A Two-Dimensional Finite Difference Program for Thermal Analysis of Rocket Thrust Chambers

Mohammad H. Naraghi
Lewis Research Center
Cleveland, Ohio

September 1987
A TWO-DIMENSIONAL FINITE DIFFERENCE PROGRAM FOR
THERMAL ANALYSIS OF ROCKET THRUST CHAMBERS

Mohammad H. Naraghi*
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

A two-dimensional finite difference computer model for thermal analysis of rocket thrust chambers has been developed. The model uses an iterative scheme for calculating the temperature distribution within the chamber wall and implements a successive overrelaxation formula for a quick convergence. The inputs of the model are the dimensions of the thrust chamber wall, types of materials used, heat transfer coefficients and temperatures of the hot gas and the coolant. The resulting output of the program consists of the nodal temperature distribution, heat transfer to the coolant and heat transfer from the hot gas.

INTRODUCTION

The purpose of this report is to describe the two-dimensional finite difference model developed for evaluation of the temperature distribution in the wall of a rocket thrust chamber. The coating on the inside surface of the chamber is subject to high combustion gas temperatures, while the outer walls of the nozzle are exposed to space where only radiation heat transfer must be considered. A coolant flows through a series of cooling channels located inside the chamber wall to maintain the entire component at reasonably moderate temperatures.

The first part of this report describes the finite difference method used for the present analysis. Next, the subroutine is described, and, finally results of a sample run are presented.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>heat transfer coefficient</td>
</tr>
<tr>
<td>k</td>
<td>conductivity</td>
</tr>
<tr>
<td>R</td>
<td>radius</td>
</tr>
<tr>
<td>$R_1, R_2, R_3, R_4$</td>
<td>thermal resistances</td>
</tr>
<tr>
<td>$T_{i,j}$</td>
<td>temperature at node $(i,j)$</td>
</tr>
</tbody>
</table>

---

*NASA Summer Faculty Fellow from Manhattan College, Department of Mechanical Engineering, Riverdale, New York 10471 (work funded by NASA Grant NAG 3-672).
\[ \Delta R \text{ radial mesh size} \]
\[ \Delta \phi \text{ circumferential mesh size} \]
\[ \epsilon \text{ relative error for terminating iterations} \]
\[ \epsilon_0 \text{ emissivity of the outer surface} \]
\[ \sigma \text{ Stefan Boltzmann coefficient} \]
\[ \omega \text{ successive overrelaxation coefficient} \]

Subscripts
A material A
B material B
c coolant
g gas
i node i
j node j
o ambient

Superscripts
n iteration number

THE FINITE DIFFERENCE MODEL

Consider the geometry of a rocket thrust chamber cross section as shown in figure 1. The thrust chamber is made of three materials: nickel, copper, and a soot coating. It also consists of a number of cooling channels. Because of the symmetry of the configuration, only half of a cooling channel cell is considered here (see fig. 2). Since no heat is transferred through the two sides of the cell, they are assumed to be insulated. A finite difference grid is superimposed on the aforementioned cell as is shown in figure 3. The finite difference equations are then written for each nodal point in terms of its neighboring nodes (ref. 1). The finite difference equation for a node located in the middle of a material is given by

\[
T_{i,j} = \frac{T_{i+1,j} \frac{1}{R_1} + T_{i,j-1} \frac{1}{R_2} + T_{i-1,j} \frac{1}{R_3} + T_{i,j+1} \frac{1}{R_4}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}
\]
where

\[ R_1 = \frac{R}{2} \frac{\Delta \phi}{\Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1+1,j}} \right) \]

\[ R_2 = \frac{\Delta R}{2(R + \Delta R/2) \Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1,j-1}} \right) \]

\[ R_3 = \frac{R}{2} \frac{\Delta \phi}{\Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1-1,j}} \right) \]

\[ R_4 = \frac{\Delta R}{2(R - \Delta R/2) \Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1,j+1}} \right) \]

Similar equations are derived for other nodes, i.e., boundary nodes and nodes at the interface between two different materials. These equations are given in appendix A. In general, the finite difference equations give the temperature of each node in terms of the temperatures of neighboring nodes and/or heat transfer coefficients, conductivities, hot gas, and coolant temperatures.

The thermal conductivities of the materials used for the combustion wall are functions of temperature and these functions are represented by the curves in figures 4 to 6 (ref. 3). The gas and coolant temperatures, and the heat transfer coefficients for both the hot gas side and the coolant side are also known.

