NASA
Technical Paper 1259

AVRADCOM
Technical Report 78-19(PL)

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JULY 1978

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Scientific and Technical
Information Office

1978

CONTENTS

FORTRAN PROGRAM FOR CALCULATING COOLANT FLOW AND METAL TEMPERATURES OF A FULL-COVERAGE-FILM-COOLED VANE OR BLADE

by Peter L. Meitner

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SUMMARY

A FORTRAN computer program called FCFC has been developed that calculates the coolant flow and the wall temperatures of a full-coverage-film-cooled vane or blade. Coolant flow is treated as one-dimensional and compressible. Heat transfer to the coolant due to impingement on the shell inner surface and convection in the film-cooling holes is calculated. Coolant supply pressures and main-stream gas static pressures can vary from hole row to row, and centrifugal effects can be included for blade calculations. Heat-transfer calculations can be excluded so that the program can be used as a flow program only.

The vane or blade metal temperatures are calculated for the shell inner and outer surfaces. All these temperatures are average values for a shell outer-surface area associated with each film-cooling hole row. The heat-transfer calculations are one-dimensional through the wall and neglect conduction from adjacent areas. A thermal-barrier coating may be specified on the shell outer surface. With this option, the program also calculates the interface temperature between the metal and the ceramic coating.

The program input is the chamber geometry (hole sizes, hole spacings, etc.); coolant supply temperature and pressures; and main-stream gas heat-transfer coefficients, pressure, and velocity and temperature distributions. The physical properties of the coolant and the thermal conductivities of the metal and the ceramic coating are input as functions of temperature. The coolant flow coefficients for the impingement and film-cooling holes are input as functions of Mach number. The program output is a summary of the geometric data and the calculated coolant-flow and heat-transfer results.

This report presents the analytical procedure and identifies the necessary assumptions. It describes program input and output, explains error messages, illustrates two examples, and provides a program listing.

INTRODUCTION

Full-coverage film cooling is a very effective scheme for protecting turbine components from the hostile operating environment of high main-stream gas temperature and pressure. Full-coverage film cooling permits higher operating temperatures and pressures than convection cooling for greater overall cycle efficiency (lower specific fuel consumption) at acceptable coolant flow rates (ref. 1). For maximum effectiveness, compressor discharge air is first impinged on the inner surface of the vane or blade shell to remove heat by convection (ref. 2). The cooling air is then bled out through a large number of evenly distributed holes in the shell. The coolant forms a continuous, relatively cool, insulating layer between the shell outer surface and the hot main-stream gas.

Numerous experiments and analyses of various aspects of full-coverage film cooling have appeared in the open literature, and the analysis of this report is based in part on the results of references 3 to 6. Reference 3 approximates full-coverage film cooling as a form of transpiration cooling and derives the equations for metal and coolant temperature distribution for specified coolant flow, specified shell outer-surface temperature, and specified back-side-impingement and internal-wall heat-transfer coefficients. Reference 4 describes a computer program that calculates the heat-transfer coefficients for a turbulent boundary layer on a porous wall and reference 5 describes a discrete-hole blowing model for full-coverage film cooling. Reference 6 establishes flow coefficients for a typical full-coverage-film-cooled geometry.

Although these reports describe many aspects of full-coverage film cooling, these aspects have not been combined into an overall analytical procedure. Such a procedure has been developed and is reported herein. The coolant flow and the wall and coolant temperature distributions are calculated for a given vane or blade geometry; given coolant supply temperature and pressure; and given main-stream gas heat-transfer, temperature, pressure, and velocity conditions. Heat and flow balances are performed for each specified row of film-cooling holes and its associated portion of the shell outer surface. The flow and heat-transfer equations are solved simultaneously on the basis of compressible, one-dimensional fluid flow and one-dimensional heat transfer. For the heat-transfer calculations the equations of reference 3 are expanded and modified for a two-layer model to allow the inclusion of a thermal-barrier coating. Centrifugal pumping effects are included for blade calculations.

The computer program is in FORTRAN IV and is operational on a UNIVAC 1100/42 computer. The program consists of 1650 cards and occupies 22 500 36-bit words of memory. Its execution time is typically less than 15 seconds.

This report explains the analytical procedure used to develop a computer program called FCFC (full-coverage film cooling), which performs the described calculations.

The report lists the formulas used, identifies the necessary assumptions, describes the required program input, illustrates two examples, discusses the program output, explains the program error messages, and provides a program listing.

METHOD OF ANALYSIS

Geometry and Terminology

Figure 1 shows a section of a typical full-coverage-film-cooled blade. Internal ribs, together with an insert, divide the blade cross section into individual chambers. The large variations in main-stream gas pressure and velocity around the airfoil periphery make chambers necessary to control and meter the coolant flow at the most advantageous local mass flux ratio, $m = (\rho V)_c/(\rho V)_g$. (All symbols are defined in appendix A.) The analysis described herein is for a single chamber in a vane or blade. The entire vane or blade is analyzed by performing the calculations for every chamber in that vane or blade.

Figure 2 shows a cross section of a chamber and identifies the coolant flow stations. Station 1 is the supply plenum, station 2 is the impingement orifice plane, station 3 is the impingement plenum, and stations 4 and 5 are the inlet and outlet of the film-cooling holes, respectively. Station 6 is the main-stream gas flow immediately adjacent to the shell outer surface. For subsonic flow through the film-cooling holes, the static pressures at stations 5 and 6 will be equal. For sonic flow, however, the static pressure will be greater at station 5 than at station 6.

The film-cooling holes in the shell are oriented by the angles α and β, as shown in figure 3. The angle α is formed by the hole centerline and its projection in the tangent plane. The angle β lies in the tangent plane and is measured from a chordwise line through the hole centerline and its projection in the tangent plane. An angle of $\beta = 0^\circ$ implies in-line holes (alined in the main-stream gas flow direction), while $\beta = 90^\circ$ implies radially oriented (spanwise) holes.

Assumptions

The flow and heat-transfer calculations of this analysis are performed with the following assumptions:

(1) Coolant flow is one-dimensional from the supply plenum into the main-stream gas.

(2) For a rotating blade, the radial pressure variation in the impingement plenum is that of a stationary column of air under the influence of a rotating field.

(3) For a rotating blade with compound-angle holes ($\beta > 0$ and hole entrances and exits at different radial locations), the pressure changes in the film-cooling holes due to centrifugal pumping are much less than the normal pressure drop across the holes.

(4) Each film-cooling hole row cools only its associated area of shell outer surface.

(5) Heat transfer is one-dimensional through the vane or blade shell (stations 4 to 5). Calculations are performed for each specified row of film-cooling holes (including back-side impingement and convective heat transfer in the holes), but conduction between adjacent rows is neglected.

(6) The calculated back-side impingement heat-transfer coefficients are averaged over the entire inner surface (back side) of the shell. Specific impingement rows are not associated with specific film-cooling rows, or conversely.

Flow Analysis

Overall balanced coolant flow can exist through a full-coverage-film-cooled chamber even if one or more holes have reverse flow, that is, for example, if main-stream gas flow travels from station 5 to station 4 in the film-cooling holes or coolant flow travels from station 3 to station 1 in the impingement holes. However, such a situation is unacceptable from a design standpoint since any inflow of hot main-stream gas will render the design useless. Therefore, the flow analysis does not allow reverse flow. The detailed flow equations are presented in appendix B.

For a given vane or blade chamber, the main-stream static pressures (station 6) can vary in the chordwise, as well as in the spanwise, direction. For a vane the coolant pressure in the impingement plenum (station 3) will be constant, but for a rotating blade this pressure will vary in the radial direction. For proper flow balancing, therefore, each chamber in a vane or blade must be subdivided into either spanwise or chordwise rows of impingement and film-cooling holes, as shown in the following sections.

Vane. - Figure 4 shows the outline of a typical full-coverage-film-cooled vane and one of its pressure-side chambers, which has been divided into rows of impingement holes and film-cooling holes with associated shell outer-surface areas. Each shell area is assumed to be cooled solely by the coolant flow through the holes within that area. A vane impingement row consists of one or more equal-size impingement holes that have a common supply pressure. A vane film-cooling row consists of one or more equal-size film-cooling holes and the associated shell outer-surface area, which has constant main-stream gas temperature, pressure, and heat-transfer coefficients acting over its surface. A vane chamber can be divided into either spanwise or chordwise rows of holes, as illustrated in figure 4.

Before the coolant impingement inflow and film-cooling outflow can be calculated, the pressure in the impingement plenum (station 3) must be known. However, in any design, only the supply pressures (station 1) and the main-stream gas static pressures (station 6) are known. The impingement plenum pressure for balanced coolant inflow and outflow must be obtained in an iterative manner as follows: Avoiding reverse flow at the impingement and film-cooling holes requires that the impingement plenum pressure be less than the lowest specified impingement supply pressure and more than the highest specified main-stream gas static pressure. Initially, the plenum pressure is taken to be the average of these pressures, and the coolant inflow and outflow are calculated. If the resulting outflow is greater or less than the inflow, the plenum pressure is decreased or increased, respectively, in the next flow iteration. The procedure is continued until the inflow and outflow are within a relative tolerance of 0.1 percent.

Blade. - Figure 5 shows the outline of a typical full-coverage-film-cooled blade and one of its pressure-side chambers, which has been divided into chordwise rows of impingement holes and film-cooling holes with associated shell outer-surface areas. As for the vane, each shell area is assumed to be cooled solely by the coolant flow through the holes within that area. A blade impingement row consists of one or more equal-size impingement holes that have a common supply pressure as well as a common radial location (distance from shaft centerline). A blade film-cooling row consists of one or more equal-size film-cooling holes at a common radial location and the associated shell outer-surface area, which has constant main-stream gas temperature, pressure, and heat-transfer coefficients acting over its surface. A blade may be divided only into chordwise impingement and film-cooling rows of holes, as shown in figure 5.

In a rotating blade, the pressures in the supply and impingement plenums (stations 1 and 3, respectively) will vary from hub to tip. The radial supply pressure distribution must be specified and the resulting impingement plenum pressure distribution determined to calculate the coolant flow through the blade. Since there will be many rows of impingement and film-cooling holes along the span, the coolant flow from station 1 to station 6 will be essentially one-dimensional, with little distance traveled in the radial direction. The radial pressure variation in the impingement plenum can thus be assumed to be that of a stationary column of coolant under the influence of a rotating field. For a given pressure at a specific radial station (p_0 at station r_0), the pressure at any other radius r is given by

$$p(r) = p_0 \exp\left[\frac{\omega^2\left(r^2 - r_0^2\right)}{2RTg_c}\right]$$

An allowable range of base pressure is established at the minimum specified radius such that no reverse flow can occur at any impingement or film-cooling row. The total coolant inflow and outflow are then balanced by the iterative procedure described previously for a vane, with the impingement plenum pressure at each impingement and film-cooling row calculated by the preceding equation.

Heat-Transfer Analysis

Metal and coolant temperature distributions are calculated for each shell outer-surface area associated with a specific film-cooling row. The detailed equations are presented in appendix B. These calculations cannot be done in a closed form and must be accomplished in an iterative manner according to the following procedure: In appendix B, the following expression for shell outer-surface temperature is obtained by considering heat flux through a wall:

$$T_{w,o} = T_g - \frac{(T_g - T_{c,\infty})\left[\eta G_c C_p + (1 - \eta)\,\Delta h_g\right]}{h_g(0,x) - \eta\ \Delta h_g + \eta G_c C_p}$$

This equation cannot be solved directly, since the overall effectiveness η is also a function of $T_{w,o}$. The overall effectiveness can be expressed in terms of the nondimensional coolant-outlet temperature as

$$\eta = \theta_{c,1}(1) = C_2\left(1 - \frac{a_1^2}{\lambda}\right)e^{a_1} + C_3\left(1 - \frac{a_2^2}{\lambda}\right)e^{a_2}$$

or

$$\eta = \theta_{c,2}(1) = C_4 + C_5\left(1 - \frac{\alpha_1^2}{\lambda_2}\right)e^{\alpha_1} + C_6\left(1 - \frac{\alpha_2^2}{\lambda_2}\right)e^{\alpha_2}$$

without and with a shell outer-surface coating, respectively. The expressions for $\theta_{c,1}$ and $\theta_{c,2}$ involve both the back-side impingement and film-cooling-hole heat-transfer coefficients. For an uncoated shell with an assumed shell outer-surface temperature $T_{w,o}$, the coolant temperatures at the inlet $T_{c,i}$ and outlet $T_{c,o}$ of the film-cooling holes and the shell inner-surface temperature $T_{w,i}$ are given by

$$T_{c,i} = (T_{w,o} - T_{c,\infty})\left[C_2\left(1 - \frac{a_1^2}{\lambda}\right) + C_3\left(1 - \frac{a_2^2}{\lambda}\right)\right] + T_{c,\infty}$$

$$T_{c,o} = \eta (T_{w,o} - T_{c,\infty}) + T_{c,\infty}$$

$$T_{w,i} = (C_2 + C_3)(T_{w,o} - T_{c,\infty}) + T_{c,\infty}$$

For a coated shell, the coolant temperature at the film-cooling hole inlet $T_{c,i}$, at the interface between the metal and the coating $T_{c,if}$, and at the film-cooling hole outlet $T_{c,o}$; the shell inner-surface temperature $T_{w,i}$; and the interface temperature $T_{w,if}$ are given by

$$T_{c,i} = (T_{w,o} - T_{c,\infty}) \left[C_2 \left(1 - \frac{a_1^2}{\lambda_1}\right) + C_3 \left(1 - \frac{a_2^2}{\lambda_1}\right) \right] + T_{c,\infty}$$

$$T_{c,if} = (T_{w,o} - T_{c,\infty}) \left[C_2 \left(1 - \frac{a_1^2}{\lambda_1}\right) e^{a_1} + C_3 \left(1 - \frac{a_2^2}{\lambda_1}\right) e^{a_2} \right] + T_{c,\infty}$$

$$T_{c,o} = \eta (T_{w,o} - T_{c,\infty}) + T_{c,\infty}$$

$$T_{w,i} = (T_{w,o} - T_{c,\infty})(C_2 + C_3) + T_{c,\infty}$$

$$T_{w,if} = (T_{w,o} - T_{c,\infty})\left(C_2 e^{a_1} + C_3 e^{a_2}\right) + T_{c,\infty}$$

The overall iterative solution scheme is illustrated by the flow diagram of figure 6. Equation numbers for cases with a thermal-barrier coating are marked with an asterisk. The impingement and film-cooling hole heat-transfer coefficients are functions of the calculated wall temperatures or coolant temperatures (through the physical properties) as indicated. The procedure of figure 6 is performed for every row of film-cooling holes at every flow-balancing iteration. The generated value of coolant-outlet temperature $T_{c,o}$ affects the density and thus the calculated weight flow in the next flow iteration.

PROGRAM INPUT

The input to FCFC consists of a title card, a series of tabular input cards, and a series of cards describing each chamber to be analyzed. The tabular inputs are the only formatted data input. The data for each specific chamber are input in NAMELIST form.

An input data form is shown in table I. The required input cards are the title card, the tabular input cards, and the chamber input cards.

Title Card

The title card must always be present and is used to identify the particular set of runs. All 80 columns can be used.

Tabular Input Cards

The tabular input cards describe the required coolant and material physical properties, as well as the coolant flow coefficients. Each set consists of three or more cards as follows:

Card 1: NP in I2 format, where NP is the number of points in the table

Cards 2a, 2b, 2c: the NP x-values describing the table in ascending order and in 8F10.0 format (a maximum of 24 points)

Cards 3a, 3b, 3c: the corresponding NP y-values in 8F10.0 format

The tables to be input, along with the required SI or U.S. customary units, are shown in table II.

Tables 1 to 6 must always be supplied. Tables 7 and 8 can be deleted if there is no main-stream flow; tables 9 and 10, if no heat-transfer calculations are to take place (FCFC used for flow analysis only); and table 10, if there is no ceramic coating. To delete a table, input zero in card column 2 of the NP card. The tables of impingement-hole discharge coefficient $(CD)_i$, film-cooling hole total-pressure loss coefficient $(KT)_{nmg}$, and film-cooling hole flow reduction due to main-stream gas flow RT (tables 5, 6, and 7, respectively) are given in reference 6. The program flow calculations are based on flow coefficients as defined in reference 6. The impingement-hole discharge coefficient (CD) is defined as the ratio of actual to ideal flow, the film-cooling hole total-pressure loss coefficient is defined as

$$(KT)_{nmg} = \frac{p_3' - p_5'}{p_5' - p_5}$$

and the film-cooling hole flow reduction due to main-stream gas flow is defined as

$$RT = \frac{\text{Actual coolant flow with main-stream gas flow}}{\text{Calculated coolant flow with no main-stream gas flow}}$$

The RT values of reference 6 are for a compound film-cooling hole angle β of 0°. Table 8 is used to correct RT for other values of β (from 0° to 90°).

The program FCFC generates a spline curve fit from each inputted set of tabular data. The curve-fitting procedure requires the slopes at the end points. These slopes are calculated from the first two and last two data points. For this reason, these points should be chosen such that fairing a straight line between them gives a good approximation to the slope of the curve at the end points. For all tables, at least three input points are needed. If the program calls for a value at an x-location outside the range of the input table, the value at the nearest end point is used and an appropriate warning message is printed out.

The input coordinates for table 8 are rotated through an angle of 45°, and the spline fitting takes place in the rotated coordinate system. This gives a better curve fit for data with rapid changes in slope such as occur in input table 8.

Chamber Input Cards

The data for each chamber are preceded by $DATT, which is punched starting in card column 2. The variable names (starting in card column 2 or beyond) are followed by an equal sign and the value or values of the variable, separated by commas. For each chamber, the number of impingement hole rows NIR and the number of film-cooling hole rows NFCR are specified; the maximum allowable rows are 25 and 50, respectively. Subscripted variables are associated with specific rows; that is, the N^{th} subscripted value is associated with the N^{th} row of holes. When fewer than the maximum number of rows are specified, subscripted variables need only have as many input values as the specified number of rows. Integer values must be input without decimal points. The last data value for each chamber is followed by a $ instead of a comma. The input data are retained for multiple chamber inputs. Thus, if a variable is common to successive chambers, it has to be input just once for the initial chamber. The chamber geometry input variables are defined by figure 7. All chamber input variables, along with the required SI or U.S. customary units, are shown in table III.

The variables IUNTS to OMG in table III specify the types of calculations desired. These variables have been assigned default values as shown. The variables NIR to RGAS are associated with the impingement hole rows: NIR is the number of specified impingement hole rows, and NIHPR to P1T are subscripted variables associated with the impingement rows. As such, each variable must have at least NIR input values. The variable HSP1, the hole spacing for each impingement row, is used in determining the backside impingement heat-transfer coefficient (eq. (B11)). This correlation is based on a square impingement array, with equal spacings in the spanwise and chordwise directions, as shown in figure 7. In practice, however, these spacings may differ and the average of the two spacings should then be specified. The variables TT and RGAS define the coolant gas; they are not subscripted and are thus constant for all rows of impingement holes.

The variables NFCR to ROV2G of table III are associated with the film-cooling hole rows. The variable NFCR is the number of specified film-cooling hole rows, and NFCHPR to ROV2G are subscripted variables that must have at least NFCR values. The variable HSP5 is the hole spacing for each film-cooling hole row (fig. 7), and, as for HSP1, an unequal array spacing should be reduced to an equivalent square spacing. The variable HFC4 (h factor at station 4; fig. 2) is a modification factor for the calculated impingement heat-transfer coefficient at each film-cooling hole row. For the film-cooling heat-transfer calculations, the calculated impingement heat-transfer coefficients are averaged over the shell back side (inner surface), since the program does not associate specific impingement rows with certain film-cooling-hole rows, or conversely. When back-side heat-transfer coefficients vary (from centrifugal effects or from impinging at less than perpendicular to the surface), HFC4 is a multiplier used to modify the back-side heat-transfer coefficient at the specified film-cooling-hole rows. (This variable has a default value of 1.0.) The variable HFC45 (h factor for stations 4 to 5; fig. 2) is a multiplier used to modify the calculated film-cooling hole heat-transfer coefficients for each row (eq. (B13)). Equation (B13) is valid for hole length-diameter ratios L/D between 1.0 and 8.0. For L/D less than 1.0, reference 7 measured heat-transfer coefficients that were as much as 50 percent greater than predicted by equation (B13) (entrance effects). The correction factor HFC45, which has a default value of 1.0, is used to account for this. The variable TMSG is the main-stream gas temperature, which must be the same as the temperature used to evaluate the main-stream gas heat-transfer coefficients.

PROGRAM OUTPUT

The FCFC output is a printout of the title card, the input data for all specified tables, and the calculated results for each chamber. The chamber output consists of the following messages and blocks of tabulated data:

----- OUTPUT FOR CHAMBER XX -----

Units and Option Messages

XX ROWS OF IMPINGEMENT HOLES

Impingement Hole Input Data

XX ROWS OF FILM COOLING HOLES

Film-Cooling Hole Input Data

IMPINGEMENT AND FILM COOLING FLOWS HAVE CONVERGED IN XX OVERALL ITERATIONS

INFLOW EQUALS XXXXX.XXX KG/HR (LBM/HR)

Impingement Flow Results

OUTFLOW EQUALS XXXXX.XXX KG/HR (LBM/HR)

Film-Cooling Flow Results

HEAT TRANSFER RESULTS

Heat-Transfer Results

Each of these blocks is described in the following subsections.

Units and Option Messages

One or more of the following messages about the system of units and the particular options used are printed out:

SI (ENGLISH) SYSTEM OF UNITS

COOLANT GAS CONSTANT = XXXXXX.XX J/(KG-K) ((FT-LBF)/(LBM-R))

THIS CASE IS FLOW ANALYSIS ONLY AND INCLUDES NO METAL TEMPERATURE CALCULATIONS

THIS CASE INCLUDES A THERMAL BARRIER COATING

THIS CASE INCLUDES CENTRIFUGAL EFFECTS. ROTATIONAL SPEED EQUALS XXXXX.XX RPM

Impingement Hole Input Data

This block of output tabulates the following for each row of impingement holes:

ROW	impingement row number
HOLES	number of holes per row
DIAMETER	hole diameter, mm; in.
WALL THICKNESS	impingement wall thickness, mm; in.
L/D	hole length-diameter ratio
HOLE SPACING	hole spacing, mm; in.
IMPINGEMENT DISTANCE	impingement distance, mm; in.
R1	distance from shaft centerline, mm; in.
P1T	supply total pressure, N/cm^2; psia

For noncentrifugal calculations, R1 is printed as zero.

Film-Cooling Hole Input Data

This block of output tabulates the following for each row of film-cooling holes:

ROW	row number
HOLES	number of holes per row
DIAMETER	hole diameter, mm; in.
THICKNESS	
WALL	wall metal thickness, mm; in.
COATING	coating thickness, mm; in.
L/D	hole length-diameter ratio
HOLE SPACING	hole spacing, mm; in.
ALPHA	hole chordwise inclination angle
BETA	hole compound inclination angle
RHOVG	main-stream gas value of ρV, $kg/m^2 \cdot hr$; $lbm/ft^2 \cdot hr$
RHOV2G	main-stream gas value of ρV^2, $kg/m \cdot hr^2$; $lbm/ft \cdot hr^2$

R4 distance from shaft centerline, mm; in.

P6 main-stream gas static back pressure, N/cm^2; psia

The L/D is that value associated with the combined thickness of the wall and any specified coating. When no main-stream flow is specified (MSBL=0), main-stream gas RHOVG and RHOV2G are printed as zero. The variable R4 is the location of the film-cooling hole centerline on the shell inner surface. For noncentrifugal calculations, R4 is printed as zero.

Impingement Flow Results

This block of output tabulates the following for each row of impingement holes:

IMP ROW row number

PSPLYT coolant supply total pressure, N/cm^2; psia

P2 static pressure, N/cm^2; psia

M2 Mach number

T2T total temperature, K; ^oF

T2 static temperature, K; ^oF

WIMP coolant inflow, kg/hr; lbm/hr

CDIMP impingement discharge coefficient

The coolant supply total pressure, shown as P1T in the section Impingement Hole Input Data, is repeated here as PSPLYT.

Film-Cooling Flow Results

This block of output tabulates the following for each row of film-cooling holes:

FC ROW row number

P3T impingement plenum pressure, N/cm^2; psia

P4 static pressure at inlet, N/cm^2; psia

M4 Mach number at inlet

T4T total temperature at inlet, K; ^oF

T4 static temperature at inlet, K; ^oF

P5T total pressure at exit, N/cm^2; psia

P5	static pressure at exit, N/cm^2; psia
M5	Mach number at exit
T5T	total temperature at exit, K; ^oF
T5	static temperature at exit, K; ^oF
TCTIF	total coolant temperature at metal-coating interface, K; ^oF
WOUT	coolant outflow, kg/hr; lbm/hr
KT	total-pressure loss coefficient
RT	reduction in coolant flow due to main-stream flow
RT CORR	correction factor for RT
RHOV RATIO	ratio of coolant-to-main-stream density times velocity
RHOVSQ RATIO	ratio of coolant-to-main-stream density times velocity squared
ITRS	number of iterations needed to achieve film-cooling flow convergence in last overall flow iteration

When no coating is specified (KCLC=0), the coolant interface total temperature prints zeros. When no main-stream flow is specified (MSBL=0), the ρV and ρV^2 ratios print zeros and RT and RT CORR print 1.0. The main-stream pressure, shown as P6 in the section Film-Cooling Hole Input Data, is repeated here as P5. If the flow through the film-cooling holes is subsonic, P5 and P6 will be equal. However, for choked flow, P5 will be that pressure determined from the compressible-flow relations at Mach 1.0 and will be greater than the specified main-stream pressure P6.

