANT FLOW RATIO FOR ROW( 4)=      0.000301
TURBINE WEIGHT FLOW AT EXIT OF ROWS 1,2,3,4=  331.759995  337.893864  340.761044  342.207428
AVERAGE BLADE HEIGHTS FOR ROWS 1,2,3,4 WITH BLADE AND WALL COOLANT=        5.599        5.781        6.478        7.568
REVISED VXI AND VXE FOR FIRST AND SECOND STAGE ROTORS=        0.340        0.411        0.434        0.453
TURBINE EXIT TOTAL TEMPERATURE WITH BLADE AND WALL COOLANT=      2118.617
AVERAGE H.T. COEFFICIENTS FOR ROWS 1,2,3,4=   0.111E+00   0.108E+00   0.897E-01   0.827E-01
CRITICAL ABSOLUTE VELOCITIES AT EXITS OF ROWS 1,2,3,4=     2275.798     2152.347     2149.425     2051.314
CRITICAL RELATIVE VELOCITIES AT EXITS OF ROWS 1,2,3,4=     2206.536     2199.173     2095.273     2093.327


                    ********************

THE LAST SET OF OUTPUT CONTAINS THE CONVERGED SOLUTION

*01* EXIT   IN  COOL
```

APPENDIX B

PROGRAM LISTING

```
      COMMON /XLOOP/ RY,RYB,RWO,RDHT,NWC,ITT,TESTY
      COMMON /CFCT/ TCI,CORRFW,CORRF,YW,TPPMTP(100),DHC,WPSTAT(5),HTEMP(
     15)
      COMMON /SV/ XVAI(5),XBAI(5),XBAE(5),XVAE(5),SAVE,BHS(5),BHR(5),RAE
     1(20),TGA(20),WF,RAT(3),RAH(3),RHOI(10),RHOE(10),VEL(10),VIL(10),PP
     2(10),TT(10),CONST2,CONST1,VILCI(10),GAMMA,R,DTR1,DTR2,FAR,WETO,VXI
     32,VXE2,VXI1,VXE1
      COMMON VXIL
      DIMENSION VUI(20), VUE(20), VI(20), VE(20), UI(20), UE(20), WUI(20
     1), WUE(20), WI2(20), WE2(20), TRTE(20), WCRE(20), BAE(20), BAI(20)
     2, VAE(20), VAI(20), VEVCR(20), VIVCR(20), UEVCR(20), UIVCR(20), WE
     3WCR(20), WIWCR(20), TRTI(20), WCRI(20), DH(20), WS(20), ETA(20), R
     4AI(20), RE(20), VUMVCR(20), TET(20), TPE(20), RT(50), SVE(20), SWE
     52(20), SVI(20), SWI2(20), DUMMY(100), NDUMMY(100), PRTI(100), PRTE
     6(100), TSTATE(100), TSTATI(100), PSTATE(100), PSTATI(100), RHOSE(1
     700), RHOSI(100)
      DIMENSION HIR(5), HER(5), CVAE(100), TPPCU(100), TPPCV(100), TPPCV
     1U(50),DUM(10),NDUM(10)
1     READ (5,51) NCASE
      READ (5,52) TCI,CORRF,CORRFW
      READ (5,53) FAR,Y,YB
      READ(5,54)TTO,PTO,RPM,DRTE,WO,DHT,RTE,RHRTE,NWC
      PTO=PTO/144.
      N=2
      NR=2
      NVUM=1
      NRTE=1
      READ (5,55) (WS(I),I=1,N)
      READ (5,56) GAMMA,R,PC
      CP=(GAMMA*R)/(GAMMA-1.)
      CP=CP/778.
      READ (5,55) ETAT,(ETA(I),I=1,N)
      READ (5,55) (RE(I),I=1,N)
      READ (5,55) (VUMVCR(I),I=1,NVUM)
      READ (5,55) VXEL,VXEI,VXII,VXIL
      IF(NWC.EQ.1)Y=YB
      DUM(1)=RTE
      DUM(2)=RHRTE
      NDUM(1)=N
      DUM(3)=PTO
      ITT=0
2221  CONTINUE
      ITT=ITT+1
      WRITE(6,2223)ITT
2223  FORMAT(1H ,16HITERATION NUMBER,I4)
      IF(ITT.EQ.1)GO TO 5000
      Y=RY
      YB=RYB
      IF(NWC.EQ.1)Y=YB
      WO=RWO
      DHT=RDHT
```

```
      RTE=DUM(1)
      RHRTE=DUM(2)
      N=NDUM(1)
      PTO=DUM(3)
 5000 CONTINUE
      WRITE (6,57) NCASE
      WRITE (6,40)
      WRITE (6,50)
      WRITE (6,41) TCI,CORRF,CORRFW,FAR
      TESTY=Y
      PTO=PTO*144.
      WRITE (6,42) Y,YB,TTO,PTO
      PTO=PTO/144.
      WRITE (6,43) RPM,DRTE,WO,DHT
      WRITE (6,44) RTE,RHRTE,N,NR
      WRITE (6,45) NVUM,NRTE,WS(1),WS(2)
      WRITE (6,46) GAMMA,CP,R,PC
      WRITE (6,47) ETAT,ETA(1),RE(1),RE(2)
      WRITE (6,48) VUMVCR(1),VXEL,VXEI,VXII
      WRITE (6,49) VXIL
      DHCB=1.+.5*(YB/((1.-Y)*(1.+FAR)))*(TCI/TTO)
      DHC=DHT*((1.-Y)*(1.+FAR))*DHCB
      WETO=WO/(1.+FAR*(1.-Y)-Y)
      WCBTO=YB*WETO
      WF=WO+WCBTO/2.
      YW=Y-YB
C     MINE=1 FOR SECOND STAGE
C     MINE=2 FOR FIRST STAGE
      MINE=0
      DUMMY(1)=TTO
      DUMMY(2)=PTO
      DUMMY(3)=RPM
      DUMMY(4)=DRTE
      DUMMY(5)=WF
      DUMMY(6)=DHT
      DUMMY(7)=RTE
      DUMMY(8)=RHRTE
      NDUMMY(9)=N
      NDUMMY(10)=NR
      NDUMMY(11)=NVUM
      NDUMMY(12)=NRTE
      DUMMY(13)=WS(1)
      DUMMY(14)=WS(2)
      DUMMY(15)=GAMMA
      DUMMY(16)=CP
      DUMMY(17)=R
      DUMMY(18)=PC
      DUMMY(19)=ETA(1)
      DUMMY(20)=ETA(2)
      DUMMY(21)=RE(1)
      DUMMY(22)=RE(2)
      DUMMY(23)=VUMVCR(1)
      DUMMY(24)=VXEL
      DUMMY(25)=VXEI
      DUMMY(26)=VXII
      CJ=778.
      G=32.17
 2222 CONTINUE
      NA=N
```

```
      TTO=DUMMY(1)
      PTO=DUMMY(2)
      RPM=DUMMY(3)
      DRTE=DUMMY(4)
      WF=DUMMY(5)
      DHT=DUMMY(6)
      RTE=DUMMY(7)
      RHRTE=DUMMY(8)
      N=NDUMMY(9)
      NR=NDUMMY(10)
      NVUM=NDUMMY(11)
      NRTE=NDUMMY(12)
      WS(1)=DUMMY(13)
      WS(2)=DUMMY(14)
      GAMMA=DUMMY(15)
      CP=DUMMY(16)
      R=DUMMY(17)
      PC=DUMMY(18)
      ETA(1)=DUMMY(19)
      ETA(2)=DUMMY(20)
      RE(1)=DUMMY(21)
      RE(2)=DUMMY(22)
      VUMVCR(1)=DUMMY(23)
      VXEL=DUMMY(24)
      VXEI=DUMMY(25)
      VXII=DUMMY(26)
      RT(1)=RTE
      DO 2 KL=2,NRTE
      RT(KL)=RT(KL-1)+DRTE
2     CONTINUE
      DHT=DHT*CJ
      PTO=PTO*144.0
      IF (N.EQ.1) GO TO 4
      PTE=PTO*(1.0-DHT/(CP*TTO*ETAT*CJ))**(GAMMA/(GAMMA-1.0))
      PT=PTO
      TT=TTO
      NS=N-1
      DO 3 II=1,NS
      DH(II)=WS(II)*DHT
      TPE(II)=PT*(1.0-DH(II)/(CP*TT*ETA(II)*CJ))**(GAMMA/(GAMMA-1.0))
      PT=TPE(II)
      TET(II)=TT-DH(II)/(CP*CJ)
3     TT=TET(II)
      ETA(N)=WS(N)*DHT/(CP*TT*(1.0-(PTE/PT)**((GAMMA-1.0)/GAMMA))*CJ)
4     DO 39 KL=1,NRTE
      RTE=RT(KL)
      RTE=RTE/12.0
      DO 38 K=1,NVUM
      VUEVCR=VUMVCR(K)
      KODE=0
      N=NA
      KRTE=0
C     LAST STAGE EXIT
      DH(N)=WS(N)*DHT
      TTE=TTO-DHT/(CP*CJ)
      PTE=PTO*(1.0-DHT/(CP*TTO*ETAT*CJ))**(GAMMA/(GAMMA-1.0))
      TTE2=TTE
      PTE2=PTE
      RAPS=3.1416*RPM/30.0
      KCC=1
```

```
      WHIC=0.0
5     UTE=RTE*RAPS
      RHE=RTE*RHRTE
      RME=(RHE+RTE)/2.0
      VUEM=VUEVCR*SQRT(2.0*G*GAMMA*R*TTE/(GAMMA+1.0))
      CE=VUEM*RME
      VUE(1)=CE/RTE
      VUE(2)=CE/RME
      VUE(3)=CE/RHE
      AE=3.1416*RTE**2*(1.0-RHRTE**2)
      CALL DENR (VXE,G,GAMMA,CP,R,TTE,PTE,VUE(2),WF,AE,RHOM)
      IF (VXE.GT.VXEL*SQRT(2.0*GAMMA*G*R*TTE/(GAMMA+1.0))) GO TO 36
      CALL VXR (VUE,VE,VXE,WF,TTE,PTE,G,GAMMA,CP,R,RTE,RME,RHE)
      UE(1)=UTE
      UE(2)=RME*RAPS
      UE(3)=RHE*RAPS
      WUE(3)=VUE(3)-UE(3)
      WE2(3)=VXE**2+WUE(3)**2
C     LAST STAGE INLET
      WIWEH2=1.-RE(N)
      CI=(G*DH(N)+RAPS*CE)/RAPS
      TTI=TTE+DH(N)/(CP*CJ)
      PTI=PTE/((1.0-DH(N)/(CP*CJ*TTI*ETA(N)))**(GAMMA/(GAMMA-1.0)))*PC
      TTI2=TTI
      PTI2=PTI
      RMI=RME
      RHI2=(RME-RHE)*0.55+RHE
      RHRTI1=RHRTE-.02
      RHRTI2=1.0/(2.0*RMI/RHI2-1.0)
      CALL RHRT2 (RHRTI2,GAMMA,CP,G,R,TTI,PTI,WF,RMI,CI,$2222)
      RHRTIL=RHRTI2
      KCHK=0
      TOLER=.0002
      IND=1
6     AI=3.1416*4.0*RMI**2*(1.0-RHRTI1)/(1.0+RHRTI1)
      RTI=SQRT(AI/(3.1416*(1.0-RHRTI1**2)))
      RHI=RTI*RHRTI1
      VUI(1)=CI/RTI
      VUI(2)=CI/RMI
      VUI(3)=CI/RHI
      CALL DENR (VXI,G,GAMMA,CP,R,TTI,PTI,VUI(2),WF,AI,RHOM)
      CALL VXR (VUI,VI,VXI,WF,TTI,PTI,G,GAMMA,CP,R,RTI,RMI,RHI)
      UI(3)=RHI*RAPS
      WHI2=(VUI(3)-UI(3))**2+VXI**2
      WHI2=-WHI2
      CALL MAXIM (RHRTI1,RHRTI2,WHI2,IND,TOLER)
      IF (IND.LT.6) GO TO 6
      WHI2=-WHI2
      RHRTI2=RHRTE-.002
      WC=WIWEH2*WE2(3)
7     AI1=3.1416*4.0*RMI**2*(1.0-RHRTI2)/(1.0+RHRTI2)
      RTI=SQRT(AI1/(3.1416*(1.-RHRTI2**2)))
      RHI=RTI*RHRTI2
      VUI(1)=CI/RTI
      VUI(2)=CI/RMI
      VUI(3)=CI/RHI
      CALL DENR (VXI,G,GAMMA,CP,R,TTI,PTI,VUI(2),WF,AI1,RHOM)
      CALL VXR (VUI,VI,VXI,WF,TTI,PTI,G,GAMMA,CP,R,RTI,RMI,RHI)
      UI(3)=RHI*RAPS
```

