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Final Report

AN IMPROVED COMPUTER MODEL FOR PREDICTION OF AXIAL GAS TURBINE PERFORMANCE LOSSES

By

R. M. Jenkins

August 1984

School of Engineering & Architecture
Tuskegee Institute
Tuskegee Institute, AL 36088

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA LEWIS RESEARCH CENTER
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ABSTRACT

The calculation model performs a rapid preliminary pitchline optimization of axial gas turbine annular flowpath geometry, as well as an initial estimate of blade profile shapes, given only a minimum of thermodynamic cycle requirements. No geometric parameters need be specified. The following preliminary design data are determined:

(1) the optimum flowpath geometry, within mechanical stress limits;
(2) initial estimates of cascade blade shapes;
(3) predictions of expected turbine performance.

The model uses an inverse calculation technique whereby blade profiles are generated by designing channels to yield a specified velocity distribution on the two walls. Velocity distributions are then used to calculate the cascade loss parameters. Calculated blade shapes are used primarily to determine whether the assumed velocity loadings are physically realistic. Model verification is accomplished by comparison of predicted turbine geometry and performance with an array of seven NASA single-stage axial gas turbine configurations, ranging in size from 0.6 kg/s to 63.8 kg/s mass flow and in specific work output from 153 J/g to 558 J/g at design (hot) conditions; stage loading factor ranges from 1.15 to 4.66.
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NOMENCLATURE

\( a_{cr} \) = critical sound speed, m/s

\( C_L \) = lift coefficient

\( D \) = diffusion coefficient

\( g \) = gravity constant, m/s\(^2\)

\( h \) = channel or blade height, m

\( \Delta h \) = rotor tip clearance gap, m

\( \lambda \) = velocity loading parameter defined by Eq. (23)

\( m \) = distance along axial direction, m

\( M \) = mean chord length in axial direction, m

\( p \) = static pressure, n/m\(^2\)

\( \Delta p \) = difference between blade pressure-surface static pressure and suction-surface static pressure, n/m\(^2\)

\( P \) = total or stagnation pressure, n/m\(^2\)

\( R \) = radius coordinate, measured from turbine axis of rotation, m

\( \mathcal{R} \) = acceleration parameter, defined by Eq. (21)

\( s \) = blade pitch or spacing, m

\( t \) = blade thickness, m

\( U \) = rotor speed, m/s

\( V \) = velocity measured relative to non-rotating reference frame, m/s

\( \psi \) = blade loading velocity defined by Eqs. (24a-b)

\( W \) = velocity measured relative to rotating reference frame, m/s

\( W_f \) = mass flow rate, kg/s

\( T \) = total or stagnation temperature, °K

\( Y \) = loss coefficient (pressure)

\( Z \) = number of blades
\( \alpha \) = flow angle measured with respect to absolute (non-rotating) velocities
\( \beta \) = flow angle measured with respect to relative (rotating) velocities
\( \gamma \) = ratio of gas specific heats
\( \delta \) = pressure ratio referenced to standard conditions
\( \epsilon \) = channel thickness parameter, defined by Eq. (18)
\( \eta \) = adiabatic efficiency
\( \phi \) = angular coordinate
\( \rho \) = density, kg/m\(^3\)
\( M \) = distance along axial direction normalized by chord length M
\( \theta \) = temperature ratio referenced to standard conditions
\( \sigma \) = cascade solidity

**Subscripts**
- \( c \) = centerline
- \( cg \) = clearance gap
- \( e \) = cascade exit
- \( i \) = cascade inlet
- \( m \) = maximum
- \( M \) = arbitrary location along axial direction
- \( p \) = pressure surface
- \( p_\infty \) = profile loss
- \( s \) = suction surface
- \( sf \) = secondary flow loss
- \( std \) = standard conditions
- \( tot \) = total
\( u \) = tangential
\( x \) = axial

**Superscripts**

' = absolute total or stagnation condition
'' = relative total or stagnation condition
\(*\) = parameter normalized with respect to conditions at cascade inlet
INTRODUCTION

Axial gas turbine design can be described as a search for an optimum set of geometric parameters to satisfy certain general specifications such as work output and mass throughflow. Traditionally, the search procedure begins with computations which provide a quick estimate of optimum overall configuration for a given cycle data point. Such computations usually rely upon loss correlations that mainly depend on cascade inlet and exit conditions, without regard to specific cascade geometry. Use of such correlation models implicitly assumes that detailed blade geometry does not significantly influence flow losses, an assumption which is open to question.

The relationships between blade shape, loading, and flow losses are established in more detail later in the design procedure, a process which requires detailed knowledge of individual blade shapes. Since the overall design procedure is an iteration loop involving geometry and aerodynamic losses, however, these relationships should be established as early in the preliminary design procedure as possible. This should result in a more realistic final design in less overall time.

The present optimization technique seeks to provide an initial axial turbine stage design procedure which directly links overall stage performance and flowpath geometry with internally generated cascade loadings and blade shapes. Having such detailed geometry generated internally has a threefold advantage:
(i) excessive data preparation times are eliminated;
(ii) the loss model is provided flexibility in determining blade shapes (loadings) which optimize boundary layer (Reynolds number) effects;
(iii) relations between such factors as blade chord, blade camber-line, blade stagger, etc., and the specified velocity triangles are automatically accounted for without additional correlations.

The present design procedure is "preliminary" in that calculations are performed only for an average streamsheet surface (pitchline) location within the turbine stage. Pitchline radius may vary (linearly) within a blade row; however, radial velocity components are neglected and such variation should be small. The most basic assumption of the analysis is that velocity loadings on the blading are known. These loadings are used to calculate blade profile shapes and profile (friction) losses. The blade shapes are, in turn, examined to determine whether the assumed loading is physically realistic.

**CALCULATION OF CHANNEL (BLADE) SHAPES**

Cascade channel shapes (blade profiles) are generated using a simplified technique to provide solutions to the so-called indirect problem: that of the design of a channel to yield a specified velocity distribution on the two walls. Adjacent walls then become the suction and pressure surfaces, respectively, of the individual blades. The technique is similar to that utilized by J. D. Stanitz.
For given thermodynamic-cycle requirements, wheel speed, and adiabatic efficiency, stage velocity triangles can easily be obtained along some representative pitch-line radius. If the channel velocity distribution is also known, the channel (blade) shape is generated as follows:

Continuity

\[ W_f = \left( \frac{\rho V}{\rho' a'_{cr}} \right)_i \cos \alpha_i (2\pi R_i h_i) \frac{\delta_i}{\theta_i} (\rho' a'_{cr})_{std} \quad (1) \]

Moment of Momentum

\[ \frac{W_f}{g z} \frac{d}{dm} (RV_u)_{dm} = (\Delta p) h R \frac{dm}{dm} \quad (2) \]

Integration of Eq. (2) along the entire axial chord length of the blade results in the overall change in tangential (swirl) velocity across the cascade:

\[ (RV_u)'_e - (RV_u)'_i = \frac{gz}{W_f} h_i R_i M_{std} P_{std} \int_0^1 h^* R^* \frac{\Delta P}{P_i^*} \, d/ \quad (3) \]

Note that "axial" chord is actually the vector sum of axial and radial displacements through the cascade, since the pitch-line radius may vary. Making use of the continuity equation (1), and the cascade solidity, \( \sigma \), defined as the ratio of axial chord to blade spacing, Eq. (3) can be rearranged as
If the integration of Eq. (2) is carried out only to some arbitrary point \( m \) within the blade row, the result is

\[
R^*_m \left( \frac{V_u}{a_{cr}} \right)_m \sqrt{\frac{T}{T_1}} - \left( \frac{V_u}{a_{cr}} \right)_i = \frac{(\gamma + 1)}{2\gamma} \sigma \int_0^m h^* R^* \frac{\Delta p}{\rho_1} \, dM
\]  

(5)

from which the local absolute tangential velocity at that point, \( (V_u/a_{cr})_m \), can be obtained. A more useful relation is the tangential velocity distribution relative to a blade row moving at some wheel speed \( (U/a_{cr})_m \), defined by

\[
\left( \frac{W_u}{a_{cr}} \right)_m = \left( \frac{V_u}{a_{cr}} \right)_m - \left( \frac{U}{a_{cr}} \right)_m
\]  

(6)

where

\[
\left( \frac{U}{a_{cr}} \right)_m = \left( \frac{U}{a_{cr}} \right)_i \sqrt{\frac{T}{T_1}} \left( R^*_m \right)
\]  

(7)

The term \( a'_{cr} \) is the local critical velocity defined with respect to absolute total temperature. Now, since critical velocity can also be defined with respect to relative total temperature, Eq. (6) can be rewritten as
or upon combining Eqs. (5), (6), (7), and (8),

\[
\left( \frac{W_u}{a_{cr}} \right)_{m} = \left( \frac{W_u}{a_{cr}} \right)_{i} \sqrt{\frac{T_i}{T_m}}
\]

or upon combining Eqs. (5), (6), (7), and (8),

\[
\left( \frac{W_u}{a_{cr}} \right)_{m} = \sqrt{\frac{T_i}{T_m}} \left[ \frac{1}{R_{m}^{2}} \left( \frac{V_{u}}{a_{cr}} \right)_{i} \right]
\]

\[
+ \frac{(\gamma + 1) \sigma}{p a_{cr}^{2} \cos \alpha_{i}} \int_{0}^{L} R_{m} \frac{\partial P}{\partial r} \, d\Omega - \left( \frac{V_{u}}{a_{cr}} \right)_{i} R_{m} \sqrt{\frac{T_i}{T_m}} \right]
\]

Eq. (9) specifies the relative tangential velocity component at any location M within the cascade.

GENERATION OF BLADE CAMBERLINE DISTRIBUTION

At this point in the computation it is possible to analytically define a mean camberline distribution for the cascade. Let \( W/a_{cr,p} \) and \( W/a_{cr,s} \) represent the relative critical velocity ratios along the pressure and suction surfaces of the blade, respectively; note that both quantities are known since the velocity loading is presumed to be known. It is desired to calculate the average flow direction, \( \beta_{M} \), for any location \( M \) within the blade passage. In order to do this, an additional assumption is required. It might be assumed that the channel mean velocity is the arithmetic mean of the suction surface and the pressure surface velocities,
\[
(W/a''_{cr})_m = \frac{1}{2}[(W/a''_{cr})_p + (W/a''_{cr})_s]_m
\]  

in which case

\[
\beta_m = \sin^{-1}\left(\frac{W_{u/a''_{cr}}}{W/a''_{cr}}\right)_m
\]  

On the other hand, one might assume, say, a linear variation of axial critical velocity ratio, \(W_x/a''_{cr}\), through the blade passage, in which case

\[
\beta_m = \tan^{-1}\left(\frac{W_{u/a''_{cr}}}{W_x/a''_{cr}}\right)
\]  

and \((W/a''_{cr})_m\) is approximated by

\[
(W/a''_{cr})_m = \left(\frac{W_x/a''_{cr}}{\cos \beta}\right)_m
\]  

Even more flexibility can be provided by modifying the linear variation by a variable increment; the increment is zero at the cascade inlet and exit, and some specified maximum value at a given location within the cascade. The increment must then satisfy four boundary conditions and is defined by a third order polynomial. Experience has shown that either the linear or modified linear axial velocity distributions provide the most realistic blade shapes.

If the mean camberline is described by the cylindrical coordinates \(R, m, \phi\), then the camberline is generated by the expression
\[ \frac{d}{dm} (R\phi) = R \frac{d\phi}{dm} + \phi \frac{dR}{dm} = \tan \beta + \phi \frac{dR}{dm} \]  

(14)

Equation (14) must be integrated point-by-point through the cascade.

GENERATION OF LOCAL BLADE THICKNESS

For any location \( M \) along the cascade passage, the continuity equation can be written as

\[ \frac{W_f}{z} = (\rho W \cos \beta)(h \times \text{channel width}) \]  

(15)

Define a "channel width parameter," \( \varepsilon \), by

\[ \varepsilon = \frac{\text{channel width}}{\text{blade pitch}} = \frac{\text{channel width}}{2\pi R} \]  

(16)

Equation (15) then becomes

\[ W_f = (\rho W \cos \beta)(2\pi \varepsilon h R) \]  

(17)

for a given position \( M \). Combination of Eqs. (1) and (17) yields, after rearrangement,

\[ \phi \frac{dR}{dm} \left( \frac{\rho V}{\rho^* a^*_r} \right) = \left( \frac{\rho W}{\rho^* a^*_r} \right) \left( h R \cos \beta \right) \]  

(18)

Now local blade thickness, \( t_M \), is the difference between local blade pitch and local channel width, so that Eq. (16) can be written as
Local blade thickness is then distributed equally about the camberline distribution defined by Eq. (14). Specification of the blade profile is thus complete. A representative blade section generated by this procedure is shown in Figure 1.

![Representative Blade Section Generated by Inverse Method](image)

**Figure 1:** Representative Blade Section Generated by Inverse Method

### CALCULATION OF BLADE LOADINGS

Of fundamental importance to the present optimization procedure is the selection of proper cascade blade loadings. These loadings are used to 1) calculate channel shapes (blade profiles), 2) meet required cascade solidity specifications, and 3) calculate profile (friction) losses. The loading model should be simple, yet flexible enough to accommodate a wide range of channel centerline accelerations, blade surface diffusion rates, and cascade loading requirements.

The loading model proceeds from the definition of a centerline velocity distribution, $V_c$, as
\[
\frac{V_c}{V_e} = \frac{R}{2} \left[ \sin \pi (\theta - \frac{1}{2}) - 1 \right] + 1
\]  \hspace{1cm} (20)

The parameters \(V_c\) and \(V_e\) represent (dimensionless) critical velocity ratios measured relative to the blade row, with \(V_e\) measured at the exit of the row. The parameter \(R\) is indicative of the channel centerline flow acceleration and is defined as

\[
R = 1 - \frac{V_i}{V_e}
\]  \hspace{1cm} (21)

where \(V_i\) is the critical velocity ratio relative to the blade row, measured at the inlet to the row. It should be noted that \(V_c\) is a fictitious parameter used only in the definition of blade loading and is not necessarily related to channel mean velocity, Eq. (13).

**Suction Surface Velocity**

It is assumed that the behavior of the velocity distribution on the blade suction surface is of primary importance to the overall optimization process. Although velocity diffusion occurs on both blade surfaces, the adverse effects of pressure-surface diffusion are to some degree obviated by the subsequent downstream re-acceleration of the flow along that surface; such re-acceleration does not usually occur on the suction side of the profile.

A fundamental characteristic of the suction-surface velocity distribution is deceleration of the boundary layer flow near the trailing edge of the blade row. Of interest is both the amount of such deceleration and the location along the suction surface at which such deceleration
begins. If velocity "spike" effects near the leading edge of the blade are ignored, velocity diffusion on the suction surface becomes a simple question of where maximum velocity occurs and what its value is.

Following standard practice, a "diffusion coefficient" for the suction surface velocity is defined as

$$ D_s = 1 - \frac{V}{V_m} $$

(22)

where $V_m$ represents the maximum velocity occurring anywhere on the suction surface. Figure 2 illustrates each of the pertinent velocities employed in the model. As in Reference 2, the suction surface velocity is described by a simple piecewise parabolic curve fit; $V_m$, the point of maximum velocity, is also the point where the two curve portions are matched. It has been suggested that the location of $V_m$ is dependent on the value of the channel centerline flow acceleration $R$ as

$$ V_m = 0.5 + 0.3[1 - (1 - R)^2] $$

(23)

Figure 2: Blade Velocity Loading Model
Barring user input to the contrary, $\lambda_m$ is calculated from Eq. (23). Should the user so desire, however, any value for $\lambda_m$ can be specified.

The suction surface velocity distribution is defined by the following relations:

For $M < \lambda_m$:

$$V_s = (V_i - V_m)\left[\frac{\eta}{\lambda_m}\right]^2 - 2(V_i - V_m)\left[\frac{\eta}{\lambda_m}\right] + V_i \tag{24a}$$

For $M > \lambda_m$:

$$V_s = \frac{\eta}{(\lambda_m - 1)^2} \left[\lambda_m^2 - 2\lambda_m(M - 1) - 1\right] + V_e \tag{24b}$$

It should be noted that it is, at least mathematically, possible to have negative values for the diffusion coefficient; in this case, $V_m < V_e$ and there is no real "maximum" velocity (other than $V_e$). For this situation, the piecewise curve fit degenerates to a single second-order curve of the form

$$V_s = \left[\frac{V_m - V_e}{\lambda_m(\lambda_m - 1)} - \frac{V_e - V_i}{\lambda_m}\right] \eta^2$$

$$+ \left[(V_e - V_i) \frac{\lambda_m + 1}{\lambda_m} - \frac{V_m - V_e}{\lambda_m(\lambda_m - 1)}\right] \eta + V_i \tag{25}$$

**Pressure Surface Velocity**

The pressure surface velocity distribution is obtained by assuming that the entire blade loading is distributed equally about the centerline velocity distribution $V_c$. The pressure surface distribution is then given by

...
\[ V_p = 2V_c - V_s \]  

where \( V_s \) is given by either Eq. (24) or Eq. (25). Though there is no mathematical constraint, negative (reverse direction) velocities are not desirable, and are not allowed by the model.

**OPTIMIZATION OF THE DIFFUSION COEFFICIENT**

The blade loading diagram, suction surface diffusion coefficient, and cascade solidity can be tied together through the Zweifel\(^3\) loading coefficient. The Zweifel coefficient relates cascade solidity to flow angles at the cascade inlet and outlet, and, according to reference 3, tends to assume a certain narrow range of values for optimum cascade performance. Normal design practice utilizes Zweifel coefficients in the range of, say, 0.7 to 1.0. Thus, for specified flow angles and a given Zweifel coefficient within the "optimum" range, an optimum cascade solidity can be calculated. Now, solidity is related to the individual blade velocity loading through Eq. (4). Furthermore, for known cascade inlet and outlet conditions, the assumed velocity loading model possesses only one independent variable: the suction surface diffusion coefficient.

Thus,

1. specified thermodynamic cycle requirements establish cascade inlet and outlet conditions;
2. these conditions, together with an input Zweifel coefficient will determine an optimum solidity;
3. the present model then adjusts the suction surface diffusion coefficient so that the velocity loading, when integrated
in Eq. (4), yields a calculated solidity equal to the optimum solidity.

The final velocity loading is then used to calculate both blade shapes and blade profile losses.

CALCULATION OF CASCADE PERFORMANCE LOSS

Three aerothermodynamic loss mechanisms are accounted for in the present analysis: profile loss, secondary flow loss, and rotor tip clearance loss.

Profile loss is defined here as a combination of frictional effects resulting from the flow of a viscous fluid over a solid surface and the subsequent downstream mixing of the suction surface and the pressure surface boundary layers. Both losses are accounted for through use of the Stewart mixing loss theory, which defines them in terms of overall displacement and momentum thicknesses. Secondary flow losses are due to the annulus wall boundary layers and their interaction with blade rows. Dunham's review paper presents an excellent analysis of the phenomenon. Dunham states that two separate effects must be accounted for if losses are to be properly estimated:

1. a vortex core loss, arising from fluid, originally in the upstream wall boundary layer, being subsequently shed from the trailing edge of the cascade;

2. a downstream wall boundary layer loss, wherein fluid originally in the mainstream is entrapped in a boundary layer developing on the annulus walls within the cascade.
Rotor clearance, or tip leakage, losses effect turbine performance in two ways:

1. Leakage diminishes overall work extraction from the flowing gas, since some fluid at the tip is not turned, and
2. Leakage produces an underturning of the flow felt in regions other than the tip region, which further diminishes work extraction.

Profile Loss

When calculating profile boundary layer losses it is possible to utilize models of almost any complexity imaginable. Of primary importance, and of least certainty, is the location along a given blade surface of the point of transition of the boundary layer from laminar to turbulent flow, as well as the point of separation of the boundary layer from the wall. Since the present analysis is of a preliminary design (pitch-line) nature, exceedingly complex loss models are not appropriate.

In its simplest sense, the location of the boundary layer transition point is a cascade Reynolds number effect. As Reynolds number (based on cascade exit velocity and blade mean camberline length) is increased, the transition point tends to move upstream towards the leading edge of the blading. For the laminar portion of the boundary layer, the present analysis calculates loss parameters using the Truckenbrodt approximation for boundary layer growth on a wall with pressure gradient, as described, for instance, in Reference 6. For the turbulent portion, loss parameters are calculated using a simple formulation described in Reference 7. A rough estimate of transition is made using a "critical
Reynolds number" parameter, based on boundary layer displacement thickness, again described in Reference 6. Even though this procedure might be considered "too simple," it provides a way to account for Reynolds number effects on overall cascade loss, and is consistent with the fact that velocity loadings are already assumed to be known. As with any set of assumptions, the final justification lies with how well the model predicts reality. Pertinent relationships are described in Appendix B.

Secondary Flow Loss

The correlation for secondary flow loss as suggested in the conclusion of Dunham's paper requires a knowledge of the boundary layer displacement thickness on the endwalls upstream of the cascade, a parameter which is not readily available, at least with any degree of confidence (especially for the rotor). Actually, the upstream boundary layer, or vortex core, loss adds to a second loss component, called the downstream loss. The present analysis assumes that the sum of these two loss components can be represented as a constant value. The specific expression used for secondary flow loss then becomes

\[
Y_{sf} = 0.0138 \frac{M \cos \alpha_e}{h \cos \alpha_1} \left( \frac{C_L}{s/M} \right)^2 \frac{\cos^2 \alpha_e}{\cos^3 \alpha_m}
\]

(27)

where \(Y_{sf}\) is a pressure loss coefficient, \(C_L\) is a cascade lift coefficient (defined only in terms of inlet and outlet relative flow angles), and the value 0.0138 represents the sum of the two loss components discussed above (see Figure 9 of Reference 5). The remaining parameters are described in the Nomenclature.
Tip Leakage Loss

Though recent work such as that of Lakshminarayana\textsuperscript{8} provides insight into the physics of the tip leakage loss mechanism, quantitative predictions of performance loss still require some correlation with experimental data. In this regard, the correlation reported in Reference 7, taken from data originally reported in Reference 9, shows promise. This correlation indicates that, for given blade reaction, the tip-clearance loss varies (approximately) linearly with clearance gap: furthermore, the loss increases for increasing blade reaction. The latter is intuitively correct, since high reactions (large pressure differences) cause more high-kinetic-energy flow to leak through the clearance gap.