Heat-Transfer Results

This block of output tabulates the following for each row of film-cooling holes:

FC ROW — row number

HEAT TRANSFER COEFFICIENTS:

HG0 — main-stream gas heat-transfer coefficient for coolant temperature equal to main-stream gas temperature, $J/m^2 \cdot sec \cdot K$; $Btu/ft^2 \cdot hr \cdot {}^oR$

HG1	main-stream gas heat-transfer coefficient for coolant temperature equal to shell outer-surface temperature, $J/m^2 \cdot sec \cdot K$; $Btu/ft^2 \cdot hr \cdot {}^oR$
FC-HOLE	heat-transfer coefficient in film-cooling hole, $J/m^2 \cdot sec \cdot K$; $Btu/ft^2 \cdot hr \cdot {}^oR$
IMPG	back-side impingement heat-transfer coefficient, $J/m^2 \cdot sec \cdot K$; $Btu/ft^2 \cdot hr \cdot {}^oR$
H MODIFICATION FACTORS:	
FC-HOLE	modification factor for film-cooling hole heat-transfer coefficient (inputted HFC45)
IMPG	modification factor for back-side impingement heat-transfer coefficient (inputted HFC4)
COOLED AREA	cooled area associated with each film-cooling row, cm^2; $in.^2$
GAS TEMP	main-stream gas temperature, K; ^oF
WALL TEMPERATURE:	
OUTSIDE	shell outer-surface temperature, K; ^oF
INTFACE	shell interface temperature, K; ^oF
INSIDE	shell inner-surface temperature, K; ^oF
AVG. THERM. COND.:	
METAL	metal average thermal conductivity, $J/cm \cdot sec \cdot K$; $Btu/ft \cdot hr \cdot {}^oR$
COATING	coating average thermal conductivity, $J/cm \cdot sec \cdot K$; $Btu/ft \cdot hr \cdot {}^oR$
ETA	overall effectiveness
ITR	number of iterations required to achieve metal temperature convergence in last flow iteration

The tabulated values of film-cooling hole and impingement heat-transfer coefficients include their corresponding modification factors. When no coating is specified (KCLC=0), the interface temperatures and coating thermal conductivities are set to zero. The average thermal conductivities for the metal and coating are evaluated at the average temperatures through the metal and coating, respectively.

Error Messages

Error messages have been incorporated in the calculation procedure. The messages for the main program and the various subroutines, along with possible causes and corrective actions, are as follows (where error messages that do not stop program execution are preceded by the word "WARNING"):

Main program. - The error messages for the main program are

CASE ABORTED - A REQUIRED CURVE WAS NOT INPUT OR WAS SPECIFIED BY LESS THAN 3 POINTS

Check the required input tables and add the missing data or specify at least three points.

CASE ABORTED - COATING WAS SPECIFIED BUT NO COATING THICKNESS

Specify coating thickness.

CASE ABORTED - THE SPECIFIED PRESSURES WILL RESULT IN REVERSE FLOW

Check the specified supply and back pressures or alter hole sizes.

WARNING - T2 HAS NOT CONVERGED IN 15 ITERATIONS FOR IMPINGEMENT ROW XX

This message could be caused by specifying significantly erroneous physical properties.

WARNING - T5 HAS NOT CONVERGED IN 15 ITERATIONS FOR FILM COOLING ROW XX

WARNING - T5T HAS NOT CONVERGED IN 15 ITERATIONS IN OVERALL FLOW ITERATION XX

These messages could be caused by specifying significantly erroneous physical properties or the heat-transfer-coefficient modification factor HFC45.

WARNING - THE AVERAGE PRESSURE BETWEEN STATIONS 4 AND 5 HAS NOT CONVERGED IN 15 ITERATIONS FOR FILM COOLING ROW XX

WARNING - P5T HAS NOT CONVERGED IN 15 ITERATIONS FOR FILM COOLING ROW XX

These messages could be caused by specifying significantly erroneous physical properties or the total-pressure loss coefficient curve $(KT)_{nmg}$.

IMPINGEMENT AND FILM COOLING FLOWS HAVE NOT CONVERGED IN 25 ITERATIONS

Change hole sizes and/or supply and back pressures.

Subroutine TMETO. - The error message for subroutine TMETO is

WARNING - OUTER WALL TEMPERATURE HAS NOT CONVERGED IN 15 ITERATIONS IN OVERALL FLOW ITERATION XX

This error message can be caused by specifying erroneous values of the main-stream gas heat-transfer coefficients HG0 and HG1. The message can also be caused by the initial values assumed in the iterative process. If the message appears for values of overall flow iteration that are less than the actual number of flow iterations required (given by the message "IMPINGEMENT AND FILM COOLING FLOWS HAVE CONVERGED IN XX OVERALL ITERATIONS"), the solution is valid.

Subroutine MNEW. - The error message for subroutine MNEW is

WARNING - M HAS NOT CONVERGED IN 25 ITERATIONS

Check the inputted table of total-pressure loss coefficient $(KT)_{nmg}$.

Subroutine SPLINE. - The error messages for subroutine SPLINE are

WARNING - A SPECIFIED X-VALUE (XXXXX.XXX) IS BELOW THE RANGE OF INPUT TABLE XX

WARNING - A SPECIFIED X-VALUE (XXXXX.XXX) IS ABOVE THE RANGE OF INPUT TABLE XX

Check the inputted tables and extend their range as required.

EXAMPLE PROBLEMS

The use of FCFC is illustrated by analyzing a chamber on both the vane and blade of a high-temperature, high-pressure core turbine. Example 1 demonstrates flow and heat-transfer calculations for a vane chamber with a thermal-barrier coating. Example 2 demonstrates centrifugal flow calculations without heat transfer and thus shows how FCFC can be used as a flow program only.

The inputted tables of impingement discharge coefficient $(CD)_i$, film-cooling hole total-pressure loss coefficient $(KT)_{nmg}$, and film-cooling hole flow reduction due to main-stream gas flow RT were obtained from reference 6. The main-stream gas heat-transfer coefficients HG0 and HG1 were evaluated by using the Stanford University STAN5 computer program of reference 4 which was modified to include the discrete-hole blowing model of reference 5.

Example 1

A section of the vane and chamber that were analyzed is shown in figure 8. Also shown are the impingement hole diameters; the film-cooling hole diameters; the main-stream gas pressures P6; and the associated main-stream gas values of ρV, ρV^2, HG0, and HG1. The vane material is MAR-M509 and the coating is yttria-stabilized zirconia (Y_2O_3-ZrO_2). The vane span is 3.81 centimeters (1.50 in.), and the impingement and film-cooling hole spacings are 0.381 and 0.254 centimeter (0.15 and 0.10 in.), respectively. The shell and thermal-barrier coating thicknesses are 0.127 and 0.0127 centimeter (0.050 and 0.005 in.), respectively, with an impingement distance of 0.0889 centimeter (0.035 in.). Coolant supply pressure is 404 N/cm^2 (586 psia) and coolant temperature is 811 K (1000° F). Main-stream gas hot-spot temperature is 2550 K (4130° F).

Example 2

A section of the blade and chamber that were analyzed is shown in figure 9. The blade span and the impingement and film-cooling hole spacings are the same as for the vane of example 1. Impingement and film-cooling hole sizes are constant at 0.4318 and 0.4572 millimeter (0.017 and 0.018 in.), respectively. For this example, which involves no heat-transfer calculations, the wall thickness and the impingement distances were taken to be constant at 1.016 and 0.762 millimeter (0.040 and 0.030 in.), respectively. In the actual blade, both vary from hub to tip. Coolant supply temperature was 811 K (1000° F). The analysis was further simplified by assuming an impingement and film-cooling row at each of 15 specified radial locations. (In general, impingement and film-cooling rows are staggered.) Also, each film-cooling row was taken to consist of two adjacent holes (one from each chordwise station) and was assumed to have a radial position equal to the average radial position of the two holes (fig. 9). The radial variations of coolant supply pressure P1T and main-stream gas values of static pressure P6, ρV, and ρV^2 for the 15 rows are tabulated in figure 9.

Table IV lists the input data for the two example problems. The title card, the tabular inputs, and the chamber inputs are identified. Tables V to VII show the program output for the two examples. Table V shows the title card and all tabular data. Tables VI and VII are the outputs for the vane and blade chambers, respectively.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 22, 1978,
505-04.

APPENDIX A

SYMBOLS

A	area, m^2; ft^2
a_1, a_2	parameters defined by eqs. (C5) and (C6)
CD	discharge coefficient
C_p	specific heat at constant pressure, J/(g·K); Btu/(lbm·^oR)
C_1 - C_6	constants of integration defined by eq. (C45)
D	diameter, m; ft
F	function values at specified input points
G	flow rate per unit area, kg/(m^2·hr); lbm/(ft^2·hr)
g_c	force-mass conversion constant, 1; 32.174 (lbm)(ft)/(lbf)(sec^2)
H_m	porous-wall-matrix, internal, volumetric, heat-transfer coefficient defined by eq. (C10), J/(m^3·hr·K); Btu/(ft^3·hr·^oR)
h	heat-transfer coefficient, J/(m^2·hr·K); Btu/(ft^2·hr·^oR)
h_m	porous-wall-matrix, heat-transfer coefficient, J/(m^2·hr·K); Btu/(ft^2·hr·^oR)
KT	total-pressure loss coefficient for flow into still air
k	thermal conductivity, J/(m·hr·K); Btu/(ft·hr·^oR)
L	thickness, m; ft
l	length, m; ft
M	Mach number
m	blowing ratio, $(\rho V)_c/(\rho V)_g$
N	dimensionless heat-transfer-coefficient parameter defined by eq. (C17)
Nu	Nusselt number
Pr	Prandtl number
p	pressure, N/m^2; lbf/ft^2
q	heat flux, J/(m^2·hr); Btu/(ft^2·hr)
R	gas constant, J/(kg·K); ft·lbf/(lbm·^oR)
Re	Reynolds number

RT	ratio of coolant flow with main-stream gas flow to coolant flow without main-stream gas flow
r	radius, m; ft
T	temperature, K; $^{\circ}R$
V	velocity, m/sec; ft/sec
W	flow rate, kg/hr; lbm/hr
x	distance, m; ft
y	function value at any arbitrary ordinate location
Z	porous-wall-matrix, internal surface area per unit volume, 1/m; 1/ft
α	film-cooling hole inclination angle, deg
α_1, α_2	coefficients defined by eqs. (C30) and (C31)
β	film-cooling hole compound angle; or parameter defined by eq. (C9)
γ	ratio of specific heats
η	overall effectiveness, defined by eq. (B16)
θ	dimensionless temperature parameter defined by eq. (B18)
λ	parameter defined by eq. (C8)
μ	kinematic viscosity, kg/(m·sec); lbm/(ft·sec)
ξ	dimensionless distance parameter defined by eq. (C7)
ρ	density, kg/m^3; lbm/ft^3
φ	dimensionless temperature parameter defined by eq. (B17)
Ω	parameter defined by eq. (C44)
ω	rotational speed, 1/sec

Subscripts:

a	based on impingement-jet arrival velocity
av	average
b	bulk
c	coolant
ct	coating
fc	film cooling
g	main-stream gas

i	inner surface
if	interface
imp	impingement
loc	local
m	metal
n	based on impingement hole centers
nmg	no main-stream gas
o	outer surface
w	wall
0	base
1	station at supply plenum
2	station at impingement orifice
3	station at impingement plenum
4	station at film-cooling hole inlet
5	station at film-cooling hole exit
6	station at shell outer surface in main-stream gas flow
∞	free stream; or supply

Superscript:

$'$	total

APPENDIX B

EQUATIONS

Flow Equations

Impingement flow. - The coolant flow rate through the impingement holes (treated as orifice flow) is given by

$$W_{imp} = (CD)_{imp} \rho_2 V_2 A_{imp} \tag{B1}$$

where

$$\rho_2 = \frac{p_2}{RT_1'} \left(\frac{p_1'}{p_2} \right)^{(\gamma - 1)/\gamma} \tag{B2}$$

$$V_2 = \sqrt{\frac{2\gamma R g_c T_1'}{\gamma - 1.0} \left[1.0 - \left(\frac{p_2}{p_1'} \right)^{(\gamma - 1)/\gamma} \right]} \tag{B3}$$

Film cooling flow. - The coolant flow rate through the film-cooling holes (treated as pipe flow with friction) is given by

$$W_{fc} = \rho_5 V_5 A_{fc} \tag{B4}$$

where

$$\rho_5 = \frac{p_5}{RT_5} \tag{B5}$$

$$V_5 = \sqrt{\frac{2\gamma R g_c T_5'}{\gamma - 1} \left[1.0 - \left(\frac{p_5}{p_5'} \right)^{(\gamma - 1)/\gamma} \right]} \tag{B6}$$

$$p_5' = \frac{p_3' + p_5(KT)_{nmg}}{1.0 + (KT)_{nmg}} \tag{B7}$$

Mach number change across a film-cooling hole. - Consider a constant film-cooling hole area. When the hole exit Mach number and the total temperature and pressure, as well as the change in total temperature and pressure across the hole are known, the hole entrance Mach number can be obtained as follows: If the inlet station is designated by subscript 4 and the outlet station by subscript 5, the continuity equation gives

$$\rho_4 V_4 A_4 = \rho_5 V_5 A_5 \tag{B8}$$

Equation (B8) can be expressed as

$$\frac{p_4' M_4 A_4 \sqrt{\gamma_4 R T_4'}}{RT_4' \left(1 + \frac{\gamma_4 - 1}{2} M_4^2\right)^{(\gamma_4+1)/2(\gamma_4-1)}} = \frac{p_5' M_5 A_5 \sqrt{\gamma_5 R T_5'}}{RT_5' \left(1 + \frac{\gamma_5 - 1}{2} M_5^2\right)^{(\gamma_5+1)/2(\gamma_5-1)}} \tag{B9}$$

Solving for M_4 gives

$$M_4 = \frac{p_5' M_5 A_5 \sqrt{\gamma_5 R T_5'}\, RT_4' \left(1 + \frac{\gamma_4 - 1}{2} M_4^2\right)^{(\gamma_4+1)/2(\gamma_4-1)}}{RT_5' \left(1 + \frac{\gamma_5 - 1}{2} M_5^2\right)^{(\gamma_5+1)/2(\gamma_5-1)} p_4' A_4 \sqrt{\gamma_4 R T_4'}} \tag{B10}$$

This equation is solved iteratively by Newton's method.

Heat-Transfer Equations

Back-side impingement. - The heat-transfer coefficient on the shell inner surface is calculated from the Gardon-Cobonpue impingement correlation (ref. 8)

$$h_{av} = \frac{0.286\, k (Re)_a^{0.625}}{x_n} \tag{B11}$$

Convection in film-cooling holes. - The heat-transfer coefficient in the film-cooling holes is calculated from the Davey correlation (ref. 7), from which the local Nusselt number varies along the length of the hole as

$$(Nu)_{loc} = 0.036(Re)^{0.8}(Pr)^{0.4}\left(\frac{x}{D}\right)^{-0.2}\left(\frac{T_b}{T_w}\right)^{0.18} \tag{B12}$$

From the definition of Nusselt number, the average heat-transfer coefficient over the entire length of the hole l is obtained by integrating

$$h_{av} = \frac{\int_0^l h_{loc}\,dx}{l} = 0.045\,\frac{k}{D}\,(Re)^{0.8}(Pr)^{0.4}\left(\frac{T_b}{T_w}\right)^{0.18}\left(\frac{D}{l}\right)^{0.2} \tag{B13}$$

The average heat-transfer coefficient in the portion of the hole between stations l_1 and l_2 is evaluated from

$$h_{av} = \frac{\int_{l_1}^{l_2} h_{loc}\,dx}{l_2 - l_1} = \frac{0.045\left(\frac{k}{D}\right)(Re)^{0.8}(Pr)^{0.4}\left(\frac{T_b}{T_w}\right)^{0.18} D^{0.2}\left[(l_2)^{0.8} - (l_1)^{0.8}\right]}{l_2 - l_1} \tag{B14}$$

Shell outer-surface temperature. - Heat flux through a wall can be expressed as

$$q = h_g(T_g - T_{w,o}) = G_cC_p(T_{c,o} - T_{c,\infty}) = G_cC_p\eta\,(T_{w,o} - T_{c,\infty}) \tag{B15}$$

The overall effectiveness η is defined by

$$\eta = \frac{T_{c,o} - T_{c,\infty}}{T_{w,o} - T_{c,\infty}} \tag{B16}$$

After we introduce the parameters

$$\varphi = \frac{T_g - T_{w,o}}{T_g - T_{c,\infty}} \tag{B17}$$

and

$$\theta = \frac{T_g - T_{c,o}}{T_g - T_{w,o}} \tag{B18}$$

equation (B17) can be reduced to

$$\varphi = \frac{G_c C_p \eta}{h_g + G_c C_p \eta} \tag{B19}$$

By assuming constant properties and using superposition (ref. 9),

$$h_g(\theta, x) = h_g(0, x) - \theta\left[h_g(0, x) - h_g(1, x)\right] \tag{B20}$$

or

$$h_g(\theta, x) = h_g(0, x) - \theta\, \Delta h_g \tag{B21}$$

where $h_g(0,x)$ and $h_g(1,x)$ are the heat-transfer coefficients for the coolant temperature equal to the gas temperature and the shell outer-surface temperature, respectively. These heat-transfer coefficients are obtained from a suitable boundary-layer computer program and are based on an initially assumed shell outer-surface temperature.

The dimensionless temperature groupings can be combined to give

$$\theta = \frac{1 - \eta(1 - \varphi)}{\varphi} \tag{B22}$$

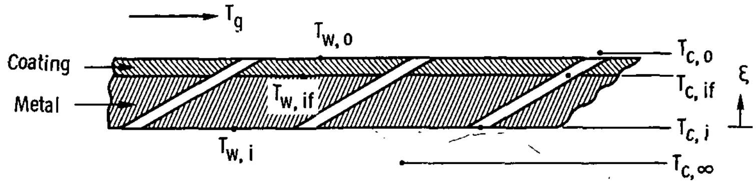
Combining equations (B19), (B21), and (B22) then gives

$$\varphi = \frac{\eta G_c C_p + (1 - \eta)\Delta h_g}{h_g(0, x) - \eta\, \Delta h_g + \eta G_c C_p} \tag{B23}$$

This equation can be solved for $T_{w,o}$ to give

$$T_{w,o} = T_g - \frac{(T_g - T_{c,\infty})\left[\eta G_c C_p + (1 - \eta)\Delta h_g\right]}{h_g(0, x) - \eta\, \Delta h_g + \eta G_c C_p} \tag{B24}$$

Full-coverage film cooling. - Consider the cross section of a coated, full-coverage-film-cooled wall as shown in sketch (a).



(a)

The coolant temperatures are designated by $T_{c,\infty}$ at the supply, $T_{c,i}$ at the film-cooling hole inlet, $T_{c,if}$ at the interface between the metal and the coating, and $T_{c,o}$ at the film-cooling hole outlet. The metal temperatures are designated by $T_{w,i}$ at the shell inner surface, $T_{w,if}$ at the interface between the wall and the coating, and $T_{w,o}$ at the shell outer surface. The main-stream gas temperature T_g is that temperature in terms of which the main-stream gas heat-transfer coefficients are evaluated.

Reference 3 develops an analytical model to predict the coolant temperature rise and the metal temperature distribution through a porous wall. The results hold for fixed values of shell outer-surface temperature $T_{w,o}$, coolant temperature $T_{c,\infty}$, and impingement and film-cooling hole heat-transfer coefficients. For a single metal layer, the coefficients resulting from the specified boundary conditions can be solved for explicitly. The solution takes the form

$$\theta_w(\xi) = C_1 + C_2 e^{a_1 \xi} + C_3 e^{a_2 \xi} \tag{B25}$$

$$\theta_c(\xi) = C_1 + C_2 \left(1 - \frac{a_1^2}{\lambda}\right) e^{a_1 \xi} + C_3 \left(1 - \frac{a_2^2}{\lambda}\right) e^{a_2 \xi} \tag{B26}$$

where

$$\theta_w(\xi) = \frac{T_w - T_{c,\infty}}{T_{w,o} - T_{c,\infty}} \tag{B27}$$

and

$$\theta_c(\xi) = \frac{T_c - T_{c,\infty}}{T_{w,o} - T_{c,\infty}} \tag{B28}$$

are the nondimensionalized temperature distributions in the wall and coolant, respectively. All symbols are defined in appendix C where the analytical model for a two-layer wall is also developed. The equations for each layer take the same form, but the six resulting constants cannot be solved for explicitly and must be evaluated numerically. The solution is

$$\theta_{w,1}(\xi_1) = C_1 + C_2 e^{a_1 \xi_1} + C_3 e^{a_2 \xi_1} \tag{B29}$$

$$\theta_{c,1}(\xi_1) = C_1 + C_2 \left(1 - \frac{a_1^2}{\lambda_1}\right) e^{a_1 \xi_1} + C_3 \left(1 - \frac{a_2^2}{\lambda_1}\right) e^{a_2 \xi_1} \tag{B30}$$

$$\theta_{w,2}(\xi_2) = C_4 + C_5 e^{\alpha_1 \xi_2} + C_6 e^{\alpha_2 \xi_2} \tag{B31}$$

$$\theta_{c,2}(\xi_2) = C_4 + C_5 \left(1 - \frac{\alpha_1^2}{\lambda_2}\right) e^{\alpha_1 \xi_2} + C_6 \left(1 - \frac{\alpha_2^2}{\lambda_2}\right) e^{\alpha_2 \xi_2} \tag{B32}$$

The subscripts 1 and 2 on θ_w and θ_c refer to the metal and coating, respectively. The constants C_1, C_2, and C_3 for the two-layer wall are different from the corresponding constants for the one-layer wall.

The overall effectiveness η is given by

$$\eta = \theta_{c,1}(1) = C_2 \left(1 - \frac{a_1^2}{\lambda}\right) e^{a_1} + C_3 \left(1 - \frac{a_2^2}{\lambda}\right) e^{a_2} \tag{B33}$$

and

$$\eta = \theta_{c,2}(1) = C_4 + C_5 \left(1 - \frac{\alpha_1^2}{\lambda_2}\right) e^{\alpha_1} + C_6 \left(1 - \frac{\alpha_2^2}{\lambda_2}\right) e^{\alpha_2} \tag{B34}$$

for an uncoated and a coated shell, respectively. For an uncoated shell, $T_{c,i}$, $T_{c,o}$, and $T_{w,o}$ are given by

$$T_{c,i} = (T_{w,o} - T_{c,\infty}) \left[C_2 \left(1 - \frac{a_1^2}{\lambda}\right) + C_3 \left(1 - \frac{a_2^2}{\lambda}\right) \right] + T_{c,\infty} \tag{B35}$$

$$T_{c,o} = \eta(T_{w,o} - T_{c,\infty}) + T_{c,\infty} \tag{B36}$$

$$T_{w,i} = (C_2 + C_3)(T_{w,o} - T_{c,\infty}) + T_{c,\infty} \tag{B37}$$

For a shell with a thermal-barrier coating, $T_{c,i}$, $T_{c,if}$, $T_{c,o}$, $T_{w,i}$, and $T_{w,if}$ are evaluated from

$$T_{c,i} = (T_{w,o} - T_{c,\infty})\left[C_2\left(1 - \frac{a_1^2}{\lambda_1}\right) + C_3\left(1 - \frac{a_2^2}{\lambda_1}\right)\right] + T_{c,\infty} \tag{B38}$$

$$T_{c,if} = (T_{w,o} - T_{c,\infty})\left[C_2\left(1 - \frac{a_1^2}{\lambda_1}\right)e^{a_1} + C_3\left(1 - \frac{a_2^2}{\lambda_1}\right)e^{a_2}\right] + T_{c,\infty} \tag{B39}$$

$$T_{c,o} = \eta(T_{w,o} - T_{c,\infty}) + T_{c,\infty} \tag{B40}$$

$$T_{w,i} = (T_{w,o} - T_{c,\infty})(C_2 + C_3) + T_{c,\infty} \tag{B41}$$

$$T_{w,if} = (T_{w,o} - T_{c,\infty})\left(C_2 e^{a_1} + C_3 e^{a_2}\right) + T_{c,\infty} \tag{B42}$$

APPENDIX C

DERIVATION OF EQUATIONS FOR METAL TEMPERATURE DISTRIBUTION AND COOLANT TEMPERATURE RISE IN A TWO-LAYER POROUS WALL

Reference 3 develops the equations for metal temperature distribution and coolant temperature rise through a single-layer porous wall with a fixed shell outer-surface temperature. The results are

$$\theta_w(\xi) = C_1 + C_2 e^{a_1 \xi} + C_3 e^{a_2 \xi} \tag{C1}$$

and

$$\theta_c(\xi) = C_1 + C_2 \left(1 - \frac{a_1^2}{\lambda}\right) e^{a_1 \xi} + C_3 \left(1 - \frac{a_2^2}{\lambda}\right) e^{a_2 \xi} \tag{C2}$$

where

$$\theta_w = \frac{T_w - T_{c,\infty}}{T_{w,o} - T_{c,\infty}} \tag{C3}$$

$$\theta_c = \frac{T_c - T_{c,\infty}}{T_{w,o} - T_{c,\infty}} \tag{C4}$$

$$a_1 = -\frac{1}{2}\left(\beta + \sqrt{\beta^2 + 4\lambda}\right) \tag{C5}$$

$$a_2 = -\frac{1}{2}\left(\beta - \sqrt{\beta^2 + 4\lambda}\right) \tag{C6}$$

$$\xi = \frac{x}{L} \tag{C7}$$

$$\lambda = \frac{H_m L^2}{k} \tag{C8}$$

$$\beta = \frac{H_m L}{G_c C_p} \tag{C9}$$

$$H_m = h_m Z \tag{C10}$$

The boundary conditions are shown to be

$$\theta_w(1) = 1 \tag{C11}$$

$$N\theta_w(0) = \theta_w'(0) \tag{C12}$$

$$\theta_c(0) = \frac{\beta}{\lambda}\,\theta_w'(0) \tag{C13}$$

and the constants of integration are

$$C_1 = 0 \tag{C14}$$

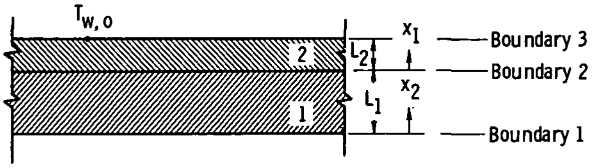
$$C_2 = \frac{N - a_2}{(N - a_2)e^{a_1} - (N - a_1)e^{a_2}} \tag{C15}$$

$$C_3 = \frac{a_1 - N}{(N - a_2)e^{a_1} - (N - a_1)e^{a_2}} \tag{C16}$$

where

$$N = \frac{h_i L}{k} \tag{C17}$$

Now consider a two-layer porous wall as shown in sketch (b).