```
      WHI21=(VUI(3)-UI(3))**2+VXI**2
      IF (WHI21.GE.WC) GO TO 8
      IF (WHI21.LE.WC) GO TO 9
8     IF (WHI2.LE.WC) GO TO 12
      IF (KCHK.EQ.1) GO TO 10
      RHRTI2=RHRTIL
      WHI2E=WHI21
      KCHK=1
      GO TO 7
9     IF (WHI2.GE.WC) GO TO 12
      IF (KCHK.EQ.1) GO TO 10
      RHRTI2=RHRTIL
      WHI2E=WHI21
      KCHK=1
      GO TO 7
10    WHI21=WHI2E
      IF (KCC.EQ.1) WCC=WC
      IF (ABS(WHI21-WC).GT.ABS(WHIC-WCC)) GO TO 11
      RTE=RTE-.125/12.0
      WHIC=WHI21
      WCC=WC
      KCC=0
      GO TO 5
11    RTE=RTE+1.0/12.0
      WHIC=0.0
      KCC=1
      WCC=WC
      KRTE=KRTE+1
      IF (KRTE.GT.30) GO TO 36
      GO TO 5
12    CALL ROOT (WHI2,WHI21,RHRTI1,RHRTI2,WC,RHRTI,TTI,PTI,GAMMA,CP,WF,R
     1,VUI,VI,RTI,RMI,RHI,RAPS,CI,VXI)
      UI(1)=RTI*RAPS
      UI(2)=RMI*RAPS
      UI(3)=RHI*RAPS
      AR=(RTI/RTE)**2
      GO TO 28
C     FIRST STAGE
13    DH(N)=WS(N)*DHT
      WIWEH2=1.-RE(N)
      RTIR=RTI
      ARLS=AR
      PTE=PTI/PC
      TTE=TTI
      TTI=TTE+DH(N)/(CP*CJ)
      PTI=PTE/((1.-DH(N)/(CP*TTI*CJ*ETA(N)))**(GAMMA/(GAMMA-1.0)))*PC
      PTE1=PTE
      TTE1=TTE
      TTI1=TTI
      PTI1=PTI
C     FIRST STAGE EXIT
      RME=RMI
C     FIRST ASSUMED MEAN EXIT WHIRL
      VUEM=0.1*SQRT(2.0*G*GAMMA*R*TTE/(GAMMA+1.0))
      VUE4=VUEM
      GO TO 15
C     SECOND ASSUMED MEAN EXIT WHIRL
14    VUEM=(-.4)*SQRT(2.0*G*GAMMA*R*TTE/(GAMMA+1.0))
```

```
15    CE=VUEM*RME
      AR=ARLS
      GO TO 17
16    IF (AR.EQ.1.1) GO TO 37
      AR=AR+.01
      IF (AR.GT.1.1) AR=1.1
17    RTE=RTIR*SQRT(AR)
      RHE=2.0*RME-RTE
      AE=3.1416*(RTE**2-RHE**2)
      VUE(1)=CE/RTE
      VUE(2)=VUEM
      VUE(3)=CE/RHE
      UE(1)=RTE*RAPS
      UE(2)=RME*RAPS
      UE(3)=RHE*RAPS
      IF (ABS(VUE(1)).LT.0.5) VUE(1)=0.0
      IF (ABS(VUE(2)).LT.0.5) VUE(2)=0.0
      IF (ABS(VUE(3)).LT.0.5) VUE(3)=0.0
      CALL DENR (VXE,G,GAMMA,CP,R,TTE,PTE,VUE(2),WF,AE,RHOM)
      IF (VXE.GT.VXEI*SQRT(2.0*GAMMA*G*R*TTE/(GAMMA+1.0))) GO TO 16
      CALL VXR (VUE,VE,VXE,WF,TTE,PTE,G,GAMMA,CP,R,RTE,RME,RHE)
      WUE(3)=VUE(3)-UE(3)
      WE2(3)=WUE(3)**2+VXE**2
C     FIRST STAGE INLET
      CI=(G*DH(N)+RAPS*CE)/RAPS
      RMI=RME
      GO TO 19
18    IF (AR.EQ.1.1) GO TO 37
      AR=AR+.01
      IF (AR.GT.1.1) AR=1.1
19    RTI=RTE*SQRT(AR)
      RHI=2.0*RMI-RTI
      AI=3.1416*(RTI**2-RHI**2)
      VUI(1)=CI/RTI
      VUI(2)=CI/RMI
      VUI(3)=CI/RHI
      CALL DENR (VXI,G,GAMMA,CP,R,TTI,PTI,VUI(2),WF,AI,RHOM)
      IF (VXI.GT.VXII*SQRT(2.0*GAMMA*G*R*TTI/(GAMMA+1.0))) GO TO 18
      CALL VXR (VUI,VI,VXI,WF,TTI,PTI,G,GAMMA,CP,R,RTI,RMI,RHI)
      UI(1)=RTI*RAPS
      UI(2)=RMI*RAPS
      UI(3)=RHI*RAPS
      WUI(3)=VUI(3)-UI(3)
      WI2(3)=WUI(3)**2+VXI**2
      WIWE21=WI2(3)/WE2(3)
      IF (KODE.EQ.1) GO TO 26
      IF (VUEM.EQ.VUE4) GO TO 20
      GO TO 21
20    WIWE2A=WIWE21
      VUEMA=VUEM
      GO TO 14
21    WIWE22=WIWE21
      IF (WIWE2A.GT.WIWEH2) GO TO 22
      IF (WIWE2A.EQ.WIWEH2) GO TO 28
      IF (WIWE2A.LT.WIWEH2) GO TO 23
22    IF (WIWE22.LT.WIWEH2) GO TO 24
      IF (WIWE22.EQ.WIWEH2) GO TO 28
      GO TO 35
23    IF (WIWE22.GT.WIWEH2) GO TO 24
```

```
      IF (WIWE22.EQ.WIWEH2) GO TO 28
      GO TO 35
24    HA=VUEM-VUEMA
      HAN=HA
      VUEA=VUEMA
25    AB=WIWEH2-WIWE2A
      CB=WIWE22-WIWE2A
      IF (ABS(HAN).LT.0.0001) HAN=0.0
      H=AB/CB*HAN
      VUEM1=VUEA+H
      VUEM=VUEM1
      KODE=1
      GO TO 15
26    IF (ABS(WIWE21-WIWEH2).LE.(ABS(WIWE22-WIWE2A)*.0001)) GO TO 28
      IF (AB*(WIWE21-WIWEH2).LT.0.0) GO TO 27
      HAN=H
      WIWE22=WIWE21
      GO TO 25
27    HAN=HAN-H
      WIWE2A=WIWE21
      VUEA=VUEM1
      GO TO 25
28    MINE=MINE+1
      VCRE=SQRT(2.*G*GAMMA*R*TTE/(GAMMA+1.))
      VCRI=SQRT(2.0*G*GAMMA*R*TTI/(GAMMA+1.0))
      VXIV=VXI/VCRI
      VXEV=VXE/VCRE
      RAE(1)=RTE*12.0
      RAE(2)=RME*12.0
      RAE(3)=RHE*12.0
      RAI(1)=RTI*12.0
      RAI(2)=RMI*12.0
      RAI(3)=RHI*12.0
      IF (MINE.EQ.1) HER(2)=RAE(1)-RAE(3)
      IF (MINE.EQ.1) HIR(2)=RAI(1)-RAI(3)
      IF (MINE.EQ.2) HER(1)=RAE(1)-RAE(3)
      IF (MINE.EQ.2) HIR(1)=RAI(1)-RAI(3)
      IF (MINE.EQ.2) RAT(1)=RAI(1)
      IF (MINE.EQ.2) RAH(1)=RAI(3)
      BHS(1)=HIR(1)
      BHR(1)=(HER(1)+HIR(1))/2.
      BHS(2)=(HIR(2)+HER(1))/2.
      BHR(2)=(HER(2)+HIR(2))/2.
      DO 29 I=1,3
      WUE(I)=VUE(I)-UE(I)
      WE2(I)=WUE(I)**2+VXE**2
      BAE(I)=ATAN2(WUE(I),VXE)*57.296
      VAE(I)=ATAN2(VUE(I),VXE)*57.296
      VEVCR(I)=SQRT(VE(I))/VCRE
      UEVCR(I)=UE(I)/VCRE
      TRTE(I)=TTE-VE(I)/(2.0*G*CJ*CP)+WE2(I)/(2.0*G*CJ*CP)
      WCRE(I)=SQRT(2.0*G*GAMMA*R*TRTE(I)/(GAMMA+1.0))
      WEWCR(I)=SQRT(WE2(I))/WCRE(I)
      WUI(I)=VUI(I)-UI(I)
      WI2(I)=WUI(I)**2+VXI**2
      BAI(I)=ATAN2(WUI(I),VXI)*57.296
      VAI(I)=ATAN2(VUI(I),VXI)*57.296
      VIVCR(I)=SQRT(VI(I))/VCRI
      UIVCR(I)=UI(I)/VCRI
```