The various curves given in Reference 7 can all be approximated by the single expression

\[
\frac{n_{cg}}{\eta} = 1 - (2.755 R^2 + 0.108 R + 1.72) \frac{\Delta h}{h}
\]

where \( n_{cg} \) = efficiency with clearance
\( \eta \) = efficiency without clearance
\( h \) = blade height
\( \Delta h \) = clearance gap

and \( R \) is blade reaction at the tip, defined by

\[
R = \frac{W_e^2 - W_i^2}{W_e^2 - W_i^2 + V_1^2}
\]

where \( W, V \) represent relative and absolute velocities, respectively.
AERODYNAMIC OPTIMIZATION OF BLADE CHORD

Both blade profile (friction) losses and cascade secondary flow losses are dependent on blade chord. Normally, blade chord is determined from manufacturing trade-offs or prior design experience. For instance, chords below a certain minimum length cannot be made economically; chords which are too large increase overall engine length (weight), etc. While chord lengths can be input to the present model, a theoretically optimum chord can be calculated simply from a consideration of the profile and secondary flow loss mechanisms.

From the Stewert analysis a cascade absolute total pressure loss \( P_e'/P_i' \) can be determined. A "profile loss coefficient," \( Y_{pl} \), can be defined as

\[
Y_{pl} = \frac{1 - P_e'/P_i'}{P_e'/P_i'(1 - P_e/P_e')}
\]  

(30)

where \( P_e \) is the static pressure at the cascade exit. A "total loss coefficient" \( Y_{tot} \) can be formed by

\[
Y_{tot} = Y_{pl} + Y_{sf}
\]

(31)

where \( Y_{sf} \) is defined by Eq. (27). Normally, profile losses are reported as a function of cascade Reynolds number, defined on the basis of cascade exit velocity and blade chord length. In the present model, cascade Reynolds number is varied systematically by varying blade chord while holding all other parameters constant. This is possible since the velocity loading is defined with respect to a dimensionless length.
parameter ($M$). Figure 3 illustrates how the different loss coefficients vary with changing rotor chord (mean camberline length). Note that, generally speaking, $Y_{pl}$ decreases with increasing chord while $Y_{sf}$ increases (blade height is held constant during the procedure). According to this simplified model there is an optimum Reynolds number, or optimum chord, which minimizes total aerodynamic loss (excluding tip leakage). The optimum value will, of course, change as cascade inlet and outlet conditions change.

![Figure 3: Typical Variation of Cascade Loss Coefficients with Reynolds Number](image)

OPTIMIZATION OF ANNULAR FLOWPATH GEOMETRY

The model considers a range of annular (hub/tip) flowpath geometries, based on calculated mean flow properties along a pitchline radius. The minimum value for pitchline radius is defined by the condition of zero acceleration of the channel centerline velocity in the rotor.
The maximum value for pitchline radius may be set by limitations on blade tip speed or by aerodynamic considerations such as rotor limit loading. In any event, the loss model described previously is applied to a range of configurations within these limits in order to determine the one configuration having optimum aerodynamic performance, as characterized by adiabatic total-total or total-static efficiency. Hub and tip radii at the rotor exit section are obtained from user-specified axial Mach number and swirl conditions. A schematic flowchart of the entire calculation procedure is shown as Figure 4.

ESTIMATION OF MECHANICAL STRESS

Since the present analysis considers such a wide range of possible designs for a single set of cycle constraints, it is desirable to calculate preliminary estimates of mechanical stress conditions for each design. Rough estimates of both average tangential disk stress and blade root stress are made utilizing expressions found in textbooks on turbomachinery design (such as References 10 and 11). Blade root stresses are calculated using a taper correction factor of 2/3, which corresponds to a linearly tapered blade with a ratio of blade tip area to blade hub area of about 0.35. The disk half-area is considered to be a trapezoidal section; the disk rim load is considered to be the sum of 1) the load due to the blades themselves, and 2) the load due to a blade attachment region, also taken to be a trapezoid. It should be noted that these stresses are directly dependent on both blade chord and blade solidity, both of which are optimized in the present analysis. It is impossible, therefore, to completely separate considerations of
Figure 4: Axial Turbine Design Optimization Procedure
aerothermodynamic optimization from considerations of mechanical integrity. It should also be noted that, while mechanical stress is calculated by the model, no design decisions are made on the basis of such calculations.

VERIFICATION OF THE PERFORMANCE LOSS MODEL

Verification of the performance loss model is accomplished by a process wherein test data, including test rig geometries normally calculated internally, are input to determine whether actual measured test-rig performance can be predicted. Thermodynamic cycle requirements input represent air-equivalent (cold) conditions rather than design (hot) conditions. Quantities such as measured mass flow, rotor torque (specific work), and rotor exit swirl angle are utilized.

Seven (7) NASA turbines have been selected to provide a means of comparison between aerodynamic performance (adiabatic efficiency) as predicted by the model and aerodynamic performance as measured during cold-air testing. These turbines are designated as

Case 1: Low-cost civilian turbojet engine (Reference 12)
Case 2: Research turbine for high temperature core engine application (Reference 13)
Case 3: 12.766 centimeter tip diameter (solid blade configuration) turbine (Reference 14)
Case 4: First stage of a 4½ stage fan-drive turbine (Reference 15)
Case 5: Compressor drive turbine for a 75 KW automotive engine (Reference 16)
Case 6: Uncooled core turbine with high work output (Reference 17)

Case 7: Low-cost turbofan engine (first stage of a two-stage turbine) (Reference 18)

These turbines range in size from 0.6 to 63.8 kg/s (1.3 to 140 lb/s) mass flow and in specific work output from 153 to 558 J/g (65 to 240 Btu/lb), all at design (hot) conditions; stage loading factor ranges from 1.15 to 4.66. For comparison, relevant design parameters for each turbine configuration are given in Table 1.

### Table 1: Comparison of Relevant Turbine Parameters (Design Conditions) for NASA Test Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Inlet Temp OK</th>
<th>Inlet Pressure N/cm²</th>
<th>Mass Flow Rate kg/s</th>
<th>Specific Work Output J/g</th>
<th>Work Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1089</td>
<td>26.3</td>
<td>3.28</td>
<td>159.3</td>
<td>1.15</td>
</tr>
<tr>
<td>2</td>
<td>2200</td>
<td>386.1</td>
<td>63.82</td>
<td>287.3</td>
<td>1.70</td>
</tr>
<tr>
<td>3</td>
<td>1478</td>
<td>91.2</td>
<td>0.95</td>
<td>307.3</td>
<td>1.67</td>
</tr>
<tr>
<td>4A</td>
<td>378</td>
<td>24.3</td>
<td>5.84</td>
<td>25.7</td>
<td>4.66</td>
</tr>
<tr>
<td>5</td>
<td>1325</td>
<td>39.8</td>
<td>0.60</td>
<td>198.1</td>
<td>2.10</td>
</tr>
<tr>
<td>6</td>
<td>2200</td>
<td>386.1</td>
<td>49.41</td>
<td>557.7</td>
<td>1.94</td>
</tr>
<tr>
<td>7</td>
<td>978</td>
<td>28.5</td>
<td>2.99</td>
<td>152.8</td>
<td>1.72</td>
</tr>
</tbody>
</table>

*Equivalent design requirements--actual conditions not given.*

For each case, the following calculations are made:

1. With no geometry input, determine the optimum rotor exit mean radius by maximizing the turbine adiabatic total-total
efficiency. This calculation is performed with design (hot) conditions of thermodynamic parameters of flow, work, etc., as well as geometric design values such as rotor tip clearance, and is done merely to demonstrate the flexibility of the model. Thus, total-total efficiency as predicted by, say, Figure 5, need not compare on a one-to-one basis with that of Figures 8 and 9. Further, \( \eta \) values shown in the geometric optimization portion of the present work differ slightly from those values given in Reference 19 due primarily to changes in the blade loading portion of the model.

(2) With detailed test-rig geometry and flow conditions input, determine the predicted total-total efficiency as a function of

(i) rotor solidity, \( \sigma_R \)

(ii) rotor exit swirl angle

In addition, for Case 1 only, a survey of optimum predicted flowpath geometry is made as a function of rotor Zweifel loading coefficient, \( \zeta \), and rotor exit swirl angle.

Case 12

Case 1 represents a turbine designed for a low-cost civilian turbojet engine application. The turbine configuration is single-stage, axial flow with a free-vortex whirl distribution. The aerodynamic design is conservative (low work factor) with moderate gas temperatures. Table 2 presents the relevant design parameters and measures test-rig values input to the performance model.
Table 2: Case 1 Performance Model Input

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Equivalent Condition</th>
<th>Test-Rig Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotative Speed, RPM</td>
<td>18075 100% of Design</td>
<td></td>
</tr>
<tr>
<td>Inlet Temperature, °K</td>
<td>288.2</td>
<td>310</td>
</tr>
<tr>
<td>Inlet Pressure, N/cm²</td>
<td>10.14</td>
<td>10.8</td>
</tr>
<tr>
<td>Specific Work, J/g</td>
<td>43.23</td>
<td>1.7% more</td>
</tr>
<tr>
<td>Mass Flow, KG/s</td>
<td>2.51</td>
<td>9.5% less</td>
</tr>
<tr>
<td>Rotor Exit Mean Radius, cm</td>
<td>10.06</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Exit Annulus Area, cm²</td>
<td>269.6</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Clearance, cm</td>
<td>0.028</td>
<td>SAME</td>
</tr>
<tr>
<td>Stator Solidity</td>
<td>1.038</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Solidity</td>
<td>1.640</td>
<td>SAME</td>
</tr>
<tr>
<td>Stator Axial Chord, cm</td>
<td>1.90</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Axial Chord, cm</td>
<td>1.76</td>
<td>SAME</td>
</tr>
<tr>
<td>Stator TE Thickness, cm</td>
<td>0.101</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor TE Thickness, cm</td>
<td>0.101</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Exit Swirl, deg</td>
<td>-3.8</td>
<td>+14.0</td>
</tr>
</tbody>
</table>

Figure 5 represents a preliminary optimization of annular flow-path geometry, wherein no geometrical constraints are input to the model. An optimum size for the turbine is chosen based on maximum total-total efficiency. The predicted size (rotor exit mean radius) compares well with the actual (design) size for the Case 1 configuration.
Figures 6 and 7 demonstrate the predicted variation of optimum turbine size with rotor Zweifel coefficient (Figure 6) and rotor exit swirl (Figure 7), all other factors being constant. Figures 8 and 9 are calculations wherein geometry is input to the model. Figure 8 is a parametric study of stage efficiency vs. rotor solidity (blade number); note that exit swirl is constrained to +14°, as opposed to the design value of -3.8°. At the design solidity, the model predicts an efficiency of 91.4, which compares well with the rig measured value of 91.0. Original design (target) efficiency was 88.0. Figure 9 represents a parametric study of predicted efficiency vs. rotor exit swirl, all other factors being constant.
Figure 6: Case 1 Geometry Optimization Study; Rotor Zweifel Coefficient Variation

Figure 7: Case 1 Geometry Optimization Study; Rotor Exit Swirl Variation
Case 2 is a half-scale model of a 50.8 cm (20 inch) turbine characterized by low aspect ratio, thick trailing edges, low solidity, and relatively large rotor tip clearance. Originally, the rotor blades had a constant section profile from hub to tip with no twist, resulting in relative ease of manufacture but a possible performance penalty. Subsequently, a free-vortex twist rotor was fabricated and tested. Due to the pitchline nature of the model used in the present code, these two conditions cannot be differentiated. Though the measured performance of both designs is reported (see Figures 11 and 12), only the untwisted rotor test-rig conditions are shown in Table 3.
Figure 9: Case 1 Efficiency vs. Rotor Exit Swirl for Fixed Stator and Rotor Solidities (Geometry Input)
Table 3: Case 2 Performance Model Input

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Equivalent Condition</th>
<th>Test-Rig Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotative Speed, RPM</td>
<td>12388</td>
<td>100% of Design</td>
</tr>
<tr>
<td>Inlet Temperature, °K</td>
<td>288.2</td>
<td>306</td>
</tr>
<tr>
<td>Inlet Pressure, N/cm²</td>
<td>10.14</td>
<td>17.24</td>
</tr>
<tr>
<td>Specific Work, J/g</td>
<td>39.57</td>
<td>0.5% LESS</td>
</tr>
<tr>
<td>Mass Flow, kg/s</td>
<td>1.207</td>
<td>1.5% LESS</td>
</tr>
<tr>
<td>Rotor Exit Mean Radius, cm</td>
<td>11.75</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Exit Annulus Area, cm²</td>
<td>140.6</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Clearance, cm</td>
<td>0.043</td>
<td>SAME</td>
</tr>
<tr>
<td>Stator Solidity</td>
<td>0.929</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Solidity</td>
<td>1.487</td>
<td>SAME</td>
</tr>
<tr>
<td>Stator Axial Chord, cm</td>
<td>1.905</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Axial Chord, cm</td>
<td>1.715</td>
<td>SAME</td>
</tr>
<tr>
<td>Stator TE Thickness, cm</td>
<td>0.089</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor TE Thickness, cm</td>
<td>0.089</td>
<td>SAME</td>
</tr>
<tr>
<td>Rotor Exit Swirl, deg</td>
<td>-17.8</td>
<td>-11.5</td>
</tr>
</tbody>
</table>

Figure 10 represents the preliminary optimization of annular flowpath geometry. As before, the predicted turbine size compares well with the actual size.

Figure 11 is a fixed geometry parametric study of efficiency vs. rotor solidity, with all other factors held constant. Rotor exit swirl is fixed at the test-rig measured value of -11.5°. The measured
Figure 10: Case 2 Preliminary Geometry Optimization Study
efficiency is shown as a band between 87.0 (untwisted rotor configuration) and 88.0 (twisted rotor configuration). Predicted performance is 86.6, compared to an original design value of 87.0. Recall that the present model cannot differentiate between the two rotor configurations. Figure 12 presents a parametric study of efficiency vs. rotor exit swirl angle, with all other factors held constant.

Case 3

Case 3 represents an uncooled solid-blade version of a cooled turbine design in the 1 kg per second, 225-375 KW size class. Work factor and solidity are considered to be near optimum by conventional design standards. Both the stator and the rotor blading are untwisted and
untapered. Typical of such small turbines, this design suffers from relatively large rotor tip clearance and secondary flow losses. Relevant test-rig conditions are given in Table 4.

Figure 13 demonstrates that the predicted annular flowpath geometry agrees well with the actual geometry. Figure 14 represents a fixed geometry parametric study of efficiency vs. rotor solidity and indicates that the rotor solidity is indeed near optimum for the thermodynamic cycle requirements of case 3. The model predicts an efficiency of 84.1 for the design solidity compared to a measured efficiency of 83.2. The original design efficiency was 85.0. Figure 15 presents a study of predicted efficiency vs. rotor exit swirl distribution. In the
### Table 4: Case 3 Performance Model Input

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Equivalent Condition</th>
<th>Test-Rig Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotative Speed, RPM</td>
<td>31460</td>
<td>100% of Design</td>
</tr>
<tr>
<td>Inlet Temperature, °K</td>
<td>288.2</td>
<td>300</td>
</tr>
<tr>
<td>Inlet Pressure, N/cm²</td>
<td>10.13</td>
<td>8.27</td>
</tr>
<tr>
<td>Specific Work, J/g</td>
<td>62.1</td>
<td>1.4% less</td>
</tr>
<tr>
<td>Mass Flow, kg/s</td>
<td>0.246</td>
<td>6.1% less</td>
</tr>
<tr>
<td>Rotor Exit Mean Radius, cm</td>
<td>5.86</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Exit Annulus Area, cm²</td>
<td>38.72</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Clearance, cm</td>
<td>0.025</td>
<td>Same</td>
</tr>
<tr>
<td>Stator Solidity</td>
<td>1.098</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Solidity</td>
<td>1.551</td>
<td>Same</td>
</tr>
<tr>
<td>Stator Axial Chord, cm</td>
<td>0.721</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Axial Chord, cm</td>
<td>0.968</td>
<td>Same</td>
</tr>
<tr>
<td>Stator TE Thickness, cm</td>
<td>0.038</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor TE Thickness, cm</td>
<td>0.050</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Exit Swirl, deg</td>
<td>-17.5</td>
<td>-11.0</td>
</tr>
</tbody>
</table>

Range of swirl angles shown the total-total efficiency appears to be almost independent of swirl. The region denoted "model limit" represents choked flow conditions at the stator exit.
Figure 13: Case 3 Preliminary Geometry Optimization Study

Figure 14: Case 3 Efficiency vs. Rotor Solidity; Comparison of Code Prediction, Original Design Value, and Test-Rig Measurement (Fixed Geometry)
Case 4

Case 4 represents the first stage of a 4\textfrac{1}{2} stage turbine designed for high stage work factor. This turbine is characterized by shrouded rotors, high turning in both stator and rotor blade rows, and nearly symmetrical mean-radius velocity diagrams. As part of a development program, the first stage alone was fabricated and its performance determined in cold air. Pertinent parameters are given in Table 5.

Figure 16 presents the geometry optimization portion of the parametric study for Case 4. In this instance the predicted and actual sizes are not in good agreement; it should be noted, however, that this
### Table 5: Case 4 Performance Model Input

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Equivalent Condition</th>
<th>Test-Rig Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotative Speed, RPM</td>
<td>3098.7</td>
<td>100% of Design</td>
</tr>
<tr>
<td>Inlet Temperature, °K</td>
<td>288.2</td>
<td>378</td>
</tr>
<tr>
<td>Inlet Pressure, N/cm²</td>
<td>10.13</td>
<td>24.3</td>
</tr>
<tr>
<td>Specific Work, J/g</td>
<td>25.65</td>
<td>100% of Design</td>
</tr>
<tr>
<td>Mass Flow, kg/s</td>
<td>5.84</td>
<td>2.4% more</td>
</tr>
<tr>
<td>Rotor Exit Mean Radius, cm</td>
<td>22.86</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Exit Annulus Area, cm²</td>
<td>656.7</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Clearance, cm</td>
<td>0.0</td>
<td>Same</td>
</tr>
<tr>
<td>Stator Solidity</td>
<td>0.955</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Solidity</td>
<td>1.517</td>
<td>Same</td>
</tr>
<tr>
<td>Stator Axial Chord, cm</td>
<td>2.29</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Axial Chord, cm</td>
<td>2.79</td>
<td>Same</td>
</tr>
<tr>
<td>Stator TE Thickness, cm</td>
<td>0.050</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor TE Thickness, cm</td>
<td>0.060</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Exit Swirl, deg</td>
<td>-52</td>
<td>Same</td>
</tr>
</tbody>
</table>

This case represents only the first stage of a multi-stage turbine, so that this result need not be surprising.

Figures 17 and 18 portray the fixed geometry parametric study for rotor solidity and exit swirl, respectively. Unlike the previous case, predicted efficiency is strongly dependent on these parameters. In this instance, the original design efficiency and the measured test-rig efficiency were identical (86.0) as compared to 85.0 for the model prediction.
Figure 16: Case 4 Preliminary Geometry Optimization Study

Figure 17: Case 4 Efficiency vs. Rotor Solidity; Comparison of Code Prediction, Original Design Value, and Test-Rig Measurement (Fixed Geometry)
Figure 18: Case 4 Efficiency vs. Rotor Exit Swirl for Fixed Stator and Rotor Solidities (Fixed Geometry)

Case 5

Case 5 represents a compressor drive turbine originally intended for use in a compact automobile. The design is characterized by a large (49°) stator inlet flow angle, required to match the swirl distribution in the tangential entry inlet manifold. Pertinent model input parameters are given in Table 6. It should be noted that the model input corresponds to the so-called "smoothed and thinned profile" test (i.e., smoothed and thinned blades) of Reference 16.
### TABLE 6: CASE 5 PERFORMANCE MODEL INPUT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Equivalent Condition</th>
<th>Test-Rig Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotative Speed, RPM</td>
<td>27673 100% of Design</td>
<td></td>
</tr>
<tr>
<td>Inlet Temperature, °K</td>
<td>288.2</td>
<td>320</td>
</tr>
<tr>
<td>Inlet Pressure, N/cm²</td>
<td>10.13</td>
<td>8.0</td>
</tr>
<tr>
<td>Specific Work, J/g</td>
<td>44.4 ~5% Less</td>
<td></td>
</tr>
<tr>
<td>Mass Flow, kg/s</td>
<td>0.325 5% Less</td>
<td></td>
</tr>
<tr>
<td>Rotor Exit Mean Radius, cm</td>
<td>5.00 SAME</td>
<td></td>
</tr>
<tr>
<td>Rotor Exit Annulus Area, cm²</td>
<td>36.47 SAME</td>
<td></td>
</tr>
<tr>
<td>Rotor Clearance, cm</td>
<td>0.025 SAME</td>
<td></td>
</tr>
<tr>
<td>Stator Solidity</td>
<td>0.557 SAME</td>
<td></td>
</tr>
<tr>
<td>Rotor Solidity</td>
<td>1.803 SAME</td>
<td></td>
</tr>
<tr>
<td>Stator Axial Chord, cm</td>
<td>1.17 SAME</td>
<td></td>
</tr>
<tr>
<td>Rotor Axial Chord, cm</td>
<td>0.91 SAME</td>
<td></td>
</tr>
<tr>
<td>Stator TE Thickness, cm</td>
<td>0.038 SAME</td>
<td></td>
</tr>
<tr>
<td>Rotor TE Thickness, cm</td>
<td>0.038 SAME</td>
<td></td>
</tr>
<tr>
<td>Rotor Exit Swirl, deg</td>
<td>-21.1 SAME</td>
<td></td>
</tr>
</tbody>
</table>

Figure 19 shows the geometry optimization portion of the parametric study for Case 5. Predicted and actual turbine size are in good, but not excellent agreement. Figures 20 and 21 present the remainder of the parametric study. As with the previous case, efficiency appears to be sensitive to rotor exit swirl. Predicted efficiency at the test-rig conditions is 83.5, which compares to a measured value of 82.5 and a design value of 85.0.
Figure 19: Case 5 Preliminary Geometry Optimization Study

Figure 20: Case 5 Efficiency vs. Rotor Solidity; Comparison of Code Prediction, Original Design Value, and Test-Rig Measurement (Fixed Geometry)
Figure 21: Case 5 Efficiency vs. Rotor Exit Swirl for Fixed Stator and Rotor Solidities (Fixed Geometry)

Case 6

Case 6 represents a single-stage "core" turbine for a turbofan engine and is characterized by relatively high hub-to-tip radius ratio and low aspect ratio. Due to relatively high requirements for work extraction, Mach number levels are also high. The vane exit flow angle is flat, about 73° from axial; the vanes are untwisted and have a constant section profile. Pertinent model input parameters are given in Table 7.