(b)

Let the shell outer-surface temperature be $T_{w,o}$ and let the subscripts 1 and 2 designate the inner and outer layer, respectively. Using the equations

$$\xi_1 = \frac{x_1}{L_1} \tag{C18}$$

$$\xi_2 = \frac{x_2}{L_2} \tag{C19}$$

$$\lambda_1 = \frac{H_{m,1}L_1^2}{k_1} \tag{C20}$$

$$\lambda_2 = \frac{H_{m,2}L_2^2}{k_2} \tag{C21}$$

$$\beta_1 = \frac{H_{m,1}L_1}{G_cC_p} \tag{C22}$$

$$\beta_2 = \frac{H_{m,2}L_2}{G_cC_p} \tag{C23}$$

results in the following wall temperature and coolant temperature expressions for each layer:

$$\theta_{w,1}(\xi_1) = C_1 + C_2e^{a_1\xi_1} + C_3e^{a_2\xi_1} \tag{C24}$$

$$\theta_{c,1}(\xi_1) = C_1 + C_2\left(1 - \frac{a_1^2}{\lambda_1}\right)e^{a_1\xi_1} + C_3\left(1 - \frac{a_2^2}{\lambda_1}\right)e^{a_2\xi_1} \tag{C25}$$

and

$$\theta_{w,2}(\xi_2) = C_4 + C_5e^{\alpha_1\xi_2} + C_6e^{\alpha_2\xi_2} \tag{C26}$$

$$\theta_{c,2}(\xi_2) = C_4 + C_5\left(1 - \frac{\alpha_1^2}{\lambda_2}\right)e^{\alpha_1 \xi_2} + C_6\left(1 - \frac{\alpha_2^2}{\lambda_2}\right)e^{\alpha_2 \xi_2} \tag{C27}$$

where

$$a_1 = -\frac{1}{2}\left(\beta_1 + \sqrt{\beta_1^2 + 4\lambda_1}\right) \tag{C28}$$

$$a_2 = -\frac{1}{2}\left(\beta_1 - \sqrt{\beta_1^2 + 4\lambda_1}\right) \tag{C29}$$

$$\alpha_1 = -\frac{1}{2}\left(\beta_2 + \sqrt{\beta_2^2 + 4\lambda_2}\right) \tag{C30}$$

$$\alpha_2 = -\frac{1}{2}\left(\beta_2 - \sqrt{\beta_2^2 + 4\lambda_2}\right) \tag{C31}$$

The six constants are evaluated from the boundary conditions as follows: As in reference 3, an energy balance at boundary 1 leads to

$$N_1\theta_{w,1}(0) = \theta'_{w,1}(0) \tag{C32}$$

and

$$\theta_{c,1}(0) = \frac{\beta_1}{\lambda_1}\,\theta_{w,1}(0) \tag{C33}$$

At the interface between the two layers (boundary 2) there must be continuity in metal and coolant temperatures, as well as continuity in heat flux. This is expressed by

$$\theta_{w,1}(1) = \theta_{w,2}(0) \tag{C34}$$

$$\theta_{c,1}(1) = \theta_{c,2}(0) \tag{C35}$$

and

$$\frac{k_1}{L_1}\,\theta'_{w,1}(1) = \frac{k_2}{L_2}\,\theta'_{w,2}(0) \tag{C36}$$

Finally, at boundary 3, the specified wall temperature gives

$$\theta_{w,2}(1) = 1 \tag{C37}$$

Substituting equations (C24) to (C27) into equations (C32) to (C37) then gives

$$N_1C_1 + (N_1 - a_1)C_2 + (N_1 - a_2)C_3 = 0 \tag{C38}$$

$$C_1 + C_2\left(1 - \frac{a_1^2}{\lambda_1} - \frac{a_1\beta_1}{\lambda_1}\right) + C_3\left(1 - \frac{a_2^2}{\lambda_1} - a_2\frac{\beta_1}{\lambda_1}\right) = 0 \tag{C39}$$

$$C_1 + C_2e^{a_1} + C_3e^{a_2} = C_4 + C_5 + C_6 \tag{C40}$$

$$C_1 + C_2\left(1 - \frac{a_1^2}{\lambda_1}\right)e^{a_1} + C_3\left(1 - \frac{a_2^2}{\lambda_1}\right)e^{a_2} = C_4 + C_5\left(1 - \frac{\alpha_1^2}{\lambda_2}\right) + C_6\left(1 - \frac{\alpha_2^2}{\lambda_2}\right) \tag{C41}$$

$$\Omega a_1e^{a_1}C_2 + \Omega a_2e^{a_2}C_3 - \alpha_1C_5 - \alpha_2C_6 = 0 \tag{C42}$$

$$C_4 + C_5e^{\alpha_1} + C_6e^{\alpha_2} = 1 \tag{C43}$$

where

$$\Omega = \frac{k_1L_2}{k_2L_1} \tag{C44}$$

From equation (C39) it can be shown that $C_1 = 0$. Other than that, no further simplification is possible and the remaining constants (C_2 to C_6) are best solved by a matrix solution from

$$
\begin{bmatrix}
(N_1 - a_1) & (N_1 - a_2) & 0 & 0 & 0 \\
e^{a_1} & e^{a_2} & -1 & -1 & -1 \\
\left(1 - \frac{a_1^2}{\lambda_1}\right)e^{a_1} & \left(1 - \frac{a_2^2}{\lambda_1}\right)e^{a_2} & -1 & -\left(1 - \frac{\alpha_1^2}{\lambda_2}\right) & -\left(1 - \frac{\alpha_2^2}{\lambda_2}\right) \\
\Omega a_1 e^{a_1} & \Omega a_2 e^{a_2} & 0 & -\alpha_1 & -\alpha_2 \\
0 & 0 & 1 & e^{\alpha_1} & e^{\alpha_2}
\end{bmatrix}
\begin{Bmatrix} C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \end{Bmatrix}
=
\begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{Bmatrix}
\qquad \text{(C45)}
$$

APPENDIX D

PROGRAM STRUCTURE AND FUNCTION

The computer program FCFC consists of the main program MAINP and the subroutines TMETO, MNEW, AIRPRP, PRBMTX, SPLINE, and XMTXSL. The calling relations between MAINP and the subroutines are shown in figure 10. The functions of MAINP and each of the subroutines are described in this appendix.

Main Program MAINP

The main program MAINP is the control program that directs the flow of the solution from input to output and calculates and balances the coolant flow. Program MAINP reads the input, makes the necessary conversions to working units, establishes the initial plenum pressure or pressure profile (for centrifugal calculations), balances the coolant outflow and inflow by an iterative procedure, prints the output, and returns the variables to the input units. Flow and heat transfer are solved simultaneously, with all heat-transfer results being obtained from the TMETO subroutine.

Subroutine TMETO

Subroutine TMETO performs all heat-transfer calculations including back-side impingement, convection in the film-cooling holes, and full-coverage film cooling. It calculates the heat picked up by the coolant at all flow stations and the inner and outer temperatures of the metal and the thermal-barrier coating.

Subroutine MNEW

Subroutine MNEW establishes the Mach number at the inlet of a constant-area film-cooling hole, for a given total temperature and pressure at the hole exit, and for a given change in total temperature and pressure across the hole (eq. (B10)).

Subroutine AIRPRP

Subroutine AIRPRP calculates the physical properties of the coolant at any specified temperature. The properties are evaluated from input tables 1 to 4 by calling subroutine

SPLINE. Subroutine AIRPRP performs any necessary unit conversions (from SI into U.S. customary units) and calculates values of different combinations of gamma: $\gamma - 1$, $(\gamma - 1)/\gamma$, $\gamma + 1$, $(\gamma + 1)/2$, $\gamma/(\gamma - 1)$, and $(\gamma - 1)/2$. The Prandtl number is evaluated from its definition $Pr = C_p \mu/k$.

Subroutine PRBMTX

Subroutine PRBMTX evaluates the function second derivatives at the specified x-locations for all input tables. The slopes at the end points are evaluated from the first two and last two data points. The calculation of the second derivatives was separated from the spline-fitting procedure of subroutine SPLINE, since the second derivatives have to be calculated only once but the spline-fitting procedure is performed many times.

Subroutine SPLINE

Subroutine SPLINE generates an interpolated (spline fitted) value of y at any x for a curve described by a finite number of points (ref. 10).

Subroutine XMTXSL

Subroutine XMTXSL is a general matrix-solution technique based on the Gauss-Jordan elimination method (ref. 11).

APPENDIX E

PROGRAM VARIABLES DICTIONARY

The variables used in the main program and in the subroutines are described here. Subscripted variables pertaining to the impingement and film-cooling rows are shown with the indexes I and J, respectively. Variables that are input arguments in a subroutine are defined in the listing of the calling program.

Main Program MAINP

A5(J)	shell outer-surface area associated with the film-cooling row
AIMP(I)	impingement-row hole area
ALPHA(J)	film-cooling-row inclination angle
ANEW	hole area at entrance of film-cooling hole (dummy variable for constant-area hole)
ANGR1,..., ANGR10	rotation angle for coordinate system of input tables 1 to 10
AO5	input argument for AOUT(J) in subroutine TMETO
AOLD	hole area at exit of film-cooling hole (dummy variable for constant-area hole)
AOUT(J)	film-cooling-row hole area
BETA(J)	film-cooling-row compound angle
CDI(I)	impingement-hole discharge coefficient
CDD	output argument for curve 5 in SPLINE subroutine
CDFC(J)	film-cooling flow reduction due to main-stream blowing
CDIFC	temporary storage for CDI(I)
CDOD	output argument for CDFC(J) in subroutine SPLINE
CFFLOW	relative tolerance for total inflow and outflow
CFMCH	relative tolerance for Mach number iteration between stations 4 and 5
CFP45	relative tolerance for P45
CFP5T	relative tolerance for P5T

CFT2	relative tolerance for T2
CFT5	relative tolerance for T5
CFT5T	relative tolerance for T5T
CFTWO	relative tolerance for shell outer-surface temperature
CP	specific heat at constant pressure
DAU	input argument for TAU(J) in subroutine TMETO
DAU2	input argument for TAUC(J) in subroutine TMETO
DFC(J)	film-cooling-row hole diameter
DI(I)	impingement-row hole diameter
FCBLR	film-cooling blowing rate (input argument in subroutine TMETO)
FCHD	input argument for DFC(J) in subroutine TMETO
FCHSP	input argument for HSP5(J) in subroutine TMETO
FLOFC	relative change between total coolant inflow and outflow
G	specific-heat ratio, γ
GAM	γ evaluated at next-to-last value of TN
GCVG	relative change between GTST and GAM
GDGM1	$\gamma/(\gamma - 1)$
GM1	$\gamma - 1$
GM1D2	$(\gamma - 1)/2$
GM1DG	$(\gamma - 1)/\gamma$
GP1	$\gamma + 1$
GP1D2	$(\gamma + 1)/2$
GTST	γ evaluated at last value of TN
H0	input argument for HG0(J) in subroutine TMETO
H1	input argument for HG1(J) in subroutine TMETO
HFC4(J)	modification factor for impingement h
HFC45(J)	modification factor for film-cooling hole convective h
HFCTR	input argument for HFC4(J) in subroutine TMETO
HG0(J)	main-stream gas h for coolant temperature equal to main-stream gas temperature

HG1(J)	main-stream gas h for coolant temperature equal to shell outer-surface temperature
HHFCTR	input argument for HFC45(J) in subroutine TMETO
HSP	ratio of film-cooling hole spacing to diameter
HSP1(I)	impingement hole spacing
HSP5(J)	film-cooling hole spacing
ICTR	indicator for centrifugal calculations
IHLD	indicator for supply row with lowest specified R1
IJ	counter for overall flow iterations
IOA	counter for chamber calculations
IUNTS	indicator for SI or U.S. customary units
JCV(J)	convergence indicator
JCVT	chamber convergence indicator
JHLD	indicator for film-cooling row with lowest specified R4
JRVFL	film-cooling reverse-flow indicator for individual rows
JRVFLT	film-cooling reverse-flow indicator for entire chamber
K	counter for overall film-cooling flow iterations
KCLC	indicator for coating or no coating
KCNVG(J)	counter for individual film-cooling flow iterations
KKLM(J)	counter for individual film-cooling-row heat-transfer calculations
MSBL	indicator for main-stream gas blowing
MTC	indicator for metal temperature calculations
NC	input table number
NFCHPR(J)	number of film-cooling holes per row
NFCR	number of film-cooling rows
NIHPR(I)	number of impingement holes per row
NIR	number of impingement rows
NPC1,..., NPC10	number of points specified for input tables 1 to 10
NREAD	integer number of input read file

NWRITE	integer number of output write file
OMG	rotative speed
P1T(I)	total pressure at station 1
P1THLD	temporary storage location for P1T
P1TMIN	minimum specified supply pressure
P2(I)	static pressure at station 2
P2T(I)	total pressure at station 2
P3T	total pressure at station 3 (vane calculations)
P3TFK	temporary storage for P3T
P3TFCR(J)	total pressure in impingement plenum at each film-cooling row (blade calculations)
P3TIR(I)	total pressure in impingement plenum at each impingement row (blade calculations)
P3TMNN	lowest allowable pressure in impingement plenum
P3TMNR	total pressure in impingement plenum at minimum specified radius
P3TMXX	highest allowable pressure in impingement plenum
P4(J)	static pressure at station 4
P4T(J)	total pressure at station 4
P45	average static pressure in film-cooling hole
P45CNV	relative change in P45
P45HLD	next-to-last iterated value of P45
P45N	last iterated value of P45
P45T	average total pressure in film-cooling hole
P5(J)	static pressure at station 5
P5HOLD	temporary storage for P5
P5MAX	highest specified back pressure for vane calculations
P5T(J)	total pressure at station 5
P5TCV(J)	relative change in P5T
P5TNEW	last iterated value of P5T
P5TOLD	next-to-last iterated value of P5T

P6(J)	static pressure at station 6
PFCR	temporary storage location for P3TFCR(J)
PHOLD	temporary storage location for P3TMXX or P3TMNN
PN45(J)	static pressure at midpoint of film-cooling hole
PRN	Prandtl number
PTN	input argument for P4T(J) in subroutine MNEW
PTO	input argument for P5T(J) in subroutine MNEW
R1(I)	radial distance at station 1
R4(J)	radial distance at station 4
REJ2(I)	Reynolds number at station 2
REJ5(J)	Reynolds number at station 5
REYN45	Reynolds number at midpoint of film-cooling hole
RGAS	gas constant
R1HLD	temporary storage location for R1(I)
R4HLD	temporary storage location for R4(J)
RHO2(I)	density at station 2
RHO4(J)	density at station 4
RHO45	density at midpoint of film-cooling hole
RHO5(J)	density at station 5
RMN	lowest specified R1(I) or R4(J)
R1MN	lowest specified R1(I)
R4MN	lowest specified R4(J)
ROV2C(J)	ρV^2 of coolant at station 5
ROVG(J)	ρV of main-stream gas
ROV2G(J)	ρV^2 of main-stream gas
ROV2R	input argument for ROV2RT(J) in subroutine SPLINE
ROVRAT(J)	$(\rho V)_c/(\rho V)_g$
ROV2RT(J)	$(\rho V^2)_c/(\rho V^2)_g$
RTCOR	output argument for RTCR(J) in subroutine SPLINE
RTCR(J)	correction factor for CDFC(J)

T2(I)	static temperature at station 2
T4(J)	static temperature at station 4
T45	average static temperature between stations 4 and 5
T5(J)	static temperature at station 5
TAU(J)	shell metal thickness
TAUC(J)	shell coating thickness
TAUI(I)	impingement insert thickness
TC	input argument for TT in subroutine TMETO
TC2(I)	coolant interface temperature (boundary 2)
T2CNVG	relative change for T2(I)
T5CNVG	relative change for T5(J)
TD	temporary storage for T4(J) or T4T(J)
T2D	input argument for T2(I) in subroutine AIRPRP
T5D	input argument for T5(J) in subroutine AIRPRP
TERM	$\left\{1.0 - [P2(I)]/P2T(I)\right\}^{(\gamma-1)/\gamma}$ or $\left\{1.0 - [P5(I)]/P5T(I)\right\}^{(\gamma-1)/\gamma}$
TG	input argument for TMSG(J) in subroutine TMETO
T2HLD	temporary storage location for T2(I)
T5HLD	temporary storage for T5(J)
TITLE	title of calculations
TMI(J)	inner-wall temperature
TMO(J)	outer-wall temperature
TMSG(J)	main-stream gas temperature
TN	output argument for T4(J) in subroutine MNEW
TO	input argument for T4(J) in subroutine MNEW
TT	coolant total supply temperature
T2T(I)	total temperature at station 2
T4T(J)	total temperature at station 4
T5T(J)	total temperature at station 5
T3TAV	average coolant total temperature at station 3
T4TAV	average coolant total temperature at station 4

TTN	input argument for T4T(J) in subroutine MNEW
TTO	input argument for T5T(J) in subroutine MNEW
T5TFTR	relative change in T5T(J)
T5TOLD(J)	next-to-last iterated value of T5T(J)
TW2(J)	wall interface temperature
V2(I)	velocity at station 2
V4(J)	velocity at station 4
V45	average velocity in film-cooling row
V5(J)	velocity at station 5
WFCR	input argument for WOUT(J) in subroutine TMETO
WIMP(I)	coolant inflow
WIMPT	total coolant inflow
WOUT(J)	coolant outflow
WOUTT	total coolant outflow
XBETA	input argument for BETA(J) in subroutine SPLINE
XCDI	average impingement discharge coefficient
XDI	average impingement hole diameter
XETA(J)	overall effectiveness
XHD(J)	impingement heat-transfer coefficient
XHH(J)	heat-transfer coefficient in film-cooling holes
XHSP1	average impingement hole spacing
XILOD	ratio of impingement distance to impingement hole diameter
XIMP(I)	impingement distance
XKA	coolant thermal conductivity
XKT	film-cooling total-pressure loss coefficient
XKTD	output argument for curve 6 in SPLINE subroutine
XLC	input argument for XLFCC(J) in subroutine TMETO
XLFC(J)	length of film-cooling hole (metal only)
XLFCC(J)	length of film-cooling hole (coating only)
XLFCPC(J)	length of film-cooling hole (metal plus coating)

XLM	input argument for XLFC(J) in subroutine TMETO
XLODFC(J)	film-cooling hole length-diameter ratio (metal only)
XLODI(I)	impingement hole length-diameter ratio
XLODXX(J)	film-cooling hole length-diameter ratio (metal plus coating)
XM2(I)	Mach number at station 2
XM4(J)	Mach number at station 4
XM5(J)	Mach number at station 5
XMD	temporary storage location for XM2(I) or XM5(J)
XMK1(24),..., XMK10(24)	calculated values of curve slopes M_k for tables 1 to 10
XMNEW	output argument for subroutine MNEW
XMOLD	input argument for XM5(J) in subroutine MNEW
XMU	coolant viscosity
XRHO2	average density at station 2
XT4TAV	average total temperature at station 4
XV2	average velocity at station 2
XX1,..., XX10	x-coordinates for input tables 1 to 10
XXAKCT(J)	coating thermal conductivity
XXAKM(J)	metal thermal conductivity
XXIMP	average impingement distance
XXKT(J)	total-pressure loss coefficient
YY1,..., YY10	y-coordinates for input tables 1 to 10
ZFC	input argument for XLODFC(J) in subroutine TMETO

Subroutine TMETO

A1	parameter defined by eq. (C5)
A2	parameter defined by eq. (C6)
AKCT	coating thermal conductivity

AKM	metal thermal conductivity
AL1	parameter defined by eq. (C30)
AL2	parameter defined by eq. (C31)
AREAR	area reduction ratio
BETA	parameter defined by eq. (C22)
BETA2	parameter defined by eq. (C23)
C2,...,C6	constants obtained by solving eq. (C45)
CMAT(24,25)	general problem matrix to be solved by subroutine XMTSOL
CN(24)	solution vector obtained from subroutine XMTSOL
COEF	coefficient (temporary storage location)
DA	parameter defined by eq. (C20)
DA2	parameter defined by eq. (C21)
DELHG	H0 - H1
DEN	denominator of eqs. (C15) and (C16)
ETA	overall effectiveness, defined by eqs. (B33) or (B34)
FACVA	arrival velocity factor
HC	HD corrected for presence of film-cooling holes
HD	coolant impingement-heat-transfer coefficient obtained from Gardon-Cobonpue correlation (eq. (B11), ref. 8)
HH	average convective-heat-transfer coefficient in film-cooling hole (metal only, eq. (B13))
HH2	average convective-heat-transfer coefficient in film-cooling hole (coating only, eq. (B14))
HM	internal volumetric-heat-transfer coefficient (metal only)
HM2	internal volumetric-heat-transfer coefficient (coating only)
KLM	counter for number of wall temperature calculation iterations
REH	Reynolds number in film-cooling hole
RENA	impingement Reynolds number based on "arrival" velocity
ROOT	$\sqrt{\beta_1^2 + 4\lambda_1}$
ROOT2	$\sqrt{\beta_2^2 + 4\lambda_2}$

TCA	average coolant temperature in film-cooling hole (metal only)
TCAO	overall average coolant temperature
TCCAV	average coolant temperature in film-cooling hole (coating only)
TCIF	coolant temperature at interface plane
TCIN	coolant temperature at inlet of film-cooling hole
TCO	coolant temperature at outlet of film-cooling hole
TCTAV	coating average temperature
TDIF	temperature difference, TG - TC
TFILM	film temperature, (TWI + TC')/2
TNEW	last iterated value of TWO
TOLD	next-to-last iterated value of TWO
TR	temperature ratio
TWAV	average wall temperature (metal only)
TWI	wall inner temperature
TWIF	wall interface temperature
TWO	wall outer temperature
TWOCVG	relative change in TWO
U	parameter defined by eq. (C17)
XLTOT	total length of film-cooling hole (metal and coating)

Subroutine MNEW

CNVCR	relative tolerance for Mach number iteration
DNM	denominator in expression for iterated Mach number
I	counter for Mach number convergence iteration
PATG	$(p_5'/p_4')(A_5/A_4)\sqrt{T_4'/T_5'}$
POWN	$(\gamma + 1)/[2(\gamma - 1)]$ evaluated at last value of γ
POWO	$(\gamma + 1)/[2(\gamma - 1)]$ evaluated at next-to-last value of γ
XMFCN	$1.0 + [(\gamma - 1)/2]M^2$ evaluated at last value of M
XMFCO	$1.0 + [(\gamma - 1)/2]M^2$ evaluated at next-to-last value of M

XMHLD	temporary storage location for XMN
XMN	Mach number
XMNEW	final iterated value of XMN
XNUM	numerator in expression for iterated Mach number

Subroutine PRBMTX

ANGROT	coordinate system rotation angle
CAN	cos (ANGROT)
F(24)	specified points that describe curve in unrotated coordinate system
FR(24)	generated points that describe curve in rotated coordinate system
L(24)	lengths of intervals between inputted F(24) in unrotated coordinate system
LR(24)	lengths of intervals between generated FR(24) in rotated coordinate system
MAT(24,25)	matrix of function second derivatives at specified XK locations
N	number of intervals generated by XK values of FR (NP1 - 1)
NP1	number of points that describe a curve, N + 1
NP2	N + 2
OPT	indicator for rotated coordinate system
SAN	sin (ANGROT)
SOL(24)	solution vector of problem matrix MAT (24,25)
XK(24)	inputted x-values corresponding to inputted points F(24) in unrotated coordinate system
XKR(24)	generated x-values for a rotated coordinate system
XPFST	slope of first interval in unrotated coordinate system
YPFSTR	slope of first interval in rotated coordinate system
YPLST	slope of last interval in unrotated coordinate system
YPLSTR	slope of last interval in rotated coordinate system

Subroutine SPLINE

ANGINV	inverse of coordinate system rotation angle (-ANGROT)
ANGROT	coordinate system rotation angle
CAN	cos (ANGROT)
CANI	cos (ANGINV)
CRIT	relative accuracy of iterated y-value for rotated coordinate system
DELXR	(XX - XXM)/10
FK	value of specified function at first point to right of desired x-location
FKM1	value of specified function at first point to left of desired x-location
FR(24)	specified y-values of table in rotated coordinate system
IND	indicator for determining whether desired x-value is outside inputted range of x
LK	length of interval
MK	value of function second derivative on right side of interval
MKM1	value of function second derivative on left side of interval
N	number of intervals that describe a curve
NC	input table number
NM1	N - 1
OPT	indicator for rotated or unrotated coordinate system
SAN	sin (ANGROT)
SANI	sin (ANGINV)
TERM1,..., TERM4	terms whose sum is equal to spline-fitted value of y
X	x-location in unrotated coordinate system
XKR(24)	specified table x-locations in rotated coordinate system
XR	x-location in rotated coordinate system
XX	specified x-value on right side of interval
XXM	specified x-value on left side of interval
Y	spline-fitted value at specified x in unrotated coordinate system

Subroutine XMTXSL

DET	matrix determinant
DIV	value of row pivot element
FCT(24)	factor used to reduce elements in pivot column to zero
ISNGL	factor for indicating singular matrix
MAT(24,49)	overall matrix obtained by adding problem matrix and identity matrix
NC	number of columns
NLST	NC + NR
NM	NR - 1
NN	NC + 1
NR	number of rows (order of matrix)
NSW	number of switches needed to make pivot element the largest element
SOL(24)	solution vector

