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Computer Program for Generating Input for Analysis of Impingement-Cooled, Axial-Flow Turbine Blade

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Computer Program for Generating Input for Analysis of Impingement-Cooled, Axial-Flow Turbine Blade.

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SUMMARY

A FORTRAN IV computer program to generate the geometrical input for the TACT1 program, which calculates transient and steady-state temperatures, pressures, and flows in a cooled turbine blade or vane with an impingement insert, has been developed and is described in this report. The spline curve-fitting technique used in previous NASA codes to calculate the flow field around an external blade shape is used in the present program, TACTGRID, in order to generate the internal geometry of an impingement-cooled blade.

TACTGRID constructs the blade internal geometry from the previously specified external blade-surface points and newly selected wall and channel thicknesses. It also generates the TACT1 calculational grid and calculates the arc length distances between nodal points in the grid that are required by TACT1 as input. The geometrical data are stored in a namelist data set for use directly by TACT1. Furthermore, TACTGRID produces a scaled computer plot of each blade slice and thus eliminates the need for any intermediate drafting.

INTRODUCTION

The design procedure for axial-flow turbine blading used at the NASA Lewis Research Center employs computer programs for calculating both the flow field around an external blade shape and its external heat-transfer characteristics (refs. 1 to 3). For blading with internal impingement cooling, a newly prepared code called TACT1 (ref. 4) is used. TACT1 is a FORTRAN IV computer program that calculates transient and steady-state temperatures, pressures, and flows in a cooled turbine blade or vane with an impingement insert.

The inputs for the computer programs of references 1 to 3 (MERIDL, TSONIC, and STAN5) are interconnected: MERIDL generates input for TSONIC, and TSONIC generates input for STAN5. The geometrical input for MERIDL, as well as that for TSONIC, can be specified quite simply with a few blade-surface points. The program then uses spline curves passing through these points to define the blade contour. The outputs of these programs cannot be directly input to TACT1, although TACT1 requires output from all three. The manual assembly of these data for input to TACT1 is a time-consuming task. Therefore, a computer program called TACTGRID was written to assemble the required data from these codes and to generate the internal geometry of an impingement-cooled blade by the use of spline curve fitting.

TACTGRID constructs the blade internal geometry from the previously specified external blade-surface points and newly selected wall and channel thicknesses. TACTGRID also generates the TACT1 calculational grid and calculates the arc length distances between nodal points in the grid that are required by TACT1 as input. The geometrical data are stored in a namelist data set for use directly by TACT1. Furthermore, TACTGRID produces a scaled computer plot of each blade slice and thus eliminates the need for any intermediate drafting. This results in a significant saving in time and improvement in accuracy.

The TACTGRID program is used at the NASA Lewis Research Center on an IBM TSS/360-67 computer. Running time for the sample problem, which involved three blade slices, was approximately 270 seconds. The bulk of the computer time is taken up with the computer plotting.

The report includes descriptions of the blade geometric model, program input and output, and program procedure. The input and output are described in general terms and illustrated by a sample blade problem.

DESCRIPTION OF TACT1

The TACT1 computer program was devised to analyze the heat-transfer and coolant-flow distribution in an impingement-cooled turbine blade or vane. As shown in figure 1, the coolant flow in this scheme enters the plenum through the blade base and flows spanwise in the plenum. The coolant is discharged from the plenum in the form of jets from holes in the plenum walls. These jets impinge on the inner surface of the blade shell and cool it. Additional cooling is obtained as the fluid moves toward the trailing edge through the channel formed by the plenum wall and the blade shell.

In the trailing-edge region of the blade, the channel formed by the blade-shell inner surfaces may have pin fins for additional heat transfer. The coolant flow is ejected from the blade through trailing-edge holes or slots.

In order to simplify flow-field calculations, the blade is divided into slices (analogous to slices of bread) bounded by planes or surfaces of revolution, as shown in figure 1. These surfaces of revolution are placed a constant radial distance apart so that each slice has a constant radial thickness. A typical blade cross section is depicted in figure 2. One-dimensional flow is assumed in the flow channels shown. For each slice an independent flow-field solution is performed that satisfies conservation of mass, momentum, and energy within that slice. In the course of these flow-field calculations, heat-transfer coefficients are evaluated for two distinct regions. In the forward region, heat is transferred by impingement cooling and forced-convection cooling in the channel. In the trailing-edge region, heat is transferred by forced-convection cooling and, when pin fins are specified, by the pin fins in crossflow. The blade-shell temperature distribution is calculated from a three-dimensional heat conduction model, which allows for heat flow through the wall and in the spanwise and chordwise directions as well.

Figure 2 shows the geometrical breakdown of a typical blade cross section into calculational stations. The stations are odd-numbered on the pressure side and even-numbered on the suction side. The inset in figure 2 shows one station broken down into its five calculational nodes, located as follows:

(a) A coating outer surface node
(b) A coating-metal interface node
(c) A midmetal node
(d) An inner surface node
(e) A mid-coolant-channel node

It is evident that an enormous amount of data must be generated to completely specify the blade geometry for use in the TACT1 code. The manual generation of these data requires the drafting of each blade cross section and the measuring of coordinates and dimensions. This process is both time consuming and subject to human error. In order to eliminate human error and reduce the time required to prepare the geometrical input for TACT1, this process was computerized as described in the following sections.

DESCRIPTION OF TACTGRID

The TACTGRID program was written to eliminate the manual drafting chores involved in designing a cooling configuration and running TACT1. These chores are now performed by the computer, which uses the external blade profiles generated during the aerodynamic design process and user-specified distributions of coating thickness, metal thickness, and impingement crossflow-channel width. The dimensions and coordinates needed for TACT1 are calculated analytically with spline fit curves. Therefore, some restrictions had to be imposed on the geometry that could be analyzed with TACTGRID. The following discussion briefly describes the functions of TACTGRID and the limitations in its use.

The internal geometry of each blade cross section is generated by constructing inward normals to the blade external surface at specified intervals. Along these normals, distances are measured that correspond to the thicknesses of the coating (if specified), the blade shell, the midpoint of the blade shell, the impingement crossflow channel, the midpoint of the channel, and the plenum wall. Spline fit curves are passed through corresponding points on each normal. These curves are called horizontal orthogonals and variously represent the contours of the interface between the blade shell and the coating, the outlines of the external surface and the flow channels, and the midlines of the blade shell and the flow channels. A family of curves orthogonal to these curves, called vertical orthogonals, is generated by the predictor-corrector method of reference 5. This method uses normals between adjacent horizontal orthogonals to generate the vertical orthogonals. The vertical orthogonals represent the TACT1 calculation stations; and the distances along them, between corresponding horizontal orthogonals, are the actual thicknesses of coating, metal, and flow channel that are input to TACT1. The distances along the horizontal orthogonals, between adjacent vertical orthogonals, are the actual chordwise lengths input to TACT1. The procedure by which TACTGRID performs these tasks is described in the Program Procedure sections that follow.

In regions of the blade where the user-specified wall and channel thicknesses have no chordwise variation, the horizontal orthogonals constitute mathematically parallel curves in the plane of the cross section, and the vertical orthogonals are just straight lines. The vertical orthogonals will become curved lines in regions of the blade where the wall or channel thicknesses are not constant. TACTGRID also calculates, and places in the namelist input data set for TACT1, the radial span for each slice.

Heretofore, the finite-difference grid for each blade slice, which results from the aforementioned nodal arrangement, had to be generated by hand; a cross section of a (manually executed) sample blade problem is shown in figure 3. TACTGRID now constructs this finite-difference grid automatically, without any intermediate drafting or human interaction. TACTGRID supplies a scaled computer drawing of each blade slice and accompanying grid as part of its normal output (fig. 4).

TACTGRID Limitations

TACT1 allows for mixed radial-axial flow of the hot gas stream, so the cutting planes (i.e., surfaces of revolution) for the slices do not have to be at constant radius. An orthogonal three-dimensional grid cannot be maintained as the end walls become greatly contoured if the grid lines are to lie along the blade surface. Therefore, TACTGRID is limited to constructing grids for blades with both cylindrical end walls and cylindrical surfaces of revolution defining the blade slices.

TACTGRID was developed specifically to automate the turbine blade design procedure at the NASA Lewis Research Center. Since the second step in this procedure - namely, the TSONIC program (ref. 2) - requires a specific type of blade profile, TACTGRID is limited to generating grids for the TSONIC profile. The TSONIC blade shape and input specifications are shown in figure 5. The profile basically consists of two circular regions mated to two spline curves. TACTGRID assumes that a TSONIC blade shape has been input and uses the computer program of reference 6 (TFORM) to transform that shape from the TSONIC coordinate system (fig. 5) to coordinates with respect to true blade chord (figs. 6 to 8). TACTGRID neglects the trailing-edge circle in constructing its grid.

In keeping with the circular specification of the leading-edge region of the blade, TACTGRID allows for no wall thickness variation in the leading-edge circular region of a slice. In this way, the orthogonal coordinate lines that are constructed in the nose region can simply be those of a cylindrical coordinate system (fig. 9). This restriction is not present in TACT1. TACTGRID does, however, allow for a completely general chordwise variation of coating, metal, and impingement-channel thicknesses in the spline regions.

TACTGRID does not permit general variation of arc length spacing between stations, although TACT1 does. Rather, the distribution is limited to six regions with uniform spacing between stations along the inner surface, within each region. The breakdown of a slice into six regions is illustrated in figure 10. Equal increments of inside-wall arc length separate stations in a given region for the first slice. Succeeding slices have stations proportionally alined with those of the first slice. This procedure is explained further in the section DIFFERENCES IN PROGRAM PROCEDURE FOR SUCCEEDING SLICES.

Figure 10 also shows that TACTGRID will only consider a straight trailing-edge channel, whereas TACT1 does not restrict the shape of the trailing-edge channel. The geometry was so limited because present designs employ only drilled holes or rectangular slots for the trailing-edge channels. This limitation reduces fabrication costs.

Geometrical Input Not Provided

TACT1 requires additional geometrical input, depending on the mode of heat transfer specified, that is not provided by TACTGRID. This input comprises the set of variables available to the designer for optimizing his cooling design. Since these variables can be obtained with no special effort, they are not provided by TACTGRID. These input variables include

(1) Impingement-hole diameter and location

(2) Pin-fin diameter and location

(3) Film-cooling-hole diameter and location

Figure 11 shows an impingement hole of diameter TDHJ at station ISTA.

TACTGRID does provide information regarding the geometrical constraints on this input, because it furnishes arc length distances along all walls. This enables the designer to prevent one station's row of holes from overlapping that of an adjacent station along the insert walls.

PROGRAM INPUT

The organization of a TACTGRID input data set for a sample blade that was aerodynamically designed for three sections (hub, mean, and tip) is illustrated in figure 12(a). The input for each blade slice contains data that are needed solely for the TACTGRID program as well as the input data set required by the TFORM program (ref. 6), which TACTGRID runs. The function of the TFORM program in constructing the TACT1 grid is explained further in the section PROGRAM PROCEDURE FOR FIRST SLICE. The TFORM input data set for each slice follows the TACTGRID input data set for that slice.

TACTGRID Input

An input form for TACTGRID is shown in figure 12(b). Although some input will be in real-number form (F format) and some in integer form (I format), all data will be entered in 10-column fields. In the following description of input variables, those FORTRAN names ending in T refer to the suction side of the blade, and those ending in B refer to the pressure side:

WRU — Width, in relative units, desired for the scaled computer drawing of the blade slice. Each computer frame is 10 relative units by 10 relative units. The plot is centered in the frame so that the left end is at (10 - WRU)/2 relative units and the right end is at 10 - (10 - WRU)/2 relative units. A WRU larger than 9 should not be specified in order to maintain a 0.5-relative-unit margin on either side of the blade for constructing the labeling arrows for the nose and trailing-edge stations (fig. 4). TACTGRID uses the IBM plotting package at the Lewis Research Center. TACTGRID can be run without the plotting by placing a C in the first column of those statements in the program that call plotting subroutines and thus changing plot calls into comment cards. The names of the various plotting routines that TACTGRID uses are listed in the appendix. The format for WRU is F10.5.

HRU — Height, in relative units, desired for the scaled computer drawing of the blade slice. The drawing of the blade slice is executed, without axes, in a rectangular box of dimensions WRU relative units by HRU relative units. The bottom of the slice (chord line) is placed 10 - HRU relative units from the bottom of the computer frame. The scales on the x- and y-axes are the same. Therefore, HRU should not be selected so small as to cause the upper surface of the blade to exceed the upper boundary of the frame. HRU should not be selected so large as to place the chord line so low in the frame that there is no room left for printing the legend and the slice number below the blade plot (fig. 4). The format for HRU is F10.5.

NSLICE — Number of slices in the blade. The blade coordinates for each slice are assumed by TACT1 to be those of a cross section in the middle of the slice. The format for NSLICE is I10.

UU — The desired user units (output units) for the problem are as follows: If UU = 1, user units are centimeters; if UU = 2, user units are inches. The format for UU is I10.

NFRAME — Number of frames desired for the plot. A larger plot can be obtained by specifying NFRAME larger than 1. TACTGRID will multiply WRU by NFRAME in determining the desired plot width for the blade. HRU should be adjusted so the blade's vertical dimensions do not exceed the borders of the frame. In no instance can the blade plot be higher than 10 relative units. The format for NFRAME is I10.

F1T, F2T, F1B, F2B — The impingement region of the blade in the spline portion is divided into three regions (II, III, and IV) of equal arc-length spacing between stations along the blade inside wall (fig. 10). The distances along the inside wall in the impingement region (determined by TACTGRID) are STWIMP on the suction side and SBWIMP on the pressure side. F1T is the fraction of the distance STWIMP from the end of region I to the end of region II on the suction side. F2T is the fraction of the distance STWIMP from the end of region I to the end of region III on the suction side. F1B is the fraction of the distance SBWIMP from the end of region I to the end of region II on the pressure side. F2B is the fraction of the distance SBWIMP from the end of region I to the end of region III on the pressure side. Thus the regions on the suction and pressure sides, respectively, are divided as follows:

Region II = (F1T*STWIMP), suction side

= (F1B*SBWIMP), pressure side

Region III = (F2T-F1T)*STWIMP, suction side

= (F2B-F1B)*SBWIMP, pressure side

Region IV = (1.-F2T)*STWIMP, suction side

= (1.-F2B)*SBWIMP, pressure side

The format for these variables is F10.5.

NVT — Number of stations (vertical orthogonals) desired in the circular region (region I) on the suction side. TACTGRID uses this same number of stations for the pressure side, as TACTGRID divides the leading-edge circular region in two and places station 1 in the middle. Station 1 is common to both the suction and pressure sides and is counted twice. The format for NVT is I10.

N1T, N2T, N3T, N1B, N2B, N3B — Number of stations (vertical orthogonals) desired in regions II, III, and IV on the suction and pressure sides, respectively. These stations are uniformly spaced with respect to the inside-wall arc length in each region. As the last vertical orthogonal in the circular region is not counted in N1T and N1B, the number of input stations equals the number of arc length intervals between stations in the respective regions. Since TACT1 requires the same number of stations on the suction and pressure sides of the blade, N1T + N2T + N3T must equal N1B + N2B + N3B. The format for these variables is I10.

N4B — Number of stations desired in the trailing-edge region between the impingement region and the straight trailing-edge channel region (region V in fig. 10). N4B actually represents the number of stations (with equal inside-wall arc length spacing between them) on the pressure side in region V. TACTGRID determines the locations of the corresponding suction-side stations for this forced-convection, channel-flow region. This procedure is explained in the section PROGRAM PROCEDURE FOR FIRST SLICE. Again, the number of input stations equals the number of arc length intervals between stations in this region. The format for N4B is I10.