```
      TRTI(I)=TTI-VI(I)/(2.0*G*CJ*CP)+WI2(I)/(2.0*G*CJ*CP)
      PRTI(I)=PTI*((TRTI(I)/TTI)**(GAMMA/(GAMMA-1.)))
      PRTE(I)=PTE*((TRTE(I)/TTE)**(GAMMA/(GAMMA-1.)))
      TSTATE(I)=TTE*(1.-((GAMMA-1.)/(GAMMA+1.))*VEVCR(I)**2.)
      TSTATI(I)=TTI*(1.-((GAMMA-1.)/(GAMMA+1.))*VIVCR(I)**2.)
      PSTATI(I)=PTI*(1.-((GAMMA-1.)/(GAMMA+1.))*VIVCR(I)**2.)**(GAMMA/(G
     1AMMA-1.))
      PSTATE(I)=PTE*(1.-((GAMMA-1.)/(GAMMA+1.))*VEVCR(I)**2.)**(GAMMA/(G
     1AMMA-1.))
      RHOSE(I)=PSTATE(I)/(R*TSTATE(I))
      RHOSI(I)=PSTATI(I)/(R*TSTATI(I))
      WCRI(I)=SQRT(2.0*G*GAMMA*R*TRTI(I)/(GAMMA+1.0))
      WIWCR(I)=SQRT(WI2(I))/WCRI(I)
      SVE(I)=SQRT(VE(I))
      SWE2(I)=SQRT(WE2(I))
      SVI(I)=SQRT(VI(I))
29    SWI2(I)=SQRT(WI2(I))
      XBAE(MINE)=BAE(2)
      XVAE(MINE)=VAE(2)
      XBAI(MINE)=BAI(2)
      XVAI(MINE)=VAI(2)
      IF (MINE.EQ.2) TGA(1)=TTI
      IF (MINE.EQ.2) TGA(2)=TRTI(2)
      IF (MINE.EQ.2) CONST2=(WI2(2)-VI(2))/(2.*G*CJ*CP)
      IF (MINE.EQ.2) TGA(3)=TTE
      IF (MINE.EQ.1) TGA(4)=TRTI(2)
      IF (MINE.EQ.1) CONST1=(WI2(2)-VI(2))/(2.*G*CJ*CP)
      IF (N.EQ.NA) GO TO 30
      GO TO 31
30    CONTINUE
      WRITE (6,58) N,WS(N),ETA(N),RE(N)
      WRITE (6,63) PSTATI(3),PSTATI(2),PSTATI(1)
      WPSTAT(3)=PSTATI(2)
      WRITE (6,71) PTI
      PP(4)=PTI
      WRITE (6,66) PRTI(3),PRTI(2),PRTI(1)
      WRITE (6,64) TSTATI(3),TSTATI(2),TSTATI(1)
      WRITE (6,70) TTI
      HTEMP(3)=TTI
      TT(4)=TTI
      WRITE (6,68) TRTI(3),TRTI(2),TRTI(1)
      RHOI(4)=RHOSI(2)
      RHOE(3)=RHOSI(2)
      RHOE(4)=RHOSE(2)
      WRITE (6,60) RHOSI(3),RHOSI(2),RHOSI(1)
      WRITE (6,62) PSTATE(3),PSTATE(2),PSTATE(1)
      WPSTAT(4)=PSTATE(2)
      WRITE (6,73) PTE
      PP(5)=PTE
      WRITE (6,67) PRTE(3),PRTE(2),PRTE(1)
      WRITE (6,65) TSTATE(3),TSTATE(2),TSTATE(1)
      WRITE (6,72) TTE
      DTR2=TTE-TTI
      TT(5)=TTE
      WRITE (6,69) TRTE(3),TRTE(2),TRTE(1)
      HTEMP(4)=TRTE(2)
      WRITE (6,61) RHOSE(3),RHOSE(2),RHOSE(1)
      GO TO 32
```

```
31    WRITE (6,59) NN,WS(NN),ETA(NN),RE(N)
      WRITE (6,63) PSTATI(3),PSTATI(2),PSTATI(1)
      WPSTAT(1)=PSTATI(2)
      WRITE (6,71) PTI
      PP(2)=PTI
      WRITE (6,66) PRTI(3),PRTI(2),PRTI(1)
      WRITE (6,64) TSTATI(3),TSTATI(2),TSTATI(1)
      TT(2)=TTI
      WRITE (6,70) TTI
      HTEMP(1)=TTI
      WRITE (6,68) TRTI(3),TRTI(2),TRTI(1)
      RHOE(1)=RHOSI(2)
      RHOI(2)=RHOSI(2)
      RHOI(3)=RHOSE(2)
      RHOE(2)=RHOSE(2)
      WRITE (6,60) RHOSI(3),RHOSI(2),RHOSI(1)
      WRITE (6,62) PSTATE(3),PSTATE(2),PSTATE(1)
      WPSTAT(2)=PSTATE(2)
      WRITE (6,73) PTE
      PP(3)=PTE
      WRITE (6,67) PRTE(3),PRTE(2),PRTE(1)
      WRITE (6,65) TSTATE(3),TSTATE(2),TSTATE(1)
      WRITE (6,72) TTE
      DTR1=TTE-TTI
      TT(3)=TTE
      WRITE (6,69) TRTE(3),TRTE(2),TRTE(1)
      HTEMP(2)=TRTE(2)
      WRITE (6,61) RHOSE(3),RHOSE(2),RHOSE(1)
32    WRITE (6,74)
      IF (MINE.EQ.1) VXI2=VXIV*VCRI
      IF (MINE.EQ.1) VXE2=VXEV*VCRE
      IF (MINE.EQ.2) VXI1=VXIV*VCRI
      IF (MINE.EQ.2) VXE1=VXEV*VCRE
      DO 33 I=1,3
      WRITE (6,75) RAE(I),BAE(I),VAE(I),VEVCR(I),UEVCR(I),WEWCR(I),RAI(I
     1),BAI(I),VAI(I),VIVCR(I),UIVCR(I),WIWCR(I),VXIV,VXEV
      WRITE (6,76) SVE(I),UE(I),SWE2(I),SVI(I),UI(I),SWI2(I)
33    CONTINUE
      IF (MINE.EQ.2) VEL(1)=SVI(2)
      IF (MINE.EQ.2) VIL(2)=SWI2(2)
      IF (MINE.EQ.2) VEL(2)=SWE2(2)
      IF (MINE.EQ.2) VIL(3)=SVE(2)
      IF (MINE.EQ.1) VEL(3)=SVI(2)
      IF (MINE.EQ.1) VIL(4)=SWI2(2)
      IF (MINE.EQ.1) VEL(4)=SWE2(2)
      IF (MINE.EQ.2) VILCI(2)=SVI(2)
      IF (MINE.EQ.2) VILCI(3)=SVE(2)
      IF (MINE.EQ.1) VILCI(4)=SVI(2)
      IF (MINE.EQ.1) VILCI(5)=SVE(2)
      IF (MINE.EQ.1) CVAE(5)=VAE(2)*3.1416/180.
      IF (MINE.EQ.2) CVAE(3)=VAE(2)*3.1416/180.
      IF (MINE.EQ.2) TPPCU(3)=UE(2)
      IF (MINE.EQ.1) TPPCU(5)=UE(2)
      TPPCV(3)=VILCI(3)
      TPPCV(5)=VILCI(5)
      GRAT=-(GAMMA-1.)/(2.*GAMMA*G*R)
      TPPCVU(3)=TPPCV(3)*SIN(CVAE(3))
      TPPCVU(5)=TPPCV(5)*SIN(CVAE(5))
      TPPMTP(3)=GRAT*(2.*TPPCU(3)*TPPCVU(3)-TPPCU(3)*TPPCU(3))
```

```
      TPPMTP(5)=GRAT*(2.*TPPCU(5)*TPPCVU(5)-TPPCU(5)*TPPCU(5))
      NN=N-1
      IF (NN.GT.0) GO TO 34
      GO TO 38
34    N=N-1
      GO TO 13
35    WRITE (6,77)
      GO TO 38
36    WRITE (6,78)
      GO TO 38
37    WRITE (6,79)
38    CONTINUE
39    CONTINUE
      CALL SURC
      GO TO 2221
C
C
40    FORMAT (1H ,38HVELOCITY DIAGRAMS *******************,/)
41    FORMAT (1H ,4HTCI=,F8.3,17X,6HCORRF=,F8.3,15X,7HCORRFW=,F8.3,14X,4
     1HFAR=,F8.3)
42    FORMAT (1H ,2HY=,F8.4,19X,3HYB=,F8.4,18X,4HTTO=,F8.3,17X,4HPTO=,F8
     1.2)
43    FORMAT (1H ,4HRPM=,F8.3,17X,5HDRTE=,F8.3,16X,3HWO=,F8.3,18X,4HDHT=
     1,F8.3)
44    FORMAT (1H ,4HRTE=,F8.3,17X,6HRHRTE=,F8.3,15X,2HN=,I3,24X,3HNR=,I3
     1)
45    FORMAT (1H ,5HNVUM=,I3,21X,5HNRTE=,I3,21X,6HWS(1)=,F8.3,15X,6HWS(2
     1)=,F8.3)
46    FORMAT (1H ,6HGAMMA=,F8.3,15X,3HCP=,F8.3,18X,2HR=,F8.3,19X,3HPC=,F
     18.3)
47    FORMAT (1H ,5HETAT=,F8.3,16X,7HETA(1)=,F8.3,14X,6HRE(1)=,F8.3,15X,
     16HRE(2)=,F8.3)
48    FORMAT (1H ,7HVUMVCR=,F8.3,14X,5HVXEL=,F8.3,16X,5HVXEI=,F8.3,16X,5
     1HVXII=,F8.3)
49    FORMAT (1H ,5HVXIL=,F8.3)
50    FORMAT (1H ,12HINPUT DATA**)
51    FORMAT (I3)
52    FORMAT (F12.6,2F6.4)
53    FORMAT (3F12.6)
54    FORMAT (8F6.1,4I2)
55    FORMAT (12F6.1)
56    FORMAT (4F6.3)
57    FORMAT (1H1,20X,5HCASE=,I3,/)
58    FORMAT (1H0,14H LAST STAGE N=,I2,3X,11HWORK SPLIT=,F6.3,3X,11HEFFI
     1CIENCY=,F6.3,3X,9HREACTION=,F6.3,/)
59    FORMAT (1H0,15H FIRST STAGE N=,I2,3X,11HWORK SPLIT=,F6.3,3X,11HEFF
     1ICIENCY=,F6.3,3X,9HREACTION=,F6.3,/)
60    FORMAT (1H ,30HINLET DENSITY AT HUB,MEAN,TIP=,3F10.3)
61    FORMAT (1H ,29HEXIT DENSITY AT HUB,MEAN,TIP=,3F10.3)
62    FORMAT (1H ,37HEXIT STATIC PRESSURE AT HUB,MEAN,TIP=,3F10.3)
63    FORMAT (1H ,38HINLET STATIC PRESSURE AT HUB,MEAN,TIP=,3F10.3)
64    FORMAT (1H ,41HINLET STATIC TEMPERATURE AT HUB,MEAN,TIP=,3F10.3)
65    FORMAT (1H ,40HEXIT STATIC TEMPERATURE AT HUB,MEAN,TIP=,3F10.3)
66    FORMAT (1H ,46HINLET TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP=,3F10
     1.3)
67    FORMAT (1H ,45HEXIT TOTAL RELATIVE PRESSURE AT HUB,MEAN,TIP=,3F10.
     13)
68    FORMAT (1H ,49HINLET TOTAL RELATIVE TEMPERATURE AT HUB,MEAN,TIP=,3
     1F10.3)
```

```
69     FORMAT (1H ,48HEXIT TOTAL RELATIVE TEMPERATURE AT HUB,MEAN,TIP=,3F
      110.3)
70     FORMAT (1H ,24HINLET TOTAL TEMPERATURE=,F12.3)
71     FORMAT (1H ,21HINLET TOTAL PRESSURE=,F12.3)
72     FORMAT (1H ,23HEXIT TOTAL TEMPERATURE=,F12.3)
73     FORMAT (1H ,20HEXIT TOTAL PRESSURE=,F12.3)
74     FORMAT (1H0,3X,4HRADE,6X,3HBAE,7X,3HVAE,7X,5HVEVCR,5X,5HUEVCR,5X,5
      1HWEWCR,5X,4HRADI,6X,3HBAI,7X,3HVAI,7X,5HVIVCR,5X,5HUIVCR,5X,5HWIWC
      2R,2X,3HVXI,3X,3HVXE)
75     FORMAT (1H ,F8.3,2F10.3,3F10.4,3F10.3,3F10.4,2F6.3)
76     FORMAT (1H ,28X,3F10.4,30X,3F10.4)
77     FORMAT (1H0,62H VUE ITERATION. NO SOLUTION. CHANGE RHRT OR EXTEND
      1VUE LIMITS )
78     FORMAT (1H0,47HEXIT TIP DIAMETER MUST BE CHANGED. NO SOLUTION.)
79     FORMAT (1H0,26H AREA RATIO GREATER THAN 1)
       END
```