Figure 22 illustrates the geometry optimization calculation for Case 6. Predicted and actual turbine size are in excellent agreement. Figure 23 presents the rotor exit swirl parametric study for this case.
Table 7: Case 6 Performance Model Input

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESIGN EQUIVALENT CONDITION</th>
<th>TEST-RIG CONDITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotative Speed, RPM</td>
<td>8081</td>
<td>100% of Design</td>
</tr>
<tr>
<td>Inlet Temperature, OK</td>
<td>288.2</td>
<td>378</td>
</tr>
<tr>
<td>Inlet Pressure, N/cm²</td>
<td>10.13</td>
<td>24.13</td>
</tr>
<tr>
<td>Specific Work, J/g</td>
<td>76.84</td>
<td>0.5% less</td>
</tr>
<tr>
<td>Mass Flow, kg/s</td>
<td>3.708</td>
<td>4% more</td>
</tr>
<tr>
<td>Rotor Exit Mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor Exit Radius, cm</td>
<td>23.5</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Exit Annulus Area, cm²</td>
<td>562.5</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Clearance, cm</td>
<td>0.030</td>
<td>Same</td>
</tr>
<tr>
<td>Stator Solidity</td>
<td>0.929</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Solidity</td>
<td>1.487</td>
<td>Same</td>
</tr>
<tr>
<td>Stator Axial Chord, cm</td>
<td>3.81</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Axial Chord, cm</td>
<td>3.43</td>
<td>Same</td>
</tr>
<tr>
<td>Stator TE Thickness, cm</td>
<td>0.127</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor TE Thickness, cm</td>
<td>0.127</td>
<td>Same</td>
</tr>
<tr>
<td>Rotor Exit Swirl, deg</td>
<td>-23.7</td>
<td>-22.6</td>
</tr>
</tbody>
</table>

Note that for the test-rig geometry the calculation model reaches the stator choke condition at a rotor exit swirl of approximately -27°. The measured swirl, on the other hand, is -22.6°, indicating that the flow is supersonic at the stator exit, a condition confirmed by the original design velocity diagrams. Strictly speaking, the model cannot be applied to this situation since it is constrained to stator exit Mach numbers less than unity. If one extrapolates the code prediction curve,
Figure 22: Case 6 Preliminary Geometry Optimization Study

however, the model predicts an efficiency level very near the 88.6 value actually measured. No solidity study was run for this case.

**Case 7**

Case 7 represents the first stage of a two-stage turbine designed to drive the compressor and fan of a low-cost turbofan engine suitable for light aircraft application. The aerodynamic design is rather conservative, with low Mach number levels and low stator turning. The turbine was tested as both a two-stage and a single-stage unit. Data for the single-stage test are given in Table 8.
Figure 23: Case 6 Efficiency vs. Rotor Exit Swirl for Fixed Stator and Rotor Solidities (Fixed Geometry)

Figure 24 indicates excellent agreement between predicted and actual turbine size, even though Case 7 is, like Case 4, the first stage of a multi-stage turbine. For fixed geometry input, Figure 25 indicates a predicted efficiency of 91.1, compared to a test efficiency of 93.0. The original design value for this turbine was 87.0. Figure 26 indicates that, within the exit swirl range studied, the predicted efficiency curve is virtually flat.
Table 8: Case 7 Performance Model Input

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Equivalent Condition</th>
<th>Test-Rig Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotative Speed, RPM</td>
<td>15336 100% of design</td>
<td></td>
</tr>
<tr>
<td>Inlet Temperature, °K</td>
<td>288.2 300</td>
<td></td>
</tr>
<tr>
<td>Inlet Pressure, N/cm²</td>
<td>10.13 13.79</td>
<td></td>
</tr>
<tr>
<td>Specific Work, J/g</td>
<td>45.83 6.5% more</td>
<td></td>
</tr>
<tr>
<td>Mass Flow, kg/s</td>
<td>1.989 0.8% more</td>
<td></td>
</tr>
<tr>
<td>Rotor Exit Mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius, cm</td>
<td>10.16 same</td>
<td></td>
</tr>
<tr>
<td>Rotor Exit Annulus Area, cm²</td>
<td>233.5 same</td>
<td></td>
</tr>
<tr>
<td>Rotor Clearance, cm</td>
<td>0.030 same</td>
<td></td>
</tr>
<tr>
<td>Stator Solidity</td>
<td>1.049 same</td>
<td></td>
</tr>
<tr>
<td>Rotor Solidity</td>
<td>1.469 same</td>
<td></td>
</tr>
<tr>
<td>Stator Axial Chord, cm</td>
<td>1.91 same</td>
<td></td>
</tr>
<tr>
<td>Rotor Axial Chord, cm</td>
<td>2.23 same</td>
<td></td>
</tr>
<tr>
<td>Stator TE Thickness, cm</td>
<td>0.050 same</td>
<td></td>
</tr>
<tr>
<td>Rotor TE Thickness, cm</td>
<td>0.050 same</td>
<td></td>
</tr>
<tr>
<td>Rotor Exit Swirl, deg</td>
<td>-26.1 -26.5</td>
<td></td>
</tr>
</tbody>
</table>
Figure 24: Case 7 Preliminary Geometry Optimization Study

Figure 25: Case 7 Efficiency vs. Rotor Solidity; Comparison of Code Prediction, Original Design Value, and Test-Rig Measurement (Fixed Geometry)
Summary of Results

Results for each of the seven cases considered in this study are summarized in Figure 27 and Table 9.

Despite obvious limitations of the model such as the pitchline nature of the analysis, simplicity of the boundary layer assumptions, etc., the results for the seven cases detailed above indicate that the model is capable of providing preliminary aerodynamic performance data with an acceptable degree of confidence. Experience with the model has shown that it is important to set up the correct stator inlet flow conditions (Mach number and pre-swirl) in order to achieve optimum results.
Finally, a description of the model and code verification results have been presented at the 18th and 19th AIAA/SAE/ASME Joint Propulsion Conferences held in Cleveland, Ohio (1982) and Seattle, Washington (1983), respectively.\(^{19-20}\)

Appendices A-E contain supporting equations and analyses for the model. Appendix F describes the required model input; Appendix G contains a sample output; and Appendix H is a listing of the FORTRAN program.
<table>
<thead>
<tr>
<th>Case</th>
<th>Predicted(^A) Efficiency</th>
<th>Measured Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91.4</td>
<td>91.0</td>
</tr>
<tr>
<td>2</td>
<td>86.6</td>
<td>87-88(^B)</td>
</tr>
<tr>
<td>3</td>
<td>84.1</td>
<td>83.2</td>
</tr>
<tr>
<td>4</td>
<td>85.0</td>
<td>86.0</td>
</tr>
<tr>
<td>5</td>
<td>83.5</td>
<td>82.5</td>
</tr>
<tr>
<td>6</td>
<td>89.3(^C)</td>
<td>88.6</td>
</tr>
<tr>
<td>7</td>
<td>91.2</td>
<td>93.0</td>
</tr>
</tbody>
</table>

\(^A\) At measured rotor solidity and exit swirl.

\(^B\) Depending on twisted vs. untwisted rotor configuration.

\(^C\) Extrapolated from Figure 23 data.
References


APPENDIX A

STANITZ METHOD SUPPORTING EQUATIONS

The Stanitz method explicitly requires the following thermodynamic flow properties:

\[
\frac{T_M}{T_i}, \frac{T'_M}{T_i}, \frac{T''_M}{P_i}, \frac{P'_M}{P_i}, \frac{P''_M}{P_i}
\]

Energy Equation:

\[
c_p T_M + \frac{V_M^2}{2gJ} = c_p T_i + \frac{V_i^2}{2gJ} + W_{\text{shaft}}
\]  

(1)

Moment of Momentum:

\[
W_{\text{shaft}} = \frac{1}{gJ} [(UV_u)_M - (UV_u)_i]
\]

(2)

Upon substitution of Eq. (2) into Eq. (1), we have

\[
\frac{T'_M}{T_i} = 1 - \frac{(UV_u)_i - (UV_u)_M}{gJc_p T_i}
\]

(3)

which can be written, after some manipulation, as

\[
\frac{T'_M}{T_i} = 1 - 2 \left( \frac{\gamma - 1}{\gamma + 1} \right) \left[ \frac{U}{a_{cr,i}} \right] \left[ \frac{V}{a_{cr,i}} \right] - R^*_M \left[ \frac{V}{a_{cr,i} M} \right] \left[ \frac{T_M}{T_i} \right]
\]

(4)

Eq. (4) can be combined with Eq. (5) of the main text to yield
Eqs. (1), (2), and the law of cosines relationship between absolute velocity, $V$, and relative velocity, $W$, can be combined to yield

$$T_M' = 1 + \frac{\left(\frac{\gamma - 1}{\gamma}\right) \frac{U}{a_{cr}'} \cos \alpha_i}{\frac{\rho V}{\rho a_{cr}'} \frac{\Delta P}{\rho} dM} \left(\int_0^M \sigma h R^* \frac{\Delta P}{\rho} dM\right)$$

From the definitions of absolute and relative total temperature we can write

$$T_M'' - T_M' = \frac{U_M^2}{2gJc_p} \left[1 - 2 \left(\frac{V}{U}\right)_M\right] \quad (7)$$

with

$$\left(\frac{V}{U}\right)_M = \frac{\left(\frac{V}{U}\right)_M}{\sqrt{\frac{T_M'}{T_i'}}}$$

Eqs. (7) and (8) may be combined to give
\[
\frac{\rho_M^i}{\rho_i} = \frac{\rho_M^i}{\rho_i} = \left(\frac{T_M^i}{T_i^i}\right)^{\frac{\gamma}{\gamma-1}}
\]

(10)

so that

\[
\frac{p_M^i}{p_i} = p_M^i\left(\frac{T_M^i}{T_i^i}\right)^{\frac{\gamma}{\gamma-1}}
\]

(11)

Since blade losses do exist, the actual relative total pressure, \(p_{M_{\text{act}}}^i\), will differ from \(p_{M_{\text{isen}}}^i\) for all values of \(M\). It will be assumed that the difference between isentropic and actual total pressure conditions varies linearly with axial distance along the mean camberline. Thus

\[
\frac{p_{M_{\text{act}}}^i - p_{M_{\text{isen}}}^i}{p_{e_{\text{act}}}^i - p_{e_{\text{isen}}}^i} = M
\]

(12)

or

\[
\left[\frac{p_M^i}{p_i}\right]_{\text{act}} = \left[\frac{p_M^i}{p_i}\right]_{\text{isen}} + \left[\frac{p_{e}^i}{p_i}\right]_{\text{act}} - \left[\frac{p_{e}^i}{p_i}\right]_{\text{isen}} \right] M
\]

(13)
Substituting Eq. (10) into Eq. (13), we have

\[
\frac{\left(\frac{p''}{M}\right) \text{act}}{\left(\frac{p''}{p'_i}\right)} = \left(\frac{T''_M}{T''_i}\right)^{\gamma-1} + \left\{ \left(\frac{p''}{p'\text{act}}\right) - \left(\frac{T''_M}{T''_i}\right)^{\gamma-1} \right\} M^n
\]  

(14)

Equation (14) is usable in both rotating and non-rotating reference frames. For stators, Eq. (14) reduces to the familiar assumption of linear total pressure loss, i.e.,

\[
\frac{p'_M}{p'_i} = 1 + \left(\frac{p'_e}{p'_i} - 1\right) M^n
\]  

(15)

The quantity \((\frac{p''_e}{p'_i})\text{act}\) is determined from the Stewart mixing hypothesis (Appendix B).

Finally, since

\[
\frac{p''_M}{p'_i} = \frac{p''_M}{p''_i} \frac{p''_i}{p'_i}
\]

we have

\[
\frac{p''_M}{p'_i} = \left\{ \frac{T''_M}{T''_i} \right\}^{\gamma-1} \left(\frac{p''_M}{p''_i}\right)
\]  

(16)

where
must be evaluated for both the suction surface and the pressure surface of each blade.

\[
\frac{T_M}{T_M^*} = 1 - \frac{\gamma - 1}{\gamma + 1} \left( \frac{W}{a_{cr}^*} \right)^2
\]
APPENDIX B
PROFILE LOSS

Profile loss is defined here as a combination of frictional effects arising from the flow of a viscous fluid over a solid surface and the subsequent downstream mixing of the suction-surface and the pressure-surface boundary layers. Pressure drag, which results from the flow of fluid past a finite-thickness trailing edge, is implicitly contained in the Stewart analyses (Appendix C).

Laminar Regime

Laminar boundary layer properties are calculated as follows:

1. The freestream velocity function \( V(x) \) and its derivative \( dV/dx \) are known.
2. The momentum thickness, \( \theta(x) \) is calculated by

\[
\frac{\theta(x)}{\ell} = \frac{V}{V_\ell} \cdot \left[ \frac{1}{2} C_f \left( \int_0^{x_\ell/\ell} \left( \frac{V_\ell}{V} \right)^5 d\left( x/\ell \right) \right) \right]^{1/2}
\]

where \( V_\ell = \) free stream velocity at the cascade exit, i.e., at \( x = \ell \)
\[ C_f = 1.328 \left( \frac{\text{Re}_\ell}{\ell} \right)^{-1/2}; \text{Re}_\ell = \text{Reynolds No.} \]
\[ x_t = \text{location where boundary layer transition occurs} \]
3. The parameter \( Z \), given by

\[
Z = \frac{\theta^2}{\nu}
\]

where \( \nu = \) dynamic viscosity, is defined.
4. The parameter $K$, given by

$$K = Z \frac{dV}{dx}$$

is defined.

5. The shape factor $A$, given by

$$K = \left(\frac{37}{315} - \frac{1}{945} A - \frac{1}{9072} A^2\right)^2 A$$

is obtained by iteration.

6. The displacement thickness, $\delta^*$, is then calculated from

$$\frac{\delta^*}{\theta} = \frac{37}{315} - \frac{1}{120} A - \frac{1}{945} \frac{37}{315} A^2$$

Transition

Reference 6 indicates that the point of instability for boundary layers in a pressure gradient (that is, the point at which disturbances begin to amplify) can be determined through consideration of a "critical" Reynolds number, $Re_{cr}$, based on boundary layer displacement thickness. Further, this critical Reynolds number is a function of the shape factor $A$. For the present model, two assumptions are made:

(1) $Re_{cr}(A)$ is obtained from a curve fit of data given in [6].

(2) The point of instability is assumed to coincide with the point of transition.
Turbulent Regime

Boundary layer momentum thickness is computed from an equation appearing in References (3) and (4):

$$
\theta(x) = \frac{0.231}{\left(\frac{\rho}{\rho a_{cr}}\right) \left(\frac{v}{a_{cr}}\right) (1+H_b)} \left\{ \int_0^x \frac{\left(\frac{\rho}{\rho a_{cr}}\right) \left(\frac{v}{a_{cr}}\right) (1+H)}{10^{0.678(2n+1)}} \right\}^{0.7886} 
$$

where $\theta$ = boundary layer momentum thickness at the blade trailing edge

$\mu$ = viscosity

$n$ = exponent in the boundary layer power-law velocity profile, taken as $1/7$

$x$ = distance along blade surface

The quantity "A" is defined as

$$
A = \frac{\gamma-1}{\gamma+1} \left(\frac{v}{a_{cr}}\right)^2 
$$

and "H" is the boundary layer form factor, defined as

$$
H = \frac{\sum_{m=0}^{\infty} \frac{(2m+1)A^m}{(2m+1)n+1}}{\sum_{m=0}^{\infty} \frac{A^m}{[(2m+1)n+1][2(m+1)n+1]}} 
$$

from Reference (7). All other parameters used in Equation (6) are defined elsewhere.
Since the form factor is also defined as

\[ H = \frac{\delta^*}{\delta} \]  

(9)

where \( \delta^* \) is boundary layer displacement thickness, Equations (6), (7), (8) and (9) adequately describe all the pertinent turbulent boundary layer parameters required to calculate profile loss. Profile loss itself is calculated from the Stewart Mixing Hypothesis of Reference (4), which is detailed in Appendix C.
APPENDIX C
STEWART MIXING HYPOTHESIS(4)

Following Stewart, we define stations at the cascade inlet, cascade exit, and (somewhere) downstream of the cascade exit, as shown in Figure C-1.

Continuity:

\[ \cos \alpha_1 \int_0^1 (\rho v_1) \frac{d(U)}{d} = (\rho v)_1 \cos \alpha_2 \]  

Axial Momentum:

\[ gp_1 + \cos^2 \alpha_1 \int_0^1 (\rho v_2)^2 \frac{d(U)}{d} = gp_2 + \cos^2 \alpha_2 (\rho v_2)^2 \]  

Tangential Momentum:

\[ \sin \alpha_1 \cos \alpha_1 \int_0^1 (\rho v_2) \frac{d(U)}{d} = \sin \alpha_2 \cos \alpha_2 (\rho v_2)^2 \]
Define

\[ 1 - \delta^* - \delta_{te} = \int_{0}^{1} \left( \frac{\rho V}{\rho_{fs} V_{fs}} \right) \frac{d(U)}{s} \]  \hspace{0.5cm} (4-a)  

\[ \theta^* = \int_{0}^{1} \left[ 1 - \left( \frac{V}{V_{fs}} \right) \right] \left( \frac{\rho V}{\rho_{fs} V_{fs}} \right) \frac{d(U)}{s} \]  \hspace{0.5cm} (4-b)  

where the subscript "fs" refers to freestream conditions (assumed isentropic).

We shall define a set of reference (total) conditions at station 1 and assume adiabatic flow throughout. Eqs. (1) and (4-a) can then be written as

\[ (1 - \delta^* - \delta_{te}) \left( \frac{\rho V_x}{\rho_{fs} a_{cr}^{1}} \right)_{fs,1} = \left( \frac{\rho V_x}{\rho_{fs} a_{cr}^{1}} \right)_{fs,2} \frac{p_{2}^{i}}{p_{fs,1}} \]  \hspace{0.5cm} (5)  

where the subscript "x" refers to the axial direction.

Eq. (4-b) can be combined with (4-a) to become

\[ \theta^* = (1 - \delta^* - \delta_{te}) - \int_{0}^{1} \left( \frac{\rho}{\rho_{fs}} \right) \left( \frac{V}{V_{fs}} \right)^{2} d(U) \]  \hspace{0.5cm} (6)  

Eq. (2) can then be written, after algebraic manipulation, as

\[ \left( \frac{\gamma + 1}{2\gamma} \right) \left( \frac{p_{1}}{p_{fs,1}} \right) + (1 - \delta^* - \delta_{te} - \theta^*) \left( \frac{\rho V_x^2}{\rho_{fs} a_{cr}^{1}} \right)_{fs,1} = \left( \frac{\gamma + 1}{2\gamma} \right) \left( \frac{p_{2}}{p_{fs,2}} \right) \left( \frac{p_{2}^{i}}{p_{fs,1}} \right) \]  \hspace{0.5cm} (7)
while Eq. (3) can be written as

\[
(1 - \delta^* - \delta_{te} - \theta^*) \left( \frac{\rho}{\rho^*} \frac{V_x}{a_{cr}} \frac{V_u}{a_{cr}} \right)_{fs,1} = \left( \frac{\rho}{\rho^*} \frac{V_x}{a_{cr}} \frac{V_u}{a_{cr}} \right)_{fs,1} \left( \frac{p^*}{p_{fs,1}} \right)^{\gamma-1} \frac{V_x}{a_{cr}} \frac{V_u}{a_{cr}} \frac{X}{a_{cr}} \frac{p_{fs,1}}{p^*} \right) 
\]

(8)

where the subscript "u" refers to the tangential direction. We shall define

\[
A_{fs,1} = \frac{\gamma-1}{\gamma+1} \left( \frac{V_x}{a_{cr}} \right)^2
\]

(9)

and set

\[
\frac{p_1}{p_{fs,1}^*} = \frac{\rho_1}{\rho_{fs,1}^*}, \quad \frac{T_1}{T_{fs,1}^*} = \left( \frac{\rho}{\rho^*} \right)_{fs,1} \left( 1 - A_{fs,1} \right)
\]

(10)

Now solve Eq. (5) for \( \frac{p^*_{fs,1}}{p_{fs,1}} \):

\[
\frac{p^*_{fs,1}}{p_{fs,1}} = \left( 1 - \delta^* - \delta_{te} \right) \left( \frac{\rho}{\rho^*} \frac{V_x}{a_{cr}} \right)_{fs,1} \left( \frac{\rho}{\rho^*} \frac{V_u}{a_{cr}} \right)_{fs,1} \left( \frac{p^*}{p_{fs,1}} \right)^{\gamma-1} \frac{V_x}{a_{cr}} \frac{V_u}{a_{cr}} \frac{X}{a_{cr}} \frac{p_{fs,1}}{p^*} \right) 
\]

(11)

Substitute Eqs. (11) and (10) into Eq. (7) and solve for \( \left( \frac{V_x}{a_{cr}} \right)^2 \):

\[
\left( \frac{V_x}{a_{cr}} \right)^2 - C \left( \frac{V_x}{a_{cr}} \right)^2 + \left( \frac{\gamma+1}{2\gamma} \right) \left( 1 - \frac{1}{\gamma+1} \left[ \left( \frac{V_x}{a_{cr}} \right)^2 + \left( \frac{V_u}{a_{cr}} \right)^2 \right] \right) = 0
\]

(12)

where
Substitute Eq. (11) into Eq. (8) and solve for \( \left( \frac{V_u}{a_{cr}} \right)_2 \):

\[
\left( \frac{V_u}{a_{cr}} \right)_2 = \frac{(1 - \delta^* - \delta_{te} - \theta^*) \frac{V_x}{a_{cr}} \left( \frac{V_x}{a_{cr}} \right)_{fs,1}}{(1 - \delta^* - \delta_{te}) \left( \frac{V_x}{a_{cr}} \right)_{fs,1}} = D
\]  