N5B — Number of stations desired in the straight trailing-edge channel region (region VI in fig. 10) on the pressure side. There is equal inside-wall arc length spacing between these stations on the pressure side. Again, the corresponding suction-side stations are determined by TACTGRID. The number of input stations equals the number of arc length intervals betwe·· stations in this region. The format for N5B is I10.

For slices beyond the first, the preceding five lines of TACTGRID input are omitted, as they apply to all the slices.

The wall and channel thicknesses are entered in namelist format for the convenience of the user. The arrays for these dimensions are contained in the TACTGRID namelist name GEO. The distance along the outer surface of the blade, for the suction- and pressure-side spline regions, is divided into 50 equal increments. The elements in the thickness arrays correspond to the 51 end points of these 50 arc length intervals. Thus a wall thickness distribution can be specified that is based on 2-percent increments of spline-region surface length (fig. 9). The arrays that specify wall and channel thicknesses are as follows:

THK1T, THK1B — Real-variable arrays of dimension 51 that specify the coating thickness distributions on the suction and pressure sides, respectively. The values must be given in the user-designated units. THK1T(1) must equal THK1B(1).

THK2T, THK2B — Real-variable arrays of dimension 51 that specify metal thickness distributions on the suction and pressure sides, respectively. The values must be given in the user-designated units. THK2T(1) must equal THK2B(1).

THK3T, THK3B — Real-variable arrays of dimension 51 that specify impingement-channel thickness distributions on the suction and pressure sides, respectively. The values must be given in the user-designated units. THK3T(1) must equal THK3B(1).

The rest of the input data is entered, once again, in the usual real-number format, as follows:

THK(1) First element in the real-variable array THK, an array of four elements. THK(1) is the coating thickness desired (in the user-designated units) at the end of the spline region on the suction side. After cutting the trailing-edge hole and so determining region VI (fig. 10), TACTGRID linearly tapers the input coating thicknesses with outer surface arc length in region VI, so that THK1T(51) = THK(1) (fig. 4). If no coating thickness taper is wanted, the input value for THK(1) should be the same as the input value for THK1T(51). The format for THK(1) is F10.5.

THK(3) Third element in the THK array. It represents the coating thickness desired (in the user-designated units) at the end of the spline region on the pressure side. The input coating thicknesses are tapered linearly with outer surface arc length in region VI, so that THK1B(51) = THK(3) (fig. 4). If no coating thickness taper is wanted, the input value for THK(3) should be the same as the input value for THK1B(51). THK(2) and THK(4) are the metal wall thicknesses on the suction and pressure sides, respectively, at the end of the spline region. These values are determined by the program in cutting the trailing-edge hole such that THK(1) + THK(2) = THK(3) + THK(4). The format for THK(3) is F10.5.

THKHOL Thickness of a straight, trailing-edge slot or the diameter of a drilled trailing-edge hole in the user-designated units. If the straight, trailing-edge channel is intended to be a drilled hole or a row of drilled holes, the channel thickness input to TACT1 by TACTGRID should be manually reduced by the user in the following manner:

$$(\mathrm{THKHOL})_{\mathrm{TACT1}} = \frac{N\pi\left[(\mathrm{THKHOL})_{\mathrm{TACTGRID}}\right]^2}{4*\mathrm{SPAN}}$$

where N is the number of holes in the slice and SPAN is the span of the slice. The format for THKHOL is F10.5.

THKWAL Thickness of the plenum wall in the user-designated units. The format for THKWAL is F10.5.

SDUMP Width of the insert at its end (fig. 10), in the user-designated units. The format for SDUMP is F10.5.

RRO — Radius of the coolant plenum outlet of the slice from the axis of the turbomachine, in the user-designated units. The format for RRO is F10.5.

RRI — Radius of the coolant plenum inlet of the slice from the axis of the turbomachine, in the user-designated units. The format for RRI is F10.5.

Z — Displacement along the TSONIC z-axis (fig. 5) of the TSONIC origin of this blade profile from the origin of the profile in the first slice, in the user-designated units. For the first slice, Z is input as 0.0. The format for Z is F10.5.

THETA — Angular displacement of the TSONIC origin of this blade profile from the origin of the profile in the first slice. THETA must be in radians. For the first slice, THETA is input as 0.0. The format for THETA is F10.5.

In general, a turbine blade may be designed with twist, taper, and lean. Twist refers to an angular displacement about the stacking axis between successive blade profiles. Taper refers to a variation in profile chord length along the span. Lean refers to an angular displacement about the turbomachine axis between successive blade profiles. If the turbine blade design employs these geometric variations, the TSONIC origin (fig. 5) of each blade profile may be different. Since TFORM sets up a separate Cartesian coordinate system for each slice, the parameters Z and THETA enable TACTGRID to transform the TFORM coordinates for a given slice back to the TFORM coordinate system of the first slice, which is taken as global.

TFORM Input

An input form for the TFORM input is shown in figure 12(c). The following description of input variables is excerpted from reference 6:

CHORD — Overall length of blade in the z-direction (fig. 5)

STGR — Angular θ-coordinate for center of trailing-edge circle of blade with respect to center of leading-edge circle (fig. 5), rad

RMI — Radius of blade section from axis of rotation. If RMI = 1, all θ-coordinates are the actual linear dimension w.

SCALE	Ratio of output dimensions to input dimensions. For example, if input is in feet and output is desired in inches, SCALE = 12 should be used.
DELX	Spacing of output coordinates in x-direction (fig. 8). DELX should be chosen to be at least CHORD*SCALE/100. DELX must be given in the output units (i.e., if input is in feet and output is in inches (SCALE = 12), DELX is in inches).
RI1, RI2	Leading-edge radii of the two blade surfaces (fig. 5)
RO1, RO2	Trailing-edge radii of the two blade surfaces (fig. 5)
BETI1, BETI2	Angles (with respect to z-direction) at tangent points of leading-edge radii with the two blade surfaces (fig. 5), deg. These must be true angles in degrees.
BETO1, BETO2	Angles (with respect to z-direction) at tangent points of trail-edge-radii with the two blade surfaces
SPLNO1, SPLNO2	Number of blade spline points given for each surface as input (maximum, 50). These include the first and last points (dummies) that are tangent to the leading- and trailing-edge radii (fig. 5).
MSP1, MSP2	Arrays of z-coordinates of spline points on the two blade surfaces, measured from blade leading edges (fig. 5). The first and last points in each array must be left blank, since these values are calculated by the program. If the last point is on a new card, a blank card must be used.
THSP1, THSP2	Arrays of θ-coordinates of spline points corresponding to MSP1 and MSP2, rad. Blanks must be used in positions corresponding to those in MSP1 and MSP2.

The TFORM input is explained further in reference 6. The input data set for TSONIC (ref. 2) is quite similar to that for TFORM and provides all the input needed for TFORM. The input data set for TSONIC is generated by MERIDL (ref. 1).

PROGRAM OUTPUT

The output of TACTGRID consists of five parts, which are enumerated and described in the following sections.

TACTGRID and TACT1 Overall Input

TACTGRID prints back its input in the labeled form illustrated by figure 12(b). This output is provided, for debugging purposes, on the first two pages of the program output (figs. 13(a) and (b)). The first output page contains TACTGRID overall input. The second page contains TACTGRID geometrical input for the particular slice. Also contained on the first output page is the date of the computer run and the first namelist input line for TACT1. The CHANLS namelist name in TACT1 pertains to the overall job. For these reasons, the output of figure 13(a) is printed only here and not repeated for the various slices. The TACT1 input is explained in detail in reference 4.

TFORM Output

The TFORM output is provided on the next three output pages (3 to 5). The first of these pages (fig. 13(c)) consists of a printout of the TFORM input data set in the form of figure 12(c). The second of these pages (fig. 13(d)) contains blade data at the input spline points. This information is used for debugging because wildly varying second derivatives at the input spline points will indicate an input error. The third of these pages (fig. 13(e)) gives the transformed blade coordinates. The first line gives the output number of x-coordinates and the orientation angle φ (fig. 8). The next lines present a tabulation of the x- and y-coordinates for the upper (suction side) and lower (pressure side) surfaces (fig. 8). Any TFORM error messages will also be printed out.

TACT1 Input

On the sixth output page (fig. 13(f)) begins the TACT1 input pertaining to the individual blade slice. The TACT1 namelist names for which TACTGRID provides input are CHANLS, CONTRL, PROPS, and GEO. Within each namelist name, TACTGRID only provides the input for those variables that are geometry related. All variables not so related are omitted from the namelist name printout. The variables provided, within their respective namelist names, are as follows:

Namelist /CHANLS/ NSLICE, NSTA, IUNITS

Namelist /CONTRL/ NFWD, NGEO

Namelist /PROPS/ SPAN, ADUMP, DHYD, APLEN, RI, RO

Namelist /GEO/ ISTA, ISTB, THK, TDLX

The value for ADUMP that the program calculates is the cross-sectional area of the plenum opening at its end, for the "cut-off" end shape assumed by TACTGRID (fig. 4). For designs employing other plenum end geometries, this input to TACT1 should be modified accordingly.

Nodal and Plenum Contour Coordinates

Representative blade coordinate output is shown in figure 13(g). TACTGRID calculates the arc length distance along each horizontal contour line (horizontal orthogonal) from an initial radial line that is the TSONIC z-axis (fig. 14). Distances clockwise of this line are positive and those counterclockwise are negative. TACTGRID also calculates the arc length distances between nodes along the vertical orthogonals joining them. Horizontal and vertical arc length coordinates as well as x, y-coordinates (the x, y-coordinates of the TFORM coordinate system set up for the first slice, fig. 7) are given for every grid node and every intersection point of a station vertical orthogonal with the insert outer and inner contours. In the arrays of output coordinates, the first index, I, indicates the vertical orthogonal line and the second index, J, indicates the horizontal orthogonal line. All output coordinates are in the user-designated units. The horizontal orthogonals are denoted as follows:

J = 1 represents the blade outer surface.

J = 2 represents the coating-metal interface line.

J = 3 represents the midmetal line.

J = 4 represents the blade inner surface.

J = 5 represents the impingement-channel midchannel line.

J = 6 represents the insert outer surface.

J = 7 represents the insert inner surface.

The output coordinates are as follows (fig. 14):

XCT(I, J), XCB(I, J)	Arrays of x-coordinates of grid points in the circular region on the suction and pressure sides, respectively. The TSONIC z-axis and the borders of the circular region are delineated by radial lines on all output blade plots (figs. 14 and 4). I = 1 corresponds to station 1 for both sides. I = 4 refers to the fourth station in the circular region (station 1 included) on the respective side. For instance, XCT(4, 3) is the x-coordinate of the midmetal node in station 6 of figure 4(a). The dimension of these arrays is 10×7.
YCT(I, J), YCB(I, J)	Arrays of y-coordinates of grid points in the circular region on the suction and pressure sides, respectively. The dimension of these arrays is 10×7.
SCT(I, J), SCB(I, J)	Arrays of horizontal arc length coordinates in the circular region on the suction and pressure sides, respectively. The dimension of these arrays is 10×7.
NCT(I, J), NCB(I, J)	Arrays of vertical arc length coordinates in the circular region on the suction and pressure sides, respectively. Here the J index refers to the distance between the outer coating node and the J + 1 node. For instance, NCT(4, 3) is the distance along the vertical orthogonal of station 6 from the outer coating node to the metal inner surface node of figure 4(a). The dimension of these arrays is 10×7.
XTT(I, J), XBB(I, J)	Arrays of x-coordinates of grid points in the spline region on the suction and pressure sides, respectively. I = 1 corresponds to the first station in the spline region. I = 4 refers to the fourth station in the spline region on the respective side. For instance, XTT(4, 3) is the x-coordinate of the midmetal node in station 14 of figure 4(a). The dimension of these arrays is 50×7.
YTT(I, J), YBB(I, J)	Arrays of y-coordinates of grid points in the spline region on the suction and pressure sides, respectively. The dimension of these arrays is 50×7.

STT(I, J), SBB(I, J)	Arrays of horizontal arc length coordinates in the spline region on the suction and pressure sides, respectively. The dimension of these arrays is 50×7.
NTT(I, J), NBB(I, J)	Arrays of vertical arc length coordinates in the spline region on the suction and pressure sides, respectively. As in the circular region, the J index refers to the distance between the outer coating node and the J + 1 node. For instance, NTT(4, 3) is the distance along the vertical orthogonal of station 14 from the outer coating node to the metal inner surface node of figure 4(a). The dimension of these arrays is 50×7.

Figure 14 illustrates the output coordinate designations for a few stations. The TSONIC computer program (ref. 2) provides the boundary condition (inviscid tangential velocity distribution) for the STAN5 boundary-layer program (ref. 3) as a function of surface length from the TSONIC origin. Therefore, the heat-transfer-coefficient distribution, or heat-flux distribution, which is output by STAN5, will likewise be in terms of surface length measured from the TSONIC origin. Since the TACT1 program requires that the heat-transfer boundary condition be specified in terms of surface length from station 1, the quantity SCT(1, 1) (or equivalently SCB(1, 1)) must be subtracted from each arc length entry when STAN5 output is used as input for TACT1.

Scaled Computer Plot of Blade Slice

TACTGRID produces a scaled computer drawing of every blade section used for a TACT1 run. The designer can select all the input variables shown in figure 12(b) without first making a blade layout on a drafting board. By a visual inspection of the computer drawing, the designer can readily detect gross errors in the geometrical dimensions selected. The labeling on each drawing includes the profile designation (title from the TFORM input data set) in the top left corner, the date of the run in the top right corner, the scale and legend in millimeters and inches centered below the profile, and the slice number centered on the bottom of the frame (fig. 4). Every calculation station is indicated with an arrow and the appropriate station number. Since the drawing is scaled, the designer can plan and draw in his design variables (impingement holes, pin fins, film-cooling holes) right on the plot, with drafting implements and an engineering scale.

PROGRAM PROCEDURE FOR FIRST SLICE

For each slice, TACTGRID first runs TFORM to change the TSONIC external blade coordinates from z, θ-coordinates (fig. 5) to x, y-coordinates, where the x-axis is tangent to the blade lower surface (fig. 7). TFORM obtains y-coordinates on the blade upper and lower surfaces for equal increments in x (fig. 8). TACTGRID then plots these x, y-points so that, if the program is being run interactively with an on-line cathode ray tube oscilloscope (CRT), the analyst can detect an input error visually.

Next, TACTGRID calculates the x, y-coordinates of the circle-spline juncture points, which were determined in z, θ-coordinates by TFORM (fig. 5), in order to resolve the profile into a spline region and a circular region (fig. 10). A different procedure is used for generating the grid in each region.

TACTGRID generates the grid in the spline region by first calculating the spline-region outer surface length on the suction and pressure sides. As mentioned earlier, TACTGRID divides these spline-region surface lengths into 50 equal increments and determines the 51 end points of these 50 increments.

TACTGRID then calculates all the nodal points in the blade shell for the circular region and plots this region's horizontal and vertical orthogonals. The orthogonal grid in the circular region is just a polar coordinate system, with the vertical orthogonals being radial lines and the horizontal orthogonals being sections of circles. The program determines the positions of the nodal points in the circular region by the number of vertical orthogonals (stations) input because stations are placed at equal angular increments (fig. 9(b)).