```
$IBFTC ROO

       SUBROUTINE ROOT (WH2,WH21,RHRT1,RHRT2,WC,RHRT,TT,PT,GAM,CP,WF,R,VU
      1,V,RT,RM,RH,RAPS,CI,VX)
       DIMENSION VU(20), V(20), U(20)
       G=32.17
       HA=RHRT2-RHRT1
       HAN=HA
       RALT=RHRT1
1      AB=WC-WH2
       C=WH21-WH2
       IF (ABS(HAN).LT.0.000001) HAN=0.0
       H=AB/C*HAN
       RHRT=RALT+H
       A=3.1416*4.0*RM**2*(1.0-RHRT)/(1.0+RHRT)
       RT=SQRT(A/(3.1416*(1.0-RHRT**2)))
       RH=RT*RHRT
       VU(1)=CI/RT
       VU(2)=CI/RM
       VU(3)=CI/RH
       GAMMA=GAM
       CALL DENR (VX,G,GAMMA,CP,R,TT,PT,VU(2),WF,A,RHOM)
       CALL VXR (VU,V,VX,WF,TT,PT,G,GAMMA,CP,R,RT,RM,RH)
       U(3)=RH*RAPS
       WHI2=(VU(3)-U(3))**2+VX**2
       IF (ABS((WH21-WH2)*.001).LE.0.09) GO TO 2
       IF (ABS(WHI2-WC).LE.ABS(WH21-WH2)*.001) RETURN
       GO TO 3
2      IF (ABS(WHI2-WC).LE.0.09) RETURN
3      IF (AB*(WHI2-WC).LT.0.0) GO TO 4
       HAN=H
       WH21=WHI2
       GO TO 1
4      HAN=HAN-H
       WH2=WHI2
       RALT=RHRT
       GO TO 1
       END
```

```
$IBFTC RHRT
      SUBROUTINE RHRT2 (RHRTI1,GAMMA,CP,G,R,TTI,PTI,WF,RMI,CI,*)
      COMMON VXIL
      DIMENSION VUI(3)
      GO TO 2
1     RHRTI1=RHRTI1-.02
      IF (RHRTI1.EQ.0.) VXIL=VXIL+.01
      IF (RHRTI1.EQ.0.) RETURN 1
2     AI=3.1416*4.0*RMI**2*(1.0-RHRTI1)/(1.0+RHRTI1)
      RTI=SQRT(AI/(3.1416*(1.0-RHRTI1**2)))
      RHI=RTI*RHRTI1
      VUI(1)=CI/RTI
      VUI(2)=CI/RMI
      VUI(3)=CI/RHI
      CALL DENR (VXI,G,GAMMA,CP,R,TTI,PTI,VUI(2),WF,AI,RHOM)
      IF (VXI.GT.VXIL*SQRT(2.0*GAMMA*R*G*TTI/(GAMMA+1.0))) GO TO 1
      RETURN
      END
```

```
$IBFTC DEN
      SUBROUTINE DENR (VX,G,GAM,CP,R,TT,PT,VUM,WF,A,RHOM)
      VX=0.7*SQRT(2.0*GAM*R*G*TT/(GAM+1.0))
      VX1=VX
      CJ=778.
1     VM=VUM**2+VX**2
      T=TT-VM/(2.0*G*CJ*CP)
      IF (T.LT.0.0) RETURN
      P=PT*(T/TT)**(GAM/(GAM-1.0))
      RHOM=P/(R*T)
      VX=WF/(RHOM*A)
      IF (ABS(VX/VX1-1.0).LT.0.001) RETURN
      VX1=VX
      GO TO 1
      END
```

```
$IBFTC VX
      SUBROUTINE VXR (VU,V,VX,WF,TT,PT,G,GAM,CP,R,RTE,RME,RHE)
      DIMENSION VU(20), V(20), T(20), P(20), RHO(20)
      VX1=VX
      CJ=778.
1     DO 2 I=1,3
      V(I)=VX**2+VU(I)**2
      T(I)=TT-V(I)/(2.0*G*CJ*CP)
      P(I)=PT*(T(I)/TT)**(GAM/(GAM-1.0))
2     RHO(I)=P(I)/(R*T(I))
      FAB=(RHO(3)-RHO(2))/(RHE-RME)
      FBC=(RHO(2)-RHO(1))/(RME-RTE)
      FABC=(FAB-FBC)/(RHE-RTE)
      HTINT=RHO(3)*(RTE**2-RHE**2)/2.0+FAB*((RTE**3-RHE**3)/3.0-(RHE*RTE
```

```
   1**2-RHE**3)/2.0)+FABC*((RTE**4-RHE**4)/4.-(RME+RHE)*(RTE**3-RHE**3
   2)/3.0+RME*RHE*(RTE**2-RHE**2)/2.0)
      VX=WF/(2.0*3.1416*HTINT)
      IF (ABS(VX/VX1-1.0).LT.0.0005) RETURN
      VX1=VX
      GO TO 1
      END
```

```
$IBFTC MAXI
      SUBROUTINE MAXIM (WA,WAMAX,WTFL,IND,TOLER)
      DIMENSION SPEED(3), WEIGHT(3)
      GO TO (1,3,5,14,23),IND
1     JUMP=1
      IF (WAMAX.LT.WA) GO TO 2
      SPEED(1)=WA
      WEIGHT(1)=WTFL
      WA=WAMAX
      IND=2
      RETURN
2     SPEED(3)=WA
      WEIGHT(3)=WTFL
      WA=WAMAX
      IND=5
      RETURN
3     SPEED(3)=WA
      WEIGHT(3)=WTFL
4     WA=(SPEED(1)+SPEED(3))/2.
      IF ((SPEED(3)-SPEED(1)).LT.TOLER) GO TO 24
      IND=3
      RETURN
5     SPEED(2)=WA
      WEIGHT(2)=WTFL
      IF (WTFL.LE.WEIGHT(1).OR.WTFL.LE.WEIGHT(3)) GO TO 12
      IND=4
6     IF (WEIGHT(3)-WEIGHT(1)) 8,9,7
7     WA=(SPEED(1)+SPEED(2))/2.0
      RETURN
8     WA=(SPEED(3)+SPEED(2))/2.0
      RETURN
9     GO TO (10,11),JUMP
10    JUMP=2
      GO TO 7
11    JUMP=1
      GO TO 8
12    IF (WEIGHT(3).GT.WEIGHT(1)) GO TO 13
      WEIGHT(3)=WTFL
      SPEED(3)=WA
      GO TO 4
13    WEIGHT(1)=WTFL
      SPEED(1)=WA
      GO TO 4
14    IF ((SPEED(3)-SPEED(1)).LT.TOLER) GO TO 24
      IF (WTFL-WEIGHT(2)) 18,21,15
15    IF (WA-SPEED(2)) 17,16,16
```

```
16    SPEED(1)=SPEED(2)
      SPEED(2)=WA
      WEIGHT(1)=WEIGHT(2)
      WEIGHT(2)=WTFL
      GO TO 6
17    SPEED(3)=SPEED(2)
      SPEED(2)=WA
      WEIGHT(3)=WEIGHT(2)
      WEIGHT(2)=WTFL
      GO TO 6
18    IF (WA-SPEED(2)) 20,19,19
19    WEIGHT(3)=WTFL
      SPEED(3)=WA
      GO TO 6
20    WEIGHT(1)=WTFL
      SPEED(1)=WA
      GO TO 6
21    IF (WA.GT.SPEED(2)) GO TO 22
      SPEED(3)=SPEED(2)
      WEIGHT(3)=WEIGHT(2)
      GO TO 5
22    SPEED(1)=SPEED(2)
      WEIGHT(1)=WEIGHT(2)
      GO TO 5
23    SPEED(1)=WA
      WEIGHT(1)=WTFL
      GO TO 4
24    IND=6
      RETURN
      END
```

```
$IBFTC SUR

      SUBROUTINE SURC
      COMMON /SV/ XVAI(5),XBAI(5),XBAE(5),XVAE(5),SAVE,BHS(5),BHR(5),RAE
     1(20),TGA(20),WF,RAT(3),RAH(3),RHOI(10),RHOE(10),VEL(10),VIL(10),PP
     2(10),TT(10),CONST2,CONST1,VILCI(10),GAMMA,R,DTR1,DTR2,FAR,WETO,VXI
     32,VXE2,VXI1,VXE1
      COMMON /BVE/ BV(10,12),AB(2),LB(2),X(2)
      COMMON /CF/ BCS(10),BCR(10),TBSAS(10),TBSAR(10),XMRC
      DIMENSION PSIS1(5), DAS1(5), PSIS2(5), DAS2(5), PSIR1(5), DAR1(5),
     1 PSIR2(5), DAR2(5), DALPAR(5), DALPAS(5)
      DIMENSION BX(10,2)
      DIMENSION B2M(10), PSIM(10), ALPHA(10), RMCLCX(10), B1S(5), B2S(5)
     1, B1R(5), B2R(5), ALPHZS(5), ALPHZR(5), PSIMS(5), PSIMR(5), ALPHAS
     2(5), ALPHAR(5), XCLCXS(5), XCLCXR(5), ARS(5), ARR(5), CXS(5), CXR(
     35), BSAS(5), BSAR(5), PS(5), PR(5), BPRS(5), BPRR(5)
      DIMENSION A(55),B(89)
      EQUIVALENCE (BX,BV(1,11))
      DATA A/30.,60.,90.,120.,150.,160.,10.,14.,20.,30.,45.,60.,70.,79.,
     175.,69.,60.,48.5,41.,37.5,73.5,69.5,64.,55.,43.,30.,22.,70.5,64.,5
     26.5,46.5,34.,22.,14.,72.,60.,48.,35.,20.,6.5,-1.,82.,52.,35.5,20.,
     33.,-11.,-19.,90.,48.,29.5,14.,-3.,-17.5,-25.5/
      DATA B/0.,20.,40.,60.,80.,100.,120.,140.,-20.,-10.,0.0,10.,20.,30.
     1,40.,50.,60.,1.06,1.015,1.0,1.02,1.075,1.155,1.305,1.57,1.985,1.07
     2,1.03,1.02,1.03,1.075,1.155,1.305,1.57,2.00,1.11,1.07,1.06,1.07,1.
```

```
311,1.18,1.315,1.60,2.1,1.14,1.10,1.09,1.105,1.15,1.225,1.38,1.68,2
4.14,1.18,1.14,1.13,1.14,1.20,1.295,1.47,1.76,2.18,1.24,1.19,1.18,1
5.20,1.26,1.37,1.54,1.80,2.22,1.38,1.30,1.27,1.29,1.36,1.48,1.66,1.
693,2.30,1.56,1.42,1.43,1.42,1.50,1.61,1.80,2.08,2.46/
      REWIND 7
      ITOT1=55
      I=6
      J=7
      WRITE(7)(A(K),K=1,I)
      IJ=I+J
      IP=I+1
      WRITE(7)(A(K),K=IP,IJ)
      KK=I+J+1
      WRITE(7)(A(K),K=KK,ITOT1)
      ITOT2=89
      I=8
      J=9
      WRITE(7)(B(K),K=1,I)
      IJ=I+J
      IP=I+1
      WRITE(7)(B(K),K=IP,IJ)
      KK=I+J+1
      WRITE(7)(B(K),K=KK,ITOT2)
      REWIND 7
      WRITE (6,19)
      VAIL=XVAI(1)
      BAIL=XBAI(1)
      BAEL=XBAE(1)
      VAEI=XVAE(2)
      BAEI=XBAE(2)
      BAII=XBAI(2)
      VAII=XVAI(2)
C     COMPUTE BLADE ENTERING AND LEAVING ANGLES
      B1S(1)=90.
      B2S(1)=90.-VAII
      B1R(1)=90.+BAII
      B2R(1)=90.+BAEI
      B1S(2)=90.-VAEI
      B2S(2)=90.-VAIL
      B1R(2)=90.+BAIL
      B2R(2)=90.+BAEL
      DB1=B1S(1)-B2S(1)
      DB2=B1R(1)-B2R(1)
      DB3=B1S(2)-B2S(2)
      DB4=B1R(2)-B2R(2)
C     READ IN DATA FOR FIGURE 2
      I=6
      J=7
      LB(1)=I
      LB(2)=J
      READ (7)     (BX(K,1),K=1,I)
      READ (7)     (BX(K,2),K=1,J)
      READ (7)     ((BV(K,L),L=1,J),K=1,I)
      ALPHZS(1)=BVTL(B1S(1),B2S(1))
      ALPHZR(1)=BVTL(B1R(1),B2R(1))
      ALPHZS(2)=BVTL(B1S(2),B2S(2))
      ALPHZR(2)=BVTL(B1R(2),B2R(2))
C     READ IN DATA FPR FIGURE 3
      NPTSB=2
```