Eq. (12) can then be written as

\[
\left( \frac{V_x}{a_{cr}} \right)_2^2 - \frac{2\gamma}{\gamma + 1} C \left( \frac{V_x}{a_{cr}} \right)_2 + \left( 1 - \frac{\gamma - 1}{\gamma + 1} D^2 \right) = 0
\]

which has the solution

\[
\left( \frac{V_x}{a_{cr}} \right)_2 = \frac{\gamma C}{\gamma + 1} - \sqrt{\frac{\gamma C}{\gamma + 1}}^2 - 1 + \frac{\gamma - 1}{\gamma + 1} D^2
\]  

Then

\[
\left( \frac{p}{\rho} \right)_2 = \left( 1 - \frac{\gamma - 1}{\gamma + 1} \left[ \left( \frac{V_x}{a_{cr}} \right)_2^2 + D^2 \right] \right)^{\frac{1}{\gamma - 1}}
\]

and

\[
\frac{p'}{p_{fs,1}} = (1 - \delta^* - \delta_{te}) \frac{\frac{\rho V_x}{\rho a_{cr}^2}}{(1 - \delta^*) \frac{\rho V_x}{\rho a_{cr}^2}}_{fs,1}
\]
For **stators**, \( P'_{fs,1} = P'_0 \) so that

\[
\frac{P'_2}{P'_0} = (1 - \delta^* - \delta_{te}) \frac{\frac{\rho V_x}{\rho' a_{cr}}}{\left[ \frac{\rho V_x}{\rho' a_{cr}} \right]_{fs,1}}
\]

(19)

For **rotors**, we will assume no radius change between the cascade exit (station 1) and the mixed plane (station 2); there may, however, be a change in radius between the cascade inlet (station 0) and the cascade exit. We have

\[
\frac{P''_2}{P''_{fs,1}} = (1 - \delta^* - \delta_{te}) \frac{\frac{\rho V_x}{\rho'' a_{cr}}}{\left[ \frac{\rho V_x}{\rho'' a_{cr}} \right]_{fs,1}}
\]

Now

\[
\frac{P''_2}{P''_{fs,1}} = \frac{P''_2}{P''_{fs,1}} \frac{P'_0}{P'_0}
\]

where \( \frac{P''_0}{P''_{fs,1}} \) is an isentropic change given by

\[
\frac{P''_0}{P''_{fs,1}} = \left( \frac{T''}{T''_{fs,1}} \right)^{\frac{\gamma}{\gamma - 1}}
\]

Thus, we have
\[
\left( \frac{P_2''}{P_0''} \right)^{\frac{\gamma}{\gamma-1}} \left( \frac{T_0''}{T_1''} \right) = (1 - \delta^* - \delta_{te}) \frac{\left( \frac{\rho W_x}{\rho_x^*c_{r_x}} \right)}{\left( \frac{\rho W_x}{\rho_x^*c_{r_x}} \right)_{mix}}
\]

(20)

where the subscript "mix" refers to station 2 conditions. Note that the LHS of Eq. (20) appears in the efficiency equation, Eq. (11) of Appendix E. Pressure loss terms are thus functions of \( \delta^* \), and \( \theta^* \); no isentropic terms appear.
APPENDIX D

BLOCKAGE CALCULATIONS

The effect of leading edge and trailing edge blockage is determined from the continuity equation and the assumption that moving from blocked to unblocked flow (and vice versa) leaves the tangential momentum (velocity) unchanged. Thus, one can easily show that, for the trailing edge,

\[
\cos \beta_{TE} = \frac{t_{TE}}{s} = \frac{1}{1 - \left(\frac{\gamma-1}{\gamma+1}\right)\left(\frac{V}{a_{cr}}\right)^2 \tan \beta_{TE}} \left(1 - \left(\frac{\gamma-1}{\gamma+1}\right)\left(\frac{V}{a_{cr}}\right)^2 \frac{\sin^2 \beta_{MIX} \tan \beta_{MIX}}{\sin^2 \beta_{TE}}\right) \tan \beta_{MIX}
\]

and for the leading edge

\[
\cos \beta_{LE} = \frac{t_{LE}}{s} = \frac{1}{1 - \left(\frac{\gamma-1}{\gamma+1}\right)\left(\frac{V}{a_{cr}}\right)^2 \tan \beta_{LE}} \left(1 - \left(\frac{\gamma-1}{\gamma+1}\right)\left(\frac{V}{a_{cr}}\right)^2 \frac{\sin^2 \beta_{MIX} \tan \beta_{MIX}}{\sin^2 \beta_{LE}}\right) \tan \beta_{MIX}
\]

where \(\beta_{TE}, \beta_{LE}, \beta_{MIX}\) = trailing edge blade angle, leading edge blade angle, and appropriate downstream and upstream flow angles, respectively.
$t_{TE}, t_{LE} =$ trailing edge and leading edge blade thickness, respectively

$s =$ blade spacing

The critical velocity ratio, $\frac{V}{a_{cr}}$, is always defined relative to the blade, whether for stators or for rotors.

It should be noted that the present model uses Equations (1) and (2) to modify (assumed) blade loadings to account for finite leading and trailing edge blade thickness.
By definition, the adiabatic efficiency of the turbine (stage) expansion process shown schematically in Figure E-1 is

\[ \eta_{T-T} = \frac{T_1' - T_{3A}}{T_1 - T_{3I}} \]  

which can be written as

\[ \eta_{T-T} = \frac{1}{1 + \frac{T_{3A}}{T_1 - T_{3I}} \left( 1 - \frac{T_{3I}}{T_1'} \right)} \]  

Denoting entropy changes by \( \Delta s \), we have

\[ \Delta s_{\text{total}} = \Delta s_{\text{stator}} + \Delta s_{\text{rotor}} \]
where

$$\Delta s = c_p n \frac{T_y}{T_x} - R \ln n \frac{p_y}{p_x} = c_p n \frac{T_y}{T_x} \left( \frac{p_y}{p_x} - 1 \right) \frac{Y-1}{Y}$$ \hspace{1cm} (4)$$

Now

$$\Delta s_{\text{total}} = \Delta s_{1' \rightarrow 3_A} \rightarrow 3'A = c_p n \frac{T_y}{T_x} \left( \frac{p_y}{p_x} \right)^{Y-1}$$ \hspace{1cm} (5)$$

$$\Delta s_{\text{stator}} = \Delta s_{1' \rightarrow 2'} = c_p n \left( \frac{p_y}{p_x} \right)^{Y-1}$$ \hspace{1cm} (6)$$

$$\Delta s_{\text{rotor}} = \Delta s_{2'' \rightarrow 3_A} \rightarrow 3'A = c_p n \left( \frac{p_y}{p_x} \right)^{Y-1}$$ \hspace{1cm} (7)$$

From Eq. (7) we can write

$$\frac{p_y}{p_x} = \frac{p_y}{p_x} \left( \frac{p_y}{p_x} \right)^{Y-1}$$ \hspace{1cm} (8)$$

so that

$$\Delta s_{\text{rotor}} = c_p n \left[ \left( \frac{p_y}{p_x} \right) \left( \frac{T_y}{T_x} \right) \frac{Y}{Y-1} \right]^{-Y-1} \hspace{1cm} (9)$$

Thus, combining Eqs. (3), (5), (6), and (9) we have
\[
\frac{T_{3}'}{T'_{3A}} = \left[ \frac{P_{2}'}{P_{1}'} \right]^{\frac{\gamma - 1}{\gamma}} \left[ \frac{T_{3}'}{T'_{3A}} \right]^{\frac{\gamma - 1}{\gamma}} = \left[ \frac{P_{3A}'}{P_{2}'} \right]^{\frac{\gamma - 1}{\gamma}} \left[ \frac{T_{3}'}{T'_{3A}} \right]^{\frac{\gamma - 1}{\gamma}}
\]

Substituting Eq. (10) into Eq. (2) yields the stage efficiency:

\[
\eta_{T-T} = \frac{1}{1 + \frac{T_{3A}'}{T_{1}'} - T_{3A}'} \left\{ 1 - \left[ \frac{P_{2}'}{P_{1}'} \right] \left[ \frac{P_{3A}'}{P_{2}'} \right] \left[ \frac{T_{3}'}{T'_{3A}} \right] \left[ \frac{T_{2}'}{T'_{3A}} \right] \right\}
\]
APPENDIX F
MODEL INPUT

The calculation model is set up to use the English system of units (ft, sec, lbm). Required program input is as follows:

1. GAMMA: ratio of gas specific heats, assumed constant throughout the calculation
2. RGAS: gas constant, ft·lbs/lbm/°R
3. SPEED: rotor rotational speed, RPM
4. P1P: turbine inlet total pressure, psia
5. T1P: turbine inlet total temperature, °R
6. RWORK: turbine work output required, BTU/lbm
7. WFLOW: mass flow rate, lbm/sec
8. RM1, RM2, RM3: pitch line radius at stator inlet, rotor inlet, and rotor exit, respectively (inches). If DSTRES = 0, input RM as zero also.
9. AREA1, AREA2, AREA3: annular flowpath area at stator inlet, rotor inlet, and rotor exit, respectively (sq. inches). If DSTRES = 0, input AREA as zero also.
10. CLEAR: rotor tip clearance, inches
11. TETS: stator trailing edge thickness, inches
12. TETR: rotor trailing edge thickness, inches
13. ALP2: stator exit flow angle, degrees. IF ALP2 = 0, angle will be calculated assuming zero rotor exit swirl. See note on ALP3.
14. ZWFS: stator Zweifel coefficient. Assumed 0.8 if none is input.
15. ZWFR: rotor Zweifel coefficient. Assumed 0.8 if none is input.
16. ALP1: stator inlet flow angle, degrees

17. CHORDS, CHORDR: stator and rotor axial chord, respectively (inches).
   If input as zero, chords will be calculated by aerodynamic optimization.

18. TELS, TELR: stator and rotor leading edge thickness, respectively (inches)

19. DSTRES: maximum allowable disk stress, psi. If DSTRES ≠ 0, program will calculate a range of possible turbine sizes and performances. If DSTRES = 0, program will perform an aerodynamic optimization for a single case only; RM and AREA must be input in this case.

20. VEXIT: rotor exit axial critical velocity ratio, $V_x/a_{cr}^*$

21. ALP3: rotor exit swirl angle, degrees. ALP3 and ALP2 cannot both be input; if both are, only ALP3 is used. If neither ALP3 or ALP2 is input, program will calculate ALP2 assuming ALP3 = 0.

22. I PLOT: key for blade plot generation. Set I PLOT = 0 for no plot.
   Note: user will have to tailor program for local plot subroutines.

23. RHODI: disk material density, $lb_m/ft^3$

24. RHOB L: blade material density, $lb_m/ft^3$

25. RHOAT: blade-disk attachment region material density, $lb_m/ft^3$
PROGRAM DEFAULT VALUES

STATOR EXIT FLOW ANGLE .......... CALCULATED FROM WORK
AND FLOW CONDITIONS
STATOR ZWEIFEL COEFFICIENT ...... 0.8
ROTOR ZWEIFEL COEFFICIENT ...... 0.8
STATOR CHORD .................. OPTIMIZED ON MINIMUM
CASCADE LOSS COEFFICIENT
ROTOR CHORD .................. OPTIMIZED ON MINIMUM
CASCADE LOSS COEFFICIENT
THE FOLLOWING IS A LIST OF POSSIBLE CONFIGURATIONS FOR THE INPUT CONDITIONS SPECIFIED

EACH CONFIGURATION IS CONSTRAINED BY THE FOLLOWING (CONSTANT) PARAMETERS

- RPM
- MASS FLOW
- TURBINE INLET TOTAL TEMPERATURE AND PRESSURE
- WORK REQUIREMENT
- ROTOR CLEARANCE
- ROTOR EXIT AXIAL MACH NO.
- ROTOR EXIT SWIRL
- STATOR AND ROTOR ZWEIFEL COEFFICIENTS

<table>
<thead>
<tr>
<th>PASS</th>
<th>ETA T-T</th>
<th>ETA T-S</th>
<th>U HUB</th>
<th>U TIP</th>
<th>ROTOR EXIT HUB RADIUS</th>
<th>ROTOR EXIT TIP RADIUS</th>
<th>BLADE STRESS (PSI)</th>
<th>DISK STRESS (PSI)</th>
<th>ROTOR LIFE (HOURS)</th>
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NOTE: PROGRAM PREDICTS STATOR (MEANLINE) CHOKING FOR THE CONDITIONS OF PASS

1. PASS 1
2. PASS 2
3. PASS 3
4. PASS 4
5. PASS 5
<p>| | | | | | | | | | |</p>
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<thead>
<tr>
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**NOTE**: Of 21 solutions obtained, 21 are (15) within the range of the specified disk stress.
The following is an aerodynamically optimized stage chosen from the possible flowpath configurations above.

### Computed Flow Parameters and Velocity Diagrams

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<thead>
<tr>
<th>Stator</th>
<th>Rotor</th>
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<tbody>
<tr>
<td>Stator Inlet Critical Velocity Ratio, ( \frac{V}{V_{CR}} )</td>
<td>0.509</td>
</tr>
<tr>
<td>Stator Inlet Swirl Velocity Ratio, ( \frac{V_u}{V_{CR}} )</td>
<td>0.383</td>
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<tr>
<td>Stator Exit Critical Velocity Ratio, ( \frac{V}{V_{CR}} )</td>
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<td>Stator Exit Axial Velocity Ratio, ( \frac{V_x}{V_{CR}} )</td>
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<td>Stator Exit Swirl Velocity Ratio, ( \frac{V_u}{V_{CR}} )</td>
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<td>Stator Exit Absolute Total Pressure</td>
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<td>Stator Absolute Total Pressure Loss Ratio</td>
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<td>Rotor Relative Total Pressure Loss Ratio</td>
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<td>Rotor Exit Absolute Total Temperature</td>
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### Stage

| Rotor Exit Hub Radius (Inches) | 1.884 |
| Rotor Exit Tip Radius (Inches) | 2.318 |
| Rotor Inlet Hub Radius (Inches) | 1.884 |
| Rotor Inlet Tip Radius (Inches) | 2.233 |
| Stator Inlet Hub Radius (Inches) | 1.884 |
| Stator Inlet Tip Radius (Inches) | 2.233 |

1183.5
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Rotor exit annulus area (sq inches)</td>
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<td>Rotor inlet annulus area (sq inches)</td>
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<td>Stage reaction</td>
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<td>Stage work coefficient based on mean radius</td>
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<tr>
<td>Stage work coefficient based on hub radius</td>
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<tr>
<td>Turbine total-total pressure ratio</td>
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**Flow Angles**

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<td>Stator exit angle</td>
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<td>Rotor exit angle</td>
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<tr>
<td>Rotor inlet angle</td>
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<tr>
<td>Rotor exit angle</td>
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<tr>
<td>Rotor exit swirl angle</td>
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### Calculations for Generation of Stator Blade Geometry

#### Computed Aerodynamic Loading

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<tr>
<th>Percent Meridional Distance</th>
<th>Suction Surface Relative Critical Velocity Ratio</th>
<th>Pressure Surface Relative Critical Velocity Ratio</th>
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<td>0.509</td>
</tr>
<tr>
<td>0.100</td>
<td>0.517</td>
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<tr>
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<td>0.563</td>
<td>0.526</td>
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<td>0.300</td>
<td>0.643</td>
<td>0.528</td>
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<td>0.547</td>
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<td>0.500</td>
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<tr>
<td>1.000</td>
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</table>

Overall blade reaction (R = 1 - VIN/VOUT) = 0.419
Pressure surface diffusion (DP = 1 - VMIN/VIN) = -0.036
Suction surface diffusion (DS = 1 - VOUT/VMAX) = -0.017

#### (Iterated) Stanitz Method Blade Exit Parameters

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<th>Iterated Value</th>
<th>Actual Value</th>
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<td>2385.000</td>
<td>2385.000</td>
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</tbody>
</table>

Exit (Absolute) Tangential Velocity: 0.7490
Exit Blade Angle: 58.6776
Solidity: 2.2719
Trailing edge thickness: 0.000
### FINAL STATOR BLADE PROFILE

**COORDINATES NORMALIZED WITH RESPECT TO BLADE CHORD**

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<tr>
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<th>PITCHLINE RADIUS</th>
<th>MEAN CAMBERLINE COORDINATE</th>
<th>BLADE SURFACE COORDINATE</th>
<th>BLADE SURFACE COORDINATE</th>
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<table>
<thead>
<tr>
<th>BLADE CHORD (INCHES)</th>
<th>BLADE SOLIDITY</th>
<th>BLADE CAMBERLINE LENGTH (INCHES)</th>
<th>BLADE STAGGER ANGLE</th>
<th>BLADE NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2473</td>
<td>2.2719</td>
<td>0.4160</td>
<td>53.21</td>
<td>121</td>
</tr>
</tbody>
</table>

---

**CALCULATIONS FOR GENERATION OF STATOR BLADE ROW AERODYNAMIC PERFORMANCE LOSSES**

---

**STEWART MIXING LOSS PARAMETERS**

- TOTAL MOMENTUM THICKNESS (DIMENSIONLESS): 0.0356
- TOTAL DISPLACEMENT THICKNESS (DIMENSIONLESS): 0.0756
- CASCADE EXIT (MIXED) CRITICAL MACH NUMBER: 0.8368
- PROFILE (FRICITION) TOTAL PRESSURE LOSS: 0.9642

---

**CASCADE LOSS COEFFICIENTS**

- PROFILE LOSS COEFFICIENT: 0.1011
- SECONDARY FLOW LOSS COEFFICIENT: 0.0556
- TOTAL CASCADE LOSS COEFFICIENT: 0.1567

---

**NOTE**

CASCADE GEOMETRY OPTIMIZED AT REYNOLDS NUMBER = 0.87E 05

---

**NOTE**

PREDICTED SUCTION SURFACE BOUNDARY LAYER TRANSITION AT 100.0 PERCENT OF CAMBER LENGTH
PREDICTED PRESSURE SURFACE BOUNDARY LAYER TRANSITION AT XXXX PERCENT OF CAMBER LENGTH
CALCULATIONS FOR GENERATION OF ROTOR BLADE GEOMETRY

*** COMPUTED AERODYNAMIC LOADING ***

<table>
<thead>
<tr>
<th>PERCENT MERIDIONAL DISTANCE</th>
<th>SUCTION SURFACE RELATIVE CRITICAL VELOCITY RATIO</th>
<th>PRESSURE SURFACE RELATIVE CRITICAL VELOCITY RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.538</td>
<td>0.538</td>
</tr>
<tr>
<td>0.100</td>
<td>0.708</td>
<td>0.383</td>
</tr>
<tr>
<td>0.200</td>
<td>0.849</td>
<td>0.285</td>
</tr>
<tr>
<td>0.300</td>
<td>0.958</td>
<td>0.244</td>
</tr>
<tr>
<td>0.400</td>
<td>1.027</td>
<td>0.258</td>
</tr>
<tr>
<td>0.500</td>
<td>1.059</td>
<td>0.321</td>
</tr>
<tr>
<td>0.600</td>
<td>1.058</td>
<td>0.416</td>
</tr>
<tr>
<td>0.700</td>
<td>1.029</td>
<td>0.530</td>
</tr>
<tr>
<td>0.800</td>
<td>0.978</td>
<td>0.648</td>
</tr>
<tr>
<td>0.900</td>
<td>0.912</td>
<td>0.757</td>
</tr>
<tr>
<td>1.000</td>
<td>0.842</td>
<td>0.842</td>
</tr>
</tbody>
</table>

OVERALL BLADE REACTION \( R=1-VIN/VOUT \) = 0.361
PRESSURE SURFACE DIFFUSION \( DP=1-VMIN/VIN \) = 0.590
SUCTION SURFACE DIFFUSION \( DS=1-VOUT/VMAX \) = 0.189

*** (ITERATED) STANITZ METHOD BLADE EXIT PARAMETERS ***

<table>
<thead>
<tr>
<th>ITERATED VALUE</th>
<th>ACTUAL VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXIT (ABSOLUTE) TEMPERATURE</td>
<td>2098.0845</td>
</tr>
<tr>
<td>EXIT (ABSOLUTE) TANGENTIAL VELOCITY</td>
<td>-0.1877</td>
</tr>
<tr>
<td>EXIT BLADE ANGLE</td>
<td>-55.9507</td>
</tr>
<tr>
<td>SOLIDITY</td>
<td>1.4372</td>
</tr>
<tr>
<td>TRAILING EDGE THICKNESS</td>
<td>0.000</td>
</tr>
</tbody>
</table>
### Final Rotor Blade Profile

**Coordinates Normalized with Respect to Blade Chord**

<table>
<thead>
<tr>
<th>Percent Meridional Distance</th>
<th>Pitchline Radius</th>
<th>Mean Camberline Coordinate</th>
<th>Blade Surface Coordinate</th>
<th>Blade Surface Coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>2.101</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.100</td>
<td>2.101</td>
<td>0.0529</td>
<td>0.0751</td>
<td>0.0307</td>
</tr>
<tr>
<td>0.200</td>
<td>2.101</td>
<td>0.0927</td>
<td>0.1489</td>
<td>0.0365</td>
</tr>
<tr>
<td>0.300</td>
<td>2.101</td>
<td>0.1124</td>
<td>0.1956</td>
<td>0.0293</td>
</tr>
<tr>
<td>0.400</td>
<td>2.101</td>
<td>0.1142</td>
<td>0.2116</td>
<td>0.0169</td>
</tr>
<tr>
<td>0.500</td>
<td>2.101</td>
<td>0.1142</td>
<td>0.2128</td>
<td>0.0157</td>
</tr>
<tr>
<td>0.600</td>
<td>2.101</td>
<td>0.1142</td>
<td>0.2014</td>
<td>0.0271</td>
</tr>
<tr>
<td>0.700</td>
<td>2.101</td>
<td>0.1142</td>
<td>0.1782</td>
<td>0.0503</td>
</tr>
<tr>
<td>0.800</td>
<td>2.101</td>
<td>0.1142</td>
<td>0.1474</td>
<td>0.0811</td>
</tr>
<tr>
<td>0.900</td>
<td>2.101</td>
<td>0.1142</td>
<td>0.1208</td>
<td>0.1077</td>
</tr>
<tr>
<td>1.000</td>
<td>2.101</td>
<td>0.1142</td>
<td>0.1142</td>
<td>0.1142</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Blade Chord (Inches)</th>
<th>Blade Solidity</th>
<th>Blade Camberline Length (Inches)</th>
<th>Blade Stagger Angle</th>
<th>Blade Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3979</td>
<td>1.4372</td>
<td>0.4965</td>
<td>6.52</td>
<td>47</td>
</tr>
</tbody>
</table>