TACTGRID then defines the blade internal shape in the spline region (fig. 9(a)) by generating normals to the outer contour in this region at the 51 end points previously determined. The coating-metal interface line, on the suction side, is formed by points at distances THK1T(I) along the 51 normals. The midmetal line is formed by points at distances THK1T(I) + (THK2T(I)/2) along these normals, and the metal inside wall is formed by points at distances THK1T(I) + THK2T(I) along the normals (fig. 9(b)). The same procedure is followed on the pressure side. Generally, the suction- and pressure-side inner walls will intersect (fig. 9(a)).

At this point, TACTGRID prepares to cut a straight, trailing-edge channel of thickness THKHOL (input) through the generated blade shell (fig. 9(a)) by an iterative procedure. Because this straight channel is to represent a drilled hole or rectangular slot, cut inwards from the trailing edge, the program employs the same reasoning as a machinist might apply in determining the angle of the cut. Logical criteria for this cut are

(1) The location of the channel should be such that the suction- and pressure-side wall thicknesses at the trailing-edge exit are equal (i.e., lines EB and FD in figs. 15 and 16 should be equal).

(2) The sides of the channel should intersect the suction- and pressure-side inner walls at points that are equidistant from the axis of the channel (points A and I in fig. 16(b)).

The program determines the orientation of the channel by a trial-and-error method consisting of two levels of iteration. The procedure is to pick a point on the suction-side inner surface as a first guess for the intersection point of the channel top surface with the suction-side inner wall. After adjusting the angle of the channel axis so that the normals to the external surface at the trailing edge are cut at equal lengths, the program checks to see if the channel intersection with the pressure-side inner surface lies directly across the channel from the suction-side intersection point. If it does not, a new suction-side inner surface point is selected, and so on. The details of this procedure are as follows (figs. 15 and 16):

(1) Outer loop: Pick point A on the suction-side inner surface and point B on the suction-side, trailing-edge normal $\overline{EG}$ (fig. 15(a)) and enter the inner loop.

(2) Inner loop: Construct a normal of length THKHOL to line $\overline{AB}$ at point B, and locate point C at the terminus of this normal (fig. 15(a)).

(3) Inner loop: Construct a line parallel to $\overline{AB}$ from point C, and determine the intersection point, D, of this line with the pressure-side, trailing-edge normal $\overline{FH}$ (fig. 15(a)).

(4) Inner loop: Calculate lengths $|\overline{EB}|$ and $|\overline{FD}|$. If $|\overline{EB}| \neq |\overline{FD}|$, move point B along EG and return to step (2). If $|\overline{EB}| = |\overline{FD}|$ (i.e., $\left||\overline{EB}| - |\overline{FD}|\right|/\mathrm{THKHOL} < 0.01$), go to step (5) (return to outer loop). Figures 15(a) and (b) illustrate the first and fifth iterations, respectively, of the inner-loop procedure for the first outer-loop iteration.

(5) Outer loop: Extend line $\overline{CD}$ (parallel to $\overline{AB}$) to intersect the pressure-side inner wall, and determine the intersection point I (fig. 16(a)).

(6) Outer loop: Construct a normal of length THKHOL to line $\overline{AB}$ at point A, and locate point J at the terminus of this normal (fig. 16(a)). I and J must coincide to meet the cutting criteria.

(7) Outer loop: By construction, I and J are colinear (fig. 16(a)). If the length $|\overline{IJ}| \neq 0$, move point A along the suction-side inner surface and return to step (2). If $|\overline{IJ}| = 0$ (i.e., $|\overline{IJ}|/\mathrm{THKHOL} < 0.01$), exit from the loop because the solution has been found. Figures 16(a) and (b) show the first and 17th iterations, respectively, of the outer-loop procedure for cutting the trailing-edge hole.

At this point, TACTGRID tapers the coating thickness linearly, with outer surface arc length, from the value found at the beginning of region VI (fig. 10) to the value specified by the designer for the trailing edge of the blade (THK(1) on the suction side and THK(3) on the pressure side). This procedure redetermines the second horizontal contour (coating-metal interface line).

The program then recomputes the coordinates of the inner wall and the midmetal line because of the material removed in cutting the trailing-edge channel.

TACTGRID now constructs the three horizontal contours needed for the impingement crossflow channel and insert walls (fig. 4) by generating normals to the blade-shell inner surface at the end points of the outer surface normals. The first horizontal contour (impingement-channel mean streamline) is formed by points at distances THK3T(I)/2 (suction side) and THK3B(I)/2 (pressure side) along the blade-shell inner surface normals. The second horizontal contour (insert outer surface) is formed by points at distances THK3T(I) (suction side) and THK3B(I) (pressure side) along the inner surface normals. The third contour (insert inner surface) is formed by points at distances THK3T(I) + THKWAL (suction side) and THK3B(I) + THKWAL (pressure side) along the normals (fig. 9(b)).

The program places calculational stations at the desired arc length positions designated by the input parameters (F1T, F2T, F1B, F2B, N1T, N2T, N3T, N1B, N2B, N3B, N4B, and N5B; see section TACTGRID Input) by calculating the spline arc length of the inside wall (for the suction and pressure sides). At this point, TACTGRID plots the inside-wall contours to provide a quick screening check for the designer who is running conversationally with a CRT. After a visual inspection, the user may decide to terminate the program and rerun with a different set of input parameters.

TACTGRID now prepares to construct the orthogonal TACT1 grid. First, the chordwise extent of the insert is determined by an iterative procedure (the details of which are described later). This procedure employs the construction of vertical orthogonal links by the method of reference 5. Once the impingement region has been thus delimited, the nodal points on the inside wall are located as described in the section TACTGRID Input. From these points on the inner surface, vertical orthogonals are generated in the blade shell that cut at right angles to all the horizontal contours previously generated. The horizontal contours thus constitute, in effect, horizontal orthogonals for the grid. As before, the method of generating the vertical orthogonals is that employed in reference 5.

The construction of a vertical orthogonal link by the aforementioned method is depicted in figure 17 (fig. 5 of ref. 5). In this figure, a vertical "orthogonal" link is generated between two horizontal orthogonals in an analogous r, z rectangular coordinate system. Beginning at nodal point (REFZ, REFR) on the lower horizontal orthogonal, a normal is constructed (line 1 in fig. 17), and the intersection (ZNL, RNL) is calculated on the upper horizontal curve. From the slope SLU at this intersection point, line 2 in figure 17 is constructed in such a way that it is perpendicular to the SLU line and also passes through (REFZ, REFR) on the lower horizontal orthogonal. After the coordinates (ZNU, RNU) of the intersection of line 2 with the SLU line are calculated, the final vertical orthogonal link is determined as the line that intersects the upper curve at an abscissa ZOM = (ZNL + ZNU)/2. This is the point (ZOM, ROM) in figure 17. Details of the procedure are given in reference 5. TACTGRID uses this same method to construct approximate "streamlines" and streamline normals in the impingement crossflow-channel region (regions II, III, and IV of fig. 10) and in the trailing-edge flow region (regions V and VI of fig. 10).

TACTGRID locates the end of the insert within the blade shell, and thus delimits the impingement region, by the following procedure (fig. 18): Beginning with the point on the pressure-side insert outer wall determined by the 25th impingement-channel normal, TACTGRID constructs vertical "orthogonal" links, as previously described, between the pressure-side insert outer wall and the suction-side insert outer wall. This point on the pressure-side insert outer wall is moved back and forth in a bisection root-finding procedure until the length of the generated vertical orthogonal link equals the specified end width of the insert, SDUMP. The first four iterations of this procedure (lines 1 to 4 in fig. 18) as well as the last iteration (21st iteration - line labeled "SDUMP") are shown in figure 18.

The practice of constructing so-called "approximate streamlines" in the coolant flow regions is motivated by a desire to minimize the errors inherent in accepting a one-dimensional flow approximation. By approximating the streamlines, TACTGRID is able to construct cross sections that are more nearly normal to the flow. The outer streamlines in the impingement crossflow channel are taken as the channel boundaries, and a mean streamline is determined by the spline curve passing through the half-length points along the inner surface normals, as previously explained. In the trailing-edge region, vertical "orthogonal" links are constructed between the pressure-side inner wall and the suction-side inner wall, from the previously determined station positions on the pressure-side inner wall. Nine points are taken equidistant along these vertical links. The horizontal spline curves that pass through these points comprise the approximate streamlines (fig. 19). TACTGRID then constructs eight vertical orthogonal links across the approximate streamlines to determine the channel cross-sectional flow areas. Figure 20 shows the resulting vertical orthogonals and the trailing-edge-channel mean streamline (dotted line), which is constructed by passing one spline curve between each pair of vertical orthogonals at their midpoints. Each horizontal spline curve between two vertical orthogonals is normal to the vertical orthogonals at its end points. Figure 20 shows that in TACTGRID the array elements NTRLDG(I, 9) play the roles of THK(3) in TACT1 and that the differences STRLDG(I) - STRLDG(I-1) are used to calculate TDLX(5) for TACT1. The points where the flow-passage vertical orthogonals intersect the suction-side inner surface in regions V and VI determine the station positions on the suction side in these regions.

If the coating, metal, and impingement-channel thicknesses have no chordwise variation, the horizontal contours previously mentioned will constitute mathematically parallel curves in the plane of the cross section (except for the wall portions in region VI), and the vertical orthogonals will be straight lines. This is a so-called "normal" coordinate system that is commonly employed in two-dimensional boundary layer calculations. However, if chordwise variation is specified, and also because of the automatic wall thickness tapering in region VI, a situation will be encountered wherein the vertical orthogonals are curved. The midmetal line and impingement-channel mean streamline, when constructed as has been explained, will not cut these vertical orthogonals precisely in two. Nonetheless, TACT1 requires that the vertical orthogonals be divided into two equal segments. Therefore, TACTGRID has built into it a procedure that will automatically redefine the midmetal horizontal orthogonals and reconstruct the vertical orthogonals, whenever the vertical orthogonals are not split precisely in two. This is an iterative procedure that alters the horizontal orthogonals and then reconstructs the vertical orthogonals, over and over again, until the vertical orthogonals are equally divided. Experience with the program has shown that when no chordwise thickness variation is specified, the midmetal and mean-streamline contours will split the vertical orthogonals closely enough in region VI that the iterative procedure is never triggered.

TACTGRID calculates the arc lengths between nodal points along the horizontal and vertical orthogonals after the vertical orthogonals have been constructed. All the horizontal contours, as well as the vertical orthogonals in the trailing-edge flow region, are represented mathematically by spline curves which are obtained by using the curve-fitting programs of references 1 and 2. TACTGRID calculates the perimeter of the inside wall of the insert, SPLNUM, as well as the cross-sectional area of the interior of the plenum, APLNUM. The cross-sectional area is calculated by using the formula for the area underneath a spline curve from subroutine INTGRL of reference 7. The hydraulic diameter of the insert, which is provided to TACT1 along with the cross-sectional area, is calculated as DHYDRP = 4*APLNUM/SPLNUM.

DIFFERENCES IN PROGRAM PROCEDURE FOR SUCCEEDING SLICES

TACTGRID employs a number of modifications to this procedure when the slice number, ISLICE, is greater than 1.

In the circular region, if ISLICE is greater than 1, TACTGRID skips the station position calculations based on the number of vertical orthogonals selected for this region and instead determines station positions by placing the stations at the same fractions of external-surface arc length that they occupied in the first slice. This is to prevent severe misalinement of stations between slices, which would invalidate the orthogonality assumption implicit in TACT1. If some of the calculation stations that were on the circle in the first slice fall beyond the circular region in the new slice, the vertical orthogonals for these stations are constructed like those for spline-region stations.

In the spline region also, if ISLICE is greater than 1, station positions are determined by placing the stations at the same fractions of external-surface arc length that they occupied in the first slice. The station vertical orthogonals are now generated in the blade shell from these points on the outside wall, rather than from points on the inside wall as was done for the first slice. The station positions on the suction-side inner surface for regions V and VI are determined as before, however; and the vertical orthogonals are generated from the inside wall in regions V and VI for the suction side. If some of the spline-region calculation stations of the first slice fall in the circular region in the new slice, the vertical orthogonals for these stations are constructed like those for circular-region stations.

The position of the plenum end is located as before, but now the end will no longer line up with calculational stations (figs. 4(b) and (c)). The stations marking the end of the impingement region will be considered as the last stations on the suction and pressure sides before the plenum end. The output coordinates of the plenum end are printed out even for slices beyond the first. However, for ISLICE greater than 1, the first index of the output coordinates for these four end points is NPLNUM + 1 rather than NPLNUM, where NPLNUM is the sum of the number of stations in regions II, III, and IV for the particular slice. For instance, the horizontal arc length coordinate of the plenum end point on the suction-side insert outer surface, in figure 4(b), will be listed in the output as STT(17,6), because there are 16 impingement-region stations in the spline region on the suction side.

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APPENDIX - PROGRAM STRUCTURE AND FUNCTION

The TACTGRID program consists of a main program, GRID1N, and seven primary subroutines (SGRID2, SGRID3, SGRID4, SGRID5, SGRID6, SGRID7, and SGRID8). These subroutines, in turn, call a number of special-purpose subroutines (secondary subroutines). The calling relations between GRID1N and the various subroutines are shown in figure 21. The vertical positions of the subroutines in figure 21 reflect their order of occurrence in the calling sequence. They are described in this order here.

As shown in figure 21, the flow of the TACTGRID program is divided among the main program GRID1N and subroutines SGRID2 to SGRID8 in a linear progression of the grid construction. This was done merely to accommodate the compilation storage limitations of the IBM TSS/360-67 computer at the Lewis Research Center, on which the TACTGRID program is mounted. The functions of GRID1N and each of the subroutines in TACTGRID are described in this appendix. The word descriptions of subroutines obtained from other sources are taken from the references cited.

Main Program GRID1N

The main program GRID1N reads in, and prints back out, all TACTGRID input. It calls subroutine TIME to obtain the date and time of the run. GRID1N contains those plot labels that are common to all the blade slice plots. It initializes the counters for the number of stations in the circular region, the impingement spline region, and the trailing-edge spline region (for the suction and pressure sides) as the values for the first slice. These values will be altered by subroutines GRID2N and GRID4N for succeeding slices.

GRID1N calls subroutine TFORM to transform the external blade contour description from (z,θ)-coordinates to Cartesian (x,y) coordinates. It converts all geometrical quantities that were not previously converted by TFORM from (z,θ)-coordinates to (x,y)-coordinates. It also converts all those variables still in the input units to the user-designated units. It retains the parameters of the first slice's coordinate system for converting later slice output coordinates to the first slice's coordinate system, which is taken as global.

GRID1N sets up the data set BLADE.PLOTS to store the plots of the blade slices. It sets up the identification number, the imaginary axes, and the scale for each slice plot. GRID1N plots the (x,y)-coordinates returned by TFORM. It also plots the two leading-edge circle centers (the circular regions on the suction and pressure sides need not have a common origin; ref. 4), the origin of the TSONIC coordinate system (same as TFORM origin), and the line joining these points. This line is the z-axis of the TSONIC coordinate system.

GRID1N calculates the angular extent of the suction- and pressure-side circular regions (from the TSONIC axis) and the slope of the profile at the four circle-spline juncture points.