APPENDIX F

PROGRAM LISTING

MAIN PROGRAM

```
      DIMENSION TITLE(16)
      DIMENSION NIHPR(25),R1(25),DI(25),TAUI(25),HSPI(25),XIMP(25),PIT(2
     *5)
      DIMENSION NFCHPR(50),R4(50),DFC(50),A5(50),TAU(50),HSP5(50),HFC4(5
     *0),HFC45(50),ALPHA(50),BETA(50),HG0(50),HG1(50),TMS6(50),P6(50),RO
     *V6(50),ROV26(50),TAUC(50),TW2(50),TC2(50)
      DIMENSION AIMP(25),XLODI(25),P3TIR(25),XM2(25),V2(25),T2(25),T2T(2
     *5),P2(25),P2T(25),CDI(25),RHO2(25),REJ2(25),WIMP(25)
      DIMENSION AOUT(50),XLFC(50),XLODFC(50),P3TFCR(50),JCV(50),KCNVG(50
     *),XM5(50),V5(50),T5(50),T5T(50),P5(50),P5T(50),T5TOLD(50),CDFC(50)
     *,XXKT(50),RHO5(50),ROVRAT(50),ROV2C(50),ROV2RT(50),REJ5(50),XLFCC(
     *50),XLFCPC(50),XLODXX(50),RTCR(50)
      DIMENSION T4(50),T4T(50),P4(50),P4T(50),V4(50),RN45(50),TMI(50),TM
     *O(50),XETA(50),XM4(50),WOUT(50),P5TCV(50),RHO4(50)
      DIMENSION XHD(50),XHH(50),XXAKM(50),KKLM(50),XXAKCT(50)
      DIMENSION XX1(24),XX2(24),XX3(24),XX4(24),XX5(24),XX6(24),XX7(24),
     *XX8(24),XX9(24),XX10(24)
      DIMENSION YY1(24),YY2(24),YY3(24),YY4(24),YY5(24),YY6(24),YY7(24),
     *YY8(24),YY9(24),YY10(24)
      DIMENSION XMK1(24),XMK2(24),XMK3(24),XMK4(24),XMK5(24),XMK6(24),XM
     *K7(24),XMK8(24),XMK9(24),XMK10(24)

      COMMON NPC1,NPC2,NPC3,NPC4,ANGR1,ANGR2,ANGR3,ANGR4,XX1,XX2,XX3,XX4
     *,YY1,YY2,YY3,YY4,XMK1,XMK2,XMK3,XMK4,NREAD,NWRITE

      NAMELIST/DATT/IUNTS,ICTR,MTC,MSBL,KCLC,OMG,RGAS,
     *NIR,NIHPR,R1,DI,TAUI,HSPI,XIMP,PIT,TT,
     *NFCR,NFCHPR,R4,DFC,A5,TAU,TAUC,HSP5,HFC4,HFC45,ALPHA,BETA,HG0,HG1,
     *TMS6,P6,ROVG,ROV26

      NREAD=5
      NWRITE=6
      READ(NREAD,5010)(TITLE(I),I=1,16)
      WRITE(NWRITE,6010)(TITLE(I),I=1,16)

      ANGR1=0.
      READ(NREAD,5020)NPC1
      IF(NPC1 .LT. 3)GOTO 130
      READ(NREAD,5030)(XX1(I),I=1,NPC1)
      READ(NREAD,5030)(YY1(I),I=1,NPC1)
      WRITE(NWRITE,6020)
      DO 10 I=1,NPC1
   10 WRITE(NWRITE,6030)(XX1(I),YY1(I))
      CALL PRBMTX(NPC1,XX1,YY1,ANGR1,XMK1)

      ANGR2=0.
      READ(NREAD,5020)NPC2
      IF(NPC2 .LT. 3)GOTO 130
```

```
      READ(NREAD,5030)(XX2(I),I=1,NPC2)
      READ(NREAD,5030)(YY2(I),I=1,NPC2)
      WRITE(NWRITE,6040)
      DO 20 I=1,NPC2
   20 WRITE(NWRITE,6050)(XX2(I),YY2(I))
      CALL PRBMTX(NPC2,XX2,YY2,ANGR2,XMK2)

      ANGR3=0.
      READ(NREAD,5020)NPC3
      IF(NPC3 .LT. 3)GOTO 130
      READ(NREAD,5030)(XX3(I),I=1,NPC3)
      READ(NREAD,5030)(YY3(I),I=1,NPC3)
      WRITE(NWRITE,6060)
      DO 30 I=1,NPC3
   30 WRITE(NWRITE,6030)(XX3(I),YY3(I))
      CALL PRBMTX(NPC3,XX3,YY3,ANGR3,XMK3)

      ANGR4=0.
      READ(NREAD,5020)NPC4
      IF(NPC4 .LT. 3)GOTO 130
      READ(NREAD,5030)(XX4(I),I=1,NPC4)
      READ(NREAD,5030)(YY4(I),I=1,NPC4)
      WRITE(NWRITE,6070)
      DO 40 I=1,NPC4
   40 WRITE(NWRITE,6050)(XX4(I),YY4(I))
      CALL PRBMTX(NPC4,XX4,YY4,ANGR4,XMK4)

      ANGR5=0.
      READ(NREAD,5020)NPC5
      IF(NPC5 .LT. 3)GOTO 130
      READ(NREAD,5030)(XX5(I),I=1,NPC5)
      READ(NREAD,5030)(YY5(I),I=1,NPC5)
      WRITE(NWRITE,6080)
      DO 50 I=1,NPC5
   50 WRITE(NWRITE,6030)(XX5(I),YY5(I))
      CALL PRBMTX(NPC5,XX5,YY5,ANGR5,XMK5)

      ANGR6=0.
      READ(NREAD,5020)NPC6
      IF(NPC6 .LT. 3)GOTO 130
      READ(NREAD,5030)(XX6(I),I=1,NPC6)
      READ(NREAD,5030)(YY6(I),I=1,NPC6)
      WRITE(NWRITE,6090)
      DO 60 I=1,NPC6
   60 WRITE(NWRITE,6030)(XX6(I),YY6(I))
      CALL PRBMTX(NPC6,XX6,YY6,ANGR6,XMK6)

      ANGR7=45.0
      READ(NREAD,5020)NPC7
      IF(NPC7 .EQ. 0 .AND. MSBL .EQ. 1)GOTO 130
      IF(NPC7 .EQ. 0)GO TO 80
      IF(NPC7 .LT. 3)GOTO 130
      READ(NREAD,5030)(XX7(I),I=1,NPC7)
      READ(NREAD,5030)(YY7(I),I=1,NPC7)
      WRITE(NWRITE,6100)
      DO 70 I=1,NPC7
   70 WRITE(NWRITE,6030)(XX7(I),YY7(I))
      WRITE(NWRITE,6110)ANGR7
      CALL PRBMTX(NPC7,XX7,YY7,ANGR7,XMK7)
   80 CONTINUE

      ANGR8=0.
      READ(NREAD,5020)NPC8
      IF(NPC8 .EQ. 0 .AND. MSBL .EQ. 1)GO TO 130
      IF(NPC8 .EQ. 0)GO TO 85
      IF(NPC8 .LT. 3)GO TO 130
      READ(NREAD,5030)(XX8(I),I=1,NPC8)
      READ(NREAD,5030)(YY8(I),I=1,NPC8)
      WRITE(NWRITE,6115)
      DO 82 I=1,NPC8
   82 WRITE(NWRITE,6030)(XX8(I),YY8(I))
      CALL PRBMTX(NPC8,XX8,YY8,ANGR8,XMK8)
   85 CONTINUE
```

```
      ANGR9=0.
      READ(NREAD,5020)NPC9
      IF(NPC9 .EQ. 0 .AND. MTC .EQ. 1)GOTO 130
      IF(NPC9 .EQ. 0)GO TO 100
      IF(NPC9 .LT. 3)GOTO 130
      READ(NREAD,5030)(XX9(I),I=1,NPC9)
      READ(NREAD,5030)(YY9(I),I=1,NPC9)
      WRITE(NWRITE,6120)
      DO 90 I=1,NPC9
   90 WRITE(NWRITE,6030)(XX9(I),YY9(I))
      CALL PRBMTX(NPC9,XX9,YY9,ANGR9,XMK9)
  100 CONTINUE

      ANGR10=0.
      READ(NREAD,5020)NPC10
      IF(NPC10 .EQ. 0 .AND. MTC .EQ. 1 .AND. KCLC .EQ. 1)GOTO 130
      IF(NPC10 .EQ. 0)GO TO 120
      IF(NPC10 .LT. 3)GOTO 130
      READ(NREAD,5030)(XX10(I),I=1,NPC10)
      READ(NREAD,5030)(YY10(I),I=1,NPC10)
      WRITE(NWRITE,6130)
      DO 110 I=1,NPC10
  110 WRITE(NWRITE,6030)(XX10(I),YY10(I))
      CALL PRBMTX(NPC10,XX10,YY10,ANGR10,XMK10)
  120 CONTINUE
      GO TO 140
  130 WRITE(NWRITE,6140)
      GO TO 2000
  140 CONTINUE

C-----THE PROGRAM ITERATIONS ARE CARRIED OUT TO RELATIVE ACCURACIES SPECIFIED
C     BY EIGHT CONVERGENCE FACTORS (DENOTED BY CFXXX). EXCEPT FOR CFFLOW,
C     THESE FACTORS ARE DEFINED AS ABS((OLD VALUE-NEW VALUE)/(NEW VALUE)).

C     CFT2  - CONVERGENCE FACTOR FOR STATIC TEMP.  AT STATION 2
C     CFT5  - CONVERGENCE FACTOR FOR STATIC TEMP.  AT STATION 5
C     CFT5T - CONVERGENCE FACTOR FOR TOTAL  TEMP.  AT STATION 5
C     CFP5T - CONVERGENCE FACTOR FOR TOTAL PRESS. AT STATION 5
C     CFP45 - CONVERGENCE FACTOR FOR STATIC PRESS. BETWEEN STATIONS 4 AND 5
C     CFMCH - CONVERGENCE FACTOR FOR MACH NUMBER BETWEEN STATIONS 4 AND 5
C     CFFLOW- CONVERGENCE FACTOR FOR TOTAL INFLOW AND OUTFLOW
C             (DEFINED AS ABS((INFLOW-OUTFLOW)/(SMALLER OF THE TWO FLOWS))
C     CFTWO - CONVERGENCE FACTOR FOR METAL OUTER WALL TEMP.

      CFT2=.001
      CFT5=.001
      CFT5T=.001
      CFP5T=.001
      CFP45=.001
      CFMCH=.001
      CFFLOW=.001
      CFTWO=.001
C
C-----SET DEFAULT VALUES
C
      IUNTS=0
      ICTR=0
      MTC=0
      MSBL=0
      KCLC=0
      RGAS=53.35
      IOA=0
      DO 145 I=1,50
      HFC4(I)=1.0
  145 HFC45(I)=1.0
  150 CONTINUE
      IOA=IOA + 1
      READ(NREAD,DATT,END=2000)
      WRITE(NWRITE,6150)IOA
      IF(IUNTS .EQ. 0)GO TO 160
      WRITE(NWRITE,6160)
      GO TO 170
```

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  160 WRITE(NWRITE,6170)
  170 CONTINUE
      IF(IUNTS .EQ. 0)GOTO 180
      WRITE(NWRITE,6180)RGAS
      GO TO 190
  180 WRITE(NWRITE,6190)RGAS
  190 CONTINUE
      IF(ICTR .EQ. 0)OMG=0.0
      IF(ICTR .EQ. 1)GO TO 200
      GO TO 210
  200 WRITE(NWRITE,6200)OMG
  210 CONTINUE
      IF(MTC .EQ. 1 .AND. KCLC .EQ. 1)GO TO 220
      GO TO 230
  220 WRITE(NWRITE,6210)
  230 CONTINUE
      IF(MTC .EQ. 0)GO TO 240
      GO TO 250
  240 WRITE(NWRITE,6220)
  250 CONTINUE
      IF(MSBL .EQ. 0)GO TO 260
      GO TO 270
  260 WRITE(NWRITE,6230)
  270 CONTINUE
      IF(IUNTS .EQ. 1)GO TO 280
      WRITE(NWRITE,6240)NIR
      GO TO 290
  280 WRITE(NWRITE,6250)NIR
  290 CONTINUE
C
C-----CONVERT INPUT UNITS (ENGLISH OR SI) TO WORKING ENGLISH UNITS
C
      OMG=OMG*3.14159/30.
      IF(IUNTS .EQ. 0)TT=TT + 460.
      IF(IUNTS .EQ. 1)TT=TT*9./5.
      IF(IUNTS .EQ. 0)RGAS=RGAS*32.174
      IF(IUNTS .EQ. 1)RGAS=RGAS*5.980

      DO 310 I=1,NIR
      XLODI(I)=TAUI(I)/DI(I)
      WRITE(NWRITE,6260)I,NIHPR(I),DI(I),TAUI(I),XLODI(I),HSPI(I),XIMP(I
     *),RI(I),PIT(I)
      IF(ICTR .EQ. 0)RI(I)=0.
      IF(IUNTS .EQ. 0)GO TO 300
      RI(I)=RI(I)/25.4
      DI(I)=DI(I)/25.4
      TAUI(I)=TAUI(I)/25.4
      HSPI(I)=HSPI(I)/25.4
      XIMP(I)=XIMP(I)/25.4
      PIT(I)=PIT(I)*1.450377
  300 CONTINUE
      PIT(I)=PIT(I)*144.
      AIMP(I)=FLOAT(NIHPR(I))*3.1416*(DI(I)/2.0)**2/144.
      DI(I)=DI(I)/12.
      TAUI(I)=TAUI(I)/12.
      XIMP(I)=XIMP(I)/12.
      HSPI(I)=HSPI(I)/12.
      IF(ICTR .EQ. 1)RI(I)=RI(I)/12.
  310 CONTINUE
      IF(IUNTS .EQ. 1)GO TO 320
      WRITE(NWRITE,6270)NFCR
      GO TO 330
  320 WRITE(NWRITE,6280)NFCR
  330 CONTINUE

      DO 370 I=1,NFCR
      IF(KCLC .EQ. 0)TAUC(I)=0.
      IF(KCLC .EQ. 1 .AND. TAUC(I) .EQ. 0.0)GO TO 340
      GO TO 350
  340 WRITE(NWRITE,6290)
      GO TO 1000
  350 CONTINUE
      XLFC(I)=(TAUC(I))/SIN(ALPHA(I)/57.29578)
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      XLFCPC(I)=(TAU(I)+TAUC(I))/SIN(ALPHA(I)/57.29578)
      XLFCC(I)=(TAUC(I))/SIN(ALPHA(I)/57.29578)
      XLODFC(I)=XLFC(I)/DFC(I)
      XLODXX(I)=XLFCPC(I)/DFC(I)
      IF(MSBL .EQ. 0)ROVG(I)=0.
      IF(MSBL .EQ. 0)ROV2G(I)=0.
      WRITE(NWRITE,6300)I,NFCHPR(I),DFC(I),TAU(I),TAUC(I),XLODXX(I),HSP5
     *(I),ALPHA(I),BETA(I),ROVG(I),ROV2G(I),R4(I),P6(I)
      IF(ICTR .EQ. 0)R4(I)=0.
      IF(IUNTS .EQ. 0)GO TO 360
      R4(I)=R4(I)/25.4
      DFC(I)=DFC(I)/25.4
      A5(I)=A5(I)/(2.54)**2
      TAU(I)=TAU(I)/25.4
      TAUC(I)=TAUC(I)/25.4
      XLFC(I)=XLFC(I)/25.4
      XLFCPC(I)=XLFCPC(I)/25.4
      XLFCC(I)=XLFCC(I)/25.4
      HSP5(I)=HSP5(I)/25.4
      HG0(I)=HG0(I)*0.176228
      HG1(I)=HG1(I)*0.176228
      TMSG(I)=TMSG(I)*9./5.-460.
      P6(I)=P6(I)*1.450377
      ROVG(I)=ROVG(I)/4.8824276
      ROV2G(I)=ROV2G(I)/1.4881639
  360 CONTINUE
      P6(I)=P6(I)*144.
      P5(I)=P6(I)
      AOUT(I)=FLOAT(NFCHPR(I))*3.1416*(DFC(I)/2.0)**2/144.
      A5(I)=A5(I)/144.
      DFC(I)=DFC(I)/12.
      TAU(I)=TAU(I)/12.
      TAUC(I)=TAUC(I)/12.
      XLFC(I)=XLFC(I)/12.
      XLFCPC(I)=XLFCPC(I)/12.
      XLFCC(I)=XLFCC(I)/12.
      HSP5(I)=HSP5(I)/12.
      IF(ICTR .EQ. 1)R4(I)=R4(I)/12.
  370 CONTINUE
      IF(ICTR .EQ. 1)GO TO 420
C
C-----(THE FOLLOWING CALCULATIONS ARE FOR NO CENTRIFUGAL EFFECTS)
C-----FIND P1TMIN AND P5MAX (MINIMUM SUPPLY PRESSURE AND MAXIMUM FILM COOLING
C     BACK PRESSURE)-GET INITIAL GUESS FOR PLENUM TOTAL PRESSURE (P3T)
C
      DO 380 I=1,NIR
      P1THLD=P1T(I)
      IF(I .EQ. 1)P1TMIN=P1THLD
      IF(P1THLD .LT. P1TMIN)P1TMIN=P1THLD
  380 CONTINUE

      DO 390 I=1,NFCR
      P5HOLD=P5(I)
      IF(I .EQ. 1)P5MAX=P5HOLD
      IF(P5HOLD .GT. P5MAX)P5MAX=P5HOLD
  390 CONTINUE
C
C     CHECK THAT P1TMIN IS GREATER THAN P5MAX
C
      IF(P1TMIN .LE. P5MAX)GO TO 400
      GO TO 410
  400 WRITE(NWRITE,6310)
      GO TO 1000
  410 CONTINUE
      P3TMXX=P1TMIN
      P3TMNN=P5MAX
      P3T=(P3TMXX + P3TMNN)/2.
      GO TO 500
  420 CONTINUE
C
C-----(THE FOLLOWING CALCULATIONS ARE FOR CENTRIFUGAL EFFECTS)
C-----FIND R1MN AND R4MN (LOWEST RADIUS FOR SUPPLY HOLES AND FC HOLES) AS WELL
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C       AS THEIR CORRESPONDING INDEXES (IHLD AND JHLD),DESIGNATING THE LOWEST
C       RADIUS BY RMN. CALCULATE THE HIGHEST AND LOWEST ALLOWABLE PRESSURES IN
C       THE PLENUM AT RMN WHICH PRECLUDE REVERSE FLOW (P3TMXX AND P3TMNN). GET AN
C       INITIAL PLENUM PRESSURE PROFILE (ASSUME T EQUALS TT).
C
        DO 430 I=1,NIR
        R1HLD=R1(I)
        IF(I .EQ. 1)R1MN=R1HLD
        IF(I .EQ. 1)IHLD=I
        IF(R1HLD .LT. R1MN)R1MN=R1HLD
        IF(R1HLD .LT. R1MN)IHLD=I
  430   CONTINUE
        RMN=R1MN

        DO 440 J=1,NFCR
        R4HLD=R4(J)
        IF(J .EQ. 1)R4MN=R4HLD
        IF(J .EQ. 1)JHLD=J
        IF(R4HLD .LT. R4MN)R4MN=R4HLD
        IF(R4HLD .LT. R4MN)JHLD=J
  440   CONTINUE
        IF(R4MN .LT. RMN)RMN=R4MN
        P3TMXX=P1T(IHLD)

        DO 450 I=1,NIR
        PHOLD=P1T(I)*2.7183**(OMG*OMG*(RMN*RMN-R1(I)*R1(I))/(2.*RGAS*TT))
        IF(PHOLD .LT. P3TMXX)P3TMXX=PHOLD
  450   CONTINUE
        P3TMNN=P6(JHLD)

        DO 460 J=1,NFCR
        PHOLD=P6(J)*2.7183**(OMG*OMG*(RMN*RMN-R4(J)*R4(J))/(2.*RGAS*TT))
        IF(PHOLD .GT. P3TMNN)P3TMNN=PHOLD
  460   CONTINUE
        IF(P3TMXX .LT. P3TMNN)GO TO 490
        P3TMNR=(P3TMXX+P3TMNN)/2.

        DO 470 I=1,NIR
        P3TIR(I)=P3TMNR*2.7183**(OMG*OMG*(R1(I)*R1(I)-RMN*RMN)/(2.*RGAS*TT
       *))
  470   CONTINUE

        DO 480 J=1,NFCR
        P3TFCR(J)=P3TMNR*2.7183**(OMG*OMG*(R4(J)*R4(J)-RMN*RMN)/(2.*RGAS*T
       *T))
  480   CONTINUE

        GO TO 500
  490   WRITE(NWRITE,6310)
        GO TO 1000
  500   CONTINUE
C
C-----THE FLOW IS SOLVED AS FOLLOWS - A PRESSURE OR PRESSURE DISTRIBUTION
C       (P3T OR P3TIR(I) &  P3TFCR(J) FOR NO CENTRIFUGAL AND CENTRIFUGAL EFFECTS,
C       RESPECTIVELY) IS ASSUMED IN THE PLENUM AND THE INFLOW AND OUTFLOW ARE
C       CALCULATED FOR THAT PRESSURE OR PRESSURE DISTRIBUTION.  THE ASSUMED
C       PRESSURE OR PRESSURE DISTRIBUTION IS THEN ADJUSTED TO EQUALIZE THE
C       INFLOW AND OUTFLOW
C
C-----IJ IS THE COUNTER FOR THE OVERALL FLOW ITERATIONS
C
        IJ=0
  510   CONTINUE
        IJ=IJ+1
C
C-----ASSUME ORIFICE TOTAL PRESSURE EQUALS SUPPLY TOTAL PRESSURE (P1T(I))
C       AND THE ORIFICE STATIC PRESSURE EQUALS THE PLENUM TOTAL PRESSURE
C       (P3T OR P3TIR(I))
C
        DO 560 I=1,NIR
        IF(ICTR .EQ. 0)P3TIR(I)=P3T
        P2T(I)=P1T(I)
        T2T(I)=TT
```

```
      DO 550 II=1,15
      P2(I)=P3TIR(I)
      IF(II .EQ. 1)T2(I)=0.950*T2T(I)
      T2D=T2(I)

      CALL AIRPRP(T2D,IUNTS,
     *G,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)

      T2HLD=T2(I)
      TERM=(1.0-(P2(I)/P2T(I))**GM1DG)
      IF(TERM .LT. 0.0)TERM=0.0
      V2(I)=SQRT((2.0*G*RGAS*T2T(I)/GM1)*TERM)
      XM2(I)=V2(I)/SQRT(G*RGAS*T2T(I)*(P2(I)/P2T(I))**GM1DG)
      IF(XM2(I) .GE. 1.0)GO TO 520
      T2(I)=T2T(I)/(1.0+GM1D2*XM2(I)*XM2(I))
      GO TO 530
  520 XM2(I)=1.0
      T2(I)=T2T(I)/(1.0+GM1D2)
      V2(I)=SQRT(G*RGAS*T2(I))
      P2(I)=P2T(I)/GP1D2**GDGM1
  530 CONTINUE
      XMD=XM2(I)
      NC=5

      CALL SPLINE(NC,NPC5,XX5,YY5,XMD,ANGR5,XMK5,CDD)

      CDI(I)=CDD
      RHO2(I)=P2(I)/(RGAS*T2(I))
      T2CNVG=ABS(T2HLD-T2(I))/T2(I)
      IF(T2CNVG .LE. CFT2)GO TO 560
      IF(II .EQ. 15)GO TO 540
      GO TO 550
  540 WRITE(NWRITE,6320)I
  550 CONTINUE
  560 REJ2(I)=RHO2(I)*V2(I)*DI(I)*CDI(I)/XMU
C
C-----GET AVERAGE VALUES FOR IMPINGEMENT H CALCULATIONS
C
      XXIMP=0.0
      XDI=0.0
      XHSP1=0.0
      XRHO2=0.0
      XCDI=0.0
      XV2=0.0

      DO 570 I=1,NIR
      XXIMP= XXIMP + XIMP(I)/FLOAT(NIR)
      XDI= XDI + DI(I)/FLOAT(NIR)
      XHSP1=XHSP1 + HSPI(I)/FLOAT(NIR)
      XRHO2= XRHO2 + RHO2(I)/FLOAT(NIR)
      XCDI=XCDI + CDI(I)/FLOAT(NIR)
  570 XV2= XV2 + V2(I)/FLOAT(NIR)
C
C-----CALCULATE INFLOW (LBM/HR)
C
      WIMPT=0.0

      DO 580 I=1,NIR
      CDIFC=CDI(I)
      WIMP(I)=CDIFC*AIMP(I)*RHO2(I)*V2(I)*32.174*3600.
      WIMPT=WIMPT + WIMP(I)
  580 CONTINUE
C
C-----------------------------------------------------------------------
C
C-----CALCULATE VELOCITY OUT THE FILM COOLING HOLE. ITERATE FOR PST.
C
C-----K IS THE COUNTER FOR THE OVERALL FILM COOLING FLOW ITERATIONS
C
      DO 760 K=1,15

      DO 590 I=1,NFCR
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      JCV(I)=0
      XM5(I)=0.
  590 CONTINUE

      DO 670 I=1,NFCR
      IF(ICTR .EQ. 0)P3TFCR(I)=P3T
      IF(JCV(I) .EQ. 1)GO TO 670
      IF(K .EQ. 1)TST(I)=TT+(TMS6(I)+460.-TT)*0.50
      IF(MTC .EQ. 0)TST(I)=TT
      TSTOLD(I)=TST(I)

      DO 650 II=1,15
      IF(II .EQ. 1)T5(I)=0.95*TST(I)
      TSD=T5(I)

      CALL AIRPRP(TSD,IUNTS,
     *6,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)