```
      B2M(1)=38.6
      PSIM(1)=1.1
      B2M(2)=10.
      PSIM(2)=.26
1     CONTINUE
C     READ IN DATA FOR FIGURE 5
      I=8
      J=9
      LB(1)=I
      LB(2)=J
      READ (7)     (BX(K,1),K=1,I)
      READ (7)     (BX(K,2),K=1,J)
      READ (7)     ((BV(K,L),L=1,J),K=1,I)
      CALL LINT (B2S(1),NPTSB,B2M,PSIM,PSIMS(1))
      PSIMR(1)=1.
      CALL LINT (B2S(2),NPTSB,B2M,PSIM,PSIMS(2))
      PSIMR(2)=1.
C     READ IN DATA FOR FIGURE 4A
      PSIS1(1)=.40
      PSIS1(2)=1.
      DAS1(1)=-33.
      DAS1(2)=10.
      PSIS2(1)=.40
      PSIS2(2)=1.
      DAS2(1)=-18.5
      DAS2(2)=-2.5
C     READ IN DATA FOR FIGURE 4B
      PSIR1(1)=.60
      PSIR1(2)=1.5
      DAR1(1)=-14.5
      DAR1(2)=10.5
      PSIR2(1)=.70
      PSIR2(2)=1.1
      DAR2(1)=-9.
      DAR2(2)=-6.
      CALL LINT (PSIMS(1),2,PSIS1,DAS1,DALPAS(1))
      CALL LINT (PSIMS(2),2,PSIS2,DAS2,DALPAS(2))
      CALL LINT (PSIMR(1),2,PSIR1,DAR1,DALPAR(1))
      CALL LINT (PSIMR(2),2,PSIR2,DAR2,DALPAR(2))
      DO 6 I=1,2
6     ALPHAS(I)=ALPHZS(I)+DALPAS(I)
      DO 7 I=1,2
7     ALPHAR(I)=ALPHZR(I)+DALPAR(I)
      XCLCXS(1)=BVTL(DB1,ALPHAS(1))
      XCLCXR(1)=BVTL(DB2,ALPHAR(1))
      XCLCXS(2)=BVTL(DB3,ALPHAS(2))
      XCLCXR(2)=BVTL(DB4,ALPHAR(2))
      XCLCXS(1)=1.056*XCLCXS(1)
      ARS(1)=2.
      ARR(1)=3.
      ARS(2)=3.
      ARR(2)=5.
      FAC=1.
8     CXS(1)=BHS(1)/(ARS(1)*FAC)
      IF (CXS(1).LT.1.) FAC=FAC-.1
      IF (CXS(1).LT.1.) GO TO 8
      CXR(1)=BHR(1)/(ARR(1)*FAC)
      IF (CXR(1).LT.1.) FAC=FAC-.1
      IF (CXR(1).LT.1.) GO TO 8
```

```
      CXS(2)=BHS(2)/(ARS(2)*FAC)
      IF (CXS(2).LT.1.) FAC=FAC-.1
      IF (CXS(2).LT.1.) GO TO 8
      CXR(2)=BHR(2)/(ARR(2)*FAC)
      IF (CXR(2).LT.1.) FAC=FAC-.1
      IF (CXR(2).LT.1.) GO TO 8
      DO 9 I=1,2
9     BCS(I)=XCLCXS(I)*CXS(I)
      DO 10 I=1,2
10    BCR(I)=XCLCXR(I)*CXR(I)
      DO 11 I=1,2
11    BSAS(I)=BHS(I)*XCLCXS(I)*CXS(I)*2.030
      DO 12 I=1,2
12    BSAR(I)=BHR(I)*XCLCXR(I)*CXR(I)*2.030
      DO 13 I=1,2
      PS(I)=PSIMS(I)*CXS(I)/(2.*SIN(.0175*B2S(I))*SIN(.0175*B2S(I))*(COT
     1AN(.0175*B2S(I))-COTAN(.0175*B1S(I))))
13    CONTINUE
      DO 14 I=1,2
      PR(I)=PSIMR(I)*CXR(I)/(2.*SIN(.0175*B2R(I))*SIN(.0175*B2R(I))*(COT
     1AN(.0175*B2R(I))-COTAN(.0175*B1R(I))))
14    CONTINUE
      XMRC=2.*3.14159*RAE(2)
      DO 15 I=1,2
15    BPRS(I)=XMRC/PS(I)
      DO 16 I=1,2
16    BPRR(I)=XMRC/PR(I)
      DO 17 I=1,2
17    TBSAS(I)=BPRS(I)*BSAS(I)
      DO 18 I=1,2
18    TBSAR(I)=BPRR(I)*BSAR(I)
      WRITE (6,20) B1S(1),B1R(1),B1S(2),B1R(2)
      WRITE (6,21) B2S(1),B2R(1),B2S(2),B2R(2)
      WRITE (6,22) ALPHAS(1),ALPHAR(1),ALPHAS(2),ALPHAR(2)
      WRITE (6,23) XCLCXS(1),XCLCXR(1),XCLCXS(2),XCLCXR(2)
      WRITE (6,24) CXS(1),CXR(1),CXS(2),CXR(2)
      WRITE (6,25) BSAS(1),BSAR(1),BSAS(2),BSAR(2)
      WRITE (6,26) PS(1),PR(1),PS(2),PR(2)
      WRITE (6,27) XMRC
      WRITE (6,28) BPRS(1),BPRR(1),BPRS(2),BPRR(2)
      WRITE (6,29) TBSAS(1),TBSAR(1),TBSAS(2),TBSAR(2)
      CALL COOLA
      RETURN
C
C
19    FORMAT (1H1,54HINITIAL SURFACE AREA CALCULATIONS *****************
     1***,//)
20    FORMAT (1H ,45HBLADE ENTERING ANGLE,BETA 1,FOR ROWS 1,2,3,4=,4F12.
     13)
21    FORMAT (1H ,44HBLADE LEAVING ANGLE,BETA 2,FOR ROWS 1,2,3,4=,4F12.3
     1)
22    FORMAT (1H ,40HBLADE CAMBER ANGLE,PHI,FOR ROWS 1,2,3,4=,4F12.3)
23    FORMAT (1H ,59HBLADE CAMBER LENGTH TO CHORD LENGTH RATIO FOR ROWS
     11,2,3,4=,4F12.3)
24    FORMAT (1H ,30HAXIAL CHORDS FOR ROWS 1,2,3,4=,4F12.3)
25    FORMAT (1H ,36HSINGLE BLADE AREAS FOR ROWS 1,2,3,4=,4F12.3)
26    FORMAT (1H ,23HPITCH FOR ROWS 1,2,3,4=,4F12.3)
27    FORMAT (1H ,26HMEAN RADIAL CIRCUMFERENCE=,F12.3)
28    FORMAT (1H ,33HNUMBER OF BLADES IN ROWS 1,2,3,4=,4F12.0)
```

```
29    FORMAT (1H ,42HTOTAL BLADE SURFACE AREAS IN ROWS 1,2,3,4=,4F12.3)
30    FORMAT (2I5)
31    FORMAT (8F10.1)
32    FORMAT (I5)
33    FORMAT (2F12.4)
      END
```

```
$IBFTC BVD

      FUNCTION BVTL (V1,V2)
      COMMON /BVE/ BV(10,12),AB(2),LB(2),X(2)
      DIMENSION BX(10,2)
      EQUIVALENCE (BX,BV(1,11))
C
C     BIVARIATE INTERPOLATION FOUR POINT FORMULA
C
      X(1)=V1
      X(2)=V2
      DO 4 I=1,2
C     IS ARG BELOW RANGE OF TABLE
      IF (X(I).LT.BX(1,I)) GO TO 2
C     NO
      N=LB(I)
      DO 1 J=2,N
1     IF (X(I).LE.BX(J,I)) GO TO 3
2     WRITE (6,5) X(1),X(2)
      CALL EXIT
3     M=J-1
      IF (I.EQ.1) K=M
4     AB(I)=(X(I)-BX(M,I))/(BX(J,I)-BX(M,I))
      I=K+1
      BVTL=BV(K,M)+(BV(I,M)-BV(K,M))*AB(1)+(BV(K,J)-BV(K,M))*AB(2)+(BV(K
     1,M)+BV(I,J)-BV(I,M)-BV(K,J))*AB(1)*AB(2)
      RETURN
C
C
5     FORMAT (1H1,27HBIVARIATE INTERP ERROR V1= ,E10.2,5H V2= ,E10.2)
      END
```

```
$IBFTC DLINT

      SUBROUTINE LINT (XX,NTAB,XTAB,YTAB,YY)
      DIMENSION XTAB(1), YTAB(1)
      DO 2 N=2,NTAB
      IF (XX-XTAB(N)) 1,1,2
1     N2=N
      N1=N-1
      GO TO 3
2     CONTINUE
      N2=NTAB
      N1=N2-1
3     IF (YTAB(N1)-YTAB(N2)) 5,4,5
```

```
4       YY=YTAB(N1)
        RETURN
5       IF (XTAB(N1)-XTAB(N2)) 7,6,7
6       YY=0.5*(YTAB(N1)+YTAB(N2))
        RETURN
7       B=(YTAB(N2)-YTAB(N1))/(XTAB(N2)-XTAB(N1))
        A=YTAB(N1)-B*XTAB(N1)
        YY=A+B*XX
        RETURN
        END
```

```
$IBFTC COOL     DEBUG
        SUBROUTINE COOLA
        REAL K
        COMMON /XLOOP/ RY,RYB,RWC,RDHT,NWC,ITT,TESTY
        COMMON /CFCT/ TCI,CORRFW,CORRF,YW,TPPMTP(100),DHC,WPSTAT(5),HTEMP(
       15)
        COMMON /SV/ XVAI(5),XBAI(5),XBAE(5),XVAE(5),SAVE,BHS(5),BHR(5),RAE
       1(20),TGA(20),WF,RAT(3),RAH(3),RHOI(10),RHOE(10),VEL(10),VIL(10),PP
       2(10),TT(10),CONST2,CONST1,VILCI(10),GAMMA,R,DTR1,DTR2,FAR,WETO,VXI
       32,VXE2,VXI1,VXE1
        COMMON /CF/ BCS(10),BCR(10),TBSAS(10),TBSAR(10),XMRC
        DIMENSION BC(20), BSA(20), TG(20), RI(20), RE(20), RVA(20), X(20),
       1 VISC(20), REAB(20), COND(20), HG(20), U(20), TMS(20), TMR(20), TM
       2A(20,20), QR(20,20), TMMICM(10,10), WCWE(10,10), TPN(10), TWF(10),
       3 TWFO(10), BSAO(10), RVO(10), WC(10), VCR(10), VOVCR(10), RORP(10)
       4, RV(10), VXI(4), VXE(4), TPR(20), PR(20), PRN(20), TCON(20), CON(
       520), TMU(20), VIS(20), TGART(10), EF(10), CXF(10), CPG(10), RATCP(
       610), BRAKT(10), WCWEC(10), TGARTA(10), PRW(10), CONDG(10), PRG(10)
       7, VISCG(9), TPPN(50), TGAMAX(10)
        DIMENSION BH(5), WBH(5), WCW(5), WRHO(5), WVEX(5), WCWT(5), WDA(5)
       1, WANNA(5), WBSA(5)
        DIMENSION WCR(10)
        DIMENSION TESTC(50)
        DIMENSION TTWF(10)
        IF(ITT.GT.1)GO TO 5001
        READ(5,43)FARC,PF,DTY
        PTD=0.
        READ (5,42) NPTD
        NPTPR=NPTD
        NPTMU=NPTD
        NPTCON=NPTD
        DO 1 I=1,NPTD
        READ (5,32) TPR(I),PRN(I),VIS(I),CON(I)
        TMU(I)=TPR(I)
        TCON(I)=TPR(I)
1       CONTINUE
        NTS=1
        READ (5,43) (TMS(I),I=1,NTS)
        NTR=1
        READ (5,43) (TMR(I),I=1,NTR)
        READ (5,43) THERME
        READ (5,43) CPC
        READ (5,52) TWALLA
```