The following numerical procedure is executed to obtain the temperature distribution:

(1) Set \( n = 0 \)

(2) Assume a temperature for each node

(3) Set \( n = n + 1 \)

(4) Find thermal conductivities based on the nodal temperatures (using the data given in figs. 4 to 6)

(5) Substitute for the nodal temperatures, conductivities and heat transfer coefficients in the right side of the finite difference equations and obtain a new temperature distribution

(6) If

\[ \left| \frac{T^n_{1,j} - T^{n-1}_{1,j}}{T^n_{1,j}} \right| < \epsilon \]
Go to step 8 otherwise, go to step 7

(7) Use a successive overrelaxation formula (ref. 2) to revise the temperature distribution for a quick convergence. Then go to step 3.

(8) Stop the calculation, the latest temperature distribution is the answer. The successive overrelaxation formula (ref. 2) used in step 7 is given by

\[ T_{i,j}^n = T_{i,j}^{n-1} + \omega (T_{i,j}^n - T_{i,j}^{n-1}) \]

This equation revises the temperature distribution for a quick convergence. The most efficient value of \( \omega \) for the geometry under consideration here is 1.9. This value of \( \omega \) is obtained by a trial and error procedure to minimize the computation time. It should be noted that the successive overrelaxation equation makes the convergence four times faster than when it is eliminated from the calculation for the configuration considered here.

THE COMPUTER PROGRAM

A listing of the computer program developed based on the finite difference model discussed in the previous section is given in the appendix B. The inputs to the program are the dimensions of the combustion chamber, hot gas and coolant temperatures and heat transfer coefficients, types of materials used at each layer, and number of nodes in the radial and circumferential directions. Conductivities of five materials are included in the program. These materials are:

(1) Copper
(2) Nickel
(3) Narloy-Z
(4) Columbium
(5) Soot (carbon)

Conductivities of these materials as functions of temperatures are given in separate subroutines that are referenced in the main program.

The output of the program includes a listing of the temperatures for each node, number of iterations, and the rate of heat transfer from the hot gas to the cooling channel. A sample output of the program is included in appendix B.

The finite difference program discussed in this report will be used as a subroutine in the three dimensional rocket temperature evaluation program. The present program provides the rate of heat transfer from hot gas to the coolant at each station. Utilizing an iterative scheme and repeating the procedure for each station, the temperature distribution and rate of heat transfer to the cooling channel can be determined for the whole thrust chamber.
APPENDIX A

This appendix presents the finite difference equations (nodal balance of energy equations) for the different type nodes.

Middle Nodes

\[
T_{1,j} = \frac{T_{1+1,1} \frac{1}{R_1} + T_{1,1-1} \frac{1}{R_2} + T_{1-1,1} \frac{1}{R_3} + T_{1,1+1} \frac{1}{R_4}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}
\]

where

\[
R_1 = \frac{R \Delta \phi}{2 \Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1+1,j}} \right)
\]

\[
R_2 = \frac{\Delta R}{2(R + \Delta R/2) \Delta \phi} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i,j-1}} \right)
\]

\[
R_1 = \frac{R \Delta \phi}{2 \Delta R} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i-1,j}} \right)
\]

\[
R_2 = \frac{\Delta R}{2(R - \Delta R/2) \Delta \phi} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i,j+1}} \right)
\]
Upper boundary node

\[
T_{1,j} = \frac{\frac{T_{1+1,j}}{R_1} + \frac{T_{1,j+1}}{R_2} + \frac{T_{1-1,j}}{R_3} + \frac{T_0}{R_4}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}
\]

where

\[
R_1 = \frac{R}{\Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1+1,j}} \right)
\]
\[
R_2 = \frac{\Delta R}{2(R - \Delta R/2)\Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1,j+1}} \right)
\]
\[
R_3 = \frac{R}{\Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1-1,j}} \right)
\]
\[
R_4 = \frac{1}{h_0 R_0 \Delta \phi}
\]