**Calculations for Generation of Rotor Blade Row Aerodynamic Performance Losses**

#### Stewart Mixing Loss Parameters

- Total Momentum Thickness (Dimensionless): 0.0425
- Total Displacement Thickness (Dimensionless): 0.0644
- Cascade Exit (Mixed) Critical Mach Number: 0.8003
- Profile (Friction) Total Pressure Loss: 0.9617

#### Cascade Loss Coefficients

- Profile Loss Coefficient: 0.1161
- Secondary Flow Loss Coefficient: 0.0504
- Total Cascade Loss Coefficient: 0.1665

Note: Cascade geometry optimized at Reynolds Number = 0.78E 05

Note: Predicted suction surface boundary layer transition at 53.0 percent of camber length. Predicted pressure surface boundary layer transition at 3.7 percent of camber length.
FINAL CALCULATIONS FOR STAGE EFFICIENCY

STAGE ADIABATIC EFFICIENCY CALCULATED FROM BLADE BOUNDARY LAYER AND SECONDARY FLOW LOSSES .......... 0.8433

STAGE EFFICIENCY DECREMENT FOR ROTOR CLEARANCE ... -0.043

FINAL STAGE TOTAL-TOTAL EFFICIENCY ............... 0.8002

FINAL STAGE TOTAL-STATIC EFFICIENCY ............... 0.6523

FINAL STAGE RATING EFFICIENCY ....................... 0.7769

STRESS DATA

ALLOWABLE AVERAGE DISK STRESS (INPUT) ...... 50000. PSI

COMPUTED AVERAGE DISK STRESS ................. 28224. PSI

COMPUTED ROOT BLADE STRESS ..................... 20531. PSI

EFFICIENCY ITERATION CONVERGED AFTER 4 PASSES
PROGRAM TO COMPUTE ADIABATIC EFFICIENCY FOR
SINGLE STAGE AXIAL GAS TURBINES

WORK PERFORMED UNDER NASA GRANT NO. NSG 3295
NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO

DIMENSION VRELS(51), VRELP(51), AM(51), RMSTR(51), HMSTR(51), TMT2P(51)
DIMENSION PMPIP(51), GRAN(51), SIG(2), COAD(2), TMT2(51), VUCRM(51)
DIMENSION WUCRM(51), WCRM(51), BETAM(51), EPSM(51), TPTPM(51), THIK(51)
DIMENSION THIKR(51), THIKL(31), THETA(51), RTHET(31), R(51), DIFF1(2)
DIMENSION HMS(51), HMP(51), WS(51), WP(51), DTE(2), PLOSS(2), DIFF2(2)
DIMENSION YPRO(2), YSF(2), YTOT(2), CHRD(200), YTOTL(200), REYN0(200)
DIMENSION FSL(51), FPL(51), BNS(51), BNUP(51), DUDXS(51), DUDXP(51)
DIMENSION FS(51), FP(51), DUDXPS, DUDXP(51)
DIMENSION CXLEN(51), RADEX(21), EADIAS(21), FADIAS(200), DPSI(21)
DIMENSION RADEXX(21), TITLE(20), VDP(200)

4000 READ(45,*,END=999) GAMMA, RGAS, SPEED, P1P, T1P, RWORK, WFLOW
READ(45,*) RM1, RM2, RM3, AREA1, AREA2, AREA3, CLEAR
READ(45,*) TETS, TETR, ALP2, ZWFS, ZWFR, ALP1, CHORDS
READ(45,*) CHORDR, TELS, TELR, DSTRES, VEXIT, ALP3, IPILOT
READ(45,*) RHODI, RHOBL, RHOAT
WRITE(6,2101)
WRITE(6,2102)
WRITE(6,2103) GAMMA, RGAS, SPEED, WFLOW, P1P, T1P, RWORK
WRITE(6,2104)
WRITE(6,2105) RM1, RM2, RM3, AREA1, AREA2, AREA3, TETS, TETR, CLEAR
WRITE(6,2201)
WRITE(6,2202) ALP1, ALP2, ZWFS, ZWFR, CHORDS, CHORDR
WRITE(6,2204) TELS, TELR, DSTRES, VEXIT, IPILOT, ALP3
WRITE(6,2245) RHODI, RHOBL, RHOAT
WRITE(6,2203)
IF(DSTRES.EQ.0.0) WRITE(6,2242)
IF(DSTRES.EQ.0.0) WRITE(6,2243)
GAMM1=(GAMMA-1.)/(GAMMA+1.)
GAMM2=(GAMMA-1.)/GAMMA
GAMM3=1./ (GAMMA-1.)
SETAL3=ALP3*3.14159/180.
IF(DSTRES.NE.0.0) RM1=0.0
IF(DSTRES.NE.0.0) RM2=0.0
IF(DSTRES.NE.0.0) RM3=0.0
IF(DSTRES.NE.0.0) AREA1=0.0
IF(DSTRES.NE.0.0) AREA2=0.0
IF(DSTRES.NE.0.0) AREA3=0.0
IF(DSTRES.NE.0.0) ALP1=ALP1*3.14159/180.
ALP3=ALP3*3.14159/180.
KPASS=0
RBEST=0.0
190 DO 19 I=1,200
CHRD(I)=0.
YTOTL(I)=0.
REYN0(I)=0.
19 CONTINUE
IPRINT=0
NPASS=1
IF(DSTRES.EQ.0.0) GO TO 175
GO TO 11
BLP2 = ALPZ
RM1 = RM1/12.
RM2 = RM2/12.
RM3 = RM3/12.

H1 = (AREA1/144.)/(2.*3.14159*RM1)
H2 = (AREA2/144.)/(2.*3.14159*RM2)
H3 = (AREA3/144.)/(2.*3.14159*RM3)

H1A = H1
H2A = H2
H3A = H3
T2P = T1P

ASTD = ACRIT(GAMMA, RGAS, TSTD)
RMSTD = 2116.22/(RGAS*TSTD)
CP = (1./GAMM2)*RGAS/778.26

U2 = 3.14159*SPEED*RMZ/30.

ACR1 = ACRIT(GAMMA, RGAS, T1P)

UACR2 = U2/ACR1
U3 = U2*RM3/RM2
UT3 = U3*(RM3+H3/2.)/RM3

ALPZ = ALPZ*3.14159/180.

SLP1 = ASS(ALP1)

V1 = VELIT(WFLOW, T1P, GAMM1, GAMM3, BLIP, AREA1, P1P, RMSTD, ASTD)

VU1 = V1*SIN(ALP1)

SWPM = (U2**2)/(25036.62*RWORK)

ETA = (0.92 + SWPM)/(E 0.0227)

P2P = 0.98*P1P

T3P = T1P - RWORK/CP

P3P = P1P*((1. - (1. - T3P/T1P)/ETA)**(1./GAMM2))

PRTURB = P1P/P3P

KALP = 0

IF(BLP2.EQ.0.0) GO TO 210

ALP2 = BLP2

BNGCHK = WFLOW*SGRT(T1P/TSTD)/(((1.-GAMM1)**GAMM3)*AREA2/144.*P2P/

114.696*RHSTD+ASTD)

ANGCHK = ACOS(BNGCHK)

ANGCHK = ANGCHK*180./3.14159

IF(IPRINT.EQ.1) WRITE(6,2200) ANGCHK

IF(ALP2.GT.ANGCHK.AND.IPRINT.EQ.1) WRITE(6,2200) ANGCHK

ALP2 = ALP2*3.14159/180.

ANGCHK = ANGCHK*3.14159/180.

IF(ALP2.GT.ANGCHK) ALP2 = ANGCHK

CAL3 = ASS(SETAL3)

V3 = VELIT(WFLOW, T3P, GAMM1, GAMM3, ALP2, AREA3, P3P, RHSTD, ASTD)

VU3 = V3*SIN(ALP2)

VWRK3 = VU3 + ACR1

VWRK2 = 32.174*778.26*CP*T1P/U3*(1.-T3P/T1P)

IF(VWRK3.GE.0.0) KALP = 1

GO TO 220

IF(SETAL3.EQ.0.0) GO TO 211

V3 = VELIT(WFLOW, T3P, GAMM1, GAMM3, SETAL3, AREA3, P3P, RHSTD, ASTD)

VU3 = V3*SIN(SETAL3)

VX3 = V3*COS(SETAL3)

ALP3 = SETAL3

ACR3 = ACRIT(GAMMA, RGAS, T3P)

VWRK3 = VU3 + ACR3

VWRK2 = 32.174*778.26*CP*T1P/U3*(1.-T3P/T1P) + RM3/RM2*VWRK3

VU2 = VWRK2 + ACR1

IF(VU2.GT.1.0) GO TO 212

ALP2 = ANGIT(WFLOW, T1P, GAMM1, GAMM3, VU2, AREA2, P2P, RHSTD, ASTD, 0)

CHEK = VU2/SIN(ALP2)

IF(CHEK.LT.1.0) GO TO 213

WRITE(6,2239)

GO TO 4000

212

213

V2 = CHEK
VX2 = V2 * COS(ALP2)
UACR3 = U3 / ACR3
GO TO 214

211 VWRK3 = 0.0
13 VWRK2 = 32.174 * 778.26 * CP * T1P / U2 * (1. - T3P / T1P) + RM3 / RM2 * VWRK3
VU2 = VWRK2 / ACR1
IF (VU2 .GE. 1.0) GO TO 15
ALP2 = ANGIT (WFLOW, T1P, GAMM1, GAMM2, VU2, AREA2, P2P, RHSTD, ASTD, 0)
CHEK = VU2 / SIN(ALP2)
IF (CHEK .LT. 1.0) GO TO 12
VWRK3 = VWRK3 - 10.
KALP = 1
GO TO 13
12 V2 = CHEK
220 ACR3 = ACRIT (GAMMA, RGAS, T3P)
VX2 = V2 * COS(ALP2)
UACR3 = U3 / ACR3
VU3 = VWRK3 / ACR3
214 TPTP2 = 1.0 - GAMM1 * (UACR3 ** 2.0) * (2.0 * VU2 / UACR2 - 1.0)
T2PP = TPTP2 * T2P
PDPP2 = TPTP2 ** (1.0 / GAMM2)
T32PP = 1.0 - GAMM1 * (UACR2 ** 2.0) * (1.0 / TPTP2) ** (1.0 - ((RM3 / RM2) ** 2.0))
T3PP = T32PP * T2PP
ADP2 = ACRIT (GAMMA, RGAS, T2PP)
ADP3 = ADP2 * SGRT (T32PP)
WU2 = VWRK2 - U2
WUPP2 = WU2 / ADP2
BETA2 = ASIN ((VU2 - UACR2) / SGRT (V2 ** 2.0 + UACR2 ** 2.0 - 2.0 * VU2 * UACR2))
WPP2 = WUPP2 / SIN (BETA2)
WU3 = VWRK3 - U3
WUPP3 = WU3 / ADP3
IF (SETAL3 .NE. 0.0) GO TO 216
IF (KALP .GE. 1) GO TO 14
V3 = VELIT (WFLOW, T3P, GAMM1, GAMM3, U3, AREA3, P3P, RHSTD, ASTD)
ALP3 = 0.0
GO TO 17
14 VUM = VU3
VUM = ABS (VUM)
ALP3 = ANGIT (WFLOW, T3P, GAMM1, GAMM3, VUM, AREA3, P3P, RHSTD, ASTD, 1)
IF (VU3 .LT. 0.0) ALP3 = -ALP3
V3 = V3 / SIN (ALP3)
17 VX3 = V3 * COS (ALP3)
216 WXPP3 = VX3 * ACR3 / ADP3
WPP3 = SGRT (WXPP3 ** 2.0 + WUPP3 ** 2.0)
WFACTM = 25036.62 * RWORK / (U3 ** 2.0)
WFACTH = WFACTM ** (((RM3 / (RM3 - H3 / 2.0)) ** 2.0)
BETA3 = ASIN (WUPP3 / WPP3)
IF (NPASS .NE. 1) GO TO 11
P32PP = T32PP ** (1.0 / GAMM2)
PLOS1 = 0.98
PLOS2 = P32PP
11 CONTINUE
IF (IPRINT .LT. 1) WRITE (6, 2100)
IF (RBEST .GT. 0.0 AND IPRINT .LE. 1) WRITE (6, 2233)
IF (IPRINT .EQ. 1) WRITE (6, 2106)
IF (IPRINT .GT. 1) WRITE (6, 2107) U1, VX3, VU1, VU3, V2, V3, VX2, WPP2
IF (IPRINT .GT. 1) WRITE (6, 2108) U2, WPP3, P2P, UACR2, PLGS1, UACR3, PLOS2, P3P, T3P, UT3
IF (DISTRES .EQ. 0.0 AND IPRINT .LE. 1) WRITE (6, 2097)
IF (DISTRES .GT. 0.0 AND IPRINT .EQ. 1) WRITE (6, 2240) WFACTM, WFACTH, PTRURB
IF (DISTRES .EQ. 0.0) GO TO 215
IF (RBEST .EQ. 0.0) RADEX (KPASS + 1) = RM3
RH3 = RH3 * 12.
RH2 = RH3
RH1 = RH3
RT3 = RT3 * 12.
ANGZ2=BETA3
ANGGAM=ABS(BETA2+BETA3)/2.
ZWEIFL=0.30
IF(ZWFR.NE.0.0) ZWEIFL=ZWFR
HEIGHT=(H2A+H3A)*6.
CHORDB=CHORDR
R3STR=RM3/RM2
H3STR=H3/H2
VUCRI=VU2
VUCRO=VU3
AIN=ALP2
VCRi=V2
RIN=RM2*12.
TIPDP=1./TPTP2
POPI=PL052
TOTIA=T3P/T1P
TOTIR=T32PP
P1PPDP=1./PDP2
TPTPM(1)=TPTP2
WCRM(1)=WPP2
TIVIS=T2PP
RH02=144.*PDP2*POPI/(RGAS*T2PP)
CALL VISCO(T3PP,VISRE)
RHORP=RH02*P32PP
RHORE=RHORP(GAMMA,WPP3)/WPP3*RHORP
VELRE=WPP3*ADP3
VELBI=WPP3
VELBI=WUPP3
TLE=TEL2
VELBO=WPP2
BETAO=BETA2
TTE=TETR
BETAO=BETA3
CONTINUE
40 IF(DSTRES.EQ.0.0) GO TO 251
IF(CHORDB.EQ.0.0.AND.RBEST.GT.0.0) GO TO 250
IF(CHORDB.NE.0.0.AND.RBEST.GT.0.0) GO TO 252
SOLEST=2.*COS(ANGZ2)*SIN(ASS(ANGZ1-ANGZ2))/(ZWFR*COS(ANGZ1))
CHORD=0.26807*HEIGHT*SOLEST/COS(ANGGAM)
ITRI=1
ICHORD=1
GO TO 500
251 IF(CHORDB.EQ.0.0) GO TO 250
252 CHORD=CHORDB
ITRI=1
ICHORD=1
GO TO 500
250 ICHORD=1
ITRI=0
CHORD=HEIGHT/4.
CHMAX=HEIGHT*3.0
500 KZWFL=0
119 SOLID=2.*COS(ANGZ2)*SIN(ASS(ANGZ1-ANGZ2))/(ZWEIFL*COS(ANGZ1))
SPAC=CHORD/SOLID
CALL BLOCK(GAMMA,TTE,SPAC,BETAO,UELBL,BETE,VTE)
BETE=BETAO
VLE=VELBO
EXTRM=0.3
CALL DRANGE(GAMMA,VLE,VTE,EXTRM,DSTART,DCHNGE)
DPBLD=DSTART
ASLD=DCHNGE
DELBD=DCHNGE
K=1
KK=0
117 CONTINUE
118 IF(IBLD.EQ.2) GO TO 115
RT2 = RTS * 12.
RT1 = RT2
AREA = 3.14159 * (RT3^2 - RH3^2)
AREAS = 3.14159 * (RT2^2 - RH2^2)
IF (IPRINT .LE. 1) WRITE (6, 2109) RH3, RT3, RH2, RT2, RT1, AREAR, AREAS,

IF (IPRINT .LE. 1) WRITE (6, 2110) RPM, ANGZ1, ANGZ2, ANGAMASS (ALP1 + ALP2) / 2.
ZWEIFL = 0.8
IF (ZWFS .NE. 0.0) ZWEIFL = ZWFS
HEIGHT = (H1A + H2A) * 6.
CHORDB = CHORDS
R3STR = RM2 / RM1
H3STR = H2 / H1
VUCRI = VI
VCRI = VU1
AIN = ALP1
VICRI = V1
RIC = RM1 * 12.
TIPDP = 1.0
POPI = PLOS1
TOTA = 1.0
TOTIR = 1.0
PPIPDP = 1.0
TPTPM (1) = 1.0
WCRM (1) = V1
TIVIS = T1P
RH02 = 144. * PIP / (RGAS * T1P)
CALL VISCO (T1P, VISRE)
RHORP = RH02 * P2P / P1P
RHORE = RHOR (GAMMA, V2) / V2 * RHORP
VELRE = V2 * ACR1
VELBL = V2
VELBL = VUCR0
TLE = TELS
VELBLO = V1
BETALE = ALP1
IF (ALP1 .EQ. 0.0) BETALE = 0.00001
TTE = TETS
BETATE = ALP2
GO TO 60
RPM = UACR2
IF (IPRINT .EQ. 1) WRITE (6, 2111)
ANGZ1 = BETA2
CALL VNEG(VLE, VTE, EXTRM, DPBLD, VRATIO)
DO 21 I = 1, 51
   AI = (1 - I) / 50.
21 CALL DIST(VLE, VTE, DPBLD, AI, VRELS(I), VRELP(I), DUDXS(I), DUDXP(I),
   EXTRM, VRATIO)
GO TO 116
115 CALL VNEG(VLE, VTE, EXTRM, DPBLD, VRATIO)
DO 22 J = 1, 51
   AJ = (J - 1) / 50.
22 CALL DIST(VLE, VTE, DPBLD, AJ, VRELS(J), VRELP(J), DUDXS(J), DUDXP(J),
   EXTRM, VRATIO)
CONTINUE
116 DO 30 J = 1, 51
   AJ = J - 1
   AM(J) = AJ / 50.
   RMSTR(J) = (R3STR - 1.0) * AM(J) + 1.0
   HMSTR(J) = (H3STR - 1.0) * AM(J) + 1.0
   TMT2P(J) = 1.0 - GAMM1 * (RPM**2) * TIPDP * (1.0 - (RMSTR(J)**2))
   PMPIP(J) = TMT2P(J)**(1.0 / GAMM2) * (TIPP - TOTIR)*((1.0 / GAMM2))**AM(J)
   PMP2S = PMPIP(J)**((1.0 / TIPDP) * (1.0 - GAMM1 * (VRELS(J)**2)))
   PMP2P = PMPIP(J)**((1.0 / TIPDP) * (1.0 - GAMM1 * (VRELP(J)**2)))
   IF (IBLD.EQ.2) GO TO 31
   DELP = PMP2P - PMP2S
   GO TO 32
31 GRAN(J) = HMSTR(J) * RMSTR(J) * DELP
32 CONTINUE
30 SUM = SIMP2(GRAN, 0.0, 0.02, 50)
   SIGM = (2.0 * GAMMA / (GAMMA + 1.0)) * RHUV(GAMMA, VCR1) * COS(AIN) * (R3STR*
   VUCRO*SGRT(TOTIA) - VUCRI) / SUM
   SIG(K) = SIGM
160 DPBLD = DPBLD + DELBD
   K = K + 1
   IF (K.EQ.2) GO TO 117
   DPBLD = DPBLD - 2.0 * DELBD
   K = 1
   KK = KK + 1
   IF (KK.GT.20) GO TO 125
   DIFF1(1) = ABS(SOLID - SIG(1))
   DIFF1(2) = ABS(SOLID - SIG(2))
   DIFF2(1) = SOLID - SIG(1)
   DIFF2(2) = SOLID - SIG(2)
   IF (DIFF1(1).LE.0.01) GO TO 120
   IF (DIFF1(2).LE.0.01) GO TO 121
   GBLD = DIFF2(1) + DIFF2(2)
   IF (GBLD.LT.0.0) GO TO 122
   IF (DIFF1(2).GT.0.01) GO TO 123
   DPBLD = DPBLD + ABLD * 1.0
   GO TO 117
122 DELBD = DELBD / 2.
   ABLD = ABLD / 2.
   GO TO 117
123 DELBD = -DELBD
   ABLD = -ABLD
   GO TO 117
120 SIGMA = SIG(1)
   IF (IBLD.EQ.2) GO TO 126
   CALL VNEG(VLE, VTE, EXTRM, DPBLD, VRATIO)
127 DO 127 I = 1, 51
   AI = (I - 1) / 50.
127 CALL DIST(VLE, VTE, DPBLD, AI, VRELS(I), VRELP(I), DUDXS(I), DUDXP(I),
   EXTRM, VRATIO)
GO TO 305
126 CALL VNEG(VLE, VTE, EXTRM, DPBLD, VRATIO)
DO 128 I=1,51
AI=(I-i)/4.