```
      TP2=TCI
      NSTAGE=2
5001  WRITE(6,41)
      WRITE (6,33)
      WRITE (6,34) PTD,FARC,PF,DTY
      WRITE (6,35) NPTD
      DO 2 I=1,NPTD
2     WRITE (6,36) TPR(I),PRN(I),VIS(I),CON(I)
      WRITE (6,37) NTS,TMS(1),NTR,TMR(1)
      WRITE (6,38) THERME,CPC,TWALLA
      NROWS=2*NSTAGE
      NROWSP=NROWS+1
      G=32.2
      BC(1)=BCS(1)
      BC(2)=BCR(1)
      BC(3)=BCS(2)
      BC(4)=BCR(2)
      BSA(1)=TBSAS(1)
      BSA(2)=TBSAR(1)
      BSA(3)=TBSAS(2)
      BSA(4)=TBSAR(2)
      WRITE (6,47) BSA(1),BSA(2),BSA(3),BSA(4)
      WBSA(1)=BSA(1)
      WBSA(2)=BSA(2)
      WBSA(3)=BSA(3)
      WBSA(4)=BSA(4)
      RI(1)=WF*144.*CORRFW/(3.14159*(RAT(1)**2.-RAH(1)**2.))
      AX=3.14159*(RAT(1)**2.-RAH(1)**2.)
      DO 3 I=2,NROWS
      RI(I)=RHOI(I)*VIL(I)*CORRF
3     CONTINUE
      DO 4 I=1,NROWS
      RE(I)=RHOE(I)*VEL(I)*CORRF
4     CONTINUE
      TPN(1)=TGA(1)
      TWF(1)=WF*CORRFW
      DO 5 I=1,NROWS
5     WC(I)=0.0
      DO 6 I=2,NROWSP
      TWF(I)=TWF(I-1)
6     TPN(I)=TT(I)
      WE=WETO*CORRFW
      WRITE (6,44) TCI
      WRITE (6,39) THERME
      WRITE (6,49) HTEMP(1),HTEMP(2),HTEMP(3),HTEMP(4)
      WRITE (6,46) TGA(1),TGA(2),TGA(3),TGA(4)
7     CONTINUE
      TGAMAX(1)=TGA(1)+PF*(TGA(1)-(TP2+DTY))
      TGAMAX(3)=TGA(3)+(TGAMAX(1)-TGA(1))/2.
      DO 8 I=1,NROWS
      RVA(I)=(RI(I)+RE(I))/2.
8     CONTINUE
C     STORE VALUES FROM PREVIOUS ITERATION
      DO 9 I=1,NROWSP
      TWFO(I)=TWF(I)
9     CONTINUE
      DO 10 I=1,NROWS
      BSAO(I)=BSA(I)
10    RVO(I)=(RI(I)+RE(I))/2.
```

```
      AXO=AX
      DO 11 I=1,NROWS
      X(I)=BC(I)/12.
11    CONTINUE
      DO 12 I=1,NROWS
      CALL LINT (TGA(I),NPTMU,TMU,VIS,VISC(I))
      REA8(I)=(RVA(I)*X(I)/VISC(I))**.8
12    CONTINUE
      DO 13 I=1,NROWS
      CALL LINT (TGA(I),NPTCON,TCON,CON,COND(I))
      CALL LINT (TGA(I),NPTPR,TPR,PRN,PR(I))
C     COMPUTE BLADE OUTSIDE HEAT TRANSFER COEFFICIENT
      HG(I)=.037*(PR(I)**.33)*COND(I)*REA8(I)/X(I)
13    CONTINUE
      DO 14 I=1,NROWS
      U(I)=HG(I)*BSA(I)/144.
14    CONTINUE
      DO 15 J=1,NTS
      TMA(1,J)=TMS(J)-PTD
      TMA(3,J)=TMS(J)-PTD
15    CONTINUE
      DO 16 J=1,NTR
      TMA(2,J)=TMR(J)-PTD
      TMA(4,J)=TMR(J)-PTD
16    CONTINUE
      NTM=NTS
      DO 17 I=1,NROWS
      DO 17 J=1,NTM
      QR(I,J)=U(I)*(TGA(I)-TMA(I,J))
17    CONTINUE
      DO 18 I=1,NROWS
      DO 18 L=1,NTM
      TMMTCM(I,L)=TMA(I,L)-TCI
      WCWE(I,L)=QR(I,L)/(WE*CPC*THERME*TMMTCM(I,L))
      IF (WCWE(I,L).LT.0.) WCWE(I,L)=0.
      WC(I)=WCWE(I,L)*WE
18    CONTINUE
      WC(1)=WC(1)*(TGAMAX(1)-TMA(1,1))/(TGA(1)-TMA(1,1))
      WC(3)=WC(3)*(TGAMAX(3)-TMA(3,1))/(TGA(3)-TMA(3,1))
      WCWE(1,1)=WC(1)/WE
      WCWE(3,1)=WC(3)/WE
      WCT=0.0
      DO 19 I=1,NROWS
19    WCT=WCT+WC(I)
      Y=(WCT/WE)+YW
      TWF(1)=WE*(1.-Y)*(1.+FARC)
C     ADIABATICALLY MIX BLADE COOLANT FLOWS WITH GAS STREAM
      DO 20 I=2,NROWSP
      TWF(I)=TWF(I-1)+WC(I-1)
      IF (I.EQ.2) TPN(I)=(((TWF(I-1)*TPN(I-1)))+(WC(I-1)*TP2))/TWF(I)
      TPPN(2)=TPN(2)+CONST2
      IF (I.EQ.3) TPPN(I)=(TWF(I-1)*TPPN(I-1)+(WC(I-1)*TP2))/TWF(I)
      TPN(3)=TPPN(3)-TPPMTP(3)
      IF (I.EQ.4) TPN(I)=(((TWF(I-1)*TPN(I-1)))+(WC(I-1)*TP2))/TWF(I)
      TPPN(4)=TPN(4)+CONST1
      IF (I.EQ.5) TPPN(I)=(TWF(I-1)*TPPN(I-1)+(WC(I-1)*TP2))/TWF(I)
      TPN(5)=TPPN(5)-TPPMTP(5)
      VCR(I)=SQRT((2.*GAMMA/(GAMMA+1.))*G*R*TPN(I))
      WCR(I)=SQRT((2.*GAMMA/(GAMMA+1.))*G*R*TPPN(I))
```

```
      VOVCR(I)=VILCI(I)/VCR(I)
      RORP(I)=(1.-((GAMMA-1.)/(GAMMA+1.))*VOVCR(I)**2.)**(1./(GAMMA-1.))
20    CONTINUE
      VXI(2)=VXI1/VCR(2)
      VXE(2)=VXE1/VCR(3)
      VXI(4)=VXI2/VCR(4)
      VXE(4)=VXE2/VCR(5)
      RI(1)=TWF(1)*144./AX
      DO 21 I=2,NROWS
21    RI(I)=(VIL(I)*PP(I)*RORP(I)/(R*TPN(I)))*CORRF
      DO 22 I=1,NROWS
      RE(I)=(VEL(I)*PP(I+1)*RORP(I+1)/(R*TPN(I+1)))*CORRF
22    RV(I)=(RI(I)+RE(I))/2.
      TGA(1)=TPN(1)
      TGA(2)=TPPN(2)
      TGA(3)=TPN(3)
      TGA(4)=TPPN(4)
      DO 23 I=1,NROWS
23    BSA(I)=BSAO(I)*(TWF(I)/TWFO(I))*(RVO(I)/RV(I))
      AX=AXO*BSA(1)/BSAO(1)
      BH(1)=BHS(1)*BSA(1)/WBSA(1)
      BH(2)=BHR(1)*BSA(2)/WBSA(2)
      BH(3)=BHS(2)*BSA(3)/WBSA(3)
      BH(4)=BHR(2)*BSA(4)/WBSA(4)
      DO 24 I=1,NROWS
C     CHECK FOR SOLUTION
24    IF (ABS(BSA(I)-BSAO(I)).GT..00001) GO TO 7
      WRITE (6,48) TGA(1),TGA(2),TGA(3),TGA(4)
      WRITE (6,50) TPN(2),TPPN(3),TPN(4),TPPN(5)
      WRITE (6,51) BSA(1),BSA(2),BSA(3),BSA(4)
      DO 25 I=1,NROWS
      DO 25 L=1,NTM
      WRITE (6,45) I,TMA(I,L),WCWE(I,L)
25    CONTINUE
9000  FORMAT(1H ,44HTURBINE WEIGHT FLOW AT EXIT OF ROWS 1,2,3,4=,4F12.6)
      IF(NWC.EQ.1)GO TO 300
C     COMPUTE WALL COOLANT FLOWS
      DO 26 I=1,NROWS
      TGART(I)=TGA(I)-150.
      EF(I)=(TWALLA-TGART(I))/(TCI-TGART(I))
      CXF(I)=1.2*X(I)
      D=XMRC/(12.*3.14159)
      CALL LINT (TGART(I),NPTCON,TCON,CON,CONDG(I))
      CALL LINT (TGART(I),NPTPR,TPR,PRN,PRG(I))
      CALL LINT (TGART(I),NPTMU,TMU,VIS,VISCG(I))
      CPG(I)=PRG(I)*CONDG(I)/VISCG(I)
      RATCP(I)=CPG(I)/CPC
      TGARTA(I)=(TCI+TGART(I))/2.
      CALL LINT (TGARTA(I),NPTPR,TPR,PRN,PRW(I))
      BRAKT(I)=((1.9*(PRW(I)**.667))/EF(I))-1.
      VISGG=VISCG(I)
      WCWEC(I)=(.329*RATCP(I)*(VISGG**.2)*(RV(I)**.8)*(.8*3.14159*D/WE)*
     1(CXF(I)**.8))/BRAKT(I)
      WCWEC(I)=2.*WCWEC(I)
      IF (WCWEC(I).LT.0.0) WCWEC(I)=0.0
      WCW(I)=WCWEC(I)*WE
26    CONTINUE
      WRITE (6,40) TWALLA
```