      TSHLD=T5(I)
      IF(P5T(I) .LE. P5(I))P5T(I)=P5(I)*1.001
      DO 620 KK=1,15
C
C-----KCNVG IS THE COUNTER FOR THE INDIVIDUAL FILM COOLING ROW FLOW ITERATIONS
C
      KCNVG(I)=KK
      P5(I)=P6(I)
      IF(KK .EQ. 1)P5T(I)=P3TFCR(I)
      P5TOLD=P5T(I)
      TERM=(1.0-(P5(I)/P5T(I))**GM1DG)
      IF(TERM .LT. 0.0)TERM=0.0
      V5(I)=SQRT((2.0*G*RGAS*TST(I)/GM1)*TERM)
      XM5(I)=V5(I)/SQRT(G*RGAS*TST(I)*(P5(I)/P5T(I))**GM1DG)
      IF(XM5(I) .GE. 1.0) GO TO 600
      T5(I)=TST(I)/(1.0+GM1D2*XM5(I)*XM5(I))
      GO TO 610
  600 XM5(I)=1.0
      T5(I)=TST(I)/(1.0+GM1D2)
      V5(I)=SQRT(G*RGAS*T5(I))
      P5(I)=P5T(I)/GP1D2**GDGM1
  610 CONTINUE

      XMD=XM5(I)
      NC=6

      CALL SPLINE(NC,NPC6,XX6,YY6,XMD,ANGR6,XMK6,XKTD)

      XKT=XKTD
      P5T(I)=(P3TFCR(I) + P5(I)*XKT)/(1.0 + XKT)
      P5TNEW=P5T(I)
      P5TCV(I)=ABS(P5TNEW-P5TOLD)/P5TNEW
      IF(P5TCV(I) .LE. CFP5T)GO TO 630
  620 CONTINUE
      WRITE(NWRITE,6330)I
  630 CONTINUE
      RHO5(I)=P5(I)/(RGAS*T5(I))
      T5CNVG=ABS(TSHLD-T5(I))/T5(I)
      IF(T5CNVG .LE. CFT5)GO TO 660
      IF(II .EQ. 15)GO TO 640
      GO TO 650
  640 WRITE(NWRITE,6340)I
  650 CONTINUE
  660 CONTINUE
      XXKT(I)=XKT
      ROV2C(I)=RHO5(I)*V5(I)*V5(I)
      IF(MSPL .EQ. 0)ROV2G(I)=1.0
      ROV2RT(I)=ROV2C(I)*32.174*3600.*3600./ROV2G(I)
      IF(MSPL .EQ. 0)ROV2RT(I)=0.0
      ROV2R=ROV2RT(I)
      XBETA=BETA(I)
      IF(MSPL .EQ. 0)GO TO 665

      NC=7
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```
      CALL SPLINE(NC,NPC7,XX7,YY7,ROV2R,ANGR7,XMK7,CDOD)
      NC=8
      CALL SPLINE(NC,NPC8,XX8,YY8,XBETA,ANGR8,XMK8,RTCOR)
  665 CONTINUE
      IF(MSBL .EQ. 0)CDOD=1.0
      IF(MSBL .EQ. 0)RTCOR=1.0
      RTCR(I)=RTCOR
      CDFC(I)=CDOD*RTCOR
      IF(MSBL .EQ. 0)ROVG(I)=1.0
      ROVRAT(I)=RHO5(I)*V5(I)*32.174*3600./ROVG(I)
      IF(MSBL .EQ. 0)ROVRAT(I)=0.0
      REJ5(I)=RHO5(I)*V5(I)*DFC(I)*CDFC(I)/XMU
  670 CONTINUE
C
C-----CALCULATE TOTAL AND STATIC PRESSURE AND TEMPERATURE AT THE ENTRANCE
C     OF THE FILM COOLING HOLE.
C
      DO 730 I=1,NFCR
      IF(JCV(I) .EQ. 1)GO TO 730
      IF(K .EQ. 1)T4T(I)=TT+(TMSG(I)+460.-TT)*0.20
      IF(MTC .EQ. 0)T4T(I)=TT

      DO 710 II=1,15
      IF(II .EQ. 1)P4T(I)=P5T(I)*1.025
      IF(II .EQ. 1)P4(I)=P5(I)*1.02
      IF(II .EQ. 1)V4(I)=V5(I)*0.98
      IF(II .EQ. 1)T4(I)=T5(I)*0.99
      P45T=(P4T(I)+P5T(I))/2.0
      P45=(P4(I)+P5(I))/2.0
      V45=(V4(I)+V5(I))/2.0
      T45=(T4(I)+T5(I))/2.0
      P45HLD=P45

      CALL AIRPRP(T45,IUNTS,
     *G,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)

      RHO45=P45/(RGAS*T45)
      REYN45=RHO45*V45*DFC(I)*CDFC(I)/XMU
      IF(REYN45 .LT. 2500.)FRFC=16.0/REYN45
      IF(REYN45 .GE. 2500.)FRFC=1.4225E-6*REYN45**1.07509
      IF(REYN45 .GE. 4000.)FRFC=0.0953/REYN45**0.2647
      DELPT=FRFC*XLFCPC(I)*RHO45*V45**2/(DFC(I)*2.0)
      P4T(I)=P5T(I) + DELPT
      PTO=P5T(I)
      PTN=P4T(I)
      AOLD=1.0
      ANEW=1.0
      TO=T5(I)
      TTO=T5T(I)
      TTN=T4T(I)
      XMOLD=XM5(I)

      CALL MNEW(CFMCH,PTO,PTN,AOLD,ANEW,TO,TTO,TTN,XMOLD,IUNTS,
     *XMNEW,TN)

      IF(XMNEW .LT. 1.0)GO TO  690
      IF(XMNEW .GE. 1.0)XMNEW=1.0
      TO=T4T(I)

      CALL AIRPRP(TO,IUNTS,
     *GAM,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)

      DO 680 J=1,10
      TN=T4T(I)/(1.0 + GM1D2)

      CALL AIRPRP(TN,IUNTS,
     *GTST,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)

      GCVG=ABS(GTST-GAM)/GTST
      IF(GCVG .LE. 0.001)GO TO 690
      GAM=GTST
  680 CONTINUE
  690 CONTINUE
```

```
      XM4(I)=XMNEW
      T4(I)=TN
      TD=T4(I)

      CALL AIRPRP(TD,IUNTS,
     *G,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)

      P4(I)=P4T(I)/(1.0+GM1D2*XM4(I)*XM4(I))**GDGM1
      V4(I)=SQRT((2.0*G*RGAS*T4T(I)/GM1)*(1.0-(P4(I)/P4T(I))**GM1DG))
      RHO4(I)=P4(I)/(RGAS*T4(I))
      P45N=(P4(I)+P5(I))/2.0
      P45CNV=ABS(P45HLD-P45N)/P45N
      IF(P45CNV .LE. CFP45)GO TO 720
      IF(II .EQ. 15)GO TO 700
      GO TO 710
  700 WRITE(NWRITE,6350)I
  710 CONTINUE
  720 CONTINUE
      RN45(I)=REYN45
      IF(MTC .EQ. 0)GO TO 730
      TC=TT-460.
      FCHSP=HSP5(I)
      FCHD=DFC(I)
      HSP=FCHSP/FCHD
      ZFC=XLODFC(I)
      H0=HG0(I)
      H1=HG1(I)
      XILOD=XXIMP/XDI
      HFCTR=HFC4(I)
      HHFCTR=HFC45(I)
      DAU=TAU(I)
      DAU2=TAUC(I)
      XLM=XLFC(I)
      XLC=XLFCC(I)
      A05=AOUT(I)
      IF(K .EQ. 1)WOUT(I)=WIMPT/(FLOAT(NFCR))
      WFCR=WOUT(I)
      FCBLR=(WOUT(I)/A5(I))
      TG=TMSG(I)

       CALL TMETO(IJ,TC,FCHSP,FCHD,H0,H1,XILOD,XRHO2,XV2,XLM,XLC,
     *XHSP1,HFCTR,HHFCTR,XCDI,DAU,ZFC,WFCR,A05,FCBLR,TG,HSP,     IUNTS,
     *ETA,TCO,TCIN,TWI,TWO,KLM,AKM,HD,HH,CFTWO,KCLC,AKCT,DAU2,TWIF,TCIF,
     *NPC9,NPC10,ANGR9,ANGR10,XX9,XX10,YY9,YY10,XMK9,XMK10)
       T4T(I)=TCIN + 460.
       TST(I)=TCO  + 460.
       TMI(I)=TWI
       TMO(I)=TWO
       XETA(I)=ETA
       XHD(I)=HD
       XHH(I)=HH
       XXAKM(I)=AKM
       XXAKCT(I)=AKCT
       KKLM(I)=KLM
       TW2(I)=TWIF
       TC2(I)=TCIF
  730  CONTINUE
C
C-----CALCULATE OUTFLOW (LBM/HR)
C
       WOUTT=0.

       DO 740 I=1,NFCR
       WOUT(I)=CDFC(I)*AOUT(I)*RHO5(I)*V5(I)*32.174*3600.
       WOUTT=WOUTT + WOUT(I)
  740  CONTINUE
C
C-----CHECK THAT TST HAS CONVERGED
C
       JCVT=0

       DO 750 I=1,NFCR
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      T5TFTR=ABS(T5T(I)-T5TOLD(I))/T5T(I)
      IF(T5TFTR .LE. CFT5T)JCV(I)=1
  750 JCVT=JCVT + JCV(I)
      IF(JCVT .EQ. NFCR)GO TO 780
  760 CONTINUE
      WRITE(NWRITE,6360)IJ
  780 CONTINUE
C
C-----COMPARE WEIGHT FLOWS AND ADJUST P3T  TO BALANCE THEM
C
      IF(WOUTT .GT. WIMPT)FLOFC=(WOUTT-WIMPT)/WIMPT
      IF(WIMPT .GT. WOUTT)FLOFC=(WIMPT-WOUTT)/WOUTT
      IF(FLOFC .LE. CFFLOW)GO TO 860
      IF(IJ .GE. 25)GO TO 850
      IF(ICTR .EQ. 1)GO TO 790
C
C-----(THESE CALCULATIONS ARE FOR NO CENTRIFUGAL EFFECTS)
C
      IF(WOUTT .GT. WIMPT)P3TMXX=P3T
      IF(WIMPT .GT. WOUTT)P3TMNN=P3T
      P3T=(P3TMXX + P3TMNN)/2.
      GO TO 510
  790 CONTINUE
C
C-----(THESE CALCULATIONS ARE FOR CENTRIFUGAL EFFECTS)
C
      IF(WOUTT .GT. WIMPT)P3TMXX=P3TMNR
      IF(WIMPT .GT. WOUTT)P3TMNN=P3TMNR
      P3TMNR=(P3TMXX + P3TMNN)/2.
      T4TAV=0.

      DO 800 J=1,NFCR
      T4TAV=T4TAV + T4T(J)
  800 CONTINUE
      T4TAV=T4TAV/FLOAT(NFCR)
      XT4TAV=T4TAV-460.
      T3TAV=(T4TAV + TT)/2.
      IF(MTC .EQ. 0)T3TAV=TT
C
C-----ESTABLISH P3T AT THE IMPINGEMENT AND FILM COOLING ROW RADII AND CHECK
C     THAT THE NEW PRESSURE DISTRIBUTION DOES NOT CAUSE INFLOW
C
      DO 810 I=1,NIR
      P3TIR(I)=P3TMNR*2.7183**(OMG*OMG*(RI(I)*RI(I)-RMN*RMN)/(2.*RGAS*T3
     *TAV))
  810 CONTINUE

      DO 830 KN=1,10
      JRVFLT=0
      P3TFK=0.
      DO 820 J=1,NFCR
      JRVFL=0
      P3TFCR(J)=P3TMNR*2.7183**(OMG*OMG*(R4(J)*R4(J)-RMN*RMN)/(2.*RGAS*T
     *3TAV))
      IF(P3TFCR(J) .LT. P5(J))JRVFL=1
      JRVFLT=JRVFLT+JRVFL
      IF(JRVFL .EQ. 1)P3THLD=P3TMNR*(1.+(P5(J)-P3TFCR(J))/P5(J))
      IF(JRVFL .EQ. 1 .AND. P3THLD .GT. P3TFK)P3TFK=P3THLD
  820 CONTINUE
      IF(JRVFLT .EQ. 0)GO TO 840
      IF(JRVFLT .GT. 0)P3TMNR=P3TFK
      IF(P3TMNR .GT. P3TMXX)P3TMNR=P3TMXX
  830 CONTINUE
      WRITE(NWRITE,6310)
      GO TO 1000
  840 CONTINUE
      GO TO 510
  850 WRITE(NWRITE,6370)
      GO TO 1000
  860 CONTINUE
C
C ----- DATA OUTPUT  -----  DATA OUTPUT  -----  DATA OUTPUT  -----DATA OUTPUT
C
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      WRITE(NWRITE,6380)IJ

      IF(IUNTS .EQ. 1)GO TO 870
      WRITE(NWRITE,6390)WIMPT
      WRITE(NWRITE,6400)
      GO TO 880
  870 WIMPT=WIMPT*0.45359
      WRITE(NWRITE,6410)WIMPT
      WRITE(NWRITE,6420)
  880 CONTINUE

      DO 910 I=1,NIR
      IF(IUNTS .EQ. 0)GO TO 890
      P1T(I)=P1T(I)*4.78803E-3
      P2T(I)=P2T(I)*4.78803E-3
      P2(I)=P2(I)*4.78803E-3
      T2T(I)=T2T(I)*5./9.
      T2(I)=T2(I)*5./9.
      WIMP(I)=WIMP(I)*0.45359
      GO TO 900
  890 CONTINUE
      P1T(I)=P1T(I)/144.
      P2T(I)=P2T(I)/144.
      P2(I)=P2(I)/144.
      T2T(I)=T2T(I)-460.
      T2(I)=T2(I)-460.
  900 CONTINUE
      WRITE(NWRITE,6430)I,P1T(I), P2(I),XM2(I),T2T(I),T2(I),WIMP(I),CDI(
     *I)
  910 CONTINUE
      IF(IUNTS .EQ. 1)GO TO 920
      WRITE(NWRITE,6440)WOUTT
      WRITE(NWRITE,6450)
      GO TO 930
  920 WOUTT=WOUTT*0.45359
      WRITE(NWRITE,6460)WOUTT
      WRITE(NWRITE,6470)
  930 CONTINUE

      DO 960 I=1,NFCR
      IF(MTC .EQ. 0)TC2(I)=TT-460.
      IF(IUNTS .EQ. 0)GO TO 940
      P4T(I)=P4T(I)*4.78803E-3
      P4(I)=P4(I)*4.78803E-3
      T4T(I)=T4T(I)*5./9.
      T4(I)=T4(I)*5./9.
      P5T(I)=P5T(I)*4.78803E-3
      P5(I)=P5(I)*4.78803E-3
      P6(I)=P6(I)*4.78803E-3
      T5T(I)=T5T(I)*5./9.
      T5(I)=T5(I)*5./9.
      TC2(I)=(TC2(I) + 460.)*5./9.
      IF(KCLC .EQ. 0)TC2(I)=0.
      PFCR=P3TFCR(I)*4.78803E-3
      WOUT(I)=WOUT(I)*0.45359
      GO TO 950
  940 CONTINUE
      P4T(I)=P4T(I)/144.
      P4(I)=P4(I)/144.
      T4T(I)=T4T(I)-460.
      T4(I)=T4(I)-460.
      P5T(I)=P5T(I)/144.
      P5(I)=P5(I)/144.
      P6(I)=P6(I)/144.
      T5T(I)=T5T(I)-460.
      T5(I)=T5(I)-460.
      IF(KCLC .EQ. 0)TC2(I)=0.
      PFCR=P3TFCR(I)/144.
  950 CONTINUE
      WRITE(NWRITE,6480)I,PFCR,P4(I),XM4(I),T4T(I),T4(I),P5T(I),P5(I),
     *XM5(I),T5T(I),T5(I),TC2(I),WOUT(I),XXKT(I),CDFC(I),RTCR(I),ROVRAT(
     *I),ROV2RT(I),KCNVG(I)
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  960 CONTINUE
      IF(MTC .EQ. 0)GO TO 1000
      WRITE(NWRITE,6495)
      IF(IUNTS .EQ. 1)GO TO 970
      WRITE(NWRITE,6490)
      GO TO 980
  970 CONTINUE
      WRITE(NWRITE,6500)
  980 CONTINUE

      DO 995 I=1,NFCR
      IF(IUNTS .EQ. 1)GO TO 985
      A5(I)=A5(I)*144.
      GO TO 990
  985 CONTINUE
      HG0(I)=HG0(I)*5.67446
      HG1(I)=HG1(I)*5.67446
      XHH(I)=XHH(I)*5.67446
      XHD(I)=XHD(I)*5.67446
      A5(I)=A5(I)*929.0304
      TMSG(I)=(TMSG(I)+460.)*5./9.
      TMO(I)=(TMO(I) + 460.)*5./9.
      TW2(I)=(TW2(I) + 460.)*5./9.
      IF(KCLC .EQ. 0)TW2(I)=0.
      TMI(I)=(TMI(I) + 460.)*5./9.
      XXAKM(I)=XXAKM(I)*0.017296
      XXAKCT(I)=XXAKCT(I)*0.017296
  990 WRITE(NWRITE,6510)I,HG0(I),HG1(I),XHH(I),XHD(I),HFC45(I),HFC4(I),
     *A5(I),TMSG(I),TMO(I),TW2(I),TMI(I),XXAKM(I),XXAKCT(I),XETA(I),KKLM
     *(I)
  995 CONTINUE
 1000 CONTINUE
C
C-----RETURN VARIABLES TO ORIGINAL INPUT UNITS
C
      OMG=OMG*30./3.14159
      IF(IUNTS .EQ. 0)TT=TT-460.
      IF(IUNTS .EQ. 1)TT=TT*5./9.
      IF(IUNTS .EQ. 0)RGAS=RGAS/32.174
      IF(IUNTS .EQ. 1)RGAS=RGAS/5.980

      DO 1020 I=1,NIR
      IF(IUNTS .EQ. 1)GO TO 1010
      DI(I)=DI(I)*12.
      TAUI(I)=TAUI(I)*12.
      HSP1(I)=HSP1(I)*12.
      XIMP(I)=XIMP(I)*12.
      R1(I)=R1(I)*12.
      GO TO 1020
 1010 CONTINUE
      R1(I)=R1(I)*304.8
      DI(I)=DI(I)*304.8
      TAUI(I)=TAUI(I)*304.8
      HSP1(I)=HSP1(I)*304.8
      XIMP(I)=XIMP(I)*304.8
 1020 CONTINUE

      DO 1040 I=1,NFCR
      IF(IUNTS .EQ. 1)GO TO 1030
      DFC(I)=DFC(I)*12.
      HSP5(I)=HSP5(I)*12.
      TAU(I)=TAU(I)*12.
      TAUC(I)=TAUC(I)*12.
      R4(I)=R4(I)*12.
      IF(MTC .EQ. 0)A5(I)=A5(I)*144.
      GO TO 1040
 1030 CONTINUE
      R4(I)=R4(I)*304.8
      DFC(I)=DFC(I)*304.8
      TAU(I)=TAU(I)*304.8
      TAUC(I)=TAUC(I)*304.8
      HSP5(I)=HSP5(I)*304.8
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      ROV6(I)=ROV6(I)*4.8824276
      ROV26(I)=ROV26(I)*1.4881639
      IF(MTC .EQ. 0)A5(I)=A5(I)*929.0304
 1040 CONTINUE
C
C-----FORMAT STATEMENTS
C
 5010 FORMAT(16A5)
 5020 FORMAT(I2)
 5030 FORMAT(8F10.0)
 6010 FORMAT(1H1,//,16A5,//)
 6020 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,43HINPUT POINTS FOR COOLANT GAMMA VERSUS T ARE,/,12X,1
     *HX,9X,1HY,/)
 6030 FORMAT(5X,2F10.4)
 6040 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,47HINPUT POINTS FOR COOLANT VISCOSITY VERSUS T ARE,/,1
     *2X,1HX,9X,1HY,/)
 6050 FORMAT(5X,F10.4,2X,E12.4)
 6060 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,51HINPUT POINTS FOR COOLANT SPECIFIC HEAT VERSUS T ARE
     *,/,12X,1HX,9X,1HY,/)
 6070 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,58HINPUT POINTS FOR COOLANT THERMAL CONDUCTIVITY VERSU
     *S T ARE,/,12X,1HX,9X,1HY,/)
 6080 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,49HINPUT POINTS FOR IMP. DISCH. COEFF. VERSUS M2 ARE,/
     *,12X,1HX,9X,1HY,/)
 6090 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,67HINPUT POINTS FOR FILM COOLING TOT. PRESS. LOSS COEF
     *F. VERSUS M5 ARE,/,12X,1HX,9X,1HY,/)
 6100 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,49HINPUT POINTS FOR FILM COOLING PT VERSUS ROV2P ARE,/
     *,12X,1HX,9X,1HY,/)
 6110 FORMAT(/,5X,16HROTATION ANGLE =,F10.3,2X,7HDEGREES,/)
 6115 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,38HINPUT POINTS FOR RTCOR VERSUS BETA ARE,/,12X,1HX,9X
     *,1HY,/)
 6120 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,48HINPUT POINTS FOR METAL CONDUCTIVITY VERSUS T ARE,/,
     *12X,1HX,9X,1HY,/)
 6130 FORMAT(/,1X,57H---------------------------------------------------
     *------,/,5X,50HINPUT POINTS FOR COATING CONDUCTIVITY VERSUS T ARE,
     */,12X,1HX,9X,1HY,/)
 6140 FORMAT(/,5X,84HCASE ABORTED - A REQUIRED CURVE WAS NOT INPUT OR WA
     *S SPECIFIED BY LESS THAN 3 POINTS,/)
 6150 FORMAT(1H1,10X,28H----------OUTPUT FOR CHAMBER,I5,10H----------,/)
 6160 FORMAT(/,5X,18HSI SYSTEM OF UNITS)
 6170 FORMAT(/,5X,23HENGLISH SYSTEM OF UNITS)
 6180 FORMAT(/,5X,21HCOOLANT GAS CONSTANT=,1X,F10.3,2X,8HJ/(KG-K))
 6190 FORMAT(/,5X,21HCOOLANT GAS CONSTANT=,1X,F10.3,2X,16H(FT-LBF)/(LBM-
     *R))
 6200 FORMAT(/,5X,63HTHIS CASE INCLUDES CENTRIFUGAL EFFECTS. ROTATIONAL
     *SPEED EQUALS,F10.2,2X,4HRPM.)
 6210 FORMAT(/,5X,44HTHIS CASE INCLUDES A THERMAL BARRIER COATING)
 6220 FORMAT(/,5X,78HTHIS CASE IS FLOW ANALYSIS ONLY AND INCLUDES NO MET
     *AL TEMPERATURE CALCULATIONS)
 6230 FORMAT(/,5X,36HTHIS CASE HAS NO MAIN STREAM BLOWING)
 6240 FORMAT(///, 1X,I5,2X,25HROWS OF IMPINGEMENT HOLES,//, 5X,3HROW,2X,
     *5HHOLES,2X,13HDIAMETER (IN),4X,4HWALL,8X,3HL/D,9X,4HHOLE,5X,11HIMP
     *INGEMENT,6X,2HR1,9X,3HPIT,/,33X,9HTHICKNESS,16X,7HSPACING,4X,8HDIS
     *TANCE,6X,4H(IN),6X,6H(PSIA),//)
 6250 FORMAT(///, 1X,I5,2X,25HROWS OF IMPINGEMENT HOLES,//, 5X,3HROW,2X,
     *5HHOLES,2X,13HDIAMETER (MM),4X,4HWALL,8X,3HL/D,9X,4HHOLE,5X,11HIMP
     *INGEMENT,6X,2HR1,9X,3HPIT,/,33X,9HTHICKNESS,16X,7HSPACING,4X,8HDIS
     *TANCE,6X,4H(MM),5X,9H(N/CM**2),//)
 6260 FORMAT( 5X,I3,4X,I3,4X,F7.4,6X,F7.3,5X,F7.3,5X,F7.3,5X,F7.3,5X,F7.
     *3,5X,F8.3)
 6270 FORMAT(///, 1X,I5,2X,26HROWS OF FILM COOLING HOLES,//, 1X,3HROW,2X
     *,5HHOLES,2X,13HDIAMETER (IN),7X,9HTHICKNESS,7X,3HL/D,9X,4HHOLE,5X,
     *5HALPHA,
     *    5X,4HBETA,7X,5HRHOVG,7X,6HRHOV2G,9X,2HP4,6X,2HP6,/,30X,15HWALL-
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     *---COATING,2X,7H(TOTAL),6X,
     *7HSPACING,3X,5H(DEG),5X,5H(DEG),2X,14H(LBM/FT**2*HR),3X,14H(LBM/FT
     **HR**2),1X,4H(IN),3X,6H(PSIA),//)
6280 FORMAT(///, 1X,I5,2X,26HROWS OF FILM COOLING HOLES,//, 1X,3HROW,2X
     *,5HHOLES,2X,13HDIAMETER (MM),7X,9HTHICKNESS,7X,3HL/D,9X,4HHOLE,5X,
     *5HALPHA,
     *   ,5X,4HBETA,7X,5HRHOVG,7X,6HRHOV2G,9X,2HP4,6X,2HP6,/,30X,15HWALL-
     *---COATING,2X,7H(TOTAL),6X,
     *7HSPACING,3X,5H(DEG),5X,5H(DEG),2X,12H(KG/M**2*HR),2X,12H(KG/M*HR*
     **2),4X,4H(MM),1X,9H(N/CM**2),//)
6290 FORMAT(/,5X,62HCASE ABORTED - COATING WAS SPECIFIED BUT NOT COATIN
     *G THICKNESS)
6300 FORMAT( 1X,I3,4X,I3,4X,F7.4,5X,F7.3,3X,F7.3,3X,F7.3,5X,F6.3,4X,F6.
     *3,3X,F6.3,2X,E12.5,E12.5,4X,F7.3,2X,F8.3)
6310 FORMAT(//,5X,66HCASE ABORTED - THE SPECIFIED PRESSURES WILL RESULT
     * IN REVERSE FLOW,//)
6320 FORMAT(/,5X,67HWARNING - T2 HAS NOT CONVERGED IN 15 ITERATIONS FOR
     * IMPINGEMENT ROW,I5)
6330 FORMAT(/,3X,59HWARNING-P5T HAS NOT CONVERGED IN 15 ITERATIONS FOR
     *F.C. ROW,I5)
6340 FORMAT(/,5X,68HWARNING - T5 HAS NOT CONVERGED IN 15 ITERATIONS FOR
     * FILM COOLING ROW,I5)
6350 FORMAT(/,5X,111HWARNING - THE AVERAGE PRESSURE BETWEEN STATIONS 4
     *AND 5 HAS NOT CONVERGED IN 15 ITERATIONS FOR FILM COOLING ROW ,I5)
6360 FORMAT(/,5X,73HWARNING - T5T HAS NOT CONVERGED IN 15 ITERATIONS IN
     *OVERALL FLOW ITERATION,I5)
6370 FORMAT(/,5X,70HIMPINGEMENT AND FILM COOLING FLOWS HAVE NOT CONVERG
     *ED IN 25 ITERATIONS)
6380 FORMAT(//,5X,52HIMPINGEMENT AND FILM COOLING FLOWS HAVE CONVERGED
     *IN,I5,2X,18HOVERALL ITERATIONS,////)
6390 FORMAT(10X,13HINFLOW EQUALS,F9.3,2X,6HLBM/HR,///)
6400 FORMAT(3X,3HIMP,2X,6HPSPLYT,6X,        2HP2,5X,2HM2,6X,3HT2T,5X,
     *2HT2,7X,4HWIMP,3X,5HCDIMP,/,3X,3HROW,2X,6H(PSIA),21X,
     *          3H(F),12X,8H(LBM/HR),/)
6410 FORMAT(10X,13HINFLOW EQUALS,F9.3,2X,5HKG/HR,///)
6420 FORMAT(3X,3HIMP,2X,6HPSPLYT,6X,        2HP2,5X,2HM2,6X,3HT2T,5X,
     *2HT2,7X,4HWIMP,3X,5HCDIMP,/,3X,3HROW,1X,9H(N/CM**2),19X,
     *          3H(K),13X,7H(KG/HR),/)
6430 FORMAT(2X,I3,2X,F7.3,3X,         F7.3,1X,F5.3,4X,F5.0,2X,F5.0,3X,F7
     *.3,2X,F5.3)
6440 FORMAT(///,10X,14HOUTFLOW EQUALS,F9.3,2X,6HLBM/HR,///)
6450 FORMAT(1X,2HFC,4X,3HP3T,7X,2HP4,5X,2HM4,3X,3HT4T,4X,2HT4,1X,1H/,3X
     *,3HP5T,6X,2HP5,6X,2HM5,3X,3HT5T,4X,2HT5,1X,1H/,   5HTCTIF,4X,4HWOU
     *T,3X,2HKT,4X,2HRT,5X,2HRT,4X,
     *                          4HRHOV,4X,6HRHOVSQ,1X,4HITRS,/,1X,3HROW,2X,
     *6H(PSIA),17X,3H(F),7X,1H/,1X,6H(PSIA),18X,3H(F),7X,1H/,1X,3H(F),3X
     *,8H(LBM/HR),13X,4HCORR,3X,5HRATIO,3X,5HRATIO,/)
6460 FORMAT(///,10X,14HOUTFLOW EQUALS,F9.3,2X,5HKG/HR,///)
6470 FORMAT(1X,2HFC,4X,3HP3T,7X,2HP4,5X,2HM4,3X,3HT4T,4X,2HT4,1X,1H/,3X
     *,3HP5T,6X,2HP5,6X,2HM5,3X,3HT5T,4X,2HT5,1X,1H/,   5HTCTIF,4X,4HWOU
     *T,3X,2HKT,4X,2HRT,5X,2HRT,4X,
     *                          4HRHOV,4X,5HRHOVSQ,1X,4HITRS,/,1X,3HROW,1X,
     *9H(N/CM**2),15X,3H(K),7X,1H/,   9H(N/CM**2),16X,3H(K), 7X,1H/,1X,3
     *H(K),3X,7H(KG/HR),14X,4HCORR,3X,5HRATIO,3X,5HRATIO,/)
6480 FORMAT(1X,I2,1X,F8.3,1X,F8.3,1X,F5.3,1X,F5.0,1X,F5.0,   1H/,   F8.
     *3,1X,F8.3,1X,F5.3,1X,F5.0,1X,F5.0,   1H/,   F5.0,1X,F7.3,1X,F5.3,
     *1X,F5.3,1X,F6.3,1X,F7.3,1X,F7.3,3X,I2)
6490 FORMAT(///,2X,2HFC,2X,26HHEAT-TRANSFER-COEFFICIENTS,2X,13HH-MOD-FA
     *CTORS,4X,6HCOOLED,4X,3HGAS,8X,16HWALL-TEMPERATURE,7X,17HAVG.-THERM
     *.-COND.,5X,3HETA,7X,3HITR,
     *            /,1X,3HROW,2X,3HHG0,3X,3HHG1,2X,7HFC-HOLE,1X,4HIMPG,5X,7H
     *FC-HOLE,2X,4HIMPG,5X,4HAREA, 5X,4HTEMP,4X,7HOUTSIDE,2X,7HINTFACE,2
     *X,6HINSIDE,3X,5HMETAL,3X,7HCOATING,3X,9H(TCO-TC)/,
     *            /,13X,16H(BTU/FT**2*HR*F),22X,7H(IN**2),4X,3H(F),6X,
     *3H(F),5X,3H(F),5X,3H(F),7X,13H(BTU/FT*HR*F),4X,8H(TWO-TC),/)
6495 FORMAT(//,10X,21HHEAT TRANSFER RESULTS)
6500 FORMAT(///,2X,2HFC,2X,26HHEAT-TRANSFER-COEFFICIENTS,2X,13HH-MOD-FA
     *CTORS,4X,6HCOOLED,4X,3HGAS,8X,16HWALL-TEMPERATURE,7X,17HAVG.-THERM
     *.-COND.,5X,3HETA,7X,3HITR,
     *            /,1X,3HROW,2X,3HHG0,3X,3HHG1,2X,7HFC-HOLE,1X,4HIMPG,5X,7H
     *FC-HOLE,2X,4HIMPG,5X,4HAREA, 5X,4HTEMP,4X,7HOUTSIDE,2X,7HINTFACE,2
```