For forced convection \( h_0 \) is known

for free convection

\[
h_0 = \frac{0.53 h_{air}}{2R_0} \left[ g |T_{1,j} - T_0| (2R_0)^3 \right]^{0.25}
\]

for radiation to space

\[
h_0 = \sigma_0 \left( T_{1,j}^3 + T_0 T_{1,j}^2 + T_{1,j} T_0^2 + T_0^3 \right)
\]
Upper boundary (left corner)

\[ T_{1,1} = \frac{T_{2,1}}{R_1} + \frac{T_{1,2}}{R_2} + \frac{T_0}{R_3} \]

where

\[ R_1 = \frac{R}{\Delta R} \left( \frac{1}{k_{1,1}} + \frac{1}{k_{2,1}} \right) \]

\[ R_2 = \frac{\Delta R}{2(R - \Delta R/2)\Delta \phi} \left( \frac{1}{k_{1,1}} + \frac{1}{k_{1,2}} \right) \]

\[ R_3 = \frac{2}{h_0 R_0 \Delta \phi} \]
upper boundary (right corner)

\[
T_{1,j} = \frac{T_{i-1,1} + T_{1,j+1} + T_0}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}
\]

where

\[
R_1 = \frac{R}{\Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{i-1,j}} \right)
\]

\[
R_2 = \frac{\Delta R}{2(R - \Delta R/2)\Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{i,j+1}} \right)
\]

\[
R_3 = \frac{2}{h_0 R_0 \Delta \phi}
\]
Left boundary

\[
T_{i,j} = \frac{T_{i,j+1}}{R_1} + \frac{T_{i+1,j}}{R_2} + \frac{T_{i,j-1}}{R_3}
\]

where

\[
R_1 = \frac{\Delta R}{2(R - \Delta R/2)\Delta \phi} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i,j+1}} \right)
\]

\[
R_2 = \frac{R}{2 \Delta R} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i+1,j}} \right)
\]

\[
R_3 = \frac{\Delta R}{2(R + \Delta R/2)\Delta \phi} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i,j-1}} \right)
\]
Right boundary

\[ T_{i,j} = \frac{T_{i+1,j} + T_{i-1,j} + T_{i,j-1}}{R_1 + \frac{1}{R_2} + \frac{1}{R_3}} \]

where

\[ R_1 = \frac{\Delta R}{2(R - \Delta R/2)\Delta \phi} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i,j-1}} \right) \]
\[ R_2 = \frac{R \Delta \phi}{2 \Delta R} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i+1,j}} \right) \]
\[ R_3 = \frac{\Delta R}{2(R + \Delta R/2)\Delta \phi} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i,j-1}} \right) \]
Lower boundary node

\[ T_{1,j} = \frac{T_{i+1,j} + T_{i,j-1} + T_{i-1,j} + T_g}{R_1 + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}} \]

where

\[ R_1 = \frac{R}{\Delta R} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i+1,j}} \right) \]

\[ R_2 = \frac{\Delta R}{2(R + \Delta R/2)k_{i,j}} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i,j-1}} \right) \]

\[ R_3 = \frac{R}{\Delta R} \left( \frac{1}{k_{i,j}} + \frac{1}{k_{i-1,j}} \right) \]

\[ R_4 = \frac{1}{h_g R_1 \Delta \phi} \]
Lower left side boundary node

\[
T_{1,j} = \frac{T_{i+1,j} + T_{i,j-1} + T_{q}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}
\]

where

\[
R_1 = \frac{R \Delta \phi}{\Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1+1,j}} \right)
\]

\[
R_2 = \frac{\Delta R}{2(R + \Delta R/2) \Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1,j-1}} \right)
\]

\[
R_3 = \frac{2}{h g R_1 \Delta \phi}
\]
Lower right side boundary node

\[
T_{i,j} = \frac{T_{i,j-1}}{R_1} + \frac{T_{i-1,j}}{R_2} + \frac{T_g}{R_3}
\]

where

\[
R_1 = \frac{\Delta R}{2(R + \Delta R/2)\Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1,j-1}} \right)
\]

\[
R_2 = \frac{R \Delta \phi}{\Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1-1,j}} \right)
\]

\[
R_3 = \frac{2}{h_g R_1 \Delta \phi}
\]
Upper cooling channel wall

\[ T_{i,j} = \frac{T_{i+1,j} + T_{i,j-1} + T_{i-1,j} + T_{c}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}} \]

where

\[ R_1 = \frac{R \Delta \phi}{\Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{i+1,j}} \right) \]

\[ R_2 = \frac{\Delta R}{2(R + \Delta R/2) \Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{i,j-1}} \right) \]

\[ R_3 = \frac{R \Delta \phi}{\Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1-1,j}} \right) \]

\[ R_4 = h_c R \Delta \phi \]
Cooling channel side wall

\[
T_{1,j} = \frac{T_{1,1-1} + \frac{T_{1-1,1}}{R_2} + \frac{T_{1,1+1}}{R_3} + \frac{T_c}{R_4}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}
\]

where

\[
R_1 = \frac{\Delta R}{2(R + \Delta R/2)\Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1,j-1}} \right)
\]

\[
R_2 = \frac{R \Delta \phi}{2 \Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1-1,j}} \right)
\]

\[
R_3 = \frac{\Delta R}{2(R - \Delta R/2)\Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1,j+1}} \right)
\]

\[
R_4 = \frac{1}{\Delta R h_c}
\]