CALL DIST(VLE, VTE, DPBLD, AI, VRELS(I), VRELPI, DUAXS(I), DUAXP(I),

1EXTRM, VRATIO)

DO 306 I=1,51
PMP2S = PMPIP(I) * ((1./TIPDP*(1.0-GAMM1*(VRELS(I)**2)))
I**((1./GAMM2))
PMP2P = PMPIP(I) * ((1./TIPDP*(1.0-GAMM1*(VRELPI)**2)))
I**((1./GAMM2))

IF(IBLD.EQ.2) GO TO 310
DELP=PMP2P-PMP2S
GO TO 320

310 DELP=PMP2S-PMP2P

320 GRAN(I)=HMSTR(I)*RMSTR(I)*DELP

CONTINUE

GO TO 130

121 SIGMA=SIG(2)

DPBLD=DPBLD+DELBD

GO TO 130

125 SIGMA=SIG(2)

WRITE(6,2129)

CONTINUE

IF(DSTRES.NE.0.0.AND.IBLD.EQ.2) CALL SDISK(RH3, RT3, CHORD, RHODI,

1RHOB3, RHAT, SPEED, SIGMA, AREA, STRES, STRESS)

C ASSUME THE ROTOR SEES THE ROTOR INLET RELATIVE TOTAL TEMPERATURE

IF(DSTRES.NE.0.0.AND.IBLD.EQ.2) CALL ALIPE(STRESB, T2PPH, BLIFE)

IF(IPRINT.EQ.1 ) WRITE(6,2112)

IF(IPRINT.EQ.1 ) WRITE(6,2113)

IF(IPRINT.EQ.0)GO TO 502

DO 2000 J=1,51,5

WRITE(6,2114) AM(J), VRELS(J), VRELPI

2000 CONTINUE

IF(DSTRES.NE.0.0.AND.RBEST.EQ.0.0) GO TO 501

IF(ITRIG.EQ.0) GO TO 501

IF(KZWFL.EQ.1.AND.IPRINT.EQ.1) WRITE(6,2143)XWEIFL

501 TMT2(1)=1.0

VUCRM(1)=VUCRI

WUCRM(1)=(VUCRI-RPM)*SR(TIPDP)

BETAM(1)=BETLE

EPSM(1)=1.0-TLE/(SPAC*COS(BETLE))

THIK(1)=RMSTR(1)*((1.0-EPSM(1))/SIGMA)

ANGCK=TAN(BETLE)

BNGCK=TAN(BETLE)

WXCRI=VRELS(1)*COS(ANGZ1)

WXR0=VRELS(51)*COS(ANGZ2)

DO 40 K=2,51

KNT=K-1

AKNT=KNT

IF(KNT.NE.1)GO TO 43

SUMM=0.5*(GRAN(1)+GRAN(2))*0.02

GO TO 41

43 SUMM=SIMPZ(GRAN, 0.0, 0.02, KNT)

41 IF(IBLD.EQ.2) GO TO 44

TMT2(K)=1.0

GO TO 42

44 TMT2(K)=1.0+GAMM2*RPM*SIGMA*SUMM/(RHOV(GAMMA,VCR)+COS(AIN))

42 VUCRM(K)=(VUCRI+(GAMMA+1.0)*SIGMA*SUMM/(2.*GAMMA*RHOV(GAMMA, VCR)

1*COS(AIN)))/(RMSTR(K)*SR(TMT2(K)))

IF(IBLD.EQ.2) GO TO 45
TPTPM(K)=1.0
GO TO 46

TPTPM(K)=1.0-GAMM1*(RPM**2)/TMT2(K)**2*(2.*VUCRM(K)**2)*
1SRT(TMT2(K))/(RPM*RMSTR(K)-1.0)

wUCRM(K)=(VUCRM(K)-RPM*RMSTR(K)**2)*SRT(1./TMT2(K)))/SRT(TPTPM(K))

wCRM(K)=wUCRM(K)/SRT(1./TMT2(K))

ARGCK=wUCRM(K)/wCRM

IF(IBLD.EQ.2) GO TO 51

IF(ARGCK.LE.ANGCK) GO TO 52

BETAM(K)=BETTE

wCRM(K)=wUCRM(K)/SIN(BETTE)

GO TO 53

51 IF(wUCRM(K).LT.0.0) GO TO 54

IF(ARGCK.LE.ANGCK) GO TO 52

BETAM(K)=BETLE

wCRM(K)=wUCRM(K)/SIN(BETLE)

GO TO 53

54 IF(ASS(ARGCK).LT.ASS(ANGCK)) GO TO 52

BETAM(K)=SETTE

wCRM(K)=wUCRM(K)/SIN(BETTE)

GO TO 53

52 BETAM(K)=ATAN(ARGCK)

wCRM(K)=SRT(wUCRM(K)**2+RUCR(M)**2)

53 EPSM(K)=RHOV(GAMMA,WCRM(K))**2/((1./TIPDP)**2*(1./
1PMPIP(K))*SRT(TMT2P(K))+(RHOV(GAMMA,WCRM(K))**2)+(HMSTR(K)**2)*
2COS(BETAM(K))**2)

THIK(K)=RMSTR(K)**2*(1.0-EPSM(K))/SIGMA

CONTINUE

SUM=0.

CXLN(I)=1.E-10

DO 55 I=2,51

SUM=SUM+ABS(0.02/COS(BETAM(I))+BETAM(I-1)+BETAM(I))/2.

CXLN(I)=SUM

CONTINUE

THIKR(1)=THIK(1)/2.

THIKL(1)=-THIK(K)/2.

THETA(1)=0.0

RTHET(1)=0.0

R(1)=RIN

AMAVE=GAMM1*(VELBL**2)

CALL HM(AMAVE,HFAVE)

ANGMN=ATAN((TAN(ANGZ1)+TAN(ANGZ2))/2.)

CLSC=2.*(TAN(ANGZ1)-TAN(ANGZ2))*COS(ANGMN)

SECO=0.0138

YSEC=(COS(ANGZ2)/COS(ANGZ1))**2*(0.0075*(CLSC**2)+(COS(ANGZ2)**2)/
1*(COS(ANGMN)**2)+0.035)

PSPTTE=(1.-AMAVE)***(1./%AMM2)

DO 90 I=1,51

AKS=(1.-GAMM1*(VRELS(I)**2))**0.467

AKP=(1.-GAMM1*(VRELP(I)**2))**0.467

AMS=GAMM1*(VRELS(I)**2)

AMP=GAMM1*(VRELP(I)**2)

CALL HM(AMS,HMS(I))

CALL HM(AMP,HMP(I))

TVIS=TMT2P(I)*TVIS

CALL VISCO(TVIS,VIS)

ASON=ACRIT(GAMMA,RGAS,TVIS)

WS(I)=VRELS(I)*ASON

WP(I)=VRELP(I)*ASON

ZS=WS(I)

ZP=WP(I)

RHOS=RHOV(GAMMA, VRELS(I))/VRELS(I)**4*(PMPI/TVIS)**2*RHOZ

RHOP=RHOV(GAMMA, VRELP(I))/VRELP(I)**4*(PMPI/TVIS)**2*RHOZ

ROS(I)=RHOS

ROP(I)=RHOP
CXACT = CHORD * CXLEN(I)
REOS = RHOS * ZS * CXACT / VIS / 12.
REOP = RHOP * ZP * CXACT / VIS / 12.
EXPOS = 1. / (2.6 * (REOS ** (1. / 14.)))
EXPOP = 1. / (2.6 * (REOP ** (1. / 14.)))
IF (REOS .LT. 4000.) EXPOS = 0.212
IF (REOP .LT. 4000.) EXPOP = 0.212
VEXOS = 1. / EXPOS
VEXOP = 1. / EXPOP

FS(I) = (((RHOU(GAMMA, VREL((I)) * (VREL((I))**(1. + HMS((I))))))**1.268)
1 * ((VIS / (RHOS * ZS))**0.268) * AKS) / (10. ** (0.678 * (2. * EXPOS + 1.)))

2 / COS(BETAM(I))
FP(I) = (((RHOU(GAMMA, VREL((I)) * (VREL((I))**(1. + HMP((I))))))**1.268)
1 * ((VIS / (RHOP * ZP)) **0.268) * AKP) / (10. ** (0.678 * (2. * EXPOP + 1.)))

2 / COS(BETAM(I))

BNUS(I) = VIS / RHOS
BNUP(I) = VIS / RHOP
DUDXS(I) = 12. * DUDXS(I) * ASGN * COS(BETAM(I))
DUDXP(I) = 12. * DUDXP(I) * ASGN * COS(BETAM(I))

CONTINUE

92 CHRD(ICHORD) = CHORD
REYN = RHORE * VELRE * SUM * CHORD / (12. * VISRE)
93 RNOSE = TLE / 24.
REZN0 = WS(I) * RNOSE / BNUS(I)
IF (RNOSE .NE. 0.0) THES0 = 0.21 * RNOSE / SGRT(REZNO)
IF (RNOSE .EG. 0.0) THES0 = 0.0
THEPO = THES0
CAMLT = CHORD * SUM
XLEN = 0.02
CFLAM = 1.228 / SGRT(REYN)

INGS = 1
INGP = 1
IFLAGS = 0
IFLAGP = 0
DO 95 I = 2, 51
J = I - 1
IF (IFLAGS .EG. 1) GO TO 96
INGLE = INGS + 1

THESJ = ((VELBL / VREL((I)))**3) * 0.5 * CFLAM * SGRT(SIMPZ(FSL, 0.0, XLEN, J)) * 1
CAMLT + THES0
ZTRUKS = ((THESJ / 12.)**2) / BNUS(I)
FTRUKS = ZTRUKS * DUDXS(I) / CHORD
FLAMS = FIT(FTRUKS)
HLAMS = (0.3 - 1./120. * FLAMS) / (37./315.-1./945.*FLAMS-1./9072.*1

(FLAMS**2))

DELJS = HLAMS * THESJ
BLREYS = WS(I) * DELJS / 12. / BNUS(I)
RECRTS = RECRIT(FLAMS)
IF (BLREYS .GE. RECRTS) IFLAG = 1
IF (IFLAGP .EG. 1) GO TO 95
INGLEP = INGP + 1

THEPJ = ((VELBL / VREL((I)))**3) * 0.5 * CFLAM * SGRT(SIMPZ(FPL, 0.0, XLEN, J)) * 1
CAMLT + THEPO
ZTRUKP = ((THEPJ / 12.)**2) / BNUP(I)
FTRUKP = ZTRUKP * DUDXP(I) / CHORD
FLAMP = FIT(FTRUKP)
HLAMP = (0.3 - 1./120. * FLAMP) / (37./315.-1./945.*FLAMP-1./9072.*1

(FLAMP**2))

DELJP = HLAMP * THEPJ
BLREYP = WS(I) * DELJP / 12. / BNUP(I)
RECRTP = RECRIT(FLAMP)
IF (BLREYP .GE. RECRTP) IFLAGP = 1

CONTINUE

YLEN = CHORD / 600.
SPACE=CHORD/SIGMA*COS(BETAM(51))
NS=52-INGS
NP=52-INGP
IS=NS-1
IP=NP-1
DO 97 I=1,NS
  J=INGS+I-1
  GS(I)=FS(J)
CONTINUE
DO 98 I=1,NP
  J=INGP+I-1
  GP(I)=FP(J)
CONTINUE
THES3=((0.156/((RHOV(GAMMA,VRELS(51)))*(VRELS(51)**(1.+HMS(51))))
  *1.268)*SIMP2(GS,0.0,YLEN,15)+(ROS(INGS)*(WS(INGS)**(2.+HMS(INGS)
  2))/(ROS(51)*(WS(51)**(2.+HMS(51))))*(THE3J/12.))**1.26E**0.7886)
3*12.
THEP3=((0.156/((RHOV(GAMMA,VRELATED(51)))*(VRELATED(51)**(1.+HMP(51))))
  *1.268)*SIMP2(GP,0.0,YLEN,IP)+(ROP(INGP)*(WP(INGP)**(2.+HMP(INGP)
  2))/(ROP(51)*(WP(51)**(2.+HMP(51))))*(THE3J/12.))**1.268)**0.78E6)
3*12.
TSTAR=(THES3+THEP3)/SPACE
DELS3=HFAVE*THES3
IF(IFLAGS.EQ.0)DELS3=DELSJ
DELP3=HFAVE*THEP3
IF(IFLAGS.EQ.0)DELP3=DELPJ
DSTAR=(DELS3+DELP3)/SPACE
DTE(1)=TETS/SPACE
DTE(2)=TETR/SPACE
AFS1=GAMM1*(WCRM(51)**2)
BLK1=1.0-DSTAR-DTE(IBLD)-TSTAR
BLK2=1.0-DSTAR-DTE(IBLD)
CSTW1=((1.-AFS1)*((GAMMA+1.)/(2.*GAMMA))+Bt-OKI*((I.iCRM(51)*
  iCOS(BETAM(51)))**2))/(BLOKZ*WCRM(51)*C0S(SETAM(51)))
CSTW3=GAMMA*CSTW1/(GAMMA+1.)-SGRT(((GAMMA*CSTW1/(GAMMA+i.))**2)-1.0+
  1GAMM1*(DSTW**2))
RHI=(1.-GAMM1*(WXMIX**2+DSTW**2))**GAMM3
PLOSS(IBLD)=BLOK2*RHOV(GAMMA,wCRM(51))*COS(BETAM(51))/(RHI**
  1WXMIX)
SPLOSS=PLOSS(IBLD)
YPRO(IBLD)=(1.-PLOSS(IBLD))/(PLOSS(IBLD)*(1.-PSPTTE))
YSF(IBLD)=YSEC*CHORD/HEIGHT
YTOT(IBLD)=YPRO(IBLD)+YSF(IBLD)
PLOSS(IBLD)=1.0/(1.0+YTOT(IBLD)*(1.-PSPTTE))
IF(ITRIG.EQ.1)GO TO 94
YTOTL(ICHORD)=YTOT(IBLD)
IF(ICHORD.LE.2)GO TO 400
IF(YTOTL(ICHORD).GT.YTOTL(ICHORD-1).AND.YTOTL(ICHORD-1).GT.
  YTOTL(ICHORD-2))GO TO 91
ICHORD=ICHORD+1
ICHORD=CHORD+0.02
IF(ICHORD.GT.CHMAX)GO TO 91
IF(TTE.EQ.0.0)GO TO 92
GO TO 500
MINMUM=ICHORD-2
CHORD=CHRD(MINMUM)
ITRIG=1
KZW=1
IF(TTE.EQ.0.0)GO TO 92
GO TO 500
CONTINUE
TRANS=CXLEN(INGS)*CHORD/CAMLT*100.
TRAN=CXLEN(INGP)*CHORD/CAMLT*100.
ALPHA=RIN*(R3STR-1.)/CHORD
DO 70 N=2,51
KN=0
NN=N-1
TO=THETA(NN)
R(N)=RIN*RMSTR(N)
BE=BETAM(NN)
IF(BE.EQ.0.) BE=0.000001
RHS1=R(NN)*THETA(NN)+(TAN(BE)+TO*ALPHA)*0.02*CHORD
TO=RHS1/R(N)
RHS2=R(NN)*THETA(NN)+(TAN(BE)+TO*ALPHA)*0.02*CHORD
IF(ABS(RHS2-RHS1)/R(N)<0.00002) 71,71,72
72 KN=KN+1
IF(KN>100) 73,73,74
73 RHS1=RHS2
GO TO 75
74 IF(IPRINT.EQ.1) WRITE(6,2118)
75 THETA(N)=R(NN)*THETA(N)/CHORD
THIKR(N)=R(NN)*THETA(N)/2.
THIKL(N)=R(NN)*THETA(N)-THIK(N)/2.
CONTINUE
PITCH=1./SIGMA
DISTAN=ABS(RTHET(51))
STAGR=ATAN(DISTAN)
STAGR=STAGR*180./3.14159
CAMLTH=CHORD*SUM
ZNUM=2.*3.14159*RIN*SIGMA/CHORD
NUMBER=2.*ZNUM
IF(IPRINT.EQ.1) WRITE(6,2115)
101 T3IT=TMT2(51)*TIP
ANIT=BETAM(51)*180./3.14159
IF(IBLD.EQ.2) GO TO 102
IF(IPRINT.EQ.1) WRITE(6,2117)T3IT,TIP,VUCRM(51),VUCRO,ANIT,ANACT,
1SIGMA,SOLID,TCAL,TETR
GO TO 103
102 IF(IPRINT.EQ.1) WRITE(6,2117)T3IT,T3P,VUCRM(51),VUCRO,ANIT,ANACT,
1SIGMA,SOLID,TCAL,TETR
103 CONTINUE
IF(IPRINT.EQ.1) WRITE(6,2100)
IF(IBLD.EQ.2) GO TO 80
IF(IPRINT.EQ.1) WRITE(6,2119)
GO TO 81
80 IF(IPRINT.EQ.1) WRITE(6,2120)
81 IF(IPRINT.EQ.1) WRITE(6,2121)
DO 82 I=1,51,5
82 IF(IPRINT.EQ.1) WRITE(6,2122)AM(I),R(I),RTHET(I),THIKR(I),THIKL(I)
CONTINUE
IF(IPRINT.EQ.1) WRITE(6,2123)
IF(IPRINT.EQ.1) WRITE(6,2124)CHORD,SIGMA,CAMLTH,STAGR,NUMBER
IF(IBLD.EQ.2) GO TO 110
IF(IPRINT.EQ.1) WRITE(6,2125)
GO TO 111
110 IF(IPRINT.EQ.1) WRITE(6,2126)
111 IF(IPRINT.EQ.1) WRITE(6,2127)
VMIX=SQRT(WXMI**2+DSTW**2)
DSTN=ABS(DSTW)
IF(IPRINT.EQ.1) WRITE(6,2128)TSTAR,DSTAR,VMIX,SPLOSS
IF(IPRINT.EQ.1) WRITE(6,2144)YPRO(IBLD),YSF(IBLD),YTOT(IBLD),REYN
IF(IBLD.EQ.2) TRNS,TRANP
IF(IPRINT.EQ.1) WRITE(6,2100)
IBLD=IBLD+1
IF(IBLD.LT.3) GO TO 20
ETATT=1./(1.0+(T3P/(TIP-T3P)*(1.0-((PLOSS(1)*PLOSS(2))**GAMM2))))
IF(IPRINT.EQ.1) WRITE(6,2099)
IF(IPRINT.EQ.1) WRITE(6,2132)
IF(IPRINT.EQ.1) WRITE(6,2133) ETATT
VX3C=VX3*ACR3
VX2C=VZ*ACR1*COS(ALP2)
VUM3C=VUMK3
UM3C=U3
VUM2C=VUMK2
UM2C=U2
R3C=1.+H3/(2.*RM3)
R2C=1.+H2/(2.*RM2)
R3CI=1./R3C
R2CI=1./R2C
REACT=(VX3C**2+(R3CI*VUM3C—R3C*UM3C)**2—VX2C**2—(R2C.*VUM2C—R2C*UM2C)**2)/(VX3C**2+(R3CI*VUM3C—R3C*UM3C)**2+2.*UM2C*VUM2C—(R2C*UM2C)**2)
HROTOR=(H2+H3)*6.
ETATTM= ETATT*(1.—CLEAR/HROTOR*(2.755*(REACT**2)+0.105*REACTC+11.72))
DELETA=ETATTM-ETATT
IF(IPRINT.EQ.1) WRITE(6,2145)DELETA,ETATTM
PTTEX=P1P*((l.—(1.—T3P/T1P)**GAMM2)/**(1./GAMM2))
PSTEX=PTTEX*((1.—GAMM1*(VX3**2))**(1./GAMM2))
PXTEX=PSTEX/**(1.—GAMM1*(VX3**2))**(1./GAMM2))
ETATX=(ETA*(1.—(PTTEX/PIP)**GAMM2)/(1.—(PSTEX/P1P)**GAMM2))+DELETA
ETATST=(ETA*(1.—(PTTEX/PIP)**GAMM2)/(1.—(PSTEX/P1P)**GAMM2))
1DELETA
IF(IPRINT.EQ.1) WRITE(6,2220) ETA,ST,ETATX
IF(DSTRES.NE.0.0) GO TO 600
HUBR=(RM3—H3/2.)*12.
TIPR=(RM3+H3/2.)*12.
REARA=3.14159*(TIPR**2—HUBR**2)
CALL SDISK(HUBR,TIPR,CHORD,RHO,ROD,ROA,T,B,P,SIGMA,REARA,ISTRES,STRESS)
IF(IPRINT.EQ.1) WRITE(6,2241)STRESS,STRESS
SEFFY(NPASS)=ETATST
PCHEK=ABS(ETATT-ETA)
IF(PCHEK.LE.0.002.AND.DSTRES.EQ.0.0) IPRINT=1
IF(PCHEK.EQ.0.002.AND.BEST.GT.0.0) IPRINT=1
IF(NPASS.EQ.1) GO TO 150
DETA=ABS(SEFFY(NPASS)-SEFFY(NPASS-1))
IF(DETA.LE.0.002) GO TO 142
IF(NPASS.GT.6) GOTO 141
140 NPASS=NPASS+1
ETA=ETATT
P2P=PLOSS(1)*P1P
PLOS1=PLOSS(1)
PLOS2=PLOSS(2)*(T2PP**(1./GAMM2))
P2PP=PLOS2
IF(DSTRES.NE.0.0) GO TO 180
GO TO 10
141 WRITE(6,2134)
142 CONTINUE
IF(BEST.GT.0.0)WRITE(6,2234)DSTRES,STRESS,STRESS
IF(IPRINT.EQ.1)WRITE(6,2142)NPASS
IF(DSTRES.EQ.0.0) GO TO 4000
IF(BEST.GT.0.0) GO TO 4000
KPASS=KPASS+1
EDAIA8(KPASS)=1.—ETATTM
DPSI(KPASS)=STRESS
UHUBC=UT3*RH3/RT3
IF(KPASS.EQ.1)WRITE(6,2100)
IF(KPASS.EQ.1)WRITE(6,2230)
IF(KPASS.EQ.1)WRITE(6,2244)
IF(KPASS.EQ.1)WRITE(6,2231)
WRITE(6,2232)KPASS,ETATTM,ETATST,STRESS,STRESS,1BLIFE
IF (VZ.GE.1.0) WRITE (6, 2237) KPASS
IF (NPP3.GE.1.0) WRITE (6, 2232) KPASS
IF (KPASS.LE.20) GO TO 190
K = 0
DO 450 I = 1, 21
IF (DPSI(I).GT.DSTRES) GO TO 450
K = K + I
FADIAS(K) = EADIAS(I)
RADEXX(K) = RADEX(I)
450 CONTINUE
IF (K.EQ.0) GO TO 460
WRITE (6, 2236) K
IF (K.EQ.1) MINE7A = K
IF (K.GT.1) CALL SMALST (FADIAS, K, MINETA)
RSEST = RADEXX (MINETA)
KPASS = 0
GO TO 190
460 WRITE (6, 2235)
GO TO 4000
1000 FORMAT (7F10.3)
1001 FORMAT (6F10.3, I1)
1002 FORMAT (3F10.3)
2097 FORMAT (///)
2098 FORMAT (///56X, 11H FLOW ANGLES/56X, 11H----------)
2099 FORMAT (////////)
2100 FORMAT (1H1)
2101 FORMAT (50X, 24H PROGRAM INPUT PARAMETERS/50X, 24H------------------)
2102 FORMAT (EX, SGAMMA, 6X, 4HRGAS, 6X, 1HRGAS SPEED, 6X, 1H Mass FLOW RATE
1, 6X, 13TURBINE INLET, 6X, 13TURBINE INLET, 6X, 13H WORK REQUIRED/32X,
25HRPM, 12X, 2H(LB-SEC), 9X, 14H PRESSURE (PSI), 5X, 14T TEMPERATURE, R,
38X, 8H (BTU/LS)/)
13 FORMAT (7X, F6.3, 4X, F7.3, 7X, F7.1, 12X, F7.3, 12X, F7.1, 12X, F7.3)
2104 FORMAT (///2X, 12H STATOR INLET, 2X, 11H Rotor SPEED, 6X, 14H MAss FLOW RATE
1, 6X, 13TURBINE INLET, 6X, 13TURBINE INLET, 6X, 13H WORK REQUIRED/32X,
25HRPM, 12X, 2H(LB-SEC), 9X, 14H PRESSURE (PSI), 5X, 14T TEMPERATURE, R,
38X, 8H (BTU/LS)/)
2105 FORMAT (5X, F6.3, 8X, F6.3, 6X, F6.3, 7X, F7.3, 6X, F7.3, 6X, F6.3, 6X,
1F6.3, 9X, F6.3)
2106 FORMAT (///40X, 46H COMPUTED FLOW PARAMETERS AND VELOCITY DIAGRAMS/
140X, 46H----------------------)
2107 FORMAT (22X, 6H STATOR, 60X, 5H Rotor/22X, 6H----------, 60X, 5H----------/2X,
150H STATOR INLET CRITICAL VELOCITY RATIO, V/VCR .........., F7.3, 5X,
250H Rotor EXIT AXIAL CRITICAL VELOCITY RATIO, VX/VCR ......., F7.3, 5X,
350H STATOR INLET SWIRL VELOCITY RATIO, VU/VCR .........., F7.3, 5X,
450H Rotor EXIT SWIRL VELOCITY RATIO, VU/VCR .........., F7.3, 5X,
550H STATOR EXIT CRITICAL VELOCITY RATIO, V/VCR .........., F7.3, 5X,
650H Rotor EXIT CRITICAL VELOCITY RATIO, V/VCR .........., F7.3, 5X,
750H STATOR EXIT AXIAL VELOCITY RATIO, VX/VCR .........., F7.3, 5X,
850H Rotor EXIT RELATIVE VELOCITY RATIO, W/VCR .........., F7.3, 5X)
2108 FORMAT (2X, 50H STATOR EXIT SWIRL VELOCITY RATIO, VU/VCR .........., F7.3,
2/2X, 49H STATOR EXIT RELATIVE VELOCITY RATIO, W/WCR .........., F7.3,
35X, 50H Rotor EXIT BLADE SPEED RATIO, U/VCR .........., F7.3, 5X,
450H STATOR ABSOLUTE TOTAL PRESSURE LOSS RATIO .........., F7.3, 5X,
550H Rotor EXIT BLADE SPEED RATIO, U/VCR .........., F7.3, 5X,
650H Rotor ABSOLUTE TOTAL PRESSURE LOSS RATIO .........., F7.3, 5X,
749H Rotor EXIT ABSOLUTE TOTAL PRESSURE .........., F6.3, 46X,
849H Rotor EXIT ABSOLUTE TOTAL TEMPERATURE .........., F6.1, 64X,
949H Rotor TIP SPEED (FT PER SEC) .........., F8.1)
2109 FORMAT (///59X, 59STAGE/59X, 5H----------/37X, 49H Rotor EXIT HUB RADIUS (I
1INCHES) ................., F7.3/37X, 49H Rotor EXIT TIP RADIUS (INCHES)
2142 FORMAT(///41X,37HEFFICIENCY ITERATION CONVERGED AFTER 12,17H PASSES)
2143 FORMAT(/27X,75HNOTE ... BASIC LOADING DISTRIBUTION COULD NOT SAT
1IF SOLIDITY REQUIREMENT/27X.56HFOR OPTIMUM ZWEIFEL COEFFICIENT ..
2. ZWEIFEL CHANGED TO F5.2)
2144 FORMAT(/46X,33HCASCADE LOSS COEFFICIENTS ***//40X,24HPROFILE L
OSS COEFFICIENT,15X,F6.4/40X,31HSECONDARY FLOW LOSS COEFFICIENT,EX
2. F6.4//40X,30HTOTAL CASCADE LOSS COEFFICIENT,9X.F6.4//29X.59HNOTE
3. CASCADE GEOMETRY OPTIMIZED AT REYNOLDS NUMBER = 6.92)
2145 FORMAT(/35X,52HSTAGE EFFICIENCY DECREMENT FOR ROTOR CLEARANCE ... 1
,5X,F6.3//35X,52HFINAL STAGE TOTAL-TOTAL EFFICIENCY ........................
2. ,F6.4)
2146 FORMAT(37X.45HSTAGE WORK COEFFICIENT BASED ON MEAN RADIUS ..F7.3//
127X.45HSTAGE WORK COEFFICIENT BASED ON HUB RADIUS ... F7.3//37X.
245HTURBINE TOTAL-TOTAL PRESSURE RATIO ..................F7.3//)
2200 FORMAT(/10X,87H** WARNING ** INPUT STATOR EXIT ANGLE IS TOO L
1ARGE TO SATISFY CONTINUITY REQUIREMENTS//26X.17HANGLE CHANGED TO ,
2F6.2,1X.7DEGREES)
2201 FORMAT(/1/9X,12HSTATOR INLET,6X,11HSTATOR EXIT,6X,14HSTATOR Z
WEIFEL,6X,12HRotor ZWEIFEL,6X,12HSTATOR CHORD,6X,11HRotor CHORD/10
*0X, 210MFLOW ANGLE,7X,10MFLOW ANGLE,8X,11HCoefficient,9X,11HCoefficient
3.9X,8H(INCHES),9X,8H(INCHES)/)
2203 FORMAT(/45X,22HPROGRAM DEFAULT VALUES//31X.54HSTATOR EXIT F
low ANGLE .......... CALCULATED FROM WORK/65X,1HANDB FLOW CONDITIONS/
231X.37HSTATOR ZWEIFEL COEFFICIENT ......... 0.3 //31X.37HRotor ZWEIF
EL COEFFICIENT .......... 0.3//31X.54HSTATOR CHORD/4. Optimized ON MINIMUM/65X.24HCASCADE LOSS COEFFICIENT/7X.54HRot
SOR CHORD .................. OPTIMIZED ON MINIMUM/65X.24HCASCADE
6 LOSS COEFFICIENT)
2204 FORMAT(/10X,11HSTATOR L.E.,8X,10HRotor L.E.,8X,9HALLOWABLE,8X,
11HROTOR EXIT,6X,17HBLADE PLOT OPTION,8X,10HRotor EXIT/11X,9HTHICK
NESS,9X,9HTHICKNESS,8X,11HDISK STRESS,7X,10HAXIAL MACH,12X,11HO =
3NO PLOT,10X,11HSWIRL ANGLE/12X,8H(INCHES),10X,8H(INCHES),11X,5H(PS
4I),12X,6HNUMBER,14X,8H = PLOT///13X,F5.3,13X,F5.3,12X,F7.0,11X,
5F5.3,19X,11,18X,F6.2/)
2210 FORMAT(/23X,65HNOTE .... MAXIMUM ALLOWABLE STATOR ANGLE FOR INPUT
1 CONDITIONS IS F5.2,3H DEGREES)
2220 FORMAT(/35X,52HFINAL STAGE TOTAL-STATIC EFFICIENCY ....................
1...F6.4//35X,52HFINAL STAGE RATING EFFICIENCY ............................
2. ,F6.4)
2221 FORMAT(/8X, ' NOTE ..... PREDICTED SUCTION SURFACE BOUNDARY LAYER
1 TRANSITION AT ,F5.1, ' PERCENT OF CAMBER LENGTH'17X, ' PREDICTED
2PRESSURE SURFACE BOUNDARY LAYER TRANSITION AT ,F4.1, ' PERCENT OF
3CAMBER LENGTH')
2230 FORMAT(/15X.85HTHE FOLLOWING IS A LIST OF POSSIBLE CONFIGURATIONS
1 FOR THE INPUT CONDITIONS SPECIFIED/15X,85H-------------------------------
2---------------------------------------------------------------//
2231 FORMAT(2X,4PASS,3X,7HETA T-T,3X,7HETA T-S,3X,5HUB HUB,3X,5HUB TIP,
13X,10HRotor EXIT,3X,17HBLADE PLOT OPTION,8X,10HRotor EXIT,11X,11HDISK ST
RESS,3X,10HRotor LIFE/29X,5H(PSI),3X,5H(PSI),3X,10HUB RADIUS,3X,1
1HTIP RADIUS,6X,
35H(PSI),10X,5H(PSI),7X,7H(HOURS)/46X,6H(INCHES),5X,6H(INCHES)//)
2232 FORMAT(' X,12.4X,F6.4,4X,F6.4,4X,F5.0,5X,F6.3,5X,F6.3,2X,
1F7.0,7X,F7.0,3X,E10.4)
2233 FORMAT(/55X,10HSWIRL THE FOLLOWING IS AN AERODYNAMICALLY OPTIMIZED ST
AGE CHOSEN FROM THE POSSIBLE FLOWPATH CONFIGURATIONS ABOVE//)
2234 FORMAT(/55X,11HSWIRL STRESS DATA/55X,1H------------------------------//
35X,45HALLOWABLE
1AVERAGE DISK STRESS (INPUT) ............ F8.0,4H PSI//35X,45HCOMPUTED A
2VERAGE DISK STRESS ................. F8.0,4H PSI//53X,45HCOMPUTED R
3OHT BLADE STRESS ................. F8.0,4H PSI//)
2235 FORMAT(/20X,82HWARNING ** NO SOLUTION WHICH SATISFIES THE SPECIF
TED DISK STRESS HAS BEEN FOUND **/**