```
     *X,6HINSIDE,3X,5HMETAL,3X,7HCOATING,3X,9H(TCO-TC)/,
     *          /,13X,16H(J/(M**2*SEC*K)),22X,7H(CM**2),4X,3H(K),6X,
     *3H(K),5X,3H(K),5X,3H(K),6X,14H(J/(CM*SEC*K)),4X,8H(TWO-TC)/)
6510 FORMAT(1X,I2,1X,F5.0,1X,F6.0,1X,F6.0,1X,F6.0,2X,F5.3,3X,F5.3,3X,F7
     *.3,5X,F5.0,4X,F5.0,3X,F5.0,3X,F5.0,4X,F6.3,4X,F6.3,3X,F7.4,6X,I2)
      GO TO 150
2000 STOP
      END
```

SUBROUTINE TMETO

```
      SUBROUTINE TMETO(IJ,TC,FCHSP,FCHD,HO,H1,XILOD,XRHO2,XV2,XLM,XLC,
     *     XHSPI,HFCTR,HHFCTR,XCDI,DAU,ZFC,WFCR,AOS,FCBLR,TG,HSP,    IUNT
     *S,ETA,TCO,TCIN,TWI,TWO,KLM,AKM,HO,HH,CFTWO,KCLC,AKCT,DAU2,TWIF,TCI
     *F,
     *NPC9,NPC10,ANGR9,ANGR10,XX9,XX10,YY9,YY10,XMK9,XMK10)

      DIMENSION CMAT(24,25),CN(24)
      DIMENSION XMK1(24),XMK2(24),XMK3(24),XMK4(24),XMK9(24),XMK10(24)
      DIMENSION XX1(24),XX2(24),XX3(24),XX4(24),XX9(24),XX10(24)
      DIMENSION YY1(24),YY2(24),YY3(24),YY4(24),YY9(24),YY10(24)
      COMMON NPC1,NPC2,NPC3,NPC4,ANGR1,ANGR2,ANGR3,ANGR4,XX1,XX2,XX3,XX4
     *,YY1,YY2,YY3,YY4,XMK1,XMK2,XMK3,XMK4,NREAD,NWRITE

      TDIF=TG-TC
      TCIN=TC+TDIF*.20
      TWI=TC+TDIF*.25
      TCIF=TC+TDIF*.30
      TWIF=TC+TDIF*.35
      TCO=TC+TDIF*.40
      TWO=TC+TDIF*.45

      DO 70 KLM=1,15
      TOLD=TWO
      TFILM=0.5*(TWI+TC)+460.

      CALL AIRPRP(TFILM,IUNTS,
     *G,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)
C
C-----ARRIVAL VELOCITY FACTOR
C
      IF(XILOD  .LT. 3.780)FACVA=1.0
      IF(XILOD  .GT. 3.780)FACVA=-.009193*XILOD*XILOD  + .051495*XILOD
     *+ .93715
      IF(XILOD  .GT. 7.590)FACVA=0.002597*XILOD*XILOD  - .107042*XILOD
     *+ 1.460519
      IF(XILOD  .GT. 14.34)FACVA=0.001090*XILOD*XILOD  - .060825*XILOD
     *+ 1.105854
      RENA=FACVA*XRHO2*XV2*XHSPI/XMU
      RENA=RENA*XCDI
C
C-----GARDON AND COBONPUE IMPINGEMENT CORRELATION
C
      HD=(0.286*XKA/XHSPI)*RENA**0.625
      HD=HD*HFCTR
      AREAR=1.0-3.14159/(4.0*HSP*HSP)
      HC=AREAR*HD
      TCA=0.5*(TCO+TCIN)+460.
      IF(KCLC .EQ. 1)TCA=0.5*(TCIF+TCIN)+460.
      CALL AIRPRP(TCA,IUNTS,
     *G,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)

      TR=((TWO+TWI)/2.0)+460.
      IF(KCLC .EQ. 1)TR=((TWIF+TWI)/2.0)+460.
      TWAV=TR
```

```
      IF(IUNTS .EQ. 1)TWAV=TR*5./9.
      NC=9

      CALL SPLINE(NC,NPC9,XX9,YY9,TWAV,ANGR9,XMK9,AKM)

      IF(IUNTS .EQ. 1)AKM=AKM*57.8176
      IF(KCLC .EQ. 1)TCTAV=(TWIF+TWO)/2. + 460.
      IF(KCLC .EQ. 1 .AND. IUNTS .EQ. 1)TCTAV=TCTAV*5./9.
      IF(KCLC .EQ. 0)AKCT=0.
      IF(KCLC .EQ. 0)GO TO 10
      NC=10

      CALL SPLINE(NC,NPC10,XX10,YY10,TCTAV,ANGR10,XMK10,AKCT)

      IF(IUNTS .EQ. 1)AKCT=AKCT*57.8175
   10 CONTINUE
      U=HC*DAU/AKM
      TR=(TCA/TR)**0.18
C
C-----H IN THE FILM COOLING HOLE CALCULATED FROM T.B. DAVEY CORRELATION
C
      COEF=(0.045*XKA*TR/FCHD)*(1.0/ZFC)**0.2
      REH=(WFCR*FCHD)/(A05*XMU*32.1739*3600.)
      HH=COEF*(REH**0.8)*(PRN**0.4)
      HM=HH*3.14159*FCHD*FCHD*ZFC/(FCHSP*FCHSP*DAU)
      HM=HM*HHFCTR
      DA=HM*DAU*DAU/AKM
      IF(KCLC .EQ. 1)XLTOT=XLM+XLC
      IF(KCLC .EQ. 1)TR=(((TCO+TCIF)/2.+460.)/((TWO+TWIF)/2.+460.))**.18
      IF(KCLC .EQ. 1)GO TO 20
      GO TO 30
   20 TCCAV=(TCIF+TCO)/2.

      CALL AIRPRP(TCCAV,IUNTS,
     *G,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)

      REH=(WFCR*FCHD)/(A05*XMU*32.1739*3600.)
   30 CONTINUE
      IF(KCLC .EQ. 1)HH2=0.045*XKA*(REH**0.8)*(PRN**0.4)*TR*(FCHD**0.2)*
     *(XLTOT**0.8-XLM**0.8)/(FCHD*(XLTOT-XLM))
      IF(KCLC .EQ. 1)HM2=HH2*3.14159*FCHD*XLC/(FCHSP*FCHSP*DAU2)
      IF(KCLC .EQ. 1)HM2=HM2*HHFCTR
      IF(KCLC .EQ. 1)DA2=HM2*DAU2*DAU2/AKCT
      TCAO=0.5*(TCO+TC)+460.

      CALL AIRPRP(TCAO,IUNTS,
     *G,GM1,GM1DG,GP1,GP1D2,GDGM1,GM1D2,XMU,PRN,XKA,CP)

      BETA=DAU*HM/(FCBLR*CP)
      IF(KCLC .EQ. 1)BETA2=DAU2*HM/(FCBLR*CP)
      ROOT=(BETA*BETA+4.0*DA)**0.5
      IF(KCLC .EQ. 1)ROOT2=(BETA2*BETA2+4.0*DA2)**0.5
      A1=-0.5*(BETA+ROOT)
      A2=-0.5*(BETA-ROOT)
      IF(KCLC .EQ. 1)AL1=-0.5*(BETA2+ROOT2)
      IF(KCLC .EQ. 1)AL2=-0.5*(BETA2-ROOT2)
      IF(KCLC .EQ. 1)GO TO 40
      DEN=(U-A2)*EXP(A1)-(U-A1)*EXP(A2)
      C2=(U-A2)/DEN
      C3=(A1-U)/DEN
      ETA=C2*(1.0-A1*A1/DA)*EXP(A1)+C3*(1.0-A2*A2/DA)*EXP(A2)
      IF(ETA .GE. 1.0)ETA=0.9999
      DELHG=H0-H1
      TWO=TG-((TG-TC)*(ETA*FCBLR*CP+(1.0-ETA)*DELHG))/(H0-ETA*DELHG+ETA*
     *FCBLR*CP)
      TNEW=TWO
      TCO=ETA*(TWO-TC)+TC
      TCIN=(C2*(1.0-A1*A1/DA)+C3*(1.0-A2*A2/DA))*(TWO-TC)+TC
      TWI=(C2+C3)*(TWO-TC)+TC
      GO TO 50
   40 CONTINUE
      CMAT(1,1)=U-A1
```

```
      CMAT(1,2)=U-A2
      CMAT(1,3)=0.
      CMAT(1,4)=0.
      CMAT(1,5)=0.
      CMAT(1,6)=0.
      CMAT(2,1)=(AKM/AKCT)*(DAU2/DAU)*A1*EXP(A1)
      CMAT(2,2)=(AKM/AKCT)*(DAU2/DAU)*A2*EXP(A2)
      CMAT(2,3)=0.
      CMAT(2,4)=-AL1
      CMAT(2,5)=-AL2
      CMAT(2,6)=0.
      CMAT(3,1)=EXP(A1)
      CMAT(3,2)=EXP(A2)
      CMAT(3,3)=-1.
      CMAT(3,4)=-1.
      CMAT(3,5)=-1.
      CMAT(3,6)=0.
      CMAT(4,1)=(1.0-A1*A1/DA)*EXP(A1)
      CMAT(4,2)=(1.0-A2*A2/DA)*EXP(A2)
      CMAT(4,3)=-1.
      CMAT(4,4)=-(1.0-AL1*AL1/DA2)
      CMAT(4,5)=-(1.0-AL2*AL2/DA2)
      CMAT(4,6)=0.
      CMAT(5,1)=0.
      CMAT(5,2)=0.
      CMAT(5,3)=1.
      CMAT(5,4)=EXP(AL1)
      CMAT(5,5)=EXP(AL2)
      CMAT(5,6)=1.

      CALL XMTXSL(5,CMAT,CN)

      C2=CN(1)
      C3=CN(2)
      C4=CN(3)
      C5=CN(4)
      C6=CN(5)
      ETA=C4+C5*(1.0-AL1*AL1/DA2)*EXP(AL1)+C6*(1.0-AL2*AL2/DA2)*EXP(AL2)
      IF(ETA .GE. 1.0)ETA=0.9999
      DELHG=H0-H1
      TWO=TG-((TG-TC)*(ETA*FCBLR*CP+(1.0-ETA)*DELHG))/(H0-ETA*DELHG+ETA*
     *FCBLR*CP)
      TNEW=TWO
      TCO=ETA*(TWO-TC)+TC
      TWIF=(C2*EXP(A1)+C3*EXP(A2))*(TWO-TC)+TC
      TCIF=(C2*(1.0-A1*A1/DA)*EXP(A1)+C3*(1.0-A2*A2/DA)*EXP(A2))*(TWO-TC
     *)+TC
      TCIN=(C2*(1.0-A1*A1/DA)+C3*(1.0-A2*A2/DA))*(TWO-TC)+TC
      TWI=(C2+C3)*(TWO-TC)+TC
   50 CONTINUE
      TWOCVG=ABS(TNEW-TOLD)/TNEW
      IF(KLM .EQ. 1)GO TO 70
      IF(TWOCVG .LE. CFTWO)GO TO 80
      IF(KLM .EQ. 15)GO TO 60
      GO TO 70
   60 WRITE(NWRITE,600)IJ
   70 CONTINUE
   80 CONTINUE
      IF(KCLC .EQ. 0)TWIF=0.
      IF(KCLC .EQ. 0)TCIF=0.
  600 FORMAT(/,5X,93HWARNING - OUTER WALL TEMPERATURE HAS NOT CONVERGED
     *IN 15 ITERATIONS IN OVERALL FLOW ITERATION,I5)
      RETURN
      END
```

SUBROUTINE MNEW

```
      SUBROUTINE MNEW(CFMCH,PTO,PTN,AOLD,ANEW,TO,TTO,TTN,XMOLD,IUNTS,
     *XMNEW,IN)
```

```
      DIMENSION XX1(24),XX2(24),XX3(24),XX4(24)
      DIMENSION YY1(24),YY2(24),YY3(24),YY4(24)
      DIMENSION XMK1(24),XMK2(24),XMK3(24),XMK4(24)
      COMMON NPC1,NPC2,NPC3,NPC4,ANGR1,ANGR2,ANGR3,ANGR4,XX1,XX2,XX3,XX4
     *,YY1,YY2,YY3,YY4,XMK1,XMK2,XMK3,XMK4,NREAD,NWRITE

      CALL AIRPRP(TO,IUNTS,
     *GO,GMI,GMIDG,GPI,GPID2,GDGMI,GMID2,XMU,PRN,XKA,CP)
C
C-----FOR THE FIRST ITERATION EVALUATE GAMMA AT THE GIVEN TOTAL TEMP.
C     AND LET THE FIRST GUESS AT XMNEW BE XMOLD
C
      CALL AIRPRP(TTN,IUNTS,
     *GN,GMI,GMIDG,GPI,GPID2,GDGMI,GMID2,XMU,PRN,XKA,CP)

      XMN=XMOLD
      DO 10 I=1,25
      PATG=(PTO/PTN)*(AOLD/ANEW)*SQRT(TTN/TTO)*SQRT(GO/GN)
      XMFCN=1.0 + ((GN-1.0)/2.0)*XMN*XMN
      XMFCO=1.0 + ((GO-1.0)/2.0)*XMOLD*XMOLD
      POWN=(GN+1.0)/(2.0*(GN-1.0))
      POWO=(GO+1.0)/(2.0*(GO-1.0))
      XNUM=XMN-PATG*XMOLD*(XMFCN)**POWN/((XMFCO)**POWO)
      DNM=1.0-PATG*(GN+1.0)*XMOLD*XMN*XMFCN**((-GN+3.0)/(2.0*(GN-1.0)))/
     *(2.0*XMFCO**POWO)
      XMHLD=XMN
      XMN=XMN-XNUM/DNM
      TN=TTN/(1.0+((GN-1.0)/2.0)*XMN*XMN)

      CALL AIRPRP(TN,IUNTS,
     *GN,GMI,GMIDG,GPI,GPID2,GDGMI,GMID2,XMU,PRN,XKA,CP)

      CNVCR=ABS(XMHLD-XMN)/XMN
      IF(CNVCR .LE. CFMCH)GO TO 20
   10 CONTINUE
      WRITE(NWRITE,600)
   20 CONTINUE
      XMNEW=XMN
  600 FORMAT(/,5X,46HWARNING - M HAS NOT CONVERGED IN 25 ITERATIONS)
      RETURN
      END
```

SUBROUTINE AIRPRP

```
      SUBROUTINE AIRPRP(TD,IUNTS,
     *G,GMI,GMIDG,GPI,GPID2,GDGMI,GMID2,XMU,PRN,XKA,CP)

      DIMENSION XX1(24),YY1(24),XMK1(24)
      DIMENSION XX2(24),YY2(24),XMK2(24)
      DIMENSION XX3(24),YY3(24),XMK3(24)
      DIMENSION XX4(24),YY4(24),XMK4(24)
      COMMON NPC1,NPC2,NPC3,NPC4,ANGR1,ANGR2,ANGR3,ANGR4,XX1,XX2,XX3,XX4
     *,YY1,YY2,YY3,YY4,XMK1,XMK2,XMK3,XMK4,NREAD,NWRITE

      IF(IUNTS .EQ. 1)TD=TD*5./9.

      NC=1
      CALL SPLINE(NC,NPC1,XX1,YY1,TD,ANGR1,XMK1,G)
      NC=2
      CALL SPLINE(NC,NPC2,XX2,YY2,TD,ANGR2,XMK2,XMU)
      NC=3
      CALL SPLINE(NC,NPC3,XX3,YY3,TD,ANGR3,XMK3,CP)
      NC=4
      CALL SPLINE(NC,NPC4,XX4,YY4,TD,ANGR4,XMK4,XKA)

      IF(IUNTS .EQ. 1)XMU=XMU*.067197
      IF(IUNTS .EQ. 1)CP=CP*0.23901
```

```
      IF(IUNTS .EQ. 1)XKA=XKA*57.8176
      IF(IUNTS .EQ. 1)TD=TD*9./5.
      PPN=CP*XMU*3600./XKA
      GM1=G-1.0
      GM1DG=GM1/G
      GP1=G+1.0
      GP1D2=GP1/2.0
      GDGM1=1.0/GM1DG
      GM1D2=GM1/2.0
C
C-----THE FOLLOWING MU HAS DIMENSION OF SLUG/(FT*SEC)
C
      XMU=XMU/32.1739
      RETURN
      END
```

SUBROUTINE PRBMTX

```
      SUBROUTINE PRBMTX(NP1,XK,F,ANGR,SOL)
C
C-----THIS SUBROUTINE GENERATES THE PROBLEM MATRIX (MAT(I,J)) FROM THE
C     INPUTED X AND Y VALUES AND CALLS XMTSOL TO SOLVE IT
C
      DIMENSION XK(24),F(24),XKR(24),FR(24),SOL(24)
      DIMENSION XX1(24),YY1(24),XMK1(24)
      DIMENSION XX2(24),YY2(24),XMK2(24)
      DIMENSION XX3(24),YY3(24),XMK3(24)
      DIMENSION XX4(24),YY4(24),XMK4(24)
      REAL L(24),LR(24),MAT(24,25)
      INTEGER OPT
      COMMON NPC1,NPC2,NPC3,NPC4,ANGR1,ANGR2,ANGR3,ANGR4,XX1,XX2,XX3,XX4
     *,YY1,YY2,YY3,YY4,XMK1,XMK2,XMK3,XMK4,NREAD,NWRITE

      N=NP1-1
      NP2=N+2
      OPT=1
      IF(ANGR .EQ. 0.0)OPT=0
      IF(OPT .EQ. 0)GO TO 20
      ANGROT=ANGR*3.141593/180.
      CAN=COS(ANGROT)
      SAN=SIN(ANGROT)

      DO 10 I=1,NP1
      XKR(I)=XK(I)*CAN + F(I)*SAN
      FR(I)=F(I)*CAN - XK(I)*SAN
   10 CONTINUE
   20 CONTINUE

      DO 30 I=1,N
      IF(OPT .EQ. 0)GO TO 30
      LR(I)=XKR(I+1)-XKR(I)
   30 L(I)=XK(I+1)-XK(I)
C
C-----GET SLOPES AT THE END POINTS
C
      YPFST=(F(2)-F(1))/(XK(2)-XK(1))
      YPLST=(F(NP1)-F(N))/(XK(NP1)-XK(N))
      IF(OPT .EQ. 1)YPFSTR=(FR(2)-FR(1))/(XKR(2)-XKR(1))
      IF(OPT .EQ. 1)YPLSTR=(FR(NP1)-FR(N))/(XKR(NP1)-XKR(N))
C
C-----INITIALIZE THE ENTIRE MATRIX TO ZERO
C
      DO 40 I=1,NP1
      DO 40 J=1,NP2
   40 MAT(I,J)=0.
      MAT(1,1)=L(1)/3.
```

```
      MAT(I,2)=L(1)/6.
      MAT(1,NP2)=(F(2)-F(1))/L(1)-YPFST
      MAT(NP1,N)=L(N)/6.
      MAT(NP1,NP1)=L(N)/3.
      MAT(NP1,NP2)=YPLST-(F(NP1)-F(N))/L(N)
      IF(OPT .EQ. 1)MAT(1,1)=LR(1)/3.
      IF(OPT .EQ. 1)MAT(1,2)=LR(1)/6.
      IF(OPT .EQ. 1)MAT(1,NP2)=(FR(2)-FR(1))/LR(1)-YPFSTR
      IF(OPT .EQ. 1)MAT(NP1,N)=LR(N)/6.
      IF(OPT .EQ. 1)MAT(NP1,NP1)=LR(N)/3.
      IF(OPT .EQ. 1)MAT(NP1,NP2)=YPLSTR-(FR(NP1)-FR(N))/LR(N)