Cooling channel lower wall

\[
T_{1,j} = \frac{T_{i+1,j}}{R_1} + \frac{T_{i,j+1}}{R_2} + \frac{T_{i-1,j}}{R_3} + \frac{T_c}{R_4}
\]

where

\[
R_1 = \frac{R}{\Delta R} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1+1,j}} \right)
\]

\[
R_2 = \frac{\Delta R}{2(R - \Delta R/2)\Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1,j+1}} \right)
\]

\[
R_3 = \frac{R}{\Delta \phi} \left( \frac{1}{k_{1,j}} + \frac{1}{k_{1-1,j}} \right)
\]

\[
R_4 = \frac{1}{R \Delta \phi h_c}
\]
Interface between two materials (middle node)

\[
T_{1,j} = \frac{T_{1+1,1} + T_{1,j+1} + T_{1-1,1} + T_{1,j-1}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}
\]

where

\[
R_{A_1} = R_1 \frac{\Delta \phi}{\Delta R_A} \left( \frac{1}{k_{A_{1,j}}} + \frac{1}{k_{A_{1+1,j}}} \right)
\]

\[
R_{B_1} = R_1 \frac{\Delta \phi}{\Delta R_B} \left( \frac{1}{k_{B_{1,j}}} + \frac{1}{k_{B_{1+1,j}}} \right)
\]

\[
R_1 = \frac{R \Delta \phi}{\Delta R_A \left( \frac{1}{k_{A_{1,j}}} + \frac{1}{k_{A_{1+1,j}}} \right) + \Delta R_B \left( \frac{1}{k_{B_{1,j}}} + \frac{1}{k_{B_{1+1,j}}} \right)}
\]

\[
R_2 = \frac{\Delta R_A}{2(R \Delta R_A / 2) \Delta \phi} \left( \frac{1}{k_{A_{1,j}}} + \frac{1}{k_{A_{1,j+1}}} \right)
\]

\[
R_3 = \frac{R \Delta \phi}{\Delta R_A \left( \frac{1}{k_{A_{1,j}}} + \frac{1}{k_{A_{1-1,j}}} \right) + \Delta R_B \left( \frac{1}{k_{B_{1,j}}} + \frac{1}{k_{B_{1-1,j}}} \right)}
\]

\[
R_4 = \frac{\Delta R_B}{2(R + \Delta R_B / 2) \Delta \phi} \left( \frac{1}{k_{B_{1,j}}} + \frac{1}{k_{B_{1,j-1}}} \right)
\]
Interface between two materials (left boundary node)

\[
T_{i,j} = \frac{T_{i+1,j} + T_{i,j+1} + T_{i,j-1}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}
\]

where

\[
R_1 = \frac{R \Delta \phi}{\Delta R_A \left( \frac{1}{k_{A1,j}} + \frac{1}{k_{A_1,j+1}} \right) + \Delta R_B \left( \frac{1}{k_{B1,j}} + \frac{1}{k_{B_1,j+1}} \right)}
\]

\[
R_2 = \frac{\Delta R_A}{2(R \Delta R_A / 2) \Delta \phi} \left( \frac{1}{k_{A1,j}} + \frac{1}{k_{A_1,j+1}} \right)
\]

\[
R_3 = \frac{\Delta R_B}{(R + \Delta R_B / 2) \Delta \phi} \left( \frac{1}{k_{B1,j}} + \frac{1}{k_{B_1,j-1}} \right)
\]
Interface between two materials (right boundary node)

\[
T_{i,j} = \frac{T_{i-1,j} R_1 + T_{i, j+1} R_2 + T_{i, j-1} R_3}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}
\]