```
      WCWECT=0.
      DO 27 I=1,NROWS
      WCWECT=WCWECT+WCWEC(I)
27    CONTINUE
      DO 28 I=1,NROWS
      WRITE (6,53) I,WCWEC(I)
28    CONTINUE
      RTCI=R*TCI
      WRHO(1)=WPSTAT(1)/RTCI
      WRHO(2)=WPSTAT(2)/RTCI
      WRHO(3)=WPSTAT(3)/RTCI
      WRHO(4)=WPSTAT(4)/RTCI
      WVEX(1)=VXI1/2.
      WVEX(2)=VXE1/2.
      WVEX(3)=VXI2/2.
      WVEX(4)=VXE2/2.
      WCWT(1)=WCW(1)
      DO 29 I=2,4
29    WCWT(I)=WCWT(I-1)+WCW(I)
      DO 30 I=1,4
      WDA(I)=(WCWT(I)/(WRHO(I)*WVEX(I)))*144.
      WANNA(I)=XMRC*BH(I)
30    WBH(I)=BH(I)*(WANNA(I)+WDA(I))/WANNA(I)
300   CONTINUE
      IF(NWC.EQ.1)WCW(1)=0.0
      IF(NWC.EQ.1)WCW(2)=0.0
      IF(NWC.EQ.1)WCW(3)=0.0
      IF(NWC.EQ.1)WCW(4)=0.0
      TTWF(2)=TWF(2)+WCW(1)
      TTWF(3)=TWF(3)+WCW(1)+WCW(2)
      TTWF(4)=TWF(4)+WCW(1)+WCW(2)+WCW(3)
      TTWF(5)=TWF(5)+WCW(1)+WCW(2)+WCW(3)+WCW(4)
      WRITE(6,9000)TTWF(2),TTWF(3),TTWF(4),TTWF(5)
      IF(NWC.EQ.1)WRITE(6,64)BH(1),BH(2),BH(3),BH(4)
      IF(NWC.EQ.2)WRITE(6,65)WBH(1),WBH(2),WBH(3),WBH(4)
      YB=WCT/WE
      YW=WCWECT
      IF(NWC.EQ.1)YW=0.
      Y=YW+YB
      WRITE (6,66) VXI(2),VXE(2),VXI(4),VXE(4)
      IF(NWC.EQ.1)WRITE(6,62)TPN(5)
      IF(NWC.EQ.1)GO TO 302
      WTPE=(TPN(5)*TWF(5)+TCI*WCWECT*WE)/(TWF(5)+WCWECT*WE)
      WRITE (6,63) WTPE
302   CONTINUE
      WRITE (6,67) HG(1),HG(2),HG(3),HG(4)
      WRITE (6,68) VCR(2),VCR(3),VCR(4),VCR(5)
      WRITE(6,69)WCR(2),WCR(3),WCR(4),WCR(5)
69    FORMAT (1H ,54HCRITICAL RELATIVE VELOCITIES AT EXITS OF ROWS 1,2,3
     1,4=,4F12.3)
      WRITE (6,54)
C     COMPUTE VALUES FOR RERUN IF NECESSARY
      TESTC(ITT)=ABS(Y-TESTY)
      IF(TESTC(ITT).LE..0010)WRITE(6,6000)
6000  FORMAT(1H ,54HTHE LAST SET OF OUTPUT CONTAINS THE CONVERGED SOLUTI
     1CN)
      IF(TESTC(ITT).LE..0010)STOP
      IF(ITT.EQ.1) GO TO 31
      IF(ABS(TESTC(ITT)-TESTC(ITT-1)).LT..0005)GO TO 500
```

```
31    CONTINUE
      WON=WE*(1.+FAR*(1.-Y)-Y)
      DHCB=1.+.5*(YB/((1.-Y)*(1.+FAR)))*(TCI/TGA(1))
      DHTN=DHC/(((1.-Y)*(1.+FAR))*DHCB)
      RYB=YB
      RY=Y
      RDHT=DHTN
      RWO=WON
      RETURN
500   IF(Y.GT.TESTY)Y=Y-TESTC(ITT)/2.
      IF(Y.LT.TESTY)Y=Y+TESTC(ITT)/2.
      YB=Y-YW
      GO TO 31
C
32    FORMAT (4F12.7)
33    FORMAT (1H ,12HINPUT DATA**)
34    FORMAT (1H ,4HPTD=,F8.3,17X,5HFARC=,F8.3,16X,3HPF=,F8.3,18X,4HDTY=
     1,F8.3)
35    FORMAT (1H ,5HNPTD=,I3)
36    FORMAT (1H ,4HTPR=,F8.3,17X,4HPRN=,F8.3,17X,4HVIS=,E9.3,17X,4HCON=
     1,E9.3)
37    FORMAT (1H ,4HNTS=,I3,22X,4HTMS=,F8.3,17X,4HNTR=,I3,22X,4HTMR=,F8.
     13)
38    FORMAT (1H ,7HTHERME=,F8.3,14X,4HCPC=,F8.3,17X,7HTWALLA=,F8.3,///)
39    FORMAT (1H ,44HASSUMED BLADE THERMAL COOLING EFFECTIVENESS=,F8.3)
40    FORMAT (1H ,31HASSUMED WALL METAL TEMPERATURE=,F12.6)
41    FORMAT (1H1,40HCOOLANT CALCULATION ********************,//)
42    FORMAT (I3)
43    FORMAT (6F12.6)
44    FORMAT (1H ,26HCOOLANT INLET TEMPERATURE=,F12.3)
45    FORMAT (1H ,34HASSUMED METAL TEMPERATURE FOR ROW(,I2,2H)=,F12.3,10
     1X,25HBLADE COOLANT FLOW RATIO=,F12.6)
46    FORMAT (1H ,57HINITIAL TOTAL INLET TEMPERATURE RELATIVE TO ROWS 1,
     12,3,4=,4F12.3)
47    FORMAT (1H ,51HINITIAL TOTAL BLADE SURFACE AREAS FOR ROWS 1,2,3,4=
     1,4F12.3)
48    FORMAT (1H ,57HREVISED TOTAL INLET TEMPERATURE RELATIVE TO ROWS 1,
     12,3,4=,4F12.3)
49    FORMAT (1H ,56HINITIAL TOTAL EXIT TEMPERATURE RELATIVE TO ROWS 1,2
     1,3,4=,4F12.3)
50    FORMAT (1H ,56HREVISED TOTAL EXIT TEMPERATURE RELATIVE TO ROWS 1,2
     1,3,4=,4F12.3)
51    FORMAT (1H ,51HREVISED TOTAL BLADE SURFACE AREAS FOR ROWS 1,2,3,4=
     1,4F12.3)
52    FORMAT (E12.3,F12.3)
53    FORMAT (1H ,32HWALL COOLANT FLOW RATIO FOR ROW(,I2,2H)=,F12.6)
54    FORMAT (1H ,///,20X,20H********************,///)
62    FORMAT (1H ,50HTURBINE EXIT TOTAL TEMPERATURE WITH BLADE COOLANT=,
     1F12.3)
63    FORMAT (1H ,59HTURBINE EXIT TOTAL TEMPERATURE WITH BLADE AND WALL
     1COOLANT=,F12.3)
64    FORMAT(1H ,58HAVERAGE BLADE HEIGHTS FOR ROWS 1,2,3,4 WITH BLADE CO
     1OLANT=,4F12.3)
65    FORMAT(1H ,67HAVERAGE BLADE HEIGHTS FOR ROWS 1,2,3,4 WITH BLADE AN
     1D WALL COOLANT=,4F12.3)
```