      DO 50 I=2,N
      IM1=I-1
      IM2=I-2
      IP1=I+1
      MAT(I,IM1)=L(IM1)/6.
      MAT(I,I)=(L(IM1)+L(I))/3.
      MAT(I,IP1)=L(I)/6.
      MAT(I,NP2)=(F(IP1)-F(I))/L(I) - (F(I)-F(IM1))/L(IM1)
      IF(OPT .EQ. 1)MAT(I,IM1)=LR(IM1)/6.
      IF(OPT .EQ. 1)MAT(I,I)=(LR(IM1)+LR(I))/3.
      IF(OPT .EQ. 1)MAT(I,IP1)=LR(I)/6.
   50 IF(OPT .EQ. 1)MAT(I,NP2)=(FR(IP1)-FR(I))/LR(I)-(FR(I)-FR(IM1))/LR(
     *IM1)

      CALL XMTXSL(NP1,MAT,SOL)

      RETURN
      END
```

SUBROUTINE SPLINE

```
      SUBROUTINE SPLINE(NC,NP1,XK,F,X,ANGR,XMKN,Y)
C
C-----THIS SUBROUTINE GIVES A CURVE FIT VALUE OF Y FOR A SPECIFIED X
C-----XMKN(24) IS THE SOLUTION VECTOR OBTAINED FROM THE INPUTED X AND Y
C     VALUES IN SUBROUTINE PRBMTX
C
      REAL MKM1,MK,LK
      DIMENSION F(24),XK(24),XMKN(24)
      DIMENSION XKR(24),FR(24)
      DIMENSION XX1(24),YY1(24),XMK1(24)
      DIMENSION XX2(24),YY2(24),XMK2(24)
      DIMENSION XX3(24),YY3(24),XMK3(24)
      DIMENSION XX4(24),YY4(24),XMK4(24)
      COMMON NPC1,NPC2,NPC3,NPC4,ANGR1,ANGR2,ANGR3,ANGR4,XX1,XX2,XX3,XX4
     *,YY1,YY2,YY3,YY4,XMK1,XMK2,XMK3,XMK4,NREAD,NWRITE
      INTEGER OPT

      N=NP1-1
      NM1=N-1
      OPT=1
      IF(ANGR .EQ. 0.0)OPT=0
      IF(OPT .EQ. 0)GO TO 15
      ANGROT=ANGR*3.141593/180.
      CAN=COS(ANGROT)
      SAN=SIN(ANGROT)

      DO 10 I=1,NP1
      XKR(I)=XK(I)*CAN + F(I)*SAN
      FR(I)=F(I)*CAN - XK(I)*SAN
   10 CONTINUE
   15 CONTINUE
C
C-----FOR A GIVEN X, FIND THE XK THAT BRACKET IT AND CALCULATE GENERATED F
```

```
      IND=0
      IF(X .EQ. XK(1))IND=-1
      IF(X .LT. XK(1))IND=-2
      IF(IND .LT. 0)Y=F(1)
      IF(IND .LT. 0)GO TO 80
      IF(X .EQ. XK(NP1))IND=1
      IF(X .GT. XK(NP1))IND=2
      IF(IND .GT. 0)Y=F(NP1)
      IF(IND .GT. 0)GO TO 80

      DO 30 I=2,NP1
      IND=0
      IF(X .EQ. XK(I))Y=F(I)
      IF(X .EQ. XK(I))GO TO 110
      IF(XK(I-1) .LT. X .AND. XK(I) .GT. X)GO TO 20
      GO TO 30
   20 CONTINUE
      IM1=I-1
      MKM1=XMKN(IM1)
      MK=XMKN(I)
      XXM=XK(I-1)
      XX=XK(I)
      FK=F(I)
      FKM1=F(I-1)
      LK=XK(I)-XK(I-1)
      IF(OPT .EQ. 1)XXM=XKR(I-1)
      IF(OPT .EQ. 1)XX=XKR(I)
      IF(OPT .EQ. 1)FK=FR(I)
      IF(OPT .EQ. 1)FKM1=FR(I-1)
      IF(OPT .EQ. 1)LK=XKR(I)-XKR(I-1)
      GO TO 40
   30 CONTINUE
   40 CONTINUE
      IF(OPT .EQ. 0)GO TO 70
      Y1L=(MKM1*(XX-XXM)**3)/(6.*LK)+(FKM1/LK-LK*MKM1/6.)*(XX-XXM)
      Y2L=(1.0/TAN(ANGROT))*XXM-X/SIN(ANGROT)
      IF(Y1L .GT. Y2L)INDC=1
      IF(Y2L .GT. Y1L)INDC=-1
      INDCP=INDC
      INDCP1=-INDCP
      DELXR=(XX-XXM)/10.
      XR=XXM

      DO 50 I=1,30
      XR=XR+DELXR
      TERM1=(MKM1*(XX-XR)**3)/(6.*LK)
      TERM2=(MK*(XR-XXM)**3)/(6.*LK)
      TERM3=(FK/LK-MK*LK/6.)*(XR-XXM)
      TERM4=(FKM1/LK-LK*MKM1/6.)*(XX-XR)
      Y1=TERM1+TERM2+TERM3+TERM4
      Y2=(1.0/TAN(ANGROT))*XR-X/SIN(ANGROT)
      IF(Y1 .GT. Y2)INDC=1
      IF(Y2 .GT. Y1)INDC=-1
      CRIT=ABS(Y1-Y2)/ABS(Y1)
      IF(CRIT .LE. 0.0002)GO TO 60
      IF(INDC .EQ. INDCP1)DELXR=-DELXR/10.
      IF(INDC .EQ. INDCP1)INDCP=INDCP1
      IF(INDC .EQ. INDCP1)INDCP1=-INDCP
   50 CONTINUE
   60 CONTINUE
      ANGINV=-ANGROT
      SANI=SIN(ANGINV)
      CANI=COS(ANGINV)
      Y=Y1*CANI - XR*SANI
      GO TO 110
   70 CONTINUE
      TERM1=(MKM1*(XX-X)**3)/(6.*LK)
      TERM2=(MK*(X-XXM)**3)/(6.*LK)
      TERM3=(FK/LK-MK*LK/6.)*(X-XXM)
      TERM4=(FKM1/LK-LK*MKM1/6.)*(XX-X)
      Y=TERM1+TERM2+TERM3+TERM4
```

```
      GO TO 110
   80 CONTINUE
      IF(IND .GE. -1 .AND. IND .LE. 1)GO TO 110
      IF(IND .EQ. -2)GO TO 90
      IF(IND .EQ. 2)GO TO 100
      GO TO 110
   90 WRITE(NWRITE,600)X,NC
      GO TO 110
  100 WRITE(NWRITE,610)X,NC
  110 CONTINUE
  600 FORMAT(/,5X,31HWARNING - A SPECIFIED X-VALUE (,F10.3,35H) IS BELOW
     * THE RANGE OF INPUT TABLE,I3)
  610 FORMAT(/,5X,31HWARNING - A SPECIFIED X-VALUE (,F10.3,35H) IS ABOVE
     * THE RANGE OF INPUT TABLE,I3)
      RETURN
      END
```

SUBROUTINE XMTXSL

```
      SUBROUTINE XMTXSL(NR,XMAT,SOL)
C
C-----THIS SUBROUTINE TAKES THE PROBLEM MATRIX AND SOLVES IT BY THE GAUSS-
C     JORDAN ELIMINATION METHOD
C
C-----NR IS THE NUMBER OF ROWS IN THE  MATRIX (ORDER OF MATRIX)
C-----XMAT(I,J) IS THE PROBLEM MATRIX TO BE SOLVED (INCLUDING THE FORCING F)
C-----XMAT(I,J) IS READ IN CONTINUOUSLY BY ROWS (INCLUDING THE FORCING FUNCTION)
C
C-----MAT(I,J) IS THE OVERALL MATRIX OBTAINED BY ADDING THE IDENTITY MATRIX
C     TO THE PROBLEM MATRIX
C
C-----SOL(I) IS THE SOLUTION VECTOR
C
      DIMENSION SOL(24),FCT(24),XMAT(24,25)
      DIMENSION XX1(24),YY1(24),XMK1(24)
      DIMENSION XX2(24),YY2(24),XMK2(24)
      DIMENSION XX3(24),YY3(24),XMK3(24)
      DIMENSION XX4(24),YY4(24),XMK4(24)
      COMMON NPC1,NPC2,NPC3,NPC4,ANGR1,ANGR2,ANGR3,ANGR4,XX1,XX2,XX3,XX4
     *,YY1,YY2,YY3,YY4,XMK1,XMK2,XMK3,XMK4,NREAD,NWRITE
      REAL MAT(24,49)

      NM=NR-1
      NC=NR+1
      NN=NC+1
      NLST=NC+NR

      DO 10 J=1,NC
      DO 10 I=1,NR
   10 MAT(I,J)=XMAT(I,J)
C
C-----ADD THE IDENTITY MATRIX TO GET OVERALL MATRIX
C
      DO 30 J=NN,NLST
      DO 30 I=1,NR
      MAT(I,J)=0.
      IF((J-I) .EQ. (NR+1))GO TO 20
      GO TO 30
   20 MAT(I,J)=1.
   30 CONTINUE
C
C-----MAKE THE PIVOT ELEMENT THE LARGEST ELEMENT
C
      NSW=0
      DO 50 J=1,NR
      IF(J .EQ. NR)GO TO 60
```

```
      DO 50 I=J,NM
      IP=I+1
      IF(ABS(MAT(IP,J)) .LT. ABS(MAT(J,J)))GO TO 50
      NSW=NSW+1
      DO 40 JS=1,NLST
      STOR=MAT(J,JS)
      MAT(J,JS)=MAT(IP,JS)
      MAT(IP,JS)=STOR
   40 CONTINUE
   50 CONTINUE
   60 CONTINUE
C
C-----REDUCE ELEMENTS IN PIVOT COLUMN TO ZERO, EXCEPT PIVOT
C
      DO 80 J=1,NP
      DO 70 IR=1,NR
   70 FCT(IR)=MAT(IR,J)/MAT(J,J)
      FCT(J)=0.
      DO 80 IZER=1,NR
      DO 80 JZER=J,NLST
      MAT(IZER,JZER)=MAT(IZER,JZER)-FCT(IZER)*MAT(J,JZER)
   80 CONTINUE
C
C-----GET THE DETERMINANT
C
      DET=1.0
      DO 90 K=1,NR
   90 DET=DET*MAT(K,K)
      DET=DET*((-1.)**NSW)
C
C-----TRAP SINGULARITY
C
      ISNGL=0
      IF(ABS(MAT(NR,NR)) .LT. 1.E-7 .AND. ABS(DET) .LT. 1.E-7)GO TO 100
      GO TO 110
  100 CONTINUE
      ISNGL=1
      WRITE(NWRITE,600)
  110 CONTINUE
C
C-----DIVIDE EACH ROW BY IT'S PIVOT TO GET SOLUTION VECTOR AND INVERSE MATRIX
C
      DO 120 IPIV=1,NR
      DIV=MAT(IPIV,IPIV)
      DO 120 JPIV=1,NLST
      MAT(IPIV,JPIV)=MAT(IPIV,JPIV)/DIV
  120 CONTINUE
      DO 130 IO=1,NR
  130 SOL(IO)=MAT(IO,NC)
  600 FORMAT(/,10X,36HSINGULAR MATRIX IN SUBROUTINE XMTXSL)
      RETURN
      END
```

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TABLE I. - INPUT DATA FORM

TITLE	PROJECT NUMBER	ANALYST	SHEET ___ OF ___

STATEMENT NUMBER | CONT | FORTRAN STATEMENT | IDENTIFICATION

```
TITLE
NP
NP X-VALUES (A MAXIMUM OF 24 VALUES)
NP Y-VALUES
CHAMBER INPUT VARIABLES IN NAMELIST FORM (SELECTED VARIABLES SHOWN)
 $DATT IUNTS=0,...
 NIR=5, NIHPR=9,10,3*12,...
 NFCR=7, NFCHPR=7*15, DFC=2*.010, 5*.012,...
 ROV2G=7*1.234E12 $
```

Repeated for each input table (NP, NP X-VALUES, NP Y-VALUES)

Repeated for each chamber ($DATT ... ROV2G=7*1.234E12 $)

NASA-C-836 (REV. 9-14-59)

TABLE II. - TABLE INPUTS FOR FCFC PROGRAM

Table	Table variable, y	Correlating parameter, x
1	Coolant specific-heat ratio, γ_c	Coolant temperature, T_c, K (°R)
2	Coolant viscosity, μ_c, g/cm·sec (lbm/ft·sec)	↓
3	Coolant specific-heat at constant pressure, $C_{p,c}$, J/g·K (Btu/lbm·°R)	↓
4	Coolant thermal conductivity, k_c, J/cm·sec·K (Btu/ft·hr·°R)	↓
5	Impingement-hole discharge coefficient, $(CD)_i$	Impingement-hole Mach number, M_2
6	Film-cooling-hole total-pressure loss coefficient, $(KT)_{nmg}$	Film-cooling-hole Mach number, M_5
7	Film-cooling-hole flow reduction due to main-stream-gas flow at $\beta = 0^o$, RT	$(\rho V^2)_c/(\rho V^2)_g$
8	RT correction factor, $(RT)_\beta/(RT)_{\beta=0^o}$	Compound angle, β, deg
9	Metal thermal conductivity, k_m, J/cm·sec·K (Btu/ft·hr·°R)	Metal temperature, T_m, K (°R)
10	Ceramic coating thermal conductivity, k_{ct}, J/cm·sec·K (Btu/ft·hr·°R)	Coating temperature, T_{ct}, K (°R)

TABLE III. - CHAMBER INPUT VARIABLES

(a) Variables associated with types of calculations desired

Variable	Description	Type[a]
IUNTS	Input units - 0 for U.S. customary units; 1 for SI units (default = 0)	I
ICTR	Centrifugal effects - 0 to exclude; 1 to include (default = 0)	↓
MTC	Metal temperature calculations - 0 to exclude (flow analysis only); 1 to include (default = 0)	↓
KCLC	Coating - 0 for no coating; 1 for coating (default = 0)	↓
MSBL	Main-stream blowing - 1 for blowing; 0 for no blowing (default = 0)	↓
OMG	Blade rotative speed (default = 0.), rpm	R

(b) Impingement-hole-row variables

NIR	Number of impingement-hole rows (≤25)	I
NIHPR	Number of impingement holes per row	I(NIR)
R1	Radial location of each impingement row from shaft centerline, mm; in. (Input only if ICTR=1)	R(NIR)
DI	Hole diameter of each impingement row, mm; in.	↓
TAUI	Impingement-insert thickness at each row, mm; in.	↓
HSP1	Impingement-hole spacing at each row, mm; in.	↓
XIMP	Impingement distance between insert and shell inner surface at each row, mm; in.	↓
P1T	Supply total pressure at each impingement row, N/cm^2; psia	↓
TT	Coolant supply total temperature, K; ^oF	R
RGAS	Coolant gas constant (default = 53.35), J/kg·K; ft·lbf/lbm·^oR	R

[a]Where I denotes integer; R denotes real; NIR denotes number of impingement rows; and NFCR denotes number of film-cooling rows.

TABLE III. - Concluded.

(c) Film-cooling-hole-row variables

Variable	Description	Type[a]
NFCR	Number of film-cooling rows (≤50)	I
NFCHPR	Number of film-cooling holes per row	I(NFCR)
R4	Radial location of each film-cooling row from shaft centerline, mm; in. (Input only if ICTR=1)	R(NFCR)
DFC	Hole diameter of each film-cooling row, mm; in.	↓
A5	Shell outer-surface area associated with each film-cooling row, cm^2; $in.^2$	↓
TAU	Shell metal thickness at each film-cooling row, mm; in.	↓
TAUC	Coating thickness at each film-cooling row, mm; in. (Input only if KCLC=1)	↓
HSP5	Film-cooling-hole spacing, mm; in.	↓
HFC4	Local back-side impingement-heat-transfer correction factor. (Default=1.0.)	↓
HFC45	Film-cooling-hole heat-transfer correction factor. (Default=1.0.)	↓
ALPHA	Film-cooling-hole inclination angle at each row (fig. 3), deg	↓
BETA	Film-cooling-hole compound angle at each row (fig. 3), deg	↓
HG0	Main-stream heat-transfer coefficient at coolant outlet temperature equal to main-stream-gas temperature, $J/(m^2 \cdot sec \cdot K)$; $Btu/(ft^2 \cdot hr \cdot {}^oR)$	↓
HG1	Main-stream heat-transfer coefficient at coolant outlet temperature equal to shell outer-surface temperature, $J/(m^2 \cdot sec \cdot K)$; $Btu/(ft^2 \cdot hr \cdot {}^oR)$	↓
TMSG	Main-stream-gas temperature at each film-cooling row, K; ^oF	↓
P6	Main-stream-gas static pressure at each film-cooling row, N/cm^2; psia	↓
ROVG	Main-stream-gas density times velocity, $kg/(m^2 \cdot hr)$; $lbm/(ft^2 \cdot hr)$. (Input only if MSBL=1)	↓
ROV2G	Main-stream-gas density times velocity squared, $kg/(m \cdot hr^2)$; $lbm/(ft \cdot hr^2)$. (Input only if MSBL=1)	↓

[a]Where I denotes integer; R denotes real; NIR denotes number of impingement rows; and NFCR denotes number of film-cooling rows.

TABLE IV. - INPUT LISTING FOR EXAMPLE PROBLEM

Card column 1 ↓

Title card

```
----- 2 EXAMPLES FOR FCFC PROGRAM -----
```

Tabular inputs

γ_c vs. T_c

```
10
300.      500.      700.      900.      1100.     1300.     1500.     1800.
2100.     2500.
1.40      1.386     1.365     1.345     1.329     1.316     1.304     1.288
1.270     1.238
```

μ_c vs. T_c

```
7
300.      500.      700.      1000.     1500.     1900.     2500.
 1.800E-4  2.650E-4  3.350E-4  4.200E-4  5.400E-4  6.300E-4  7.600E-4
```

$C_{p,c}$ vs. T_c

```
7
300.      500.      700.      1000.     1500.     1900.     2500.
1.004     1.025     1.067     1.138     1.234     1.305     1.548
```

k_c vs. T_c

```
7
300.      500.      700.      1000.     1500.     1900.     2500.
 2.510E-4  3.849E-4  5.062E-4  6.862E-4  9.414E-4  1.172E-3  1.736E-3
```

$(CD)_i$ vs. M

```
10
0.0       .05       .20       .30       .40       .55       .70       .85
.95       1.0
.80       .8025     .8175     .840      .875      .8975     .91       .92
.9225     .9225
```

$(KT)_{nmg}$ vs. M

```
10
0.0       .05       .20       .30       .40       .55       .70       .85
.95       1.0
.85       .8475     .84       .8275     .805      .750      .665      .5675
.50       .4665
```

RT vs. $\dfrac{(\rho V^2)_c}{(\rho V^2)_g}$

```
10
0.0       .01       .03       .06       .10       .20       .40       .60
1.0       3.2
0.0       .20       .55       .68       .76       .86       .91       .93
.945      1.0
```

$\dfrac{(RT)_\beta}{(RT)_{\beta=0^o}}$ vs. β

```
3
0.        45.       90.
1.0       1.0       1.0
```

k_m vs. T_m

```
9
700.      811.      922.      1033.     1144.     1256.     1367.     1422.
1700.
.2525     .2802     .3113     .3425     .3762     .4116     .4462     .4635
.578
```

k_{ct} vs. T_{ct}

```
3
1033.     1811.     2367.
.0131     .0149     .0163
```

Chamber inputs

Example 1

```
$DATT
IUNTS=1, ICTR=0, MTC=1, KCLC=1, MSBL=1, RGAS=287.05,
NIR=3, NIHPR=10*15, DI=10*0.3048, TAUI=10*0.635,
HSP1=10*3.81, XIMP=10*1.27, P1T=10*404., TT=811.,
NFCR=4, NFCHPR=25*15, DFC=3*0.2794, 0.2540, 21*0., A5=25*0.96774, TAU=25*1.27,
TAUC=25*0.127,
HSP5=25*2.54, HFC4=25*1., HFC45=25*1., ALPHA=40., 38., 35., 33., 21*0.,
BETA=25*0., P6=373.4, 370.8, 368.5, 364.7, 21*0., TMS6=25*2550.,
HG0=5277., 5816., 6384., 6951., 21*0., HG1=3972., 4256., 4483., 4767., 21*0.,
ROVG=4.364E6, 4.781E6, 5.107E6, 5.59E6, 21*0.,
ROV2G=3.204E12, 3.872E12, 4.439E12, 5.362E12, 21*0.$
```

Example 2