After all these functions have been completed, GRID1N turns over control of the program to subroutine SGRID2. After cycling through subroutines SGRID2 to SGRID8, control returns to GRID1N, which then stores the plot under its identification number in the data set BLADE.PLOTS, by calling subroutine ENDID. The plot is thus saved for redisplay at some future time. GRID1N does display the plot at this time as well, on the device previously selected by the user. The slice counter ISLICE is then incremented by 1, and GRID1N loops back to read the TACTGRID input for the next blade slice. The TACTGRID program is terminated by GRID1N, upon exhaustion of the input data, with a conditional READ statement.

Subroutine TIME

Subroutine TIME is a general-utility subroutine available on the IBM TSS/360-67 computer at the Lewis Research Center. It places the numerical characters for the month, day, year, hour, and minute, when called, into array ALPH. This string of characters is printed on the first page of the output and displayed in the upper right corner of the plot (fig. 4).

Subroutine TFORM

TFORM is the main program of the code in reference 6. This main program is converted into a subroutine for use by TACTGRID. As in reference 6, TFORM uses subroutines ROOT, FUNCT, and BLCD; but the spline curve subroutine of reference 6, SPLN22, has been replaced by an improved spline program, SPLISL. The function of TFORM and its slave subroutines is described in detail in reference 6.

Subroutine SPLISL

Subroutine SPLISL calculates the first and second derivatives of a cubic spline curve at the spline points. It is found in the MERIDL code and described in reference 8. The SPLISL routine is based on the end condition of specified slopes at the two end points.

Subroutine BEGID

Subroutine BEGID is a Lewis Research Center graphics system subroutine. It marks the beginning of a set of common plot orders and assigns an idenfification number to the set. By referring to the Lewis graphics system manual (ref. 9), the user should be able to replace the graphics subroutines in TACTGRID by graphics subroutines of comparable function available at his facility The word descriptions of these subroutines are taken from reference 9.

Subroutine SCALE

Subroutine SCALE is a Lewis graphics system subroutine. It scans an array of plot coordinates to determine maximum and minimum values. These values are used by the graphics package to set the scale of the plot.

Subroutine SETFRM

Subroutine SETFRM is a Lewis graphics system subroutine. It allows the user to specify the number of frames in his plot, creating a larger physical plotting area in the x-direction.

Subroutine NAXIS

Subroutine NAXIS is a Lewis graphics system subroutine. It enables the user to specify display boundaries when no axes are to be drawn. GRID1N uses this subroutine to position the blade slice plot within the frame.

Subroutine SCISS

Subroutine SCISS is a Lewis graphics system subroutine. It allows the user to set image scissoring options. Image scissoring involves truncating those portions of a display unit that extend beyond the boundaries of the plot or device. GRID1N uses this subroutine to set the scissoring at screen boundaries but employs an option which allows continued point examination after scissoring.

Subroutine GPLOT

Subroutine GPLOT is a Lewis graphics system subroutine. It enables the user to plot single or multiple curves or lines as vector, point, symbol, or vector-symbol plots.

Subroutine ENDID

Subroutine ENDID is a Lewis graphics system subroutine. It indicates the end of a set of common plot orders assigned an identification number by subroutine BEGID. At the user's option, this subroutine will save the plot order set in a user-provided partitioned data set (VPAM) or in virtual memory. GRID1N uses subroutine ENDID to save the plots of the individual blade slices in the VPAM data set BLADE.PLOTS. The identification number of each slice plot is the same as the slice number ISLICE.

Subroutine DISPLA

Subroutine DISPLA is a Lewis graphics system subroutine. It defines the end of a display or plot and initiates transmission of plot orders to the plotting device.

Subroutine TERM

Subroutine TERM is a Lewis graphics system subroutine. It closes the graphics data set and performs cleanup functions. GRID1N uses subroutine TERM to terminate the plotting and close the data set BLADE.PLOTS before terminating the program itself.

Subroutine SGRID2

Subroutine SGRID2 determines those TFORM-calculated points that are in the spline portion of the blade. It calculates the surface lengths of the suction- and pressure-side outer walls (STPNEW and SBTNEW) in order to determine where to begin tapering the wall and channel thicknesses in accordance with the input arrays THK1T, THK2T, THK3T, THK1B, THK2B, and THK3B described previously. SGRID2 plots the outside-wall spline contours for debugging purposes. Subroutine SGRID2 plots the radial lines defining the ends of the circular regions on the suction and pressure sides, for reference on the blade slice plot. For slices beyond the first, these lines need not coincide with the last circular-region stations.

SGRID2 calculates all the nodal points (and intermediate vector plotting points) in the circular region of the blade shell. It plots the circular-region horizontal and vertical orthogonals in the blade shell.

Subroutine SGRID2 calculates the normal-direction and tangential-direction arc length distances (arrays NCB, NCT, SCB, and SCT of the output) along the grid orthogonals in the blade shell for the circular portion of the blade.

Subroutine SPINSL

Subroutine SPINSL is a cubic spline-curve program used for interpolation, including interpolation of first and second derivatives. It is found in the MERIDL code and described in reference 8. It uses end conditions of specified end-point slope. SPENSL is an alternate entry point.

Subroutine SGRID3

Subroutine SGRID3 calculates the arrays of points on the horizontal orthogonals for the suction and pressure sides in the blade walls. The first horizontal orthogonal is the blade outer surface. The fourth horizontal orthogonal is the blade inner surface. SGRID3 uses the root-finding subroutine ROOT in two levels of iteration (see section PROGRAM PROCEDURE FOR FIRST SLICE) to cut the straight trailing-edge channel and employs subroutine INRSCT to locate the intersections of the outer surface normals with the channel walls. These points are used to fit the spline curve in region VI of the blade (fig. 10).

Subroutine SGRID3 constructs the three horizontal orthogonals for the impingement crossflow channel and insert walls. The second horizontal defines the insert outer contour. The third horizontal orthogonal defines the insert inner contour.

Subroutine SGRID3 calculates the surface lengths of the blade-shell inner contours for use in determining the distribution of station positions, as described previously. SGRID3 plots the blade-shell inner surface contours for debugging purposes.

Subroutine ROOT1

Subroutine ROOT1 is the bisection-method, root-finding subroutine ROOT in the older version of the MERIDL code (ref. 10). Two copies of subroutine ROOT, one called ROOT1 and the other ROOT2, are used by subroutine SGRID3. The two names are necessary because two nested loops use the bisection procedure for iteratively determining the orientation of the trailing-edge channel and a subroutine may not call itself (fig. 21).

Subroutine FUNC1

Subroutine FUNC1 is the external subroutine in the argument of ROOT1 that calculates the function whose root is to be found. In this case, for the outer iteration loop (see section PROGRAM PROCEDURE FOR FIRST SLICE), this function is the directed distance $\mathrm{sgn}(X_I - X_J)*|\overline{IJ}|/\mathrm{THKHOL}$ of figure 16(a), where $\mathrm{sgn}(a) = 1$ for $a \geq 0$ and $\mathrm{sgn}(a) = -1$ for $a < 0$.

Subroutine ROOT2

Subroutine ROOT2 is the second copy of subroutine ROOT, referred to previously, which is called by subroutine FUNC1 for the inner-loop iteration (fig. 21).

Subroutine FUNC2

Subroutine FUNC2 is the external subroutine in the argument of ROOT2 that calculates the function whose root is to be found. In this case, for the inner iteration loop (see section PROGRAM PROCEDURE FOR FIRST SLICE), this function is the difference in lengths $(|\overline{EB}| - |\overline{FD}|)/\mathrm{THKHOL}$ of figure 15(a).

Subroutine INWSCT

Subroutine INWSCT is a program for finding the intersection of two spline curves by the method of slopes. It is the INRSCT subroutine of reference 8 with two changes. The first change is that the search begins at the right end point of the search interval rather than in the middle. The other change is that the first curve is fit with subroutine SPINSL and the second curve with subroutine SPLINT, rather than both curves being fit with SPLINT, as is done in INRSCT. Subroutine INRSCT is described in reference 8. INWSCT is used by FUNC2 for finding the intersection of the trailing-edge-channel bottom surface with the blade pressure-side inner surface.

Subroutine SPLINT

Subroutine SPLINT is a cubic spline-curve program used for interpolation, including interpolation of first and second derivatives. It is found in the MERIDL code and described in reference 8. It uses the end-point condition that the second derivative at either end point is one-half that of the next spline point. SPLENT is an alternate entry point.

Subroutine INRSCT

Subroutine INRSCT is the intersection-finding program (mentioned previously) of reference 8. It is described in that reference.

Subroutine SPLNSL

Subroutine SPLNSL is a cubic spline-curve program used for interpolation, including interpolation of first and second derivatives. It is a hybrid of the two spline-curve programs SPLINT and SPINSL of reference 8. SPINSL is a spline-curve program that requires specified slopes for its end condition. SPLINT does not require the specification of slopes for its end condition. SPLNSL uses a specified slope for its left end condition and the SPLINT end condition for its right end condition. Subroutine SPLNSL is used for spline curve fitting of the midwall and impingement crossflow-channel horizontal contours, where the left-end-point slope is known (tangential to a circular-region contour) but the right-end-point slope is not. SPONSL is an alternate entry point.

Subroutine SGRID4

Subroutine SGRID4 calculates the horizontal orthogonals (approximate streamlines) for the trailing-edge flow channel (regions V and VI of fig. 10). It locates the position of the plenum end within the blade. The subroutine determines station positions in the blade shell and generates the vertical orthogonals for the blade shell and in the trailing-edge flow channel.

Subroutine SGRID4 calculates the normal-direction arc length distances (arrays NBB and NTT of the output) along the vertical orthogonals in the blade shell for the spline portion of the blade. If needed, SGRID4 redefines the midwall horizontal orthogonal and reconstructs the vertical orthogonals in the blade shell, iterating until the vertical orthogonals are split in two.

Subroutine SGRID4 plots the blade-shell vertical orthogonals in the spline region of the blade.

The procedures employed in subroutine SGRID4 are discussed in the section PROGRAM PROCEDURE FOR FIRST SLICE.

Subroutine INTSCT

Subroutine INTSCT is identical to subroutine INRSCT except that the first curve is fit with subroutine SPINSL rather than subroutine SPLINT. It is used instead of

INRSCT in the orthogonalization procedure when the horizontal orthogonal has known end-point slopes.

Subroutine FUNC4

Subroutine FUNC4 is the external subroutine in the argument of a ROOT1 call in subroutine SGRID4. It is used in determining the intersection of the suction-side plenum external contour with the pressure-side plenum external contour. This intersection point then establishes the search interval in which to seek the location of the plenum end. FUNC4 calculates the difference $\left[Y_1(x) - Y_2(x)\right]/\text{SDUMP}$, where Y_1 is the ordinate of a point on the suction-side contour and Y_2 is the corresponding ordinate on the pressure-side contour. Of course, when $Y_1(x) = Y_2(x)$, the intersection has been found.

Subroutine FUNC3

Subroutine FUNC3 is the external subroutine in the argument of a ROOT1 call in subroutine SGRID4. It constructs a vertical orthogonal link (by the method of ref. 5) between the pressure- and suction-side plenum external contours, from a search point on the pressure-side contour. It calculates the length of this vertical orthogonal link, ENDLNG. FUNC3 then evaluates the function (SDUMP - ENDLNG)/SDUMP, whose root is found by ROOT1, to determine the position of the plenum end.

Subroutine INMSCT

Subroutine INMSCT is the same as subroutine INTSCT except that the first curve is fit with subroutine SPLNSL rather than with subroutine SPINSL. It is used instead of INRSCT in the orthogonalization procedure when the horizontal orthogonal has a known left end-point slope.

Subroutine SGRID5

Subroutine SGRID5 calculates the tangential-direction arc length distances (arrays SBB and STT of the output) along the horizontal orthogonals in the blade shell for the spline region of the blade. It interpolates points between grid points in the spline region of the blade shell in order to plot the horizontal orthogonals and to calculate arc lengths between grid points accurately. The subroutine plots the horizontal orthogonals in the blade shell for the spline region of the blade.

Subroutine SGRID6

Subroutine SGRID6 constructs the orthogonal grid for the impingement crossflow channel by generating vertical orthogonals from the blade inner-surface nodal points. The routine calculates the normal-direction arc length distances (arrays NBB and NTT of the output) along vertical orthogonals in the impingement crossflow channel.

If needed, SGRID6 redefines the mean streamline and reconstructs the vertical orthogonals in the impingement crossflow channel - iterating until the vertical orthogonals are split in two. SGRID6 plots the impingement-crossflow-channel vertical orthogonals in the spline region of the blade.

Subroutine SGRID7

Subroutine SGRID7 calculates the tangential-direction arc length distances (arrays SBB and STT of the output) along the horizontal orthogonals in the impingement crossflow channel for the spline region of the blade. It interpolates points between grid points (and intersection points of vertical orthogonals with the plenum inner and outer contours) in the spline region of the impingement crossflow channel in order to plot the horizontal contours and to calculate arc lengths between stations accurately. This subroutine plots the horizontal contours in the channel (mean streamline and insert inner and outer surfaces) for the spline region of the blade.

Subroutine SGRID7 calculates the plenum perimeter, cross-sectional area, and hydraulic diameter and plots the insert end length. This is the dump hole opening if a "cutoff" design for the insert is used. SGRID7 calculates all the nodal points (and intermediate vector plotting points) in the circular region of the impingement crossflow channel. It plots the circular-region horizontal and vertical orthogonals in the channel. SGRID7 calculates the normal-direction and tangential-direction arc length distances (arrays NCB, NCT, SCB, and SCT of the output) along the grid orthogonals in the impingement crossflow channel (including insert surfaces) for the circular portion of the blade. SGRID7 calculates the channel heights and channel lengths for the stations in the trailing-edge channel, beginning with the mixing station. It plots the mean streamline and channel vertical orthogonals. SGRID7 prepares the TACT1 input data set for the individual blade slice (fig. 13(f)).

Subroutine SGRID8

Subroutine SGRID8 calculates the arrays of points used in constructing the arrows to the calculation stations and plots these arrows with the station numbers indicated.

SGRID8 calculates the scale of the plot and prints the scale and legend on the plot, as well as all other plot labels. SGRID8 transforms the output coordinates of the individual blade slices to the TFORM coordinate system set up for the first slice, which is taken as global. The subroutine then prints out these transformed coordinates in the form depicted in figure 13(g).

Subroutine NUMBER

Subroutine NUMBER is a Lewis graphics system subroutine. It allows the user to convert an integer or real number to an array of printable characters. It is used by subroutine SGRID8 to convert the station numbers to character data (A4 format) so that they can be printed on the blade slice plot by subroutine CHARS.

Subroutine CHARS

Subroutine CHARS is a Lewis graphics system subroutine. It allows the user to print character data anywhere on a plot. It is used by subroutine SGRID8 for printing the labels and station numbers on the plots of the blade slices.

REFERENCES

1. Katsanis, Theodore; and McNally, William D.: Revised FORTRAN Program for Calculating Velocities and Streamlines on the Hub-Shroud Midchannel Stream Surface of an Axial-, Radial-, or Mixed-Flow Turbomachine or Annular Duct. I - Users Manual. NASA TN D-8430, 1977.

2. Katsanis, Theodore: FORTRAN Program for Calculating Transonic Velocities on a Blade-to-Blade Stream Surface of a Turbomachine. NASA TN D-5427, 1969.

3. Crawford, M. E.; and Kays, W. M.: STAN5-A Program for Numerical Computation of Two-Dimensional Internal and External Boundary Layer Flows. NASA CR-2742, 1976.

4. Gaugler, Raymond E.: TACT1, A Computer Program for the Transient Thermal Analysis of a Cooled Turbine Blade or Vane Equipped with a Coolant Insert. I - Users Manual. NASA TP-1271, 1978.