```
66     FORMAT (1H ,54HREVISED VXI AND VXE FOR FIRST AND SECOND STAGE ROTO
      1RS=,4F12.3)
67     FORMAT (1H ,43HAVERAGE H.T. COEFFICIENTS FOR ROWS 1,2,3,4=,4E12.3)
68     FORMAT (1H ,54HCRITICAL ABSOLUTE VELOCITIES AT EXITS OF ROWS 1,2,3
      1,4=,4F12.3)
       END
```

APPENDIX C

SYMBOLS

A	area
AR	area ratio, $A_{a,1}/A_{a,2}$
BH	blade height
C_L	blade camber length
C_p	specific heat at constant pressure
C_x	blade axial chord length
D	diameter
f/a	primary burner fuel-air ratio
h	convective heat-transfer coefficient
Δh	specific enthalpy change
k	thermal conductivity
N	turbine rotative speed
P	blade pitch
PF	pattern factor, $(T''_{g,max} - \overline{T}''_g)/(\overline{T}''_g - T'_{c,2})$
Pr	Prandtl number
p	pressure
Q_A	available heat sink
Q_R	required heat sink
R	gas constant
RHRTI1	FORTRAN symbol for first assumed hub-tip radius ratio
RHRTI2	FORTRAN symbol for second assumed hub-tip radius ratio
$\mathscr{R}$	turbine hub reaction
r	radius
T	temperature
t	blade thickness
U	blade speed

V	absolute velocity
VXEL	FORTRAN symbol for limiting value on $(V_x/V_{cr})_{2,IV}$
VXIL	FORTRAN symbol for limiting value on $(V_x/V_{cr})_{1,IV}$
VXEI	FORTRAN symbol for limiting value on $(V_x/V_{cr})_{2,II}$
VXII	FORTRAN symbol for limiting value on $(V_x/V_{cr})_{1,II}$
W	relative velocity
w	weight flow
β	angle of relative velocity from tangential
γ	specific heat ratio
η	turbine efficiency
η_b	blade thermal cooling effectiveness
ρ	density
τ	stage work fraction
φ	blade camber angle
ψ	aerodynamic (tangential) blade loading coefficient
π	constant, $\pi = 3.14159$

Subscripts:

a	annulus
BM	blade metal
b	blade(s)
c	compressor
cr	critical, corresponding to conditions at Mach 1
E	engine
g	turbine main gas stream
H	value at hub radius
i	indicates substitution at HUB(H), MEAN(M), or TIP(T)
M	value at the mean radius
max	maximum value
n	n^{th} iteration
S	surface

T	value at tip radius
TOT	total
t	turbine
u	component in direction of blade speed vector
w	wall
x	component in turbine axial direction
y	cooling air
Z	Zweifel (from ref. 5)
1	inlet
2	exit
①	first stage
②	second stage
I	first blade row
II	second blade row
III	third blade row
IV	fourth blade row

Superscripts:

—	average value
"	total state condition relative to rotating blading
'	total state condition relative to stationary blading

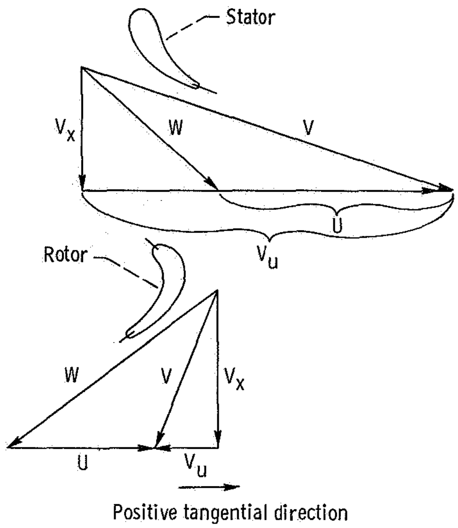
REFERENCES

1. Carter, A. F.; and Lenherr, F. K.: Analysis of Geometry and Design - Point Performance of Axial - Flow Turbines Using Specified Meridional Velocity Gradients. NASA CR-1456, 1969.
2. Wysong, R.; and Tabakoff, W.: A Computer Program for the Detailed Design of Free Vortex Turbines. Tech. Rep. No. 651, Dept. Aerospace Eng., Univ. Cincinnati, July 1965. (Available from DDC as AD619079.)
3. Evans, David G.; Furgalus, Keith A.; and Stepka, Francis S.: Turbine Aerodynamic and Cooling Requirements for a Turbojet Powered Mach 3 Transport Using Methane Fuel. NASA TN D-5928, 1970.
4. Stepka, Francis S.: Considerations of Turbine Cooling Systems for Mach 3 Flight. NASA TN D-4491, 1968.
5. Zweifel, O.: Optimum Blade Pitch for Turbo-Machines with Special Reference to Blades of Great Curvature. The Engineer's Digest, vol. 7, nos. 11 and 12, Nov. and Dec. 1946.
6. Abramowitz, Milton; and Stegun, Irene A., eds.: Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables. Appl. Math. Series 55, National Bureau of Standards, 1964.

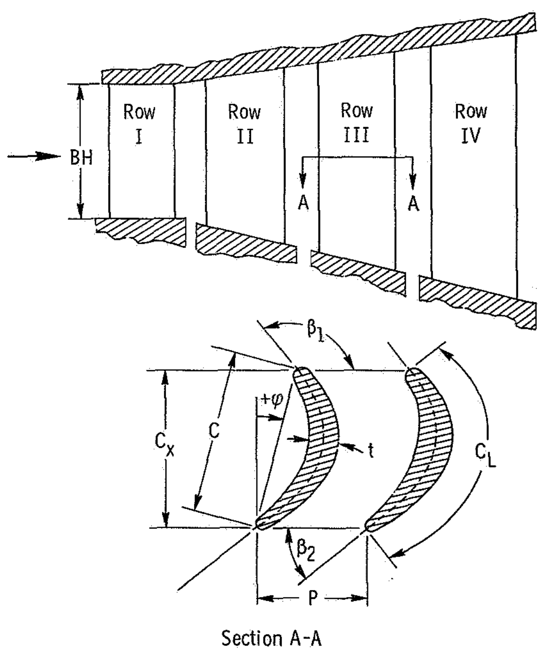
TABLE I. - DEFINITION OF UNITS USED IN

COMPUTER OUTPUT

Parameter	Units
Pressures	lbf/ft^2
Temperatures	^oR
Velocities	ft/sec
Densities	lbm/ft^3
Angles	degree
Lengths	inches
Areas	$in.^2$
Convective heat-transfer coefficients	$Btu/(sec)(ft^2)(^oR)$
Turbine weight flows	lbm/sec



(a) Velocity diagram symbols.



(b) Blade geometry symbols.

Figure 1. Nomenclature.

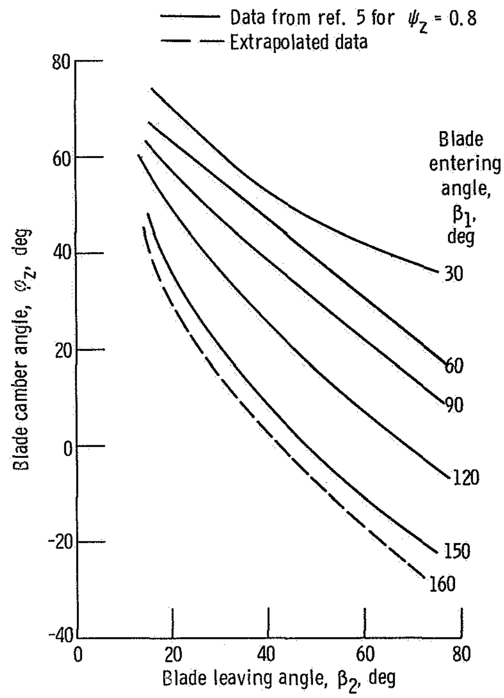


Figure 2. - Variation of turbine blade camber angle with blade entering and leaving angle.

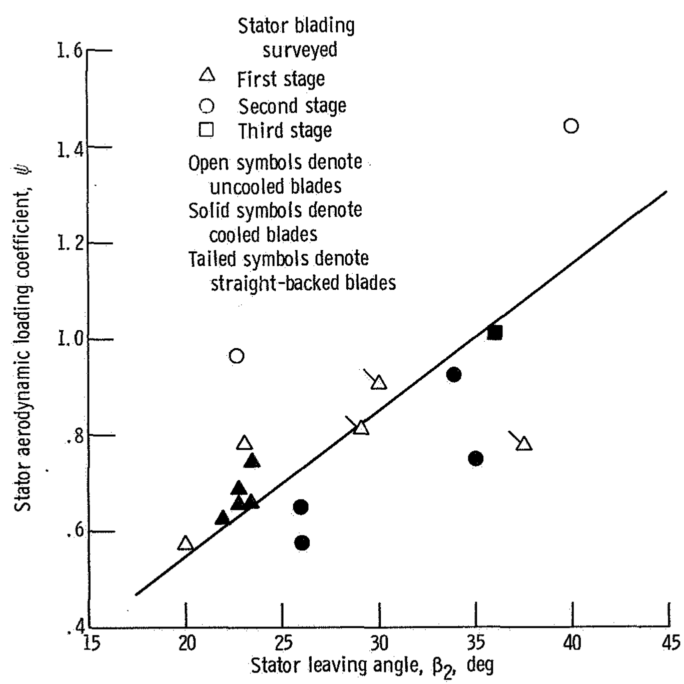
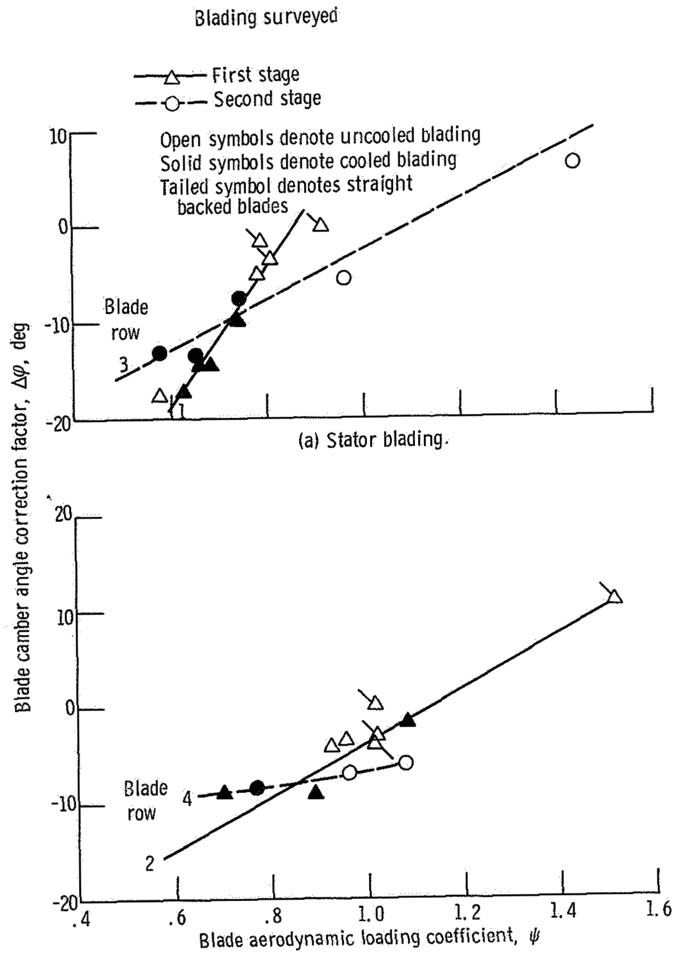


Figure 3. - Variation of stator aerodynamic loading coefficient with leaving angle for several government and commercially developed turbines.



(a) Stator blading.

(b) Rotor blading.

Figure 4. - Effect of blade loading coefficient on blade camber angle for several government and commercially developed turbines.

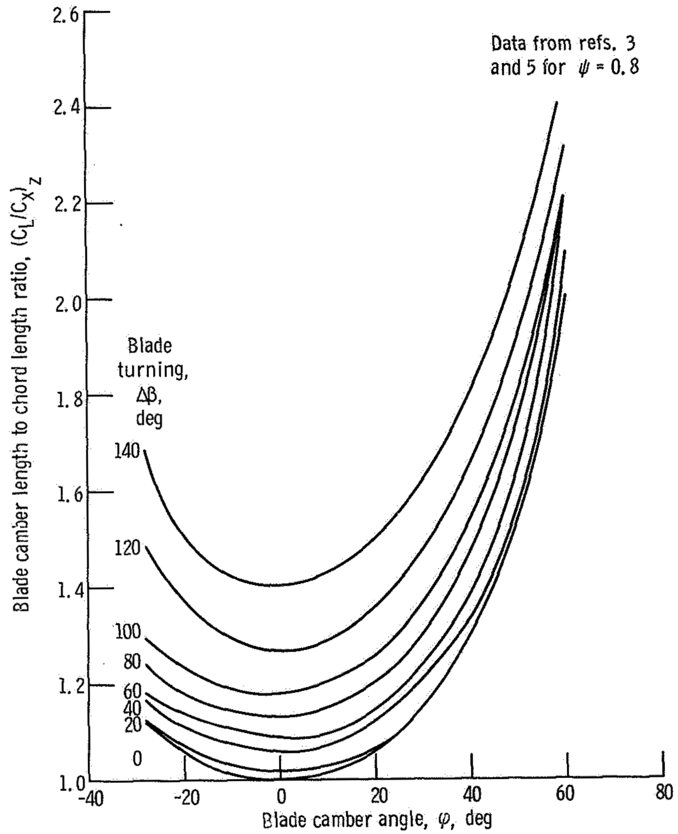


Figure 5. - Variation of blade camber length to chord length ratio with blade camber angle and blade turning.

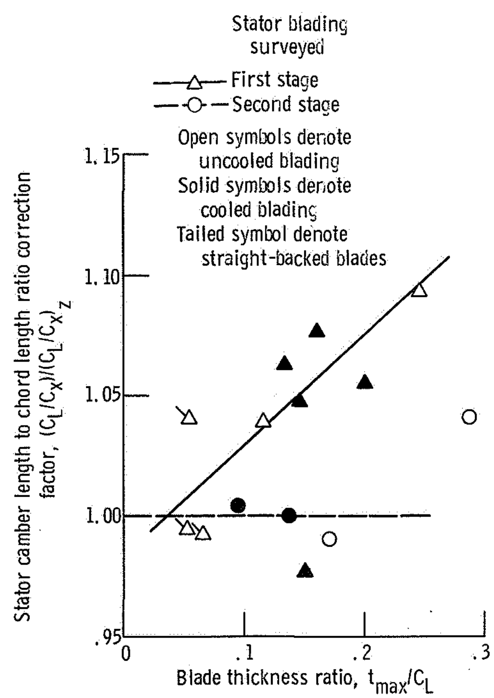
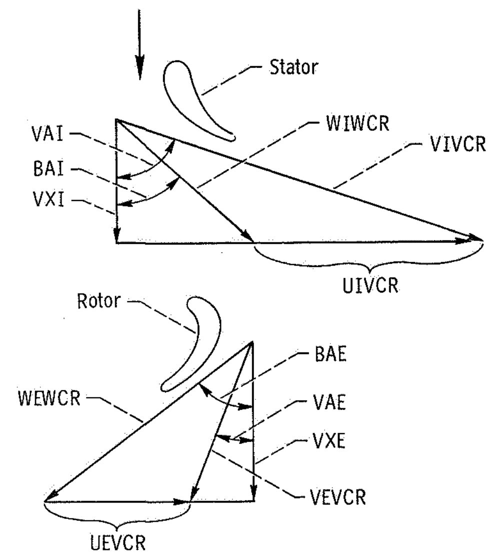


Figure 6. - Variation of correction factor for stator camber length to chord length ratio with blade thickness ratio for several government and commercially developed turbines.



RADI = $r_{1, rotor}$	RADE = $r_{2, rotor}$
VIVCR = $(V/V_{cr})_1$	VEVCR = $(V/V_{cr})_2$
UIVCR = $(U/V_{cr})_1$	UEVCR = $(U/V_{cr})_2$
WIWCR = $(W/W_{cr})_1$	WEWCR = $(W/W_{cr})_2$
VXI = $(V_x/V_{cr})_1$	VXE = $(V_x/V_{cr})_2$

Figure 7. - Velocity diagram Fortran nomenclature.

NASA-Langley, 1971 —— 1 E-6014

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

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

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

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

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

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

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

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

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

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

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

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

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546