where

\[
R_1 = \frac{R \Delta \phi}{\Delta R_A \left(\frac{1}{k_{A1,j}} + \frac{1}{k_{A1,j-1}}\right) + \Delta R_B \left(\frac{1}{k_{B1,j}} + \frac{1}{k_{B1,j-1}}\right) + \frac{1}{k_{A1,j}} + \frac{1}{k_{A1,j+1}}}
\]

\[
R_2 = \frac{\Delta R_A}{(R - \Delta R_A/2) \Delta \phi} \left(\frac{1}{k_{A1,j}} + \frac{1}{k_{A1,j+1}}\right)
\]

\[
R_3 = \frac{\Delta R_B}{(R + \Delta R_B/2) \Delta \phi} \left(\frac{1}{k_{B1,j}} + \frac{1}{k_{B1,j-1}}\right)
\]
Interface between two materials (upper left side of the cooling channel)

\[
T_{1,j} = \frac{\frac{T_{i+1,j+1}}{R_1} + \frac{T_{i,j+1}}{R_2} + \frac{T_{i-1,j}}{R_3} + \frac{T_{i,j-1}}{R_4} + \frac{T_c}{R_5}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5}}
\]

where

\[
R_1 = \frac{R}{\Delta R_B} \frac{\Delta \phi}{(k_{B1,j} + k_{B1+1,j})}
\]

\[
R_2 = \frac{\Delta R_A}{(R - \Delta R_A/2)\Delta \phi} \left( \frac{1}{k_{A1,j+1}} + \frac{1}{k_{A1,j+1}} \right)
\]

\[
R_3 = \frac{R}{\Delta \phi} \frac{\Delta R_A}{\left( \frac{1}{k_{A1,j} + 1/k_{A1+1,j}} \right)} + \frac{\Delta R_B}{\left( 1/k_{B1,j} + 1/k_{B1+1,j} \right)}
\]

\[
R_4 = \frac{\Delta R_B}{2(R + \Delta R_B/2)\Delta \phi} \left( \frac{1}{k_{B1,j}} + \frac{1}{k_{B1,j-1}} \right)
\]

\[
R_5 = \frac{2}{R \Delta \phi h_{c2} + \Delta R h_{c3}}
\]
APPENDIX B
Computer Program Listing and Sample Output