5. McNally, William D.: FORTRAN Program for Generating a Two-Dimensional Orthogonal Mesh Between Two Arbitrary Boundaries. NASA TN D-6766, 1972.

6. Katsanis, Theodore: FORTRAN Program for Calculating Axial Turbomachinery Blade Coordinates. NASA TM X-2061, 1970.

7. Katsanis, Theodore: Use of Arbitrary Quasi-Orthogonals for Calculating Flow Distribution in the Meridional Plane of a Turbomachine. NASA TN D-2546, 1964.

8. Katsanis, Theodore; and McNally, William D.: Revised FORTRAN Program for Calculating Velocities and Streamlines on the Hub-Shroud Midchannel Stream Surface of an Axial-, Radial-, or Mixed-Flow Turbomachine or Annular Duct. II - Programmers Manual. NASA TN D-8431, 1977.

9. Graphics System for TSS/360. Manual IB-1310-1002, NASA Lewis Research Center, Computer Systems Office, 1976.

10. Katsanis, Theodore; and McNally, William D.: FORTRAN Program for Calculating Velocities and Streamlines on the Hub-Shroud Midchannel Flow Surface of an Axial- or Mixed-Flow Turbomachine. II - Programmers Manual. NASA TN D-7344, 1974.

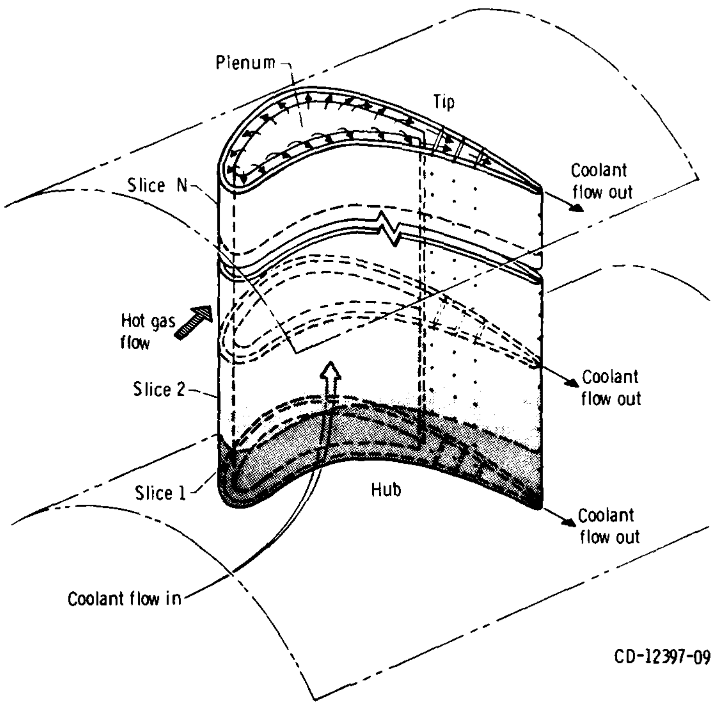


Figure 1. - Three-dimensional schematic view of a turbine blade equipped with impingement insert and pin fins.

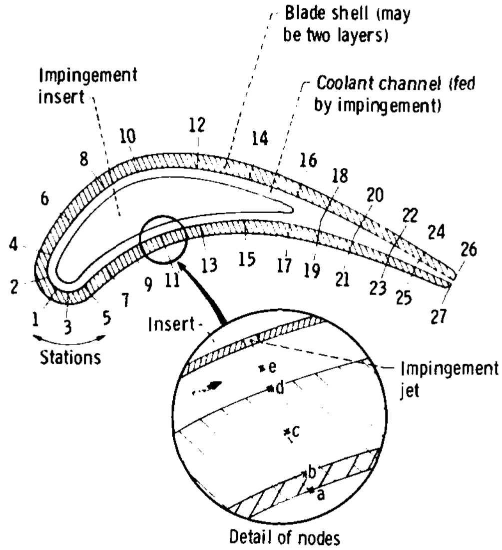


Figure 2. - Blade geometric model.

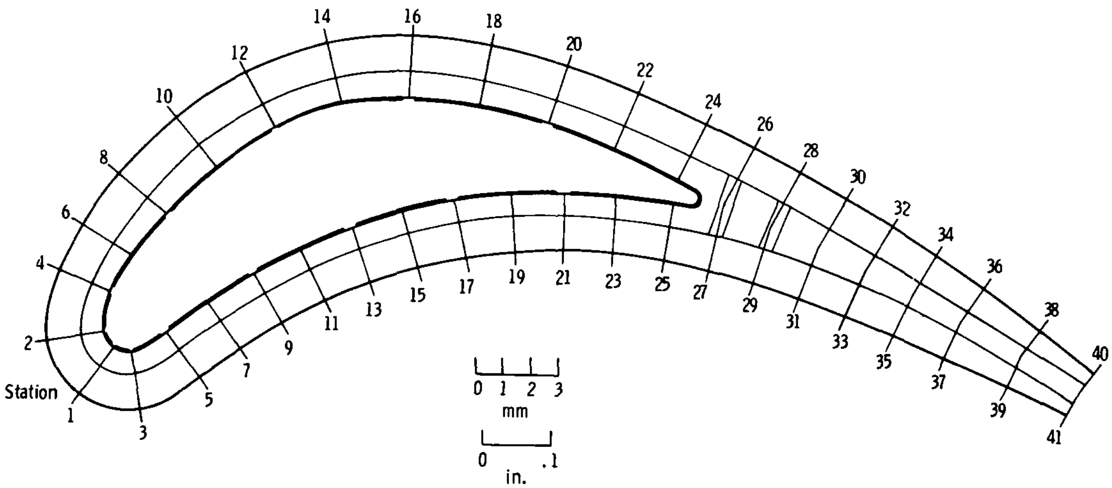
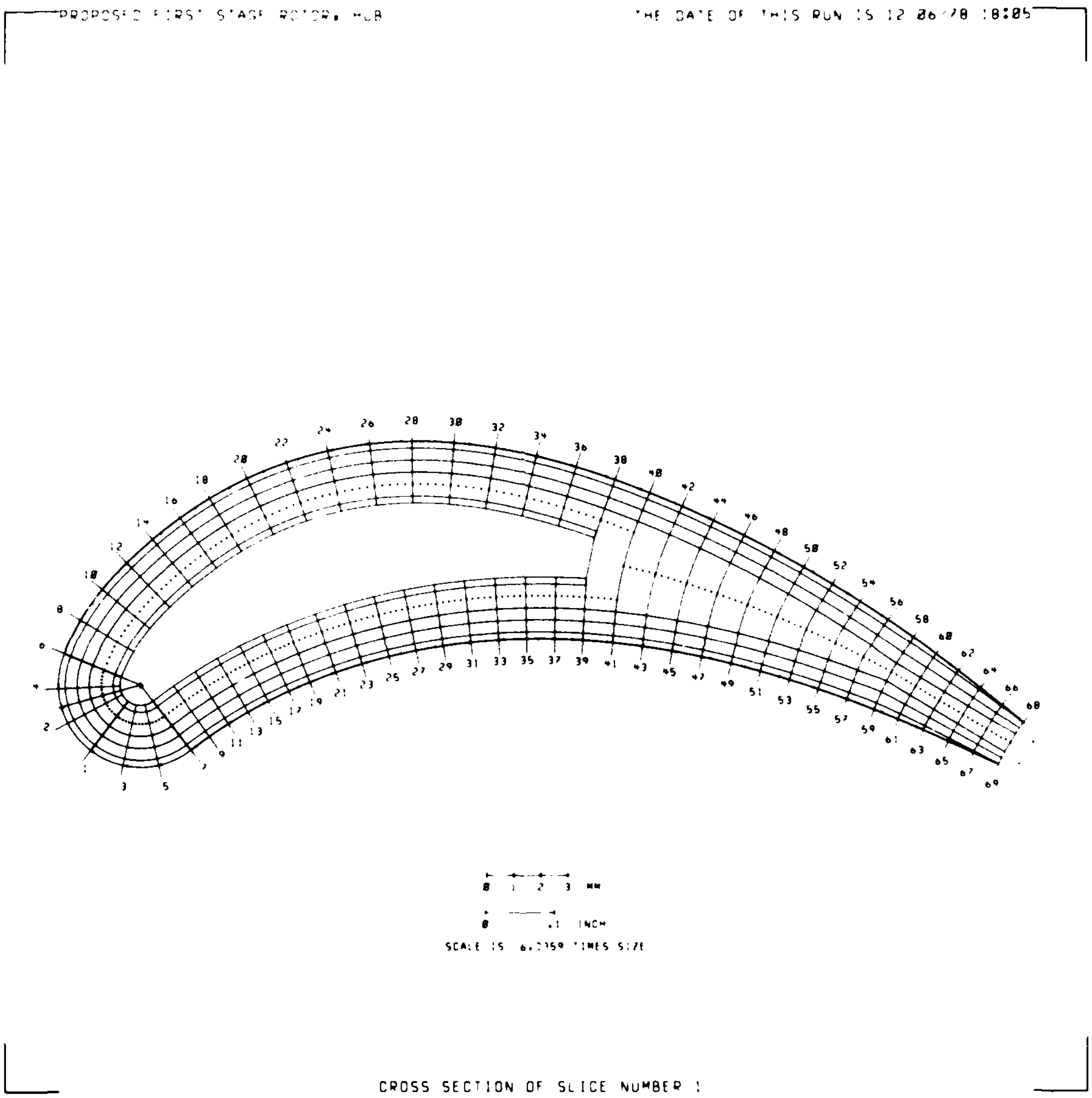
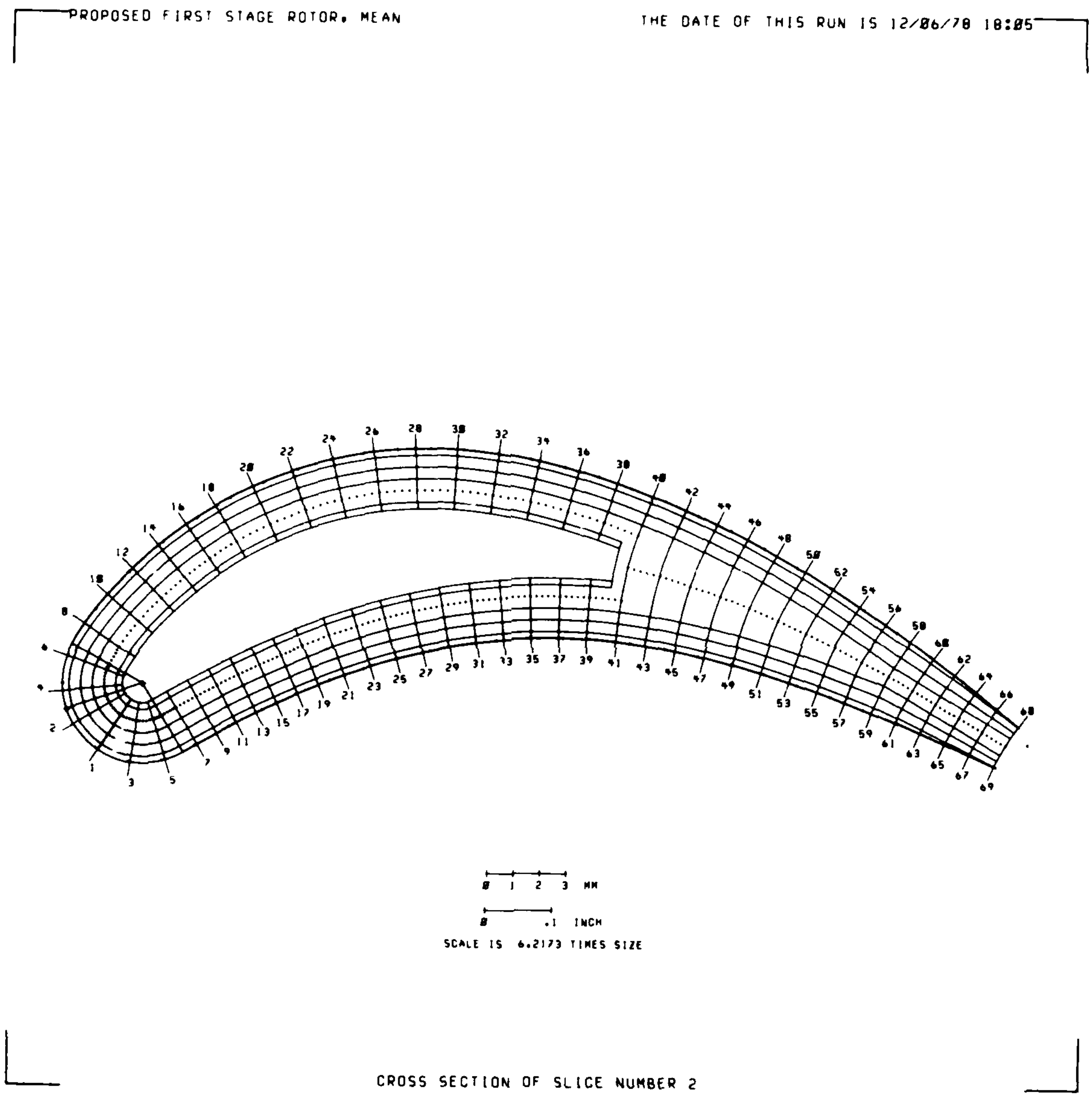


Figure 3. - Cross section of sample problem blade.



(a) Hub section of sample blade problem.

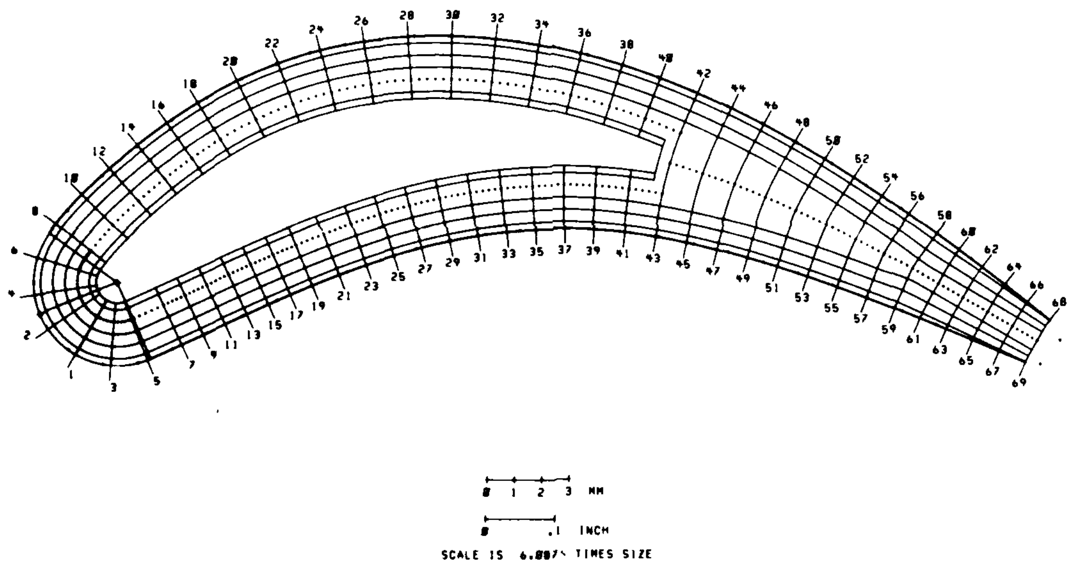
Figure 4. - Scaled computer plots of blade slices.