```
$DATT
ICTR=1, MTC=0, KCLC=0, OMG=16825.,
NIR=15, NIHPR=15*2,
R1=217.2, 219.7, 222.3, 224.8, 227.3, 229.9, 232.4, 235.0, 237.5, 240.0, 242.6,
   245.1, 247.7, 250.2, 252.7,
DI=15*0.4318, TAUI=15*0.381, HSP1=15*3.81, XIMP=15*0.762, TT=811.,
P1T=284.3, 286.4, 288.5, 290.7, 293.0, 295.2, 297.6, 299.9, 302.3, 304.8,
    307.3, 309.8, 312.4, 315.1, 317.8,
NFCR=15, NFCHPR=15*2,
R4=217.2, 219.7, 222.3, 224.8, 227.3, 229.9, 232.4, 235.0, 237.5, 240.0, 242.6,
   245.1, 247.7, 250.2, 252.7,
DFC=15*0.4572, TAU=15*1.016, HSP5=15*2.54, ALPHA=15*30., BETA=15*0.,
P6=264.5, 265.2, 266.0, 266.8, 267.6, 268.4, 269.2, 269.9, 270.7, 271.5, 272.3,
   273.1, 273.8, 274.6, 275.4,
ROVG=5.089E6, 5.108E6, 5.127E6, 5.145E6, 5.163E6, 5.182E6, 5.200E6, 5.219E6,
      5.237E6, 5.256E6, 5.275E6, 5.293E6, 5.311E6, 5.330E6, 5.348E6,
ROV2G=5.873E12, 5.902E12, 5.930E12, 5.958E12, 5.987E12, 6.015E12, 6.044E12,
       6.072E12, 6.101E12, 6.129E12, 6.158E12, 6.186E12, 6.215E12, 6.243E12,
       6.272E12$
```

TABLE V. - TITLE CARD AND TABULAR DATA

OUTPUT FOR EXAMPLE PROBLEMS

----- 2 EXAMPLES FOR FCFC PROGRAM -----

INPUT POINTS FOR COOLANT GAMMA VERSUS T ARE

X	Y
300.0000	1.4000
500.0000	1.3860
700.0000	1.3650
900.0000	1.3450
1100.0000	1.3290
1300.0000	1.3160
1500.0000	1.3040
1800.0000	1.2880
2100.0000	1.2700
2500.0000	1.2380

INPUT POINTS FOR COOLANT VISCOSITY VERSUS T ARE

X	Y
300.0000	.1800-03
500.0000	.2650-03
700.0000	.3350-03
1000.0000	.4200-03
1500.0000	.5400-03
1900.0000	.6300-03
2500.0000	.7600-03

INPUT POINTS FOR COOLANT SPECIFIC HEAT VERSUS T ARE

X	Y
300.0000	1.0040
500.0000	1.0250
700.0000	1.0670
1000.0000	1.1380
1500.0000	1.2340
1900.0000	1.3050
2500.0000	1.5480

INPUT POINTS FOR COOLANT THERMAL CONDUCTIVITY VERSUS T ARE

X	Y
300.0000	.2510-03
500.0000	.3849-03
700.0000	.5062-03
1000.0000	.6862-03
1500.0000	.9414-03
1900.0000	.1172-02
2500.0000	.1736-02

INPUT POINTS FOR IMP. DISCH. COEFF. VERSUS M2 ARE

X	Y
.0000	.8000
.0500	.8025
.2000	.8175
.3000	.8400
.4000	.8750
.5500	.8975
.7000	.9100
.8500	.9200
.9500	.9225
1.0000	.9225

TABLE V. - Concluded.

INPUT POINTS FOR FILM COOLING TOT. PRESS. LOSS COEFF. VERSUS M5 ARE

X	Y
.0000	.8500
.0500	.8475
.2000	.8400
.3000	.8275
.4000	.8050
.5500	.7500
.7000	.6650
.8500	.5675
.9500	.5000
1.0000	.4665

INPUT POINTS FOR FILM COOLING RT VERSUS ROV2R ARE

X	Y
.0000	.0000
.0100	.2000
.0300	.5500
.0600	.6800
.1000	.7600
.2000	.8600
.4000	.9100
.6000	.9300
1.0000	.9450
3.2000	1.0000

ROTATION ANGLE = 45.000 DEGREES

INPUT POINTS FOR RTCOR VERSUS BETA ARE

X	Y
.0000	1.0000
45.0000	1.0000
90.0000	1.0000

INPUT POINTS FOR METAL CONDUCTIVITY VERSUS T ARE

X	Y
700.0000	.2525
811.0000	.2802
922.0000	.3113
1033.0000	.3425
1144.0000	.3762
1256.0000	.4116
1367.0000	.4462
1422.0000	.4635
1700.0000	.5780

INPUT POINTS FOR COATING CONDUCTIVITY VERSUS T ARE

X	Y
1033.0000	.0131
1811.0000	.0149
2367.0000	.0163

TABLE VI. - EXAMPLE 1 (VANE) CHAMBER OUTPUT

----------OUTPUT FOR CHAMBER 1----------

SI SYSTEM OF UNITS

COOLANT GAS CONSTANT= 287.050 J/(KG-K)

THIS CASE INCLUDES A THERMAL BARRIER COATING

3 ROWS OF IMPINGEMENT HOLES

ROW	HOLES	DIAMETER (MM)	WALL THICKNESS	L/D	HOLE SPACING	IMPINGEMENT DISTANCE	R1 (MM)	P1T (N/CM**2)
1	15	.3048	.635	2.083	3.810	1.270	.000	404.000
2	15	.3048	.635	2.083	3.810	1.270	.000	404.000
3	15	.3048	.635	2.083	3.810	1.270	.000	404.000

4 ROWS OF FILM COOLING HOLES

ROW	HOLES	DIAMETER (MM)	THICKNESS WALL	----COATING	L/D (TOTAL)	HOLE SPACING	ALPHA (DEG)	BETA (DEG)	RHOVG (KG/M**2*HR)	RHOV2G (KG/M*HR**2)	R4 (MM)	P5 (N/CM**2)
1	15	.2794	1.270	.127	7.779	2.540	40.000	.000	.43640+07	.32040+13	.000	373.400
2	15	.2794	1.270	.127	8.121	2.540	38.000	.000	.47810+07	.38720+13	.000	370.800
3	15	.2794	1.270	.127	8.717	2.540	35.000	.000	.51070+07	.44390+13	.000	368.500
4	15	.2540	1.270	.127	10.098	2.540	33.000	.000	.55900+07	.53620+13	.000	364.700

IMPINGEMENT AND FILM COOLING FLOWS HAVE CONVERGED IN 8 OVERALL ITERATIONS

INFLOW EQUALS 20.263 KG/HR

IMP ROW	PSPLYT (N/CM**2)	P2	M2	T2T (K)	T2	WIMP (KG/HR)	CDIMP
1	404.000	390.971	.221	811.	804.	6.754	.821
2	404.000	390.971	.221	811.	804.	6.754	.821
3	404.000	390.971	.221	811.	804.	6.754	.821

OUTFLOW EQUALS 20.259 KG/HR

FC ROW	P3T (N/CM**2)	P4	M4	T4T (K)	T4 / P5T /(N/CM**2)	P5	M5	T5T (K)	T5 /TCTIF / (K)	WOUT (KG/HR)	KT	RT	RT CORR	RHOV RATIO	RHOVSQ RATIO	ITRS
1	390.971	374.327	.191	994.	987./ 382.948	373.400	.195	1029.	1022./1023.	4.833	.840	.939	1.000	1.283	.768	2
2	390.971	371.911	.205	982.	975./ 381.768	370.800	.210	1020.	1012./1014.	5.176	.839	.937	1.000	1.256	.730	2
3	390.971	369.816	.217	971.	963./ 380.726	368.500	.222	1012.	1003./1005.	5.467	.838	.936	1.000	1.243	.709	2
4	390.971	366.422	.235	1001.	991./ 379.010	364.700	.242	1044.	1035./1037.	4.783	.836	.935	1.000	1.204	.687	2

HEAT TRANSFER RESULTS

FC ROW	HEAT-TRANSFER-COEFFICIENTS HG0	HG1 (J/(M**2*SEC*K))	FC-HOLE	IMPG	H-MOD-FACTORS FC-HOLE	IMPG	COOLED AREA (CM**2)	GAS TEMP (K)	WALL-TEMPERATURE OUTSIDE (K)	INTFACE (K)	INSIDE (K)	AVG.-THERM.-COND. METAL (J/(CM*SEC*K))	COATING	ETA (TCO-TC)/(TWO-TC)	ITR
1	5277.	3972.	9733.	8890.	1.000	1.000	.968	2550.	1534.	1232.	1132.	.388	.014	.3014	3
2	5816.	4256.	10140.	8892.	1.000	1.000	.968	2550.	1543.	1234.	1133.	.389	.014	.2856	3
3	6384.	4483.	10397.	8882.	1.000	1.000	.968	2550.	1542.	1229.	1129.	.387	.014	.2743	3
4	6951.	4767.	10915.	8908.	1.000	1.000	.968	2550.	1562.	1244.	1141.	.391	.014	.3101	3

TABLE VII. - EXAMPLE 2 (BLADE) CHAMBER OUTPUT

----------OUTPUT FOR CHAMBER   2----------

SI SYSTEM OF UNITS

COOLANT GAS CONSTANT=   287.050 J/(KG-K)

THIS CASE INCLUDES CENTRIFUGAL EFFECTS. ROTATIONAL SPEED EQUALS 16825.00 RPM.

THIS CASE IS FLOW ANALYSIS ONLY AND INCLUDES NO METAL TEMPERATURE CALCULATIONS

15 ROWS OF IMPINGEMENT HOLES

ROW	HOLES	DIAMETER (MM)	WALL THICKNESS	L/D	HOLE SPACING	IMPINGEMENT DISTANCE	R1 (MM)	P1T (N/CM**2)
1	2	.4318	.381	.882	3.810	.762	217.200	284.300
2	2	.4318	.381	.882	3.810	.762	219.700	286.400
3	2	.4318	.381	.882	3.810	.762	222.300	288.500
4	2	.4318	.381	.882	3.810	.762	224.800	290.700
5	2	.4318	.381	.882	3.810	.762	227.300	293.000
6	2	.4318	.381	.882	3.810	.762	229.900	295.200
7	2	.4318	.381	.882	3.810	.762	232.400	297.600
8	2	.4318	.381	.882	3.810	.762	235.000	299.900
9	2	.4318	.381	.882	3.810	.762	237.500	302.300
10	2	.4318	.381	.882	3.810	.762	240.000	304.800
11	2	.4318	.381	.882	3.810	.762	242.600	307.300
12	2	.4318	.381	.882	3.810	.762	245.100	309.800
13	2	.4318	.381	.882	3.810	.762	247.700	312.400
14	2	.4318	.381	.882	3.810	.762	250.200	315.100
15	2	.4318	.381	.882	3.810	.762	252.700	317.800

15 ROWS OF FILM COOLING HOLES

ROW	HOLES	DIAMETER (MM)	THICKNESS WALL	----COATING	L/D (TOTAL)	HOLE SPACING	ALPHA (DEG)	BETA (DEG)	RHOVG (KG/M**2*HR)	RHOV2G (KG/M*HR**2)	R4 (MM)	P6 (N/CM**2)
1	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.50890+07	.58730+13	217.200	264.500
2	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.51080+07	.59020+13	219.700	265.200
3	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.51270+07	.59300+13	222.300	266.000
4	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.51450+07	.59580+13	224.800	266.300
5	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.51630+07	.59870+13	227.300	267.600
6	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.51820+07	.60150+13	229.900	268.400
7	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.52000+07	.60440+13	232.400	269.200
8	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.52190+07	.60720+13	235.000	269.900
9	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.52370+07	.61010+13	237.500	270.700
10	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.52560+07	.61290+13	240.000	271.500
11	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.52750+07	.61580+13	242.600	272.300
12	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.52930+07	.61860+13	245.100	273.100
13	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.53110+07	.62150+13	247.700	273.900
14	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.53300+07	.62430+13	250.200	274.600
15	2	.4572	1.016	.000	4.444	2.540	30.000	.000	.53480+07	.62720+13	252.700	275.400

IMPINGEMENT AND FILM COOLING FLOWS HAVE CONVERGED IN   9 OVERALL ITERATIONS

INFLOW EQUALS   23.452 KG/HR

IMP ROW	PSPLYT (N/CM**2)	P2	M2	T21 (K)	T2	WIMP (KG/HR)	CDIMP
1	284.300	271.933	.257	811.	802.	1.481	.828
2	286.400	273.921	.257	811.	802.	1.493	.828
3	288.500	276.028	.256	811.	802.	1.498	.828
4	290.700	278.092	.257	811.	802.	1.512	.828
5	293.000	280.196	.258	811.	802.	1.530	.828
6	295.200	282.426	.256	811.	802.	1.533	.828
7	297.600	284.610	.257	811.	802.	1.553	.828
8	299.900	286.926	.256	811.	802.	1.558	.828
9	302.300	289.194	.257	811.	802.	1.572	.828
10	304.800	291.505	.257	811.	802.	1.590	.828
11	307.300	293.954	.257	811.	802.	1.599	.828
12	309.800	296.354	.257	811.	802.	1.612	.828
13	312.400	298.896	.256	811.	802.	1.622	.828
14	315.100	301.387	.257	811.	802.	1.642	.828
15	317.800	303.924	.258	811.	802.	1.658	.828

OUTFLOW EQUALS   23.441 KG/HR

FC ROW	P31 (N/CM**2)	P4	M4	T4T (K)	T4 /	PST /(N/CM**2)	P5	M5	TST (K)	TS /	TCTIF / (K)	WOUT (KG/HR)	KT	RT	RT CORR	RHOV RATIO	RHOVSQ RATIO	ITRS
1	271.933	264.642	.150	811.	808./	268.533	264.500	.150	811.	808./	0.	.957	.843	.846	1.000	.677	.177	2
2	273.921	265.360	.162	811.	807./	269.933	265.200	.162	811.	807./	0.	1.060	.843	.864	1.000	.732	.207	2
3	276.028	266.178	.173	811.	807./	271.444	266.000	.173	811.	807./	0.	1.156	.842	.877	1.000	.783	.237	2
4	278.092	266.993	.184	811.	806./	272.933	266.800	.184	811.	806./	0.	1.242	.841	.886	1.000	.830	.265	2
5	280.196	267.808	.194	811.	806./	274.444	267.600	.194	811.	806./	0.	1.325	.840	.893	1.000	.875	.295	2
6	282.426	268.624	.204	811.	805./	276.024	268.400	.204	811.	805./	0.	1.411	.840	.899	1.000	.922	.327	2
7	284.610	269.437	.214	811.	805./	277.581	269.200	.214	811.	804./	0.	1.489	.839	.904	1.000	.965	.357	2
8	286.926	270.151	.224	811.	804./	279.164	269.900	.224	811.	804./	0.	1.577	.838	.909	1.000	1.012	.393	2
9	289.194	270.963	.233	811.	803./	280.769	270.700	.234	811.	803./	0.	1.653	.837	.913	1.000	1.053	.425	2
10	291.505	271.774	.242	811.	803./	282.397	271.500	.243	811.	803./	0.	1.730	.836	.917	1.000	1.094	.457	2
11	293.954	272.592	.252	811.	802./	284.103	272.300	.252	811.	802./	0.	1.811	.835	.921	1.000	1.136	.493	2
12	296.354	273.401	.260	811.	801./	285.783	273.100	.261	811.	801./	0.	1.887	.834	.924	1.000	1.175	.527	2
13	298.896	274.111	.270	811.	801./	287.498	273.800	.271	811.	801./	0.	1.972	.832	.927	1.000	1.219	.566	2
14	301.387	274.916	.279	811.	800./	289.231	274.600	.279	811.	800./	0.	2.047	.831	.930	1.000	1.258	.602	2
15	303.924	275.724	.287	811.	799./	290.991	275.400	.288	811.	799./	0.	2.123	.830	.933	1.000	1.296	.638	2

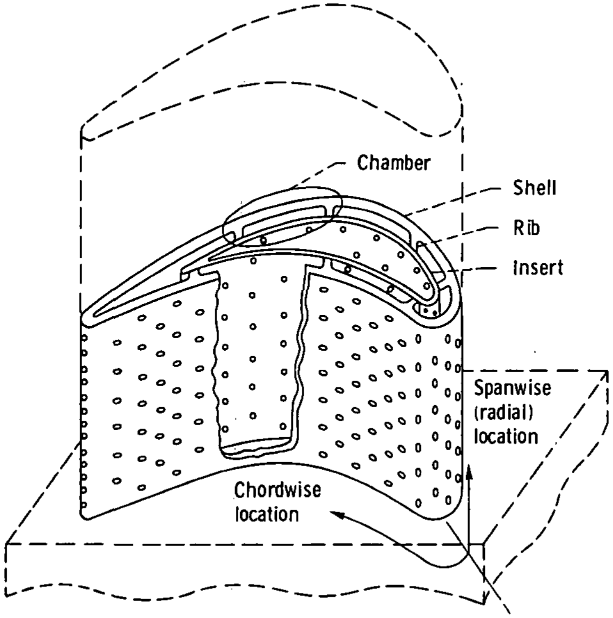


Figure 1. - Section of typical full-coverage-film-cooled blade.

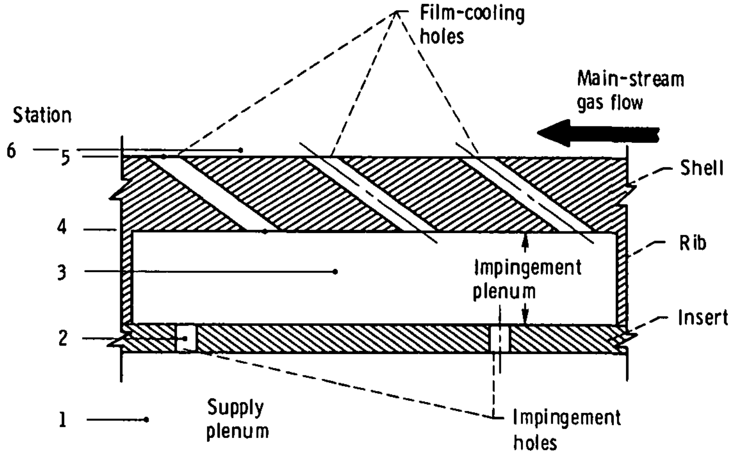


Figure 2. - Chamber cross section and station identification.

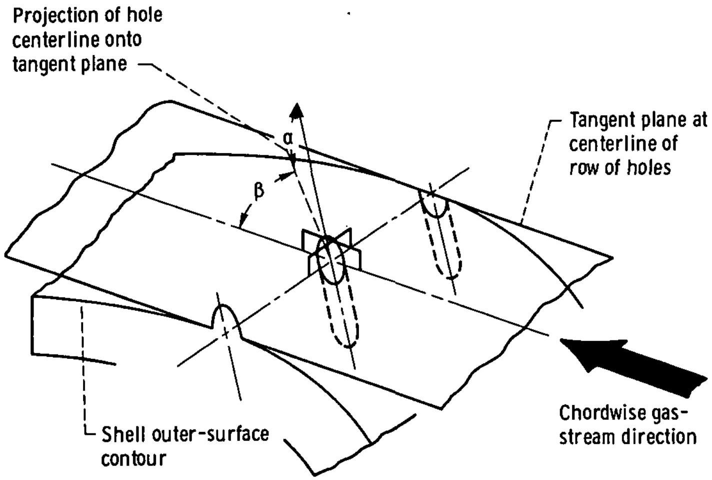


Figure 3. - Definitions of film-cooling-hole angles.

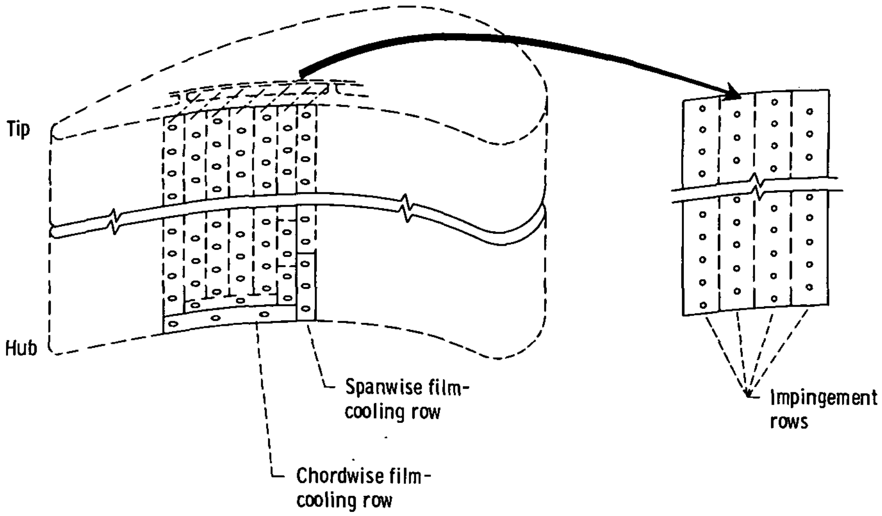


Figure 4. - Vane chamber division.

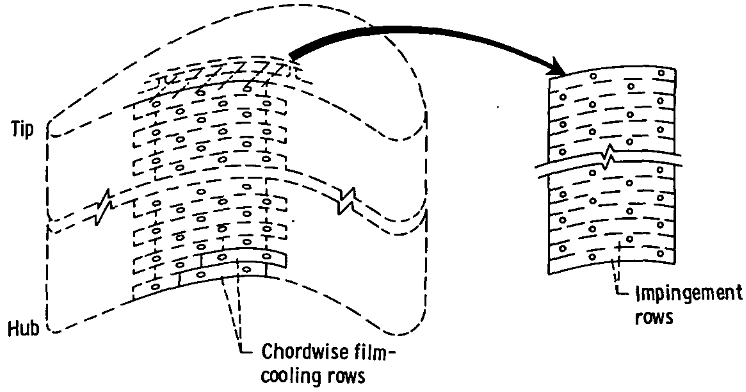


Figure 5. - Blade chamber division.

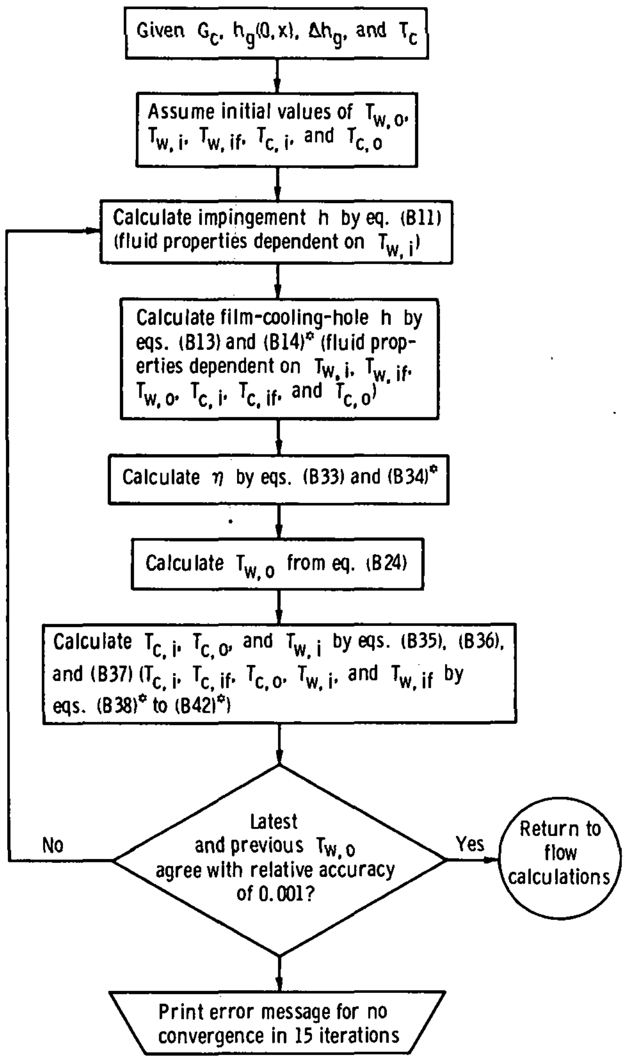


Figure 6. - Flow diagram for iterative heat-transfer calculations. (Equations for coated shell are marked with an asterisk.)

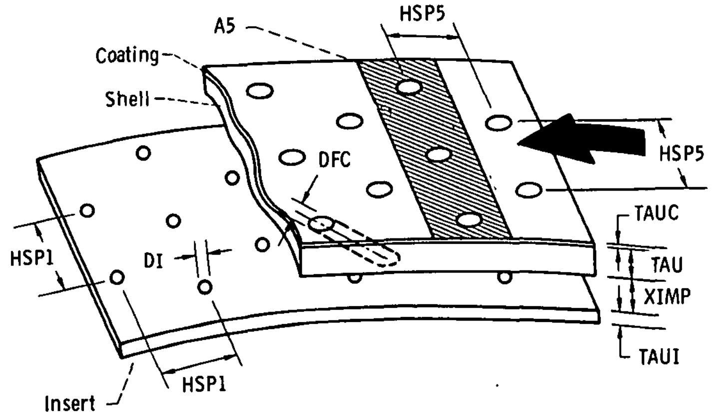
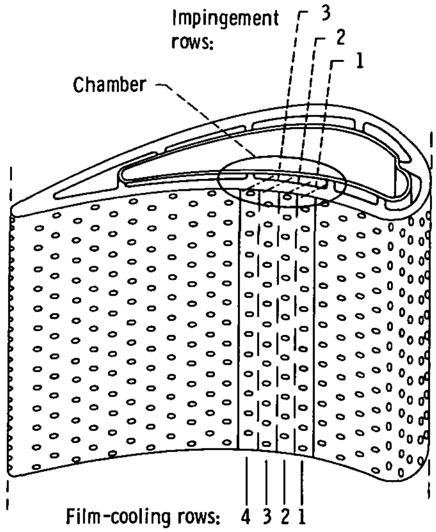


Figure 7. - Chamber geometry input variables.

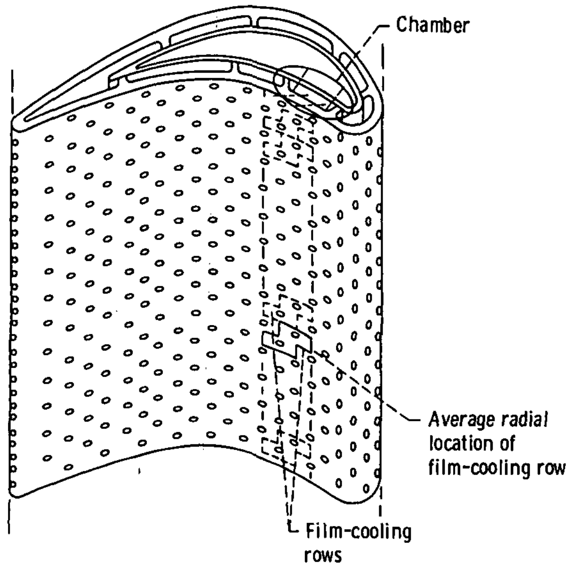


Impingement row	Number of holes per row	Hole diameter, cm
1	15	0.0508
2	15	.0508
3	15	.0508

Film-cooling row	Number of holes per row	Hole diameter, cm	Main-stream static pressure, P6, N/cm^2	Main-stream density times velocity, ρV, $kg/(m^2 \cdot hr)$	Main-stream density times velocity squared, ρV^2, $kg/(m \cdot hr^2)$	Main-stream HG0,[a] $J/(m^2 \cdot sec \cdot K)$	Main-stream HG1,[b] $J/(m^2 \cdot sec \cdot K)$
1	15	0.04064	373.4	4.364×10^6	3.204×10^{13}	5277	3972
2	↓	.04064	370.8	4.781	3.872	5816	4256
3		.04064	368.5	5.107	4.439	6384	4483
4		.0381	364.7	5.590	5.362×10^{12}	6951	4767

[a]Main-stream-gas heat-transfer coefficient for coolant temperature equal to main-stream gas temperature.
[b]Main-stream-gas heat-transfer coefficient for coolant temperature equal to shell outer temperature.

Figure 8. - Vane chamber of example 1.



Row	Radius, mm	Supply pressure, PIT, N/cm^2	Main-stream static pressure, P6, N/cm^2	Main-stream density times velocity, ρV, $kg/(m^2 \cdot hr)$	Main-stream density times velocity squared, ρV^2, $kg/(m \cdot hr^2)$
1	217.2	234.3	264.5	5.089×10^6	5.873×10^{12}
2	219.7	286.4	265.2	5.108	5.902
3	222.3	288.5	266.0	5.127	5.930
4	224.8	290.7	266.8	5.145	5.958
5	227.3	293.0	267.6	5.163	5.987
6	229.9	295.2	268.4	5.182	6.015
7	232.4	297.6	269.2	5.200	6.044
8	235.0	299.9	269.9	5.219	6.072
9	237.5	302.3	270.7	5.237	6.101
10	240.0	304.8	271.5	5.256	6.129
11	242.6	307.3	272.3	5.275	6.158
12	245.1	309.8	273.1	5.293	6.186
13	247.7	312.4	273.8	5.311	6.215
14	250.2	315.1	274.6	5.323	6.243
15	252.7	317.8	275.4	5.348	6.272

Figure 9. - Blade chamber of example 2.

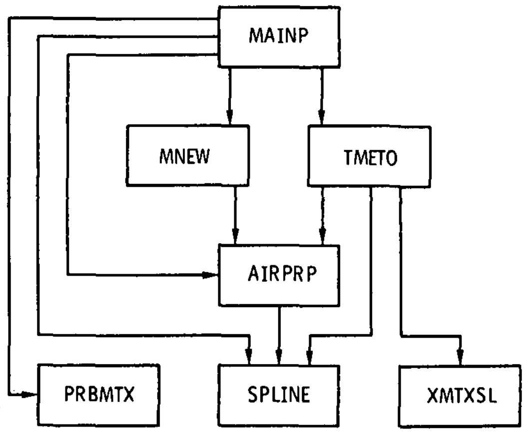


Figure 10. - Calling relations between the main program MAINP and the subroutines. (This is not a flow chart.)

1. Report No. NASA TP-1259 AVRADCOM TR 78-19(PL)	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle FORTRAN PROGRAM FOR CALCULATING COOLANT FLOW AND METAL TEMPERATURES OF A FULL-COVERAGE-FILM-COOLED VANE OR BLADE		5. Report Date July 1978
		6. Performing Organization Code
7. Author(s) Peter L. Meitner		8. Performing Organization Report No. E-9491
		10. Work Unit No. 505-04
9. Performing Organization Name and Address NASA Lewis Research Center and AVRADCOM Research and Technology Laboratories Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Paper
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546 and U.S. Army Aviation Research and Development Command, St. Louis, Mo. 63166		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A computer program that calculates the coolant flow and the metal temperatures of a full-coverage-film-cooled vane or blade has been developed. The analysis is based on compressible, one-dimensional fluid flow and on one-dimensional heat transfer and treats the vane or blade shell as a porous wall. The calculated temperatures are average values for the shell outer-surface area associated with each film-cooling hole row. A thermal-barrier coating may be specified on the shell outer surface, and centrifugal effects can be included for blade calculations. The program is written in FORTRAN IV and is operational on a UNIVAC 1100/42 computer. This report describes the method of analysis, the program input, the program output, and two example problems and provides a program listing.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Heat transfer Turbine cooling Film cooling Full-coverage film cooling	Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	90	A05

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