DATA CASE/'CASE'/,DIME/'SRB9'/
C FORTRAN PROGRAM FOR EVALUATION OF TEMPERATURE
C DISTRIBUTION IN SPACECRAFT NOZZLE
C
C DEFINITION OF A CELL FOR REGENERATIVE COOLING MODE:
C A CELL IS THE LEFT HALF OF THE WEDGE CENTERED ON A COOLANT CHANNEL
C (IE. THE RIGHT SIDE IS THE CENTERLINE OF THE CHANNEL AND THE LEFT
C SIDE IS THE CENTERLINE OF THE LAND)
C
C DEFINITION OF CELL FOR RADIATION COOLING MODE:
C A CELL IS ONE HALF THE SECTION INTO WHICH THE NOZZLE WALL IS
C DIVIDED BY THE "NUMBER OF COOLANT CHANNELS" VARIABLE (NCC)
C
CCW FULL COOLANT CHANNEL WIDTH (FEET)
COOL METHOD OF COOLING
CW RADIIANS/FULL CELL WIDTH
DIFPHIC RADIIANS/CELL CHANNEL WIDTH
DIFPHIL RADIIANS/CELL LAND WIDTH
DPHIB CIRCUMFERENTIAL INCREMENT AT CIRCUM INTERFACE (RADIANS)
DPHIC CIRCUMFERENTIAL INCREMENT WITHIN CHANNEL (RADIANS)
DPHIL CIRCUMFERENTIAL INCREMENT WITHIN LAND (RADIANS)
EM EMMISSIVITY OF CLOSE-OUT MATERIAL
HC1 COOLANT HEAT TRANSFER COEFFICIENT (INNER WALL)
HC2 COOLANT HEAT TRANSFER COEFFICIENT (SIDE WALL)
HC3 COOLANT HEAT TRANSFER COEFFICIENT (OUTER WALL)
HI HOT GAS HEAT TRANSFER COEFFICIENT (BTU/FT**2*S*R)
HO1 KNOWN OUTSIDE HEAT TRANSFER COEFFICIENT (BTU/FT**2*S*R)
IFILE FLAG TO MAKE CONTOURING FILE
IHOUT TYPE OF HEAT TRANSFER AT OUTER BOUNDARY
MTCH CHANNEL (TOP AND BOTTOM) MATERIAL
MTCOAT COATING MATERIAL
NCC NUMBER OF COOLANT CHANNELS
NPHIC NUMBER OF CIRCUM NODES WITHIN CHANNEL AREA
NPHIL NUMBER OF CIRCUM NODES IN LAND AREA (INC. CHANNEL WALL
NPHITOT TOTAL NUMBER OF CIRCUMFERENTIAL NODES
NRCHB NUMBER OF RADIAL NODES IN CHANNEL (BOTTOM PORTION)
NRCHT NUMBER OF RADIAL NODES IN CHANNEL (TOP PORTION)
NRCOAT NUMBER OF RADIAL NODES IN THE COATING
RCI INNER CHANNEL RADIUS (FEET)
RCO OUTER CHANNEL RADIUS (FEET)
RI INNER RADIUS (FEET)
RO OUTER RADIUS (FEET)
C I TC  COOLANT TEMPERATURE (DEG R)
C I TCOAT  COATING THICKNESS (FEET)
C I TI  HOT GAS TEMPERATURE (DEG R)
C I TO  OUTSIDE TEMPERATURE (DEG R)
C MATERIAL NUMBERS: (1) COPPER, (2) NICKEL, (3) SOOT (ORIGINAL)
C       (4) NARLOY-Z, (5) RSR 995-AE, (6) COLUMBIUM
WRITE(6,1)CASE,DIME
1 FORMAT(IH1///10X,2A4)
   COOL = 1
   IHOUT = 2
   IFILE = 0
   NPHIL = 4
   NPHIC = 3
   NRCLO = 5
   NRCHT = 5
   NRCHB = 4
   NRCOAT = 0
   MTCLO = 2
C IF RADIATION COOLING, MTCCH MUST BE SAME AS MTCLO
C MTCCH = 1
C MTCOAT = 3
C CCW = 0.02/12.
C RO = 1.945/12.
C RCO = 1.925/12.
C RI = 1.74/12.
C TCOAT = 0.000/12.
C IF(TCOAT.EQ.0.0)NRCOAT = 0
C NCC = 100
C TO = 530.
C EM = 0.9
C HI = 0.01419
C TC = 90.
C HC1 = 0.71424
C HC2 = 1.0*0.75406
C HC3 = 1.0*0.77978
C HO1 = 0.0
C PI = 3.1415
C CW = PI/NCC
C DIFPHIC = CCW/(2.*RCl)
C DIFPHIL = CW-DIFPHIC
C DPHIL = DIFPHIL/(NPHIL-1.)
C IF (NPHIC EQ.99) GOTO 20
C DPHIC = DIFPHIC/NPHIC
C NPHITOT = NPHIC + NPHIL
C GOTO 25
C 20 DPHIC = 0.
C NPHITOT = NPHIL
C 25 DPHIB = (DPHIC + DPHIL)/2.
C IF (COOL EQ. 2) GOTO 15
C WRITE (6,5) NPHIL,NPHIC,CW,DIFPHIL,DIFPHIC,DPHIL,DPHIC,DPHIB
C WRITE(6,2)NRCLO,NRCHT,NRCHB,NRCOAT
C GOTO 10
15 WRITE (6,8)NPHIL,CW,DPHIL
   WRITE (6,11)MTCLO,NRCLO
   WRITE (6,13)MTCOAT,NRCOAT
10 CONTINUE

2 FORMAT(///lOX,'NRCLO = ',15,2X,'NRCHT = ',15,2X,'NRCHB = ',15,2X,
1'NRCOAT =',IS)
5 FORMAT (///lOX,'NPHIL = ',14,3X,'NPHIC = ',14,3X,/IOX,'CW =',F8.6,
13X,'DIFPHIL = '.F8.6,3X,'DIFPHIC = ',F8.6,3X,/1OX,'DPHIL =',F8.6,
23X,'DPHIC = ',F8.6,3X,'DPHIB = ',F8.6)
8 FORMAT (///lOX,'NPHI = ',14,/10X,'CELL WIDTH = ',F8.6,10X,'DPHI =',
11F8.6)
11 FORMAT (///IOX,'SUBSTRATE: MATERIAL = ',13,6X,'NODES =',13)
13 FORMAT (/lOX,'COATING: MATERIAL = ',13,6X,'NODES =',13)