(b) Mean section of sample blade problem.

Figure 4. - Continued.

PROPOSED FIRST STAGE ROTOR, TIP THE DATE OF THIS RUN IS 12/06/78 10:05



CROSS SECTION OF SLICE NUMBER 3

(c) Tip section of sample blade problem.

Figure 4. - Concluded.

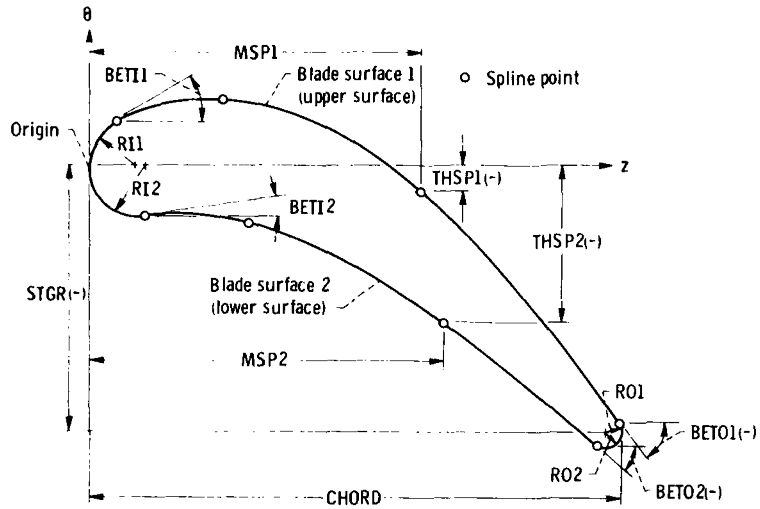


Figure 5. - Geometric input variables. Angles BETI1, BETI2, BETO1, and BETO2 must be given as true angle in degrees, not angle as measured in z-θ plane.

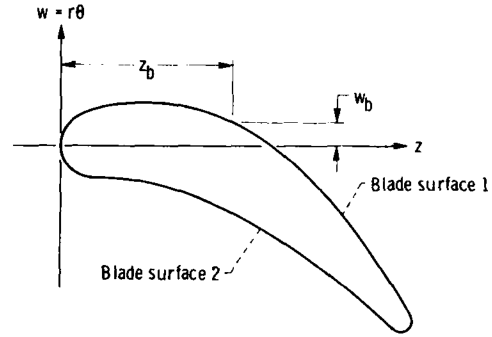


Figure 6. - Typical blade geometry.

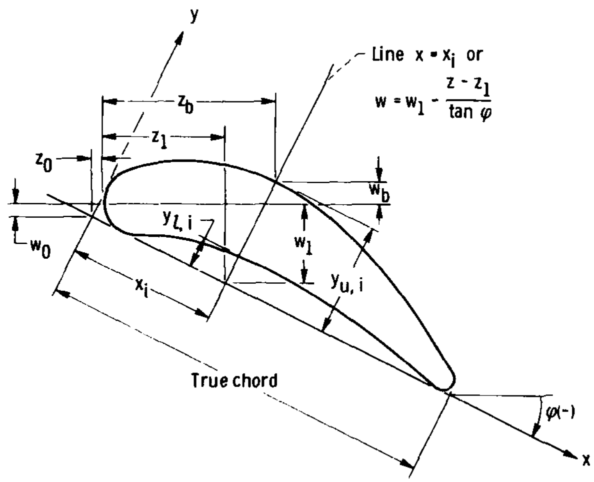


Figure 7. - Transformed coordinates and transformation constants.

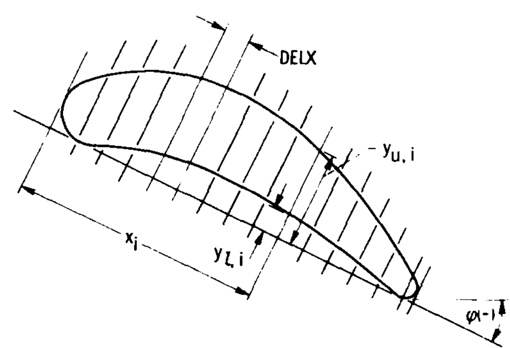
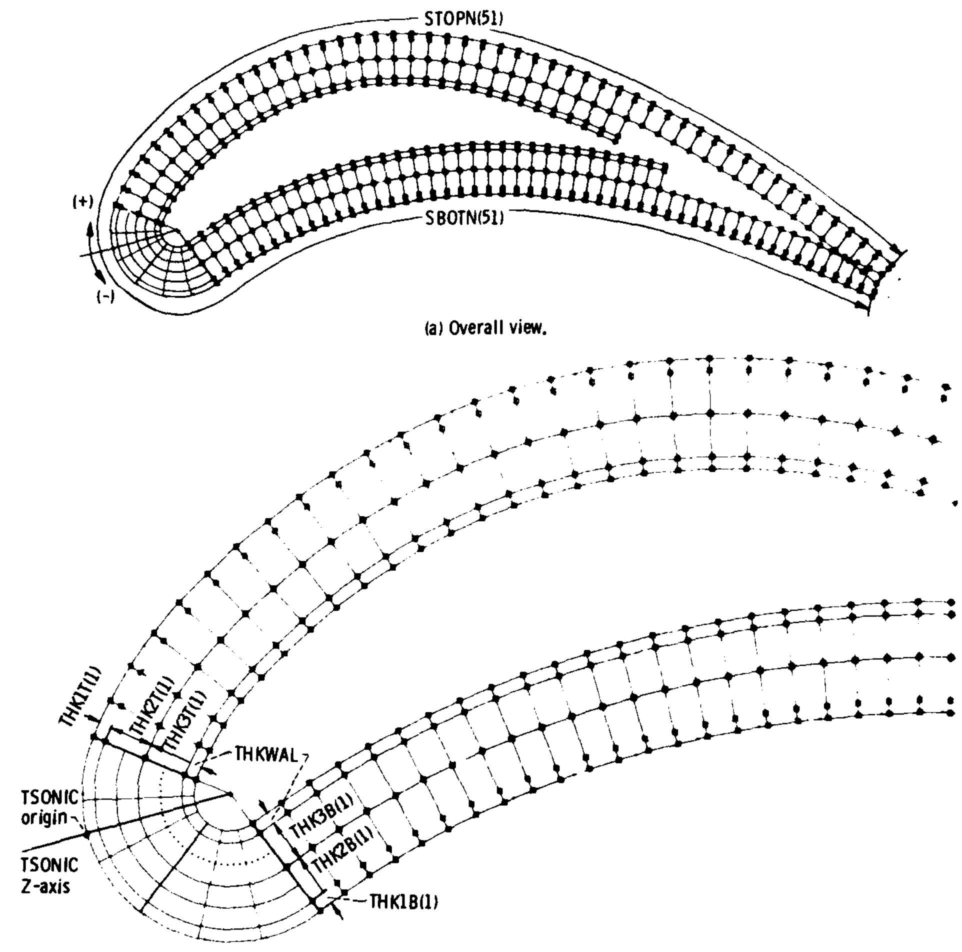


Figure 8. - Output coordinates.



(a) Overall view.

(b) Detail of blade wall and insert wall construction.

Figure 9. - Blade shell and impingement insert built up from input thickness arrays.

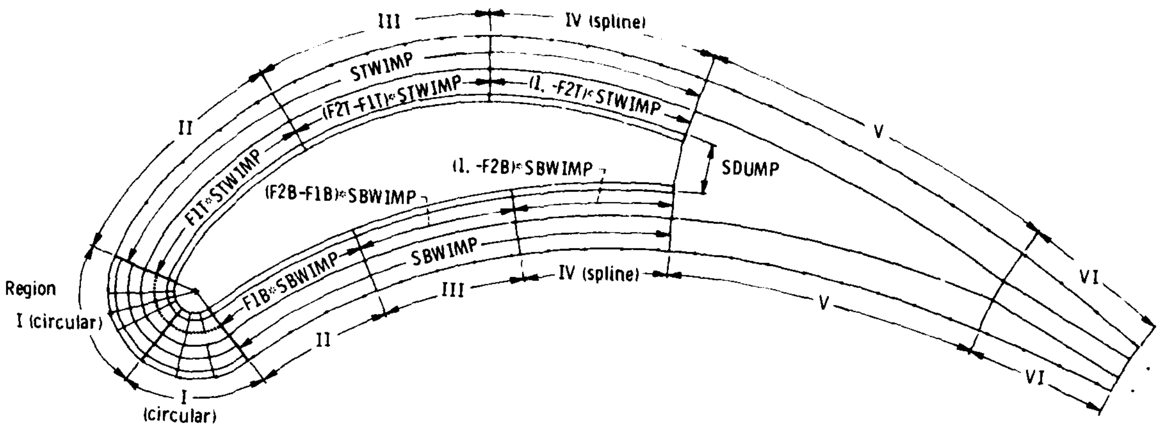


Figure 10. - Blade broken down into six regions.

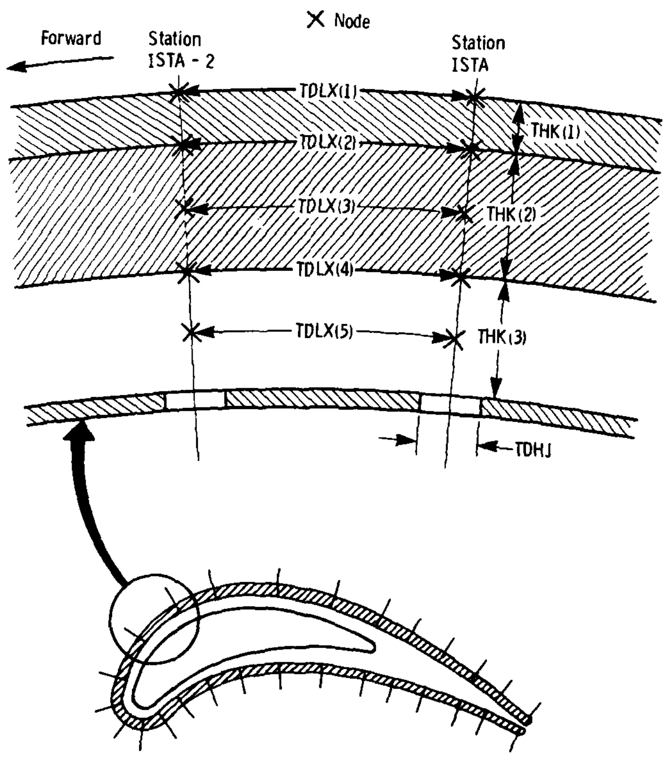


Figure 11. - Schematic geometric input variables. (SPAN and TXN are perpendicular to this plane.)

TACTGRID input

```
9.0       7.0
          3         2         1
.333333333.666666666.333333333.666666666
          4         6         5         5
          6         5         5         10        5
 &GEO THK1T=51*.010,THK2T=51*.035,THK3T=51*.035,THK1B=51*.010,THK2B=51*.035,THK3B=51*.035,&END
.0001     .0001     .030      .010      .080      8.875     8.50
0.0       0.0
```

TFORM input

```
PROPOSED FIRST STAGE ROTOR, HUB
0.03429   -0.05000  0.21589   39.37009  0.05000
0.003048  0.0008899 52.00     -56.28    7.00
0.00000   0.003810  0.01143   0.01788   0.02486   0.02921   0.00000
0.00000   0.02082   0.03001   0.02307   0.001480  -0.01812  0.00000
0.003048  0.0008899 22.00     -40.28    5.00
0.00000   0.01016   0.02032   0.03048   0.00000
0.00000   -0.006999 -0.01500  -0.04393  0.00000
```

TACT-GRID

```
 &GEO THK1T=51*.010,THK2T=51*.035,THK3T=51*.035,THK1B=51*.010,THK2B=51*.035,THK3B=51*.035,&END
.0001     .0001     .030      .010      .070      9.625     8.875
0.0       0.0
```

TFORM input

```
PROPOSED FIRST STAGE ROTOR, MEAN
0.03429   -0.05405  0.2349499 39.37009  0.05000
0.003048  0.0008899 42.00     -58.58    7.00
0.00000   0.003810  0.01143   0.01788   0.02409   0.02921   0.00000
0.00000   0.01751   0.02487   0.01850   0.0009950 -0.02175  0.00000
0.003048  0.0008899 12.00     -42.58    5.00
0.00000   0.01016   0.02032   0.03048   0.00000
0.00000   -0.009140 -0.01738  -0.04777  0.00000
```

TACT-GRID

```
 &GEO THK1T=51*.010,THK2T=51*.035,THK3T=51*.035,THK1B=51*.010,THK2B=51*.035,THK3B=51*.035,&END
.0001     .0001     .030      .010      .060      10.00     9.625
0.0       0.0
```

TFORM input

```
PROPOSED FIRST STAGE ROTOR, TIP
0.03429   -0.05750  0.2540    39.37009  0.05000
0.003048  0.0008899 32.00     -60.68    7.00
0.00000   0.003810  0.01143   0.01788   0.02340   0.02921   0.00000
0.00000   0.01470   0.02051   0.01461   0.0008370 -0.02444  0.00000
0.003048  0.0008899 2.00      -44.68    5.00
0.00000   0.01016   0.02032   0.03048   0.00000
0.00000   -0.01095  -0.01950  -0.05105  0.00000
```

(a) Sample problem input data set listing.

Figure 12. - TACTGRID input format.

1 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80
WRU	HRU						
NSLICE	UU	NFRAME					
F1T	F2T	F1B	F2B				
NVT	N1T	N2T	N3T				
N1B	N2B	N3B	N4B	N5B			
& GEO (THK1T ARRAY), (THK2T ARRAY), (THK3T ARRAY),							
(THK1B ARRAY), (THK2B ARRAY), (THK3B ARRAY), & END							
THK(1)	THK(3)	THKHOL	THKWAL	SDUMP	RRO	RRI	
Z	THETA						

(b) TACTGRID input form.

1 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80
TITLE							
CHORD	STGR	RMI	SCALE	DELX			
RI1	RO1	BETI1	BETO1	SPLNO1			
MSP1 ARRAY							
THSP1 ARRAY							
RI2	RO2	BETI2	BETO2	SPLNO2			
MSP2 ARRAY							
THSP2 ARRAY							

(c) TFORM input form.

Figure 12. - Concluded.

```
THE DATE OF THIS RUN IS 08/29/79 09:37
     WRO        HRU
   9.000      7.000
  NSLICE         UU      NFRAME
       3          2           1
     F1T        F2T         F1B        F2B
   0.333      0.667       0.333      0.667
     NVT        N1T         N2T        N3T
       4          6           5          5
     N1B        N2B         N3B        N4B        N5B
       6          5           5         10          5
&CHANLS NSLICE= 3,NSTA=69,IUNITS=2,&END
```

(a) TACTGRID and TACT1 overall input.

I	THK1T(I)	THK2T(I)	THK3T(I)	THK1B(I)	THK2B(I)	THK3B(I)
1	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
2	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
3	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
4	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
5	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
6	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
7	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
8	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
9	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
10	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
11	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
12	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
13	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
14	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
15	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
16	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
17	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
18	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
19	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
20	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
21	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
22	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
23	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
24	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
25	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
26	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
27	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
28	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
29	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
30	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
31	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
32	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
33	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
34	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
35	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
36	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
37	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
38	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
39	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
40	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
41	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
42	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
43	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
44	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
45	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
46	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
47	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
48	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
49	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
50	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350
51	0.0100	0.0350	0.0350	0.0100	0.0350	0.0350

THK(1)	THK(3)	THKHOL	THKWAL	SDUMP	RRO	RRI
0.000	0.000	0.030	0.010	0.080	8.875	8.500

Z	THETA
0.000	0.000

(b) TACTGRID geometrical input for blade slice.