2236 FORMAT(2)**X,3**H NOTE ... OF 21 SOLUTIONS OBTAINED, 13.55% ARE (IS)
WITHIN THE RANGE OF THE SPECIFIED DISK STRESS/**

2237 FORMAT(O**X,3**H NOTE ... PROGRAM PREDICTS STATOR (MEANLINE) CHOKING
1G FOR THE CONDITIONS OF PASS, 12/**

2238 FORMAT(O**X,3**H NOTE ... PROGRAM PREDICTS ROTOR (MEANLINE) CHOKING
1G FOR THE CONDITIONS OF PASS, 12/**

2239 FORMAT(2)**X,7 CONTINUITY CANNOT BE SATISFIED AT THE STATOR EXIT
FOR THE CONDITIONS SPECIFIED ... SOLUTION TERMINATION

2240 FORMAT(2)**X,3**H NOTE ......... PROGRAM PREDICTS STATOR (MEANLINE) CHOKING
FOR THE CONDITIONS OF PASS, 12/**

2241 FORMAT(2)**X,3**H NOTE ......... PROGRAM PREDICTS ROTOR (MEANLINE) CHOKING
FOR THE CONDITIONS OF PASS, 12/**

2242 FORMAT(2)**X,3**H NOTE ON FLOW ANGLE INPUT ........../25X,79H(1) STATOR
EXIT FLOW ANGLE AND ROTOR EXIT SWIRL CANNOT BE SIMULTANEOUSLY
INPUT; 25X,52H IF BOTH ARE INPUT, ONLY THE ROTOR EXIT SWIRL IS USE
3D..//25X,82H(2) IF NEITHER ANGLE IS INPUT, STATOR EXIT ANGLE IS CAL
4CULATED ASSUMING ZERO ROTOR/29X,10H EXIT SWIRL//25X,64H(3) IF STATO
5R EXIT ANGLE IS INPUT, SET ROTOR SWIRL = ZERO (SWIRL WILL BE CALCUL
6ATED)//

2243 FORMAT(2)**X,96H ADDITIONAL NOTE ..... IF FLOWPATH GEOMETRY IS INPUT
IT, ALLOWABLE DISK STRESS MUST BE INPUT AS ZERO/95X,4H----/**

2244 FORMAT(2)**X,72H EACH CONFIGURATION IS CONSTRAINED BY THE FOLLOWING
16 (CONSTANT) PARAMETERS://25X,3**H RPM/25X,9H MASS FLOW/25X,4**H TURBINE
2 INLET TOTAL TEMPERATURE AND PRESSURE/25X,16H WORK REQUIREMENT/25X,
4XIT SWIRL//25X,37H STATOR AND ROTOR ZWIFEL COEFFICIENTS/**

2245 FORMAT(2)**X,36H DISK MATERIAL, SX, 14H BLADE MATERIAL, SX, 17H DISK R
1IM MATERIAL/34X,17H DENSITY (LBS/FT3), SX, 17H DENSITY (LBS/FT3), SX,
217H DENSITY (LBS/FT3)///40X, F5.1, 16X, F5.1, 19X, F5.1/**

STOP
END

SUBROUTINE RCHOKE(VU3, VX3, G, R, T1, CON, UCHOKE)

DIMENSION ALS(2), ARS(2), DIF1(2), DIF2(2)

ACR = ACRIT(G, R, T1)
A = 100.
S = 100.
DEL = 100.
K = 0

ALS(1) = S
K = K + 1
IF(K .GE. 100) GO TO 1400
VU2 = CON/S + VU3

T2PP = Ti1*(1 - (G - 1)/((S/ACR)*2)*(2.0*(VU2/ACR)/(S/ACR) - 1.0))

ACR3 = ACRIT(G, R, T2PP)

ARS(1) = VU3 + SQR((ACR3**2 - VX3**2)
S = S - DEL

ALS(2) = S
VU2 = CON/S + VX3

T2PP = Ti1*(1 - (G - 1)/((S/ACR)*2)*(2.0*(VU2/ACR)/(S/ACR) - 1.0))
ACR3 = ACRIT(G, R, T2PP)

ARS(2) = VU3 + SQR((ACR3**2 - VX3**2)

DIF1(1) = ABS(ALS(1) - ARS(1))
DIF1(2) = ABS(ALS(2) - ARS(2))
DIF2(1) = ABS(ALS(1) - ARS(1))
DIF2(2) = ABS(ALS(2) - ARS(2))

IF(DIF1(1) .LE. SS) GO TO 1000
IF(DIF1(2) .LE. SS) GO TO 10001
G = DIF2(1) + DIF2(2)
IF(G .LT. 0.0) GO TO 200
IF(DIF1(2) .GE. DIF1(1)) GO TO 100
S=S+A*1.0
GO TO 20

200  DEL=DEL/2.
A=A/2.
GO TO 20

100  DEL=-DEL
A=-A
GO TO 20

1000  UCHOKE=ALS(1)
GO TO 1200

1001  UCHOKE=ALS(2)
GO TO 1200

1400  UCHOKE=ALS(1)
WRITE(*,1100)

1100  FORMAT(/72H*** ROTOR CHoke ITERATION LOOP NOT SATISFIED   COMPUTA-
1TION CONTINUES ***/)

1200  CONTINUE
RETURN
END

SUBROUTINE DIST(VIN,VOUT,DS,X,VSUC,VPRES,DUSUC,DUPRES,EXTRM,
1VRATIO)

REACT=1.-VIN/VOUT**2
REAC=1.-VIN/VOUT
G=X-0.5
ALMAX=0.5+EXTRM*REACT
VMAX=VOUT/(1.-DS)
IF(DS.LT.0.0) GO TO 100
VCL=VOUT*((REAC/2.)*(SIN(3.14159*G)-1.)+1.)
IF(X.GT.ALMAX) GO TO 10
VSUC=(VIN-VMAX)*((X/ALMAX)**2)-2.*(VIN-VMAX)*(X/ALMAX)+VIN
DUSUC=2.*X/(ALMAX**2)*(VIN-VMAX)-2.*(VIN-VMAX)/ALMAX
GO TO 20
10  VSUC=VOUT+(VOUT-VMAX)/((ALMAX-1.)**2)*(X**2-2.*ALMAX*(X-1.)-1.)
DUSUC=(VOUT-VMAX)/((ALMAX-1.)**2)*(2.*X-2.*ALMAX)
20  VPRES=VCL-VRATIO*(VSUC-VCL)
DUPRES=3.14159*VOUT*(VRATIO+1.)/2.*REAC*COS(3.14159*G)-VRATIO*
1DUSUC
GO TO 40

100  VCL=(VOUT-VIN)*X+VIN
A1=(VMAX-VOUT)/(ALMAX*(ALMAX-1.))-(VOUT-VIN)/ALMAX
A2=(VOUT-VIN)/(ALMAX+1.)/ALMAX-(VMAX-VOUT)/(ALMAX*(ALMAX-1.))
VSUC=A1*X*X+A2*X+VIN
DUSUC=2.*A1*X+A2
VPRES=2.*VCL-VSUC
DUPRES=2.*(VOUT-VIN)-DUSUC
40  RETURN
END

SUBROUTINE DRANGE(G,VIN,VOUT,EXTRM,DSTART,DCHNGE)

REACT=1.-VIN/VOUT**2
XMAX=0.5+EXTRM*REACT
VMIN=(VOUT-VIN)*XMAX+VIN+0.01
VMAX=SQRT((G+1.)/(G-1.))-0.01
D1=1.-VOUT/VMAX
D2=1.-VOUT/VMIN
DCHNGE=ABS((D1-D2)/10.)
DSTART=(ABS(D1-D2))*0.3+D2
RETURN
END

FUNCTION VELIT(W,T,G1,G2,ALP,AREA ,P,RHO,ACR)

DIMENSION ALS(2),ARS(2),DIF1(2),DIF2(2)
CONST=W*SQRT(T/518.7)/(COS(ALP)*AREA/144.)*(P/14.696)*RHO*ACR)
A=0.1
S=0.5
DEL=0.1
K=0