CALL COND(RI,RO,DPHIC,DPHIL,DPHIB,NRCLO,NRCHT,NRCHB,NRCOAT,
1NPHIC,NPHIL,NPHITOT,RCI,RCO,TCOAT,TO,EM,TI,HI,TC,HCl,HC2,HC3,
2MTCLO,MTCH,MTCOAT,COOL,IHOUT,H01,IFILE,NCC)
STOP
END

SUBROUTINE COND(RI,RO,DPHIC,DPHIL,DPHIB,NRCLO,NRCHT,NRCHB,NRCOAT,
1NPHIC,NPHIL,NPHITOT,RCI,RCO,TCOAT,TO,EM,TI,HI,TC,HCl,HC2,HC3,
2MTCLO,MTCH,MTCOAT,COOL,IHOUT,H01,IFILE,NCC)

COOL  METHOD OF COOLING (FROM $MAIN)
C1-2-3 (L OR C) GIVES GEOMETRY TO RESISTANCES IN AREA/LENGTH
DOT  ARRAY WITH SCALING DATA FOR CONTOURING ROUTINE
DPHI  CIRCUMFERENTIAL INCREMENT (GIVEN C OR L VALUE)
DRCHB  RADIAL INCREMENT IN BOTTOM OF CHANNEL (FROM $MAIN)
DRCHT  RADIAL INCREMENT IN TOP OF CHANNEL (FROM $MAIN)
DRCLO  RADIAL INCREMENT IN CLOSE-OUT (FROM $MAIN)
DRCOAT  RADIAL INCREMENT IN COATING (FROM $MAIN)
EE  FRACTIONAL ERROR AT END OF CONDUCTIVITY ITERATION
EM  EMISSIVITY OF CLOSE-OUT MATERIAL (FROM $MAIN)
ERR  FRACTIONAL ERROR WITHIN CONDUCTIVITY ITERATION
ERROR  RELATIVE ERROR FOR TERMINATING ITERATIONS
FC()  ARRAY WITH CONTOURING LEVELS FOR CONTOURING ROUTINE
GBROV  = G*BETA*ROU**2/VISC**2
HC1-2-3  COOLANT HEAT TRANSFER COEFFICIENT (FROM $MAIN)
HI  INSIDE HEAT TRANSFER COEFFICIENT (FROM $MAIN)
HO()  OUTSIDE HEAT TRANSFER COEFFICIENT FOR EACH NODE
HOAVE  AVERAGE OUTSIDE HEAT TRANSFER COEFFICIENT
HO1  KNOWN OUTSIDE HEAT TRANSFER COEFFICIENT (FROM $MAIN)
ICH(),)  HOLDS TYPE OF POINT
IDASH  ARRAY WITH DATA FOR CONTOURING ROUTINE
IEE  ERROR COUNTER AT END OF CONDUCTIVITY ITERATION
IERR  ERROR COUNTER WITHIN CONDUCTIVITY ITERATION
IFILE  FLAG TO MAKE CONTOURING FILE
IFLAG()  ARRAY WITH DATA FOR CONTOURING ROUTINE
IHOUT  TYPE OF HEAT TRANSFER AT OUTER BOUNDARY (FROM $MAIN)
ITER  COUNTER WITHIN SINGLE CONDUCTIVITY ITERATION
ITER1  COUNTER: NUMBER OF CONDUCTIVITY ITERATIONS
ITER2  COUNTER FOR TOTAL NUMBER OF ITERATIONS
C LOOP VARS: 1,11,12,13,11,1,J1,12,13,1,JJ,K,M
C MTCH  CHANNEL (TOP AND BOTTOM) MATERIAL (FROM $MAIN)
C MTclo  CLOSE-OUT MATERIAL (FROM $MAIN)
C MTCOAT  COATING MATERIAL (FROM $MAIN)
C NCc  NUMBER OF COOLING CHANNELS
C NPHIC-L-TOT  NUMBER OF CIRCUMFERENTIAL NODES (FROM $MAIN)
C NCON  NUMBER OF CONTOURING LEVELS IN FC()
C NR  NUMBER OF RADIAL NODES (NRclo + NRCHT + NRchB + NRcoat)
C NRchb-cht-clo-coat  NUMBER RADIAL NODES (FROM $MAIN)
C NR1  NUMBER OF RADIAL NODES (NRclo)
C NR2  NUMBER OF RADIAL NODES (NRclo + NRCHT)