Figure 13. - TACTGRID sample output.

```
PROPOSED FIRST STAGE ROTOR, HUB
     CHORD                STGR                RMI                SCALE             DELX
  0.3429000E-01  -0.5000000E-01   0.2158900           39.37009          0.5000000E-01
   BLADE SURFACE 1  --  UPPER SURFACE
     RI1                  RO1                BETI1              BETO1             SPLNO1
  0.3048000E-02   0.8898999E-03    52.00000          -56.28000          7.000000
     MSP1  ARRAY
  0.0000000       0.3810000E-02   0.1143000E-01    0.1788000E-01    0.2486000E-01    0.2921000E-01    0.0000000
     THSP1  ARRAY
  0.0000000       0.2082000E-01   0.3001000E-01    0.2307000E-01    0.1480000E-02   -0.1812000E-01    0.0000000
   BLADE SURFACE 2  --  LOWER SURFACE
     RI2                  RO2                BETI2              BETO2             SPLNO2
  0.3048000E-02   0.8898999E-03    22.00000          -40.28000          5.000000
     MSP2  ARRAY
  0.0000000       0.1016000E-01   0.2032000E-01    0.3048000E-01    0.0000000
     THSP2  ARRAY
  0.0000000      -0.6998997E-02  -0.1500000E-01  -0.4393000E-01    0.0000000
```

(c) TFORM input for blade slice.

```
             BLADE DATA AT INPUT SPLINE POINTS

                  BLADE      SURFACE    1
      M           THETA            DERIVATIVE       2ND DERIV.
  0.64614E-03     0.86921E-02      5.9287           -1810.4
  0.38100E-02     0.20820E-01      2.5064           -352.98
  0.11430E-01     0.30010E-01     -0.49750E-01      -317.91
  0.17880E-01     0.23070E-01     -2.1031           -318.79
  0.24860E-01     0.14800E-02     -3.9605           -213.40
  0.29210E-01    -0.18120E-01     -5.1321           -325.26
  0.34140E-01    -0.47712E-01     -6.9401           -408.18

                  BLADE      SURFACE    2
      M           THETA            DERIVATIVE       2ND DERIV.
  0.41898E-02    -0.13090E-01      1.8714           -321.57
  0.10160E-01    -0.69990E-02      0.27786          -212.27
  0.20320E-01    -0.15000E-01     -1.8399           -204.60
  0.30480E-01    -0.43930E-01     -3.8232           -185.82
  0.32825E-01    -0.53145E-01     -3.9254            98.618
```

(d) TFORM profile smoothness check.

```
 NO. OF POINTS =   30           PHI =  -15.74       DEGREES
    X                   Y LOWER            Y UPPER
  0.00000              0.12000            0.12000
  0.50000E-01          0.22533E-01        0.24055
  0.10000E 00          0.16786E-02        0.29761
  0.15000              0.38102E-02        0.34204
  0.20000              0.30113E-01        0.37863
  0.25000              0.64618E-01        0.40629
  0.30000              0.93299E-01        0.43177
  0.35000              0.11707            0.44969
  0.40000              0.13670            0.46259
  0.45000              0.15277            0.47086
  0.50000              0.16558            0.47482
  0.55000              0.17529            0.47476
  0.60000              0.18207            0.47094
  0.65000              0.18607            0.46358
  0.70000              0.18740            0.45297
  0.75000              0.18622            0.43944
  0.80000              0.18261            0.42331
  0.85000              0.17671            0.40485
  0.90000              0.16860            0.38428
  0.95000              0.15840            0.36182
  1.00000              0.14621            0.33759
   1.0500              0.13211            0.31148
   1.1000              0.11619            0.28335
   1.1500              0.98519E-01        0.25310
   1.2000              0.79181E-01        0.22065
   1.2500              0.58239E-01        0.18598
   1.3000              0.35841E-01        0.14909
   1.3500              0.12762E-01        0.10997
   1.4000              0.31670E-02        0.68658E-01
   1.4205              0.35035E-01        0.35035E-01
```

(e) TFORM output.

Figure 13. - Continued.

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```

(f) TACT1 input for blade slice.

Figure 13. - Continued.

SLICE NUMBER IS 1
COORDINATES FOR THE SUCTION SIDE

I	J	XCT (I,J)	YCT (I,J)	SCT (I,J)	NCT (I,J)	XTT (I,J)	YTT (I,J)	STT (I,J)	NTT (I,J)
1	1	0.04734	0.02450	-0.07749	0.01000	[illegible]	[illegible]	0.13376	0.01000
2	1	0.01379	0.06415	-0.02513	0.01000	0.06411	0.25691	0.18853	0.01000
3	1	0.00014	0.11427	0.02723	0.01000	0.10006	0.29767	0.24142	0.01000
4	1	0.00895	0.16546	0.07959	0.01000	0.13772	0.33190	0.29232	0.01000
5	1					0.17896	0.36346	0.34356	0.01000
6	1					0.22160	0.39186	0.39566	0.01000
7	1					0.27574	0.42111	0.45715	0.01000
8	1					0.33346	0.44434	0.51940	0.01000
9	1					0.39335	0.46115	0.58163	0.01000
10	1					0.45459	0.47140	0.64375	0.01000
11	1					0.51632	0.47523	0.70562	0.01000
12	1					0.57777	0.47309	0.76713	0.01000
13	1					[illegible]	0.46559	0.82823	0.01000
14	1					0.69771	0.45352	0.88878	0.01000
15	1					0.75559	0.43776	0.94877	0.01000
16	1					0.81213	0.41564	1.00833	0.01000
17	1					0.86222	0.40000	1.06192	0.01000
18	1					0.90937	0.38021	1.11305	0.01000
19	1					0.95504	0.35946	1.16322	0.01000
20	1					0.99966	0.33776	1.21264	0.01000
21	1					[illegible]	0.31505	[illegible]	0.01000
22	1					1.08606	[illegible]	1.31091	0.01000
23	1					1.12771	0.26862	1.35927	0.01000
24	1					1.16836	0.24141	1.40721	0.01001
25	1					1.20899	0.21456	1.45549	0.01007
26	1					1.24561	0.18909	1.50050	0.00915
27	1					1.27894	0.16487	1.54170	0.00726
28	1					1.31149	0.14027	1.58249	0.00551
29	1					1.34347	0.11518	1.62315	0.00375
30	1					1.37497	0.08959	1.66372	0.00196
31	1					1.40598	0.06354	1.70422	[illegible]

SLICE NUMBER IS 1
COORDINATES FOR THE SUCTION SIDE

I	J	XCT (I,J)	YCT (I,J)	SCT (I,J)	NCT (I,J)	XTT (I,J)	YTI (I,J)	STI (I,J)	NTI (I,J)
1	2	0.05340	0.03246	-0.07103	0.02750	0.04135	0.20903	0.12571	0.02750
2	2	0.02264	0.06881	-0.02304	0.02750	0.07185	0.25258	0.17893	0.02750
3	2	0.01013	0.11475	0.02496	0.02750	0.10763	0.29050	0.23068	0.02750
4	2	0.01820	0.16168	0.07295	0.02750	0.14416	0.32426	0.28089	0.02750
5	2					0.18391	0.35537	0.33136	0.02750
6	2					0.22616	0.38332	0.38204	0.02750
7	2					0.27997	0.41205	0.44306	0.02750
8	2					0.33668	0.43488	0.50422	0.02750
9	2					0.39553	0.45139	0.56537	0.02750
10	2					0.45572	0.46146	0.62642	0.02750
11	2					0.51644	0.46523	0.68729	0.02750
12	2					0.57697	0.46312	0.74787	0.02750
13	2					0.63676	0.45572	0.80813	0.02750
14	2					0.69538	0.44379	0.86797	0.02750
15	2					0.75269	0.42819	0.92736	0.02750
16	2					0.80876	0.40962	0.98644	0.02750
17	2					0.85850	0.39072	1.03966	0.02750
18	2					0.90535	0.37105	1.09047	0.02750
19	2					0.95076	0.35041	1.14037	0.02750
20	2					0.99517	0.32863	1.18972	0.02750
21	2					1.03861	0.30624	1.23869	0.02749
22	2					1.08110	0.28270	1.28726	0.02750
23	2					1.12254	0.25828	1.33536	0.02750
24	2					1.16297	0.23299	1.38305	0.02750
25	2					1.20330	0.20625	1.43143	0.02754
26	2					1.24049	0.18150	1.47612	0.02655
27	2					1.27473	0.15894	1.51712	0.02444
28	2					1.30822	0.13583	1.55780	0.02142
29	2					1.34120	0.11220	1.59837	0.01803
30	2					1.37374	0.08603	1.63830	0.01430
31	2					1.40583	0.06336	1.67938	0.01025

(g) Nodal point coordinates.

Figure 13. - Concluded.

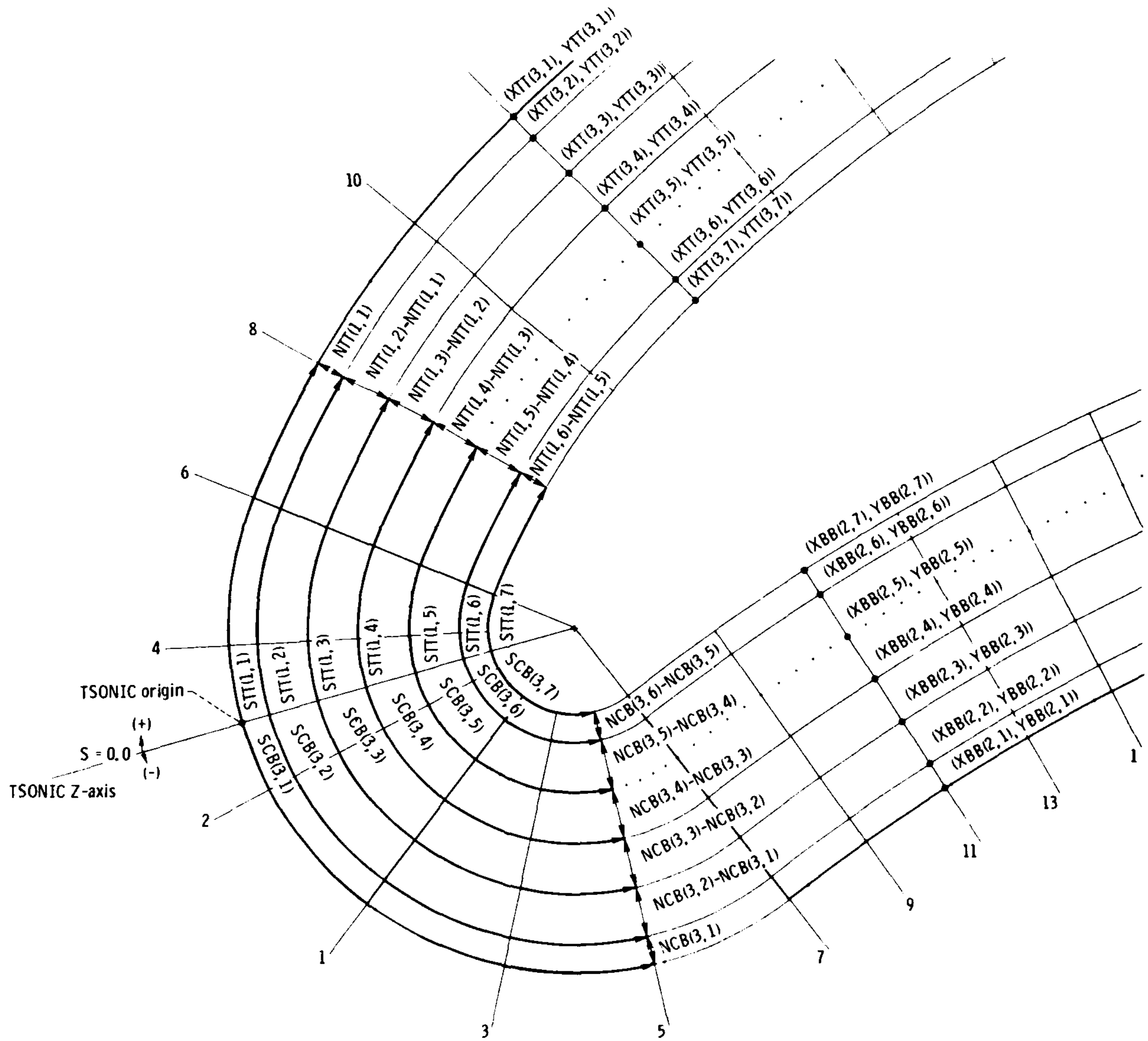
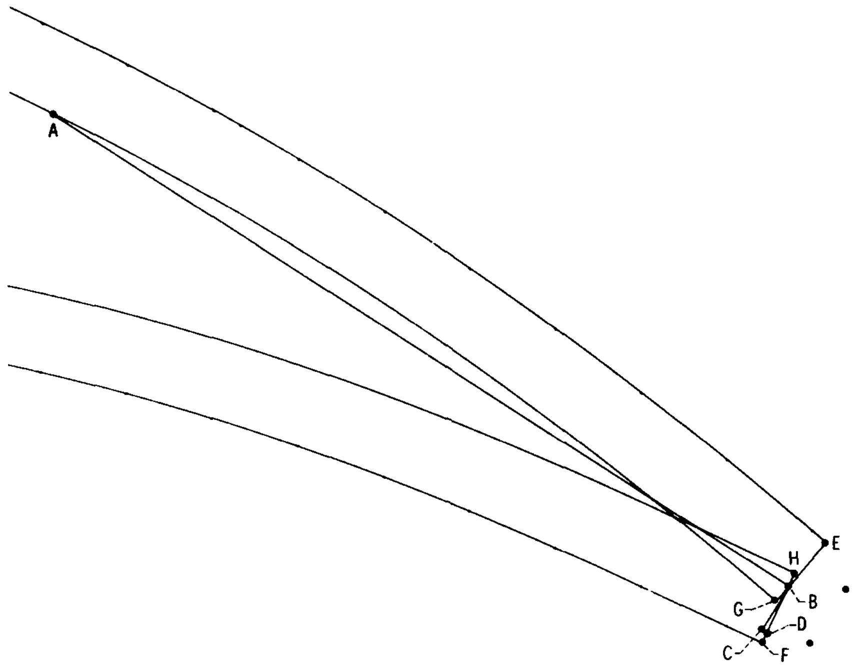
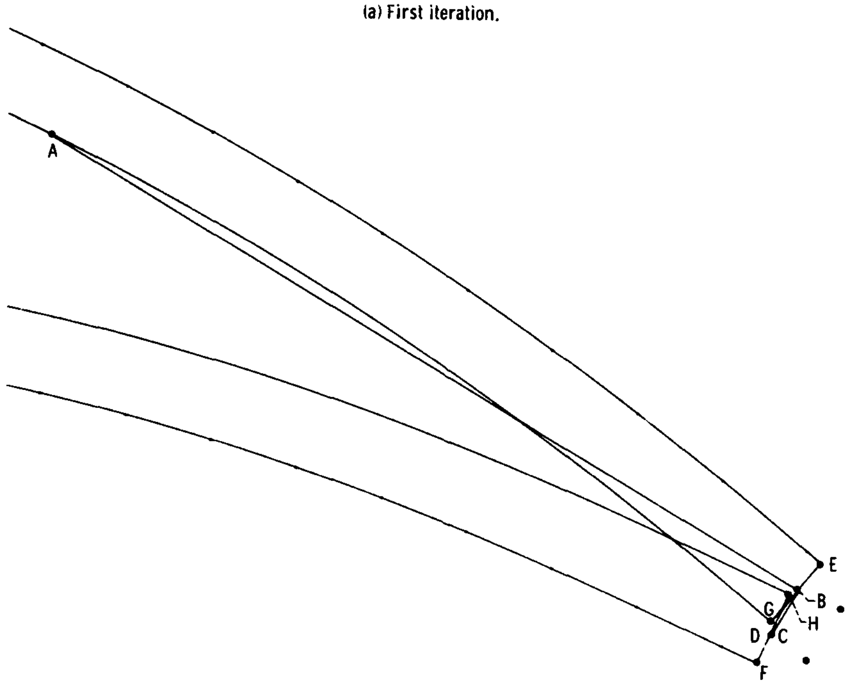


Figure 14. - Output coordinate terminology.