20  ALS(1)=5
K=K+1
IF(K.GE.100) GO TO 1400
ARS(1)=CONST*((1.-G1*(S**2.))*G2)
ALS(2)=S+DEL
ARS(2)=CONST/((1.-G1*((S+DEL)**2.))*G2)
DIF1(1)=ABS(ALS(1)-ARS(1))
DIF1(2)=ABS(ALS(2)-ARS(2))
DIF2(1)=ALS(1)-ARS(1)
DIF2(2)=ALS(2)-ARS(2)
IF(DIF1(1).LE.0.001) GO TO 1000
IF(DIF1(2).LE.0.001) GO TO 1001
G=DIF2(1)+DIF2(2)
IF(G.LT.0.0) GO TO 200
IF(DIF1(2).GT.DIF1(1)) GO TO 100
S=S+A*1.0
GO TO 20
200 DEL=DEL/2.
A=A/2.
GO TO 20
100 DEL=-DEL
A=-A
GO TO 20
1000 VELIT=ALS(1)
GO TO 1200
1001 VELIT=ALS(2)
GO TO 1200
1400 VELIT=ALS(1)
WRITE(6,1100)
1100 FORMAT(/**/E1H** BLADE EXIT VELOCITY ITERATION LOOP NOT SATISFIED
1     COMPUTATION CONTINUES ***/)
1200 CONTINUE
RETURN
END
SUBROUTINE VNEG(VIN, VOUT, EXTRM, DS, RATIO)
DIMENSION ALS(2), ARS(2), DIF1(2), DIF2(2)
IF(DS.LT.0.0) GO TO 1500
REACT=1.-VIN/VOUT)**2
REAC=1.-VIN/VOUT
ALMAX=0.5+EXTRM*REACT
VMAX=VOUT/(1.-DS)
CONST=3.14159*(ALMAX**2)*VOUT*REAC/(2.*(VIN-VMAX))
A=0.1
E=0.001
DEL=0.1
K=0
20 ALS(1)=S
K=K+1
IF(K.GE.100) GO TO 1400
ARS(1)=CONST+COS(3.14159*(S-0.5))+ALMAX
ALS(2)=S+DEL
ARS(2)=CONST+COS(3.14159*(S+DEL-0.5))+ALMAX
DIF1(1)=ABS(ALS(1)-ARS(1))
DIF1(2)=ABS(ALS(2)-ARS(2))
DIF2(1)=ALS(1)-ARS(1)
DIF2(2)=ALS(2)-ARS(2)
IF(DIF1(1).LE.0.001) GO TO 1000
IF(DIF1(2).LE.0.001) GO TO 1001
G=DIF2(1)+DIF2(2)
IF(G.LT.0.0) GO TO 200
IF(DIF1(2).GT.DIF1(1)) GO TO 100
S=S+A*1.0
GO TO 20
200 DEL=DEL/2.
A=A/2.
GO TO 20
100 DEL=-DEL
A=-A
GO TO 20
A = -A
GO TO 20
1000 XMIN=ALS(1)
GO TO 1200
1001 XMIN=ALS(2)
GO TO 1200
1400 XMIN=ALS(1)
WRITE(6,1100)
1100 FORMAT('///%1H*** BLADE PRESSURE SURFACE LOADING ITERATION LOOP NOT SATISFIED COMPUTATION CONTINUES ***///)
1200 VCL=VOUT*((REAC/2.)*(SIN(3.14159*(XMIN-0.5))-1.)+1.)
VSUC=(VIN-VMAX)*((XMIN/ALMAX)**2)-2.*(VIN-VMAX)*(XMIN/ALMAX)+VIN
VPRES=2.*VCL-VSUC
IF(VPRES.GT.0.0) GO TO 1500
RATIO=(VCL-0.01)/(VCL-VPRES)
GO TO 1600
1500 RATIO=1.0
1600 RETURN
END
SUBROUTINE ALIFE(BS,TEM,TIME)
DIMENSION S(13),X(13)
C DATA IS FOR IN-100 MATERIAL
DATA S/10600.,13500.,17000.,21700.,27000.,32500.,38500.,45000.,
151500.,58500.,66000.,74000.,84000./
DATA X/52.,51.,50.,49.,48.,47.,46.,45.,44.,43.,42.,41.,40./
IF(BS.LE.10600.) GO TO 10
IF(BS.GE.84000.) GO TO 20
K=1
KK=2
40 IF(BS.GE.S(K).AND.BS.LE.S(KK)) GO TO 30
K=K+1
KK=KK+1
GO TO 40
10 PARAM=(52.-51.)/(10600.-13500.)*(BS-13500.)+51.
GO TO 50
20 PARAM=(40.-41.)/(84000.-74000.)*(BS-74000.)+41.
GO TO 50
30 PARAM=(X(KK)-X(K))/(S(KK)-S(K))*(BS-S(K))+X(K)
50 Q=1000.*PARAM/TEM
IF(G.GE.30.) TIME=10.**10
IF(G.LT.30.) TIME=10.**G-20.
RETURN
END
FUNCTION SIMP2 (F,A,DELX,N)
C INTEGRATION OF TABULAR FUNCTION F, BY SIMPSON'S RULE, WHERE
C A=LOWER LIMIT, DELX=LENGTH OF SUBINTERVAL, N=NUMBER OF SUBINTERVAL
C IF N IS LESS THAN 2, SIMP2 IS SET TO 0
C N_MAY BE ODD OR EVEN
DIMENSION F(51)
23 IF(N-2)
14,17,17
14 SIMP2=0.0
RETURN
17 IF((N/2)**2-N) 11,12,14
12 K=N/2
ASSIGN 19 TO M
GO TO 13
11 K=(N-1)/2
ASSIGN 18 TO M
13 SUMA=0.0
DO 15 J=1,K
15 SUMA=SUMA+F(2*J)
SUMB=SUMB=0.0
22 IF(K-1) 14,20,21
21 DO 16 J=2,K
16 SUMB=SUMB+F(2*J-1)
20 \text{SIMP2}=1.3333333*\text{SUMA}+.66666667*\text{SUMB}+.33333333*\text{F(Z+K+1)}+.33333333*\text{F(Z+K+2)}+1.08333333*\text{F(Z+K)}
\text{GO TO M (19,18)}
18 \text{SIMP2=SIMP2+DELX*(4.16666667*F(Z+K+2)+.66666667*F(Z+K+1)}
1-.08333333*F(Z+K))
19 \text{RETURN}
\text{END}
\text{SUBROUTINE VISCO(T,V)}
\text{C1=1.264E-5}
\text{C2=0.600}
\text{TREF=492.}
\text{V=C1*((T/TREF)**C2)}
\text{RETURN}
\text{END}
\text{SUBROUTINE HM(AJ,FGRM)}
\text{P=1./7.}
\text{TOPSUM=0.0}
\text{BOTSUM=0.0}
\text{DO 10 J=1,10}
\text{G=J-1}
\text{TOPSUM=TOPSUM+(((2.*G+1.)*(AJ**G))/((2.*G+1.)*P+1.))}
\text{BOTSUM=BOTSUM+((AJ#*G)/(((2.*G+1.)*P+1.)*(2.*(G+1.)*P+1.)))}
10 \text{CONTINUE}
\text{FORM=TOPSUM/BOTSUM}
\text{RETURN}
\text{END}
\text{SUBROUTINE SDISK(RH,RT,CX,RH08,RHOA,S,SOL,A,STRESD,STRESS)}
\text{RH=RH/12.}
\text{RT=RT/12.}
\text{CX=CX/12.}
\text{A=A/144.}
\text{STRESS=(2.51E-7)*RHOB*A*(S**2)}
\text{STRESB=1.2*STRESS}
\text{DELRA=0.5*CX}
\text{BO=0.75*CX}
\text{PHI=0.1745}
\text{RM=(RH+RT)/2.}
\text{Z=2.*3.14159*RMS*L/S/CX}
\text{RD=RH-DELRA}
\text{BI=BO+2.*RD*TAN(PHI)}
\text{SIG1=(3.942E-7)*RHOA*((S*RD)**2)*(BI/BO+3.)/(BI/BO+1.)}
\text{TBAR=0.1*CX}
\text{ABLD=TBAR*CX}
\text{FB=STRESS/1.2*ABLD/144.}
\text{RCG=RD+DELRA*(BO+2.*CX)/(3.+(BO+CX))}
\text{VA=3.14159*RCG*(CX+BO)*DELRA}
\text{FA=RHOA/((Z*32.174)*((2.*3.14159*S/60.0)**2)*VA*RCG}
\text{FT=FA+FB}
\text{SIG2=FT/(3.14159*60.0*(BI/BO+1.))}
\text{SIG2=SIG2/144.}
\text{STRESD=SIG1+S.G2}
\text{RH=RH/12.}
\text{RT=RT/12.}
\text{CX=CX/12.}
\text{A=A/144.}
\text{RETURN}
\text{END}
\text{SUBROUTINE BLOCK(G,T,Z,BETAI,VI,BETA0,V0)}
\text{DIMENSION DIF1(2),DIF2(2),ANGLE(2),VCR1(2),SS(2)}
\text{G1=G-1.}
\text{G2=G+1.}
\text{RAD=3.14159/180.}
\text{TARGT=BETAI}
\text{A=RAD}
\text{S=BETAI-5.*RAD}
\text{DEL=RAD}
K=0

DO 15 I=1,2
SS(I)=S
VACR1=ABS(VI/SIN(S))
VCR1(I)=VACR1
IFS1=G1/G2*(VACR1**2)
VXCR1=VACR1*COS(S):

C=(1.-IFS1*(G2/(2.*G))+(1.-TET)*(VXCR1**2))/((1.-TET)*VXCR1)
D=VI
E=G*C/G2
VXCR2=E-SQRT(E**2-1.+G1/G2*(D**2))
ANGLE(I)=ATAN(D/VXCR2)
VCR2=SQRT(VXCR2**2+D**2)
IF(I.EQ.1) S=S+DEL

15 CONTINUE
K=K+1
IF(K.GE.100) GOTO 1500
DIF1(1)=ABS(ANGLE(1)-TARGET)
DIF1(2)=ABS(ANGLE(2)-TARGET)
DIF2(1)=ANGLE(1)-TARGET
DIF2(2)=ANGLE(2)-TARGET
IF(DIF1(1).LE.0.00001) GO TO 1000
IF(DIF1(2).LE.0.00001) GO TO 1001
Q=DIF2(1)+DIF2(2)
IF(Q.LT.0.0) GOTO 200
IF(DIF1(2).GT.DIF1(1)) GOTO 100
GOTO 20

200 S=S-DEL
DEL=DEL/2.
GO TO 20

100 DEL=-DEL
S=S+DEL
GO TO 20

1000 BETAO=SS(1)
VO=VCR1(1)
GO TO 1600

1001 BETAO=SS(2)
VO=VCR1(2)
GOTO 1600

1500 BETAO=SS(1)
VO=VCR1(1)
WRITE(6,1700)

1700 FORMAT(///10X,47H*** BLOCKAGE CALCULATION FAILED TO CONVERGE ***)
1600 RETURN

FUNCTION FIT(ZK)
DIMENSION AK(34), ALAM(34)
DATA ALAM/12.,11,10,9,8,7,6,7.4,7.2,7.052,7.6,8,8.6,9,9.4,10,
10.2,10.5,4,0.2,1,0.0,1,2,3,4,5,6,7,8,9,10,20,
211,12./
DATA AK/0.0948,0.0941,0.0919,0.0882,0.0831,0.0819,0.0807,0.0794,
0.0771,0.0770,0.0775,0.0727,0.0721,0.0706,0.0689,0.0599,
0.0497,0.0385,0.0264,0.0135,0,-0.0140,-0.0284,-0.0429,-0.0575,
3-0.0720,-0.0662,-0.0999,-0.1130,-0.1254,-0.1369,-0.1474,-0.1567/
IF(ZK.GE.0.0948) GO TO 10
IF(ZK.LE.-0.1567) GO TO 20

K=1
KK=2
40 IF(ZK.LE.AK(K).AND.ZK.GE.AK(KK)) GO TO 30
K=K+1
KK=KK+1
GO TO 40

10 FIT=12.
GO TO 50

20 FIT=-12.
GO TO 50
30   FIT = (ALAM(KK) - ALAM(K)) / (AK(KK) - AK(K)) * (ZK - AK(K)) + ALAM(K)
50   CONTINUE
          RETURN
          END
FUNCTION RECRIT(ZL)
DIMENSION RE(8), X(8)
DATA RE/11500., 9600., 5600., 2000., 645., ZSO., 140., 100./
IF(ZL.GE.8.0) GO TO 10
IF(ZL.LE.-6.0) GO TO 20
K = 1
KK = Z
40 IF(ZL.LE.X(K).AND.ZL.GE.X(KK)) GO TO 30
K = K + 1
KK = KK + 1
GO TO 40
10 RECRIT = 11500.
GO TO 50
20 RECRIT = 100./6.*ZL + 200.
GO TO 50
30 RECRIT = (RE(KK) - RE(K)) / (X(KK) - X(K)) * (ZL - X(K)) + RE(K)
50 CONTINUE
          RETURN
          END
SUBROUTINE AFLOW(W,T,P,VX,RHOSTD,ACRSTD,VUH,GAMMA,RH,WCAL,RT)
DIMENSION R(51), FS(51)
VMAX = SQRT(VX**Z + VUH**2)
AMAX = W*SQRT(T/518.)/(P/14.696)/(RHOSTD*ACRSTD)/RHOViGAMMA,VMAX)
1*VMAX/VX
RTMAX = SQRT(AMAX/3.14159 + RH**2)
DELR = (RTMAX - RH)/50.
KOUNT = 1
RO = RH
WO = 0.0
CONST = 2.*3.14159*VX*RHOSTD*ACRSTD*(P/14.696)/SGRT(7/51E.7)
230 DO 100 I = 1, 51
       AI = I - 1
       R(I) = RO + AI*DELR
       V = SQRT(VX**2 + (VUH*RHO/R(I))**2)
       FS(I) = ((1.-(GAMMA-1.)/(GAMMA+1.)*V**2)**(1./(GAMMA-1.)))**R(I)
100 CONTINUE
DO 200 J = 1, 50
IF(J.GT.1) GO TO 125
WCAL = CONST*(FS(1) + FS(2)) * DELR/2.+WO
GO TO 150
125 WCAL = CONST*SIMP2(FS, 0.0, DELR, J) + WO
150 IF(ABS(W-WCAL) LT.0.001) GO TO 220
IF(WCAL LT. W) GO TO 200
JJ = J - 1
WO = CONST*SIMP2(FS, 0.0, DELR, JJ) + WO
IF(JJ.EQ.1) WO = (FS(1) + FS(2)) * DELR/2.+WO
DELR = (R(J+1) - R(J))/50.
RO = R(J)
KOUNT = KOUNT + 1
IF(KOUNT LE.5) GO TO 260
200 CONTINUE
260 WRITE(6,300)WCAL, W
300 FORMAT(/5X,8Z,** WARNING ** MASS FLOW ITERATION LOOP DID NOT
1 CONVERGE ... CALCULATED FLOW =,F8.4,3X13HACTUAL FLOW =,F8.4/) 
220 RT = R(J+1)
          RETURN
          END
FUNCTION RHOV(G,V)
RHOV = ((1.-(G-1.)/(G+1.)*V**2)**(1./(G-1.)))**V
SUBROUTINE SMALST(ARRAY, LIMIT, MIN)
DIMENSION ARRAY(200)
SMALL=ARRAY(1)
MIN=1
DO 10 I=2, LIMIT
IF(ARRAY(I).GT.SMALL) GO TO 10
SMALL=ARRAY(I)
MIN=I
10 CONTINUE
RETURN
END

FUNCTION ANGIT(W, T, G1, G2, VU, AREA, P, RHO, ACR, NBLD)
DIMENSION ALS(2), ARS(2), DIF1(2), DIF2(2)
CONST=W*SQR(T/S18.7)/(VU*AREA/144.*P/14.696)*RHO*ACR
A=0.0871553
S=0.7853976
ALPMIN=ASIN(VU)
DEL=0.0871553
IF(NBLD.EQ.1) DEL=(S-ALPMIN)/10.
IF(NBLD.EQ.1) A=(S-ALPMIN)/10.
K=0
20 ALS(1)=COS(S)/SIN(S)
K=K+1
IF(K.GE.100) GO TO 1400
ARS(1)=CONST/((1.-G1*(VU/SIN(S))**2))**G2
ALS(2)=COS(S+DEL)/SIN(S+DEL)
ARS(2)=CONST/((1.-G1*(VU/SIN(S+DEL))**2))**G2
DIF1(1)=ABS(ALS(1)-ARS(1))
DIF1(2)=ABS(ALS(2)-ARS(2))
DIF2(1)=ALS(1)-ARS(1)
DIF2(2)=ALS(2)-ARS(2)
IF(DIF1(1).LE.0.002) GO TO WOO
IF(DIF1(2).LE.0.002) GO TO 1001
G=DIF2(1)*DIF2(2)
IF(G.LT.0.0) GO TO 200
IF(DIF1(2).GT.DIF1(1)) GO TO 100
S=S+A*1.0
GO TO 20
200 DEL=DEL/2.
A=A/2.
GO TO 20
100 DEL=-DEL
A=-A
GO TO 20
1000 BNGIT=ALS(1)
ANGIT=ATAN(1./BNGIT)
GO TO 1200
1001 BNGIT=ALS(2)
ANGIT=ATAN(1./BNGIT)
GO TO 1200
1400 BNGIT=ALS(1)
ANGIT=ATAN(1./BNGIT)
WRITE(6,1500)
1500 FORMAT(///15X,77H*** BLADE EXIT ANGLE ITERATION LOOP NOT SATISFIED ///)
1200 CONTINUE
RETURN
END

FUNCTION ACRIT(G, R, T)
ACRIT=SQR(2.0*G/(G+1.)*32.174*R*T)
RETURN
END

SUBROUTINE FDISK(GAMMA, VEXIT, GAMMI, GAMM2, GAMM3, NPASS, KPASS, RGAS, SPEED, P1P, T1P, RWORK, NFLOW, ALP1, RM1, RM2, RM3, H1, H2, H3, T2P, U2, UACR2,
\[ \begin{align*}

\text{PASS} = \text{KPAES} \\
T2P = T1P \\
TSTD = 518.7 \\
ASTD = \text{ACRIT} (\text{GAMMA}, \text{RGAS}, \text{TSTD}) \\
RHSTD = 2116.22 / (\text{RGAS} \times \text{TSTD}) \\
CP = (1./\text{GAMM2}) \times \text{RGAS} / 778.26 \\
\text{ACR1} = \text{ACRIT} (\text{GAMMA}, \text{RGAS}, T1P) \\
T3P = T1P - RWORK / CP \\
\text{ACR3} = \text{ACRIT} (\text{GAMMA}, \text{RGAS}, T3P) \\
\text{UMAX} = \text{ACR3} \\
VX3 = \text{VEXIT} \\
\text{CON} = 25039.737 \times \text{RWORK} \\
VX3D = VX3 \times \text{ACR3} \\
V3 = VX3 / \text{COS} (\text{ALP3}) \\
VU3 = VX3 \times \text{TAN} (\text{ALP3}) \\
\text{VWRK3} = \text{VU3} \times \text{ACR3} \\
\text{IF} (\text{KPASS} \geq 0) \text{ GO TO } 10 \\
\text{IF} (\text{RBEST} \geq 0.0) \text{ CALL } \text{ RCHOKE} (\text{VWRK3, VX3D, GAMMA, RGAS, T1P, CON, UCHOKE}) \\
\text{IF} (\text{UCHOKE} < \text{ACR3}) \text{ UMAX} = \text{UCHOKE} \\
\text{IF} (\text{ALP1} < 0.349) \text{ GO TO } 100 \\
\text{IF} (\text{ALP1} = \text{ALP3}) \text{ GO TO } 100 \\
\text{IF} (\text{ALP3} < 0.0) \text{ GO TO } 100 \\
\text{UFLAT} = \text{CON} / (\text{VX3D} + (\text{TAN} (\text{ALP1} + 0.140) - \text{TAN} (\text{ALP3}))) \\
\text{IF} (\text{UFLAT} < \text{UMAX}) \text{ UMAX} = \text{UFLAT} \\
\text{IF} (\text{RBEST} < 0.0) \text{ GO TO } 20 \\
\text{RM3} = \text{RBEST} \\
\text{U3} = \text{RM3} \times 3.14159 \times \text{SPEED} / 30. \\
\text{GO TO } 15 \\
\text{UMIN} = (\text{VWRK3} + \text{SQRT} (\text{RM3} \times 2 + \text{RM3} \times \text{CON})) / 2. + 10. \\
\text{RMN} = \text{UMIN} / (3.14159 \times \text{SPEED} / 30.). \\
\text{DEL} = (\text{UMAX} - \text{UMIN}) / 20. \\
\text{U3} = \text{UMIN} \\
\text{RM3} = \text{RMN} \\
\text{GO TO } 15 \\
\text{U3} = \text{UMIN} \times \text{PASS} \times \text{DEL} \\
\text{RM3} = \text{U3} / (3.14159 \times \text{SPEED} / 30.) \\
\text{SWPM} = (\text{U3} \times 2) / (25039.62 \times \text{RWORK}) \\
\text{WFACTM} = 1./\text{SWPM} \\
\text{IF} (\text{ALP3} \geq 0.0) \text{ STGACC} = 1. - \text{WFACTM} / 2. \\
\text{IF} (\text{NPASS} \geq 1) \text{ ETA} = (0.92 \times \text{SWPM}) / (\text{SWPM} + 0.0227) \\
\text{IF} (\text{NPASS} \geq 1) \text{ P2P = 0.98} \times \text{P1P} \\
\text{P3P} = \text{P1P} \times (1. - (1. - \text{T3P} / \text{T1P}) / \text{ETA}) \times (1. / \text{GAMM2}) \\
\text{PRTURB} = \text{P1P} / \text{P3P} \\
\text{UACR3} = \text{U3} / \text{ACR3} \\
\text{AREA3} = \text{WFLOW} \times \text{SQRT} (\text{T3P} / \text{TSTD}) / (\text{P3P} / 14.696) / (\text{RHSTD} \times \text{ASTD}) / (\text{RHGV} (\text{GAMMA}, \text{V3}) \times \text{COS} (\text{ALP3})) \\
\text{H3} = \text{AREA3} / (2. \times 3.14159 \times \text{RM3}) \\
\text{H3A} = \text{H3} \\
\text{RH3} = \text{RM3} - \text{H3} / 2. \\
\text{IF} (\text{RBEST} \geq 0.0) \text{ GO TO } 25 \\
\text{IF} (\text{KPASS} \geq 0.0) \text{ GO TO } 25 \\
\text{IF} (\text{RM3} \geq 0.083) \text{ GO TO } 25 \\
\text{UMIN} = \text{UMIN} + 10. \\
\text{GO TO } 30 \\
\text{RT3} = \text{RH3} + \text{H3} \\
\text{VWRK2} = 239111.88 \times \text{RWORK} / (\text{SPEED} \times \text{RM3}) + \text{VWRK3} \\
\text{VU2} = \text{VWRK2} / \text{ACR1} \\
\text{VX2D} = \text{VX3D} \\
\text{VX2} = \text{VX2D} / \text{ACR1} \\
\text{V2} = \text{SQRT} (\text{VU2} \times 2 + \text{VX2} \times 2) \\
\text{ALP2} = \text{ATAN} (\text{VU2} / \text{VX2}) \\
\text{U2} = \text{U3} \]
UACR2=U2/ACR1
RM2=RM3
RH2=RH3
WFACTH=WFACTN*((RM3/RH3)**2)
UT3=U3*RT3/RM3
VUH2=RM2*U2/RH2
CALL AFLOW(WFLOW,T2P,P2P,VX2,RHSTD,ASTD,VUH2,GAMMA,RM2,wCAL,RT2)
H2A=RT2-RH2
H2=WFLOW*SGRT(T1P/TSTD)/(RHSTD)*((RM3/RH2)**2)*2.3.14159*Rm2*
T2P/14.696*RHSTD*ASTD)
RT6=RT2
AREA1=3.14159*(RT2**2-RH2**2)*144.
BLP1=ABS(ALP1)
V1=VELIT(WFLOW,T1P,GAMMA1,GAMMA3,SLP1,AREA1,P1P,RHSTD,ASTD)
VU1=V1*SIN(ALP1)
H1A=H2A
RM1=RM2
H1=WFLOW*SGRT(T1P/TSTD)/(RHSTD)*COS(ALP1)**2*3.14159*
1P1P/14.696*RHSTD*ASTD)
TPTP2=1.-GAMMA1*(UACR2**2)*(2.*VU2/UACR2-1.)
T2PP=TPTP2+T2P
UACRH2=RH2/RM2*UACR2
TPTPH2=1.-GAMMA1*(UACRH2**2)*(2.*VUH2/UACRH2-1.)
T2PPH=TPTPH2+T2P
PDPP2=TPTP**2(1./GAMMA2)
T3PP2=1.-GAMMA1*(UACRZ2**2)*(1./TPTP2)*(1.-((RM3/RM2)**2))
T3PP=T32PP*T2PP
ADP2=ACRIT(RM2,RGAS,T2PP)
ADP3=ADP2*SRT(T32PP)
WU2=WU2-ACR2-2
WUPP2=WU2/ADP2
BETA2=ASIN(VU2-UACR2)/((U2**2+UACR2**2-2.*VU2*UACR2))
WPP2=WUPP2/SIN(BETA2)
WU3=WU3-2
WUPP3=WU3/ADP3
WPP3=WPP3/SRT(0.2**2+0.1**2)
W3FPS=WPP3*ADP3
W2FPS=WPP2*ADP2
W2FPS=W2FPS*ACR1
W3FPS=W3FPS*ACR3
IF(ALP3.NE.0.0) STGACC=(W3FPS**2-W2FPS**2)/(W2FPS**2-W3FPS**2)+
1W3FPS**2-W2FPS**2
BETA3=ASIN(WUPP3/WPP3)
IF(NPASS.EG.1)P32PP=T32PP**2(1./GAMMA2)
IF(NPASS.EG.1)PLOS1=0.98
IF(NPASS.EG.1)PLOS2=P32PP
RETURN
END