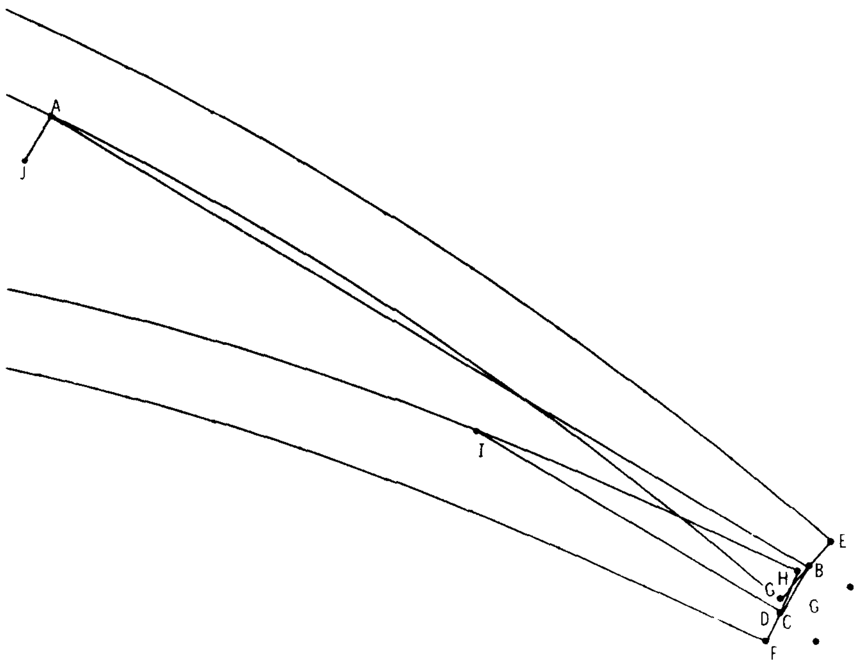


(a) First iteration.

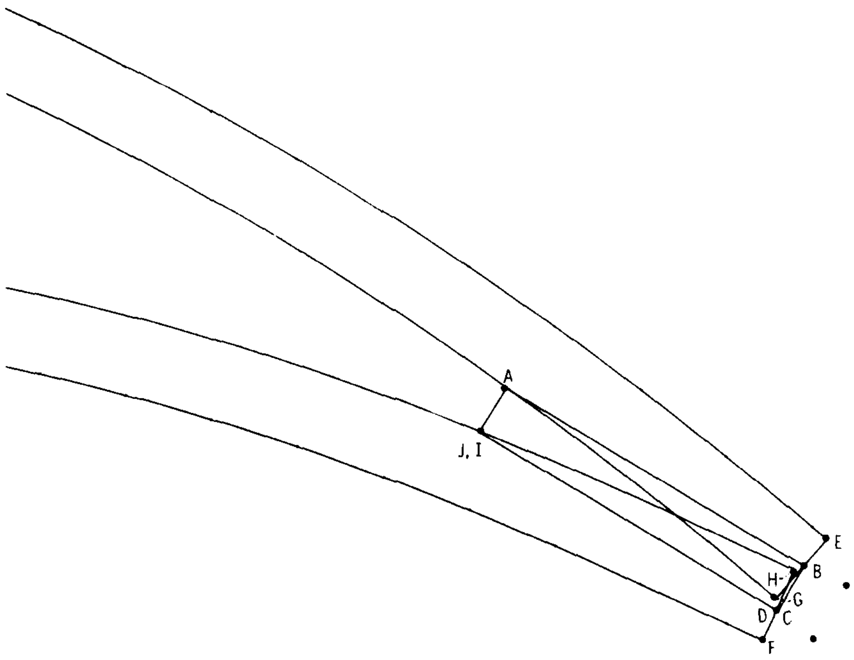


(b) Fifth iteration.

Figure 15. - Iterations of inner loop for cutting trailing-edge hole.



(a) First iteration.



(b) Seventeenth iteration.

Figure 16. - Iterations of outer loop for cutting trailing-edge hole.

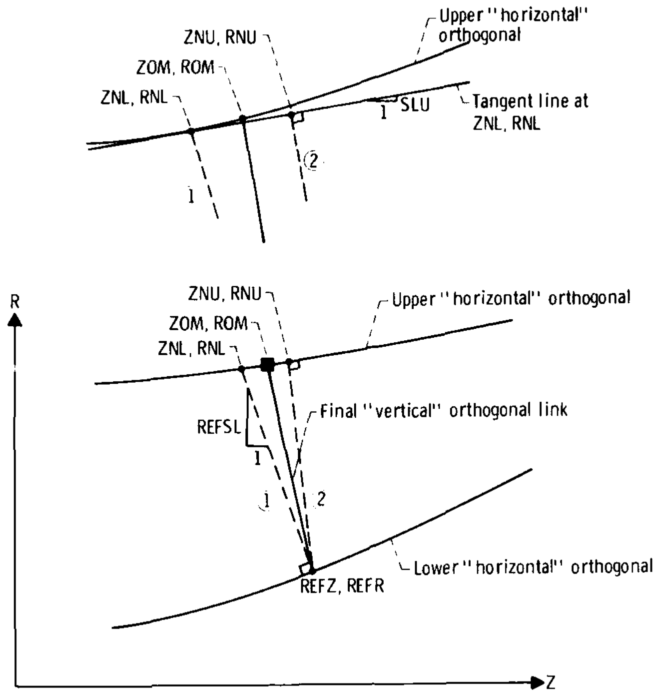


Figure 17. - Calculation procedure for a "vertical" orthogonal link.

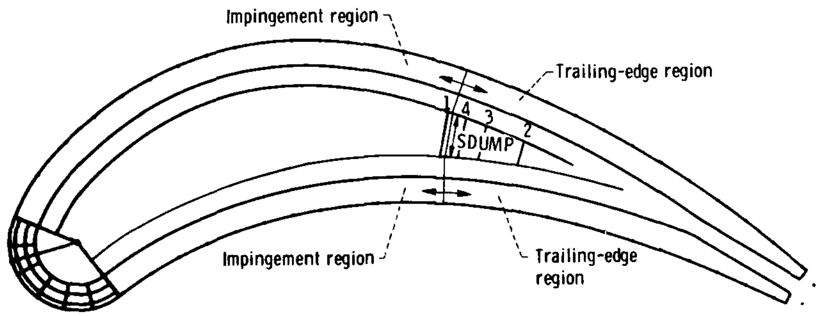


Figure 18. - Determination of location of end of insert.

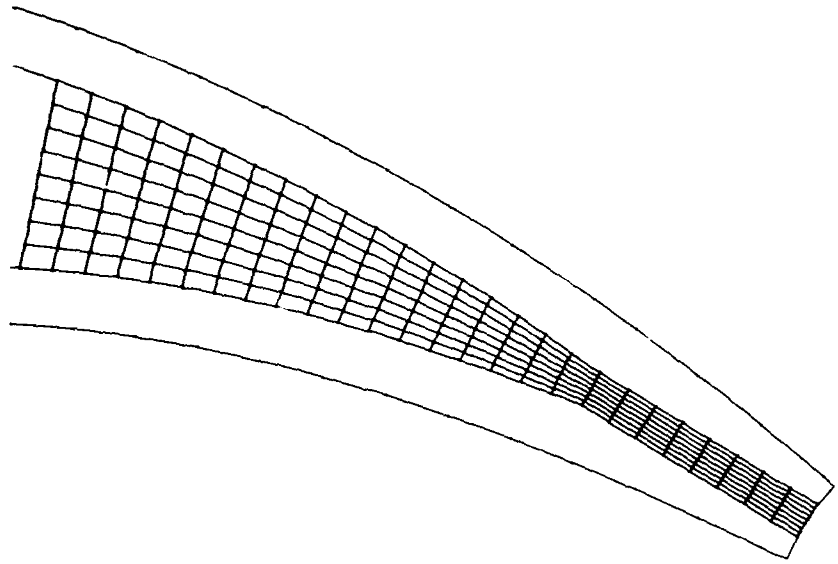


Figure 19. - Approximate streamlines.

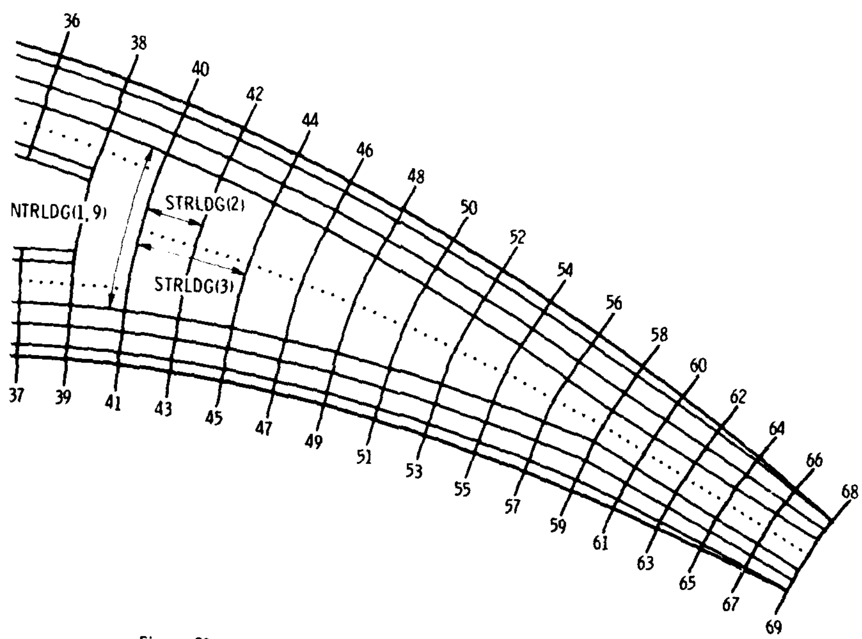


Figure 20. - Arc lengths calculated by TACTGRID in trailing-edge channel.

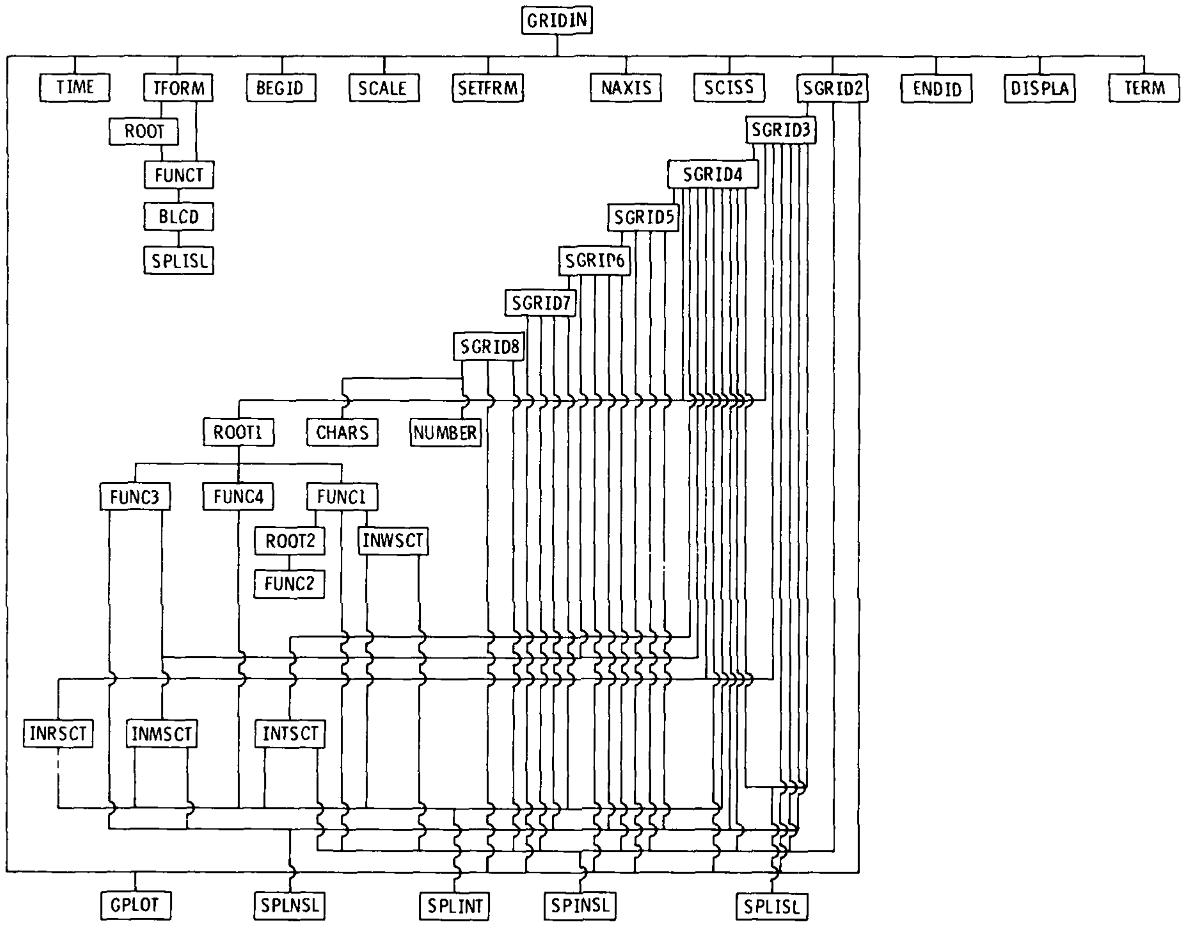


Figure 21. - Calling relation of subroutines. Called subroutines are always below the calling subroutine. (This is not a flow chart.)

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16. Abstract

A computer program called TACTGRID has been developed that generates the geometrical input for the TACT1 program, a program that calculates transient and steady-state temperatures, pressures, and cooling flows in an impingement-cooled turbine blade. Using spline curves, the TACTGRID program constructs the blade internal geometry from the previously designed external blade surface and newly selected wall and channel thicknesses. TACTGRID generates the TACT1 calculational grid, calculates arc lengths between grid points required by TACT1 as input, and prepares the namelist input data set used by TACT1 for the blade geometry. In addition, TACTGRID produces a scaled computer plot of each blade slice, detailing the grid and calculational stations, and thus eliminates the need for any intermediate drafting.

17. Key Words (Suggested by Author(s)) Computerized design; Aerodynamic configurations; Flow geometry; Profiles; Finite difference theory; Heat transfer; Jet impingement; Air cooling; Turbine blades	18. Distribution Statement Unclassified - unlimited STAR Category 34

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