C NR3  NUMBER OF RADIAL NODES (NRclo + NRCHT + NRchB)
C OMEGASOR  SOR COEFFICIENT
C PR  PRANDTL NUMBER
C Q  SUM OF ALL THE HEAT FLOWS
C QC  TOTAL HEAT FLOW TO SINGLE COOLANT CHANNEL
C QC1  HEAT FLOW TO INNER CHANNEL WALL
C QC2  HEAT FLOW TO SIDE CHANNEL WALL
C QC3  HEAT FLOW TO UPPER CHANNEL WALL
C QI  HEAT FLOW THROUGH HOT GAS WALL
C QO  HEAT FLOW TO OUTSIDE
C RAdP( , )  HOLDS RADIUS OF NODES (INCHES)
C RCI-CO-1-0  WALL RADII (FROM $MAIN)
C RKair  CONDUCTIVITY OF AIR
C RK1-2-3-4-5  DUMMY CONDUCTIVITIES (ALSO WITH CH, CLO AND COAT)
C R1-2-3-4-5  DUMMY THERMAL RESISTANCES
C SIGMA  STEFAN-BOLTZMANN CONSTANT
C T( , ,1)  TEMPERATURE DISTRIBUTION USED FOR CONDUCTIVITIES
C T( , ,2)  CONVERGING TEMPERATURE DISTRIBUTION AT SINGLE COND
C TC  COOLANT TEMPERATURE (FROM $MAIN)
C TCOAT  COATING THICKNESS (FROM $MAIN)
C T1  HOT GAS TEMPERATURE (FROM $MAIN)
C TO  OUTSIDE TEMPERATURE (FROM $MAIN)
C TR1-2-3-4-5  "DUMMY"TEMPERATURES TO DETERMINE CONDUCTIVITIES
C TT2  CONVERGENCE CHECK AT END OF CONDUCTIVITY
C
C DIMENSION T(40,40,2),ICH(40,40),RADP(40,40),HO(40),IFLAG(7)
C DIMENSION DOT(8),FC(20),IDASH(10)
C IF NCON .LE. 0 THEN ALL PRINTED OUTPUT IS SUPPRESSED
C NCON =-15
C FC(1) =1300.
C FC(2) =1250.
C FC(3) =1200.
C FC(4) =1150.
C FC(5) =1100.
C FC(6) =1050.
C FC(7) =1000.
C FC(8) =950.
C FC(9) =900.
C FC(10) =850.
C FC(11) =800.
C FC(12) =750.
C FC(13) =700.
FC(14) = 660.
FC(15) = 650.
IFLAG(1) = NRCLO + NRCHT + NRCHB + NRCOAT
IFLAG(2) = NPHITOT
IFLAG(3) = NCON
IFLAG(4) = 1
IFLAG(5) = 1
IFLAG(6) = 0
IFLAG(7) = 0
DOT(1) = 0.
DOT(2) = 0.
DOT(3) = 0.
DOT(4) = 0.
DOT(5) = 0.
DOT(6) = 0.
DOT(7) = 0.
DOT(8) = 0.
IDASH(1) = 1
OMEGA = 1.9
SIGMA = 0.173 * 10**(-8) / 3600.
RKAIR = 0.014 / 3600.
GBROV = 3.160 * 10**6
PR = 0.72
ERROR = 10**(-7)
DRCLO = (RO-RCO)/(NRCLO-1.)
IF (COOL .EQ. 1) GOTO 516
DRCHT = 0.
DRCHB = 0.
GOTO 517
516 DRCHT = (RCO-RCI)/NRCHT
DRCHB = (RCI-RI)/NRCHB
517 IF (NRCOAT .EQ. 0) GO TO 512
DRCOAT = TCOAT/NRCOAT
512 NR1 = NRCLO
NR2 = NRCLO + NRCHT
NR3 = NRCLO + NRCHT + NRCHB
NR = NRCLO + NRCHT + NRCHB + NRCOAT
IF (COOL .EQ. 2) GOTO 6
WRITE(6,2) DRCLO, DRCHT, DRCHB, DRCOAT, DPHIC, DPHIL, NR, NR1, NR2, NR3
GOTO 7
6 WRITE (6,9) DRCLO, DRCOAT, NPHIL, NR1, NR
7 CONTINUE
2 FORMAT (/10X, 'DRCLO = ',F8.6, /10X, 'DRCHT = ',F8.6, /10X, 'DRCHB = ',
F8.6, /10X, 'DRCOAT = ',F8.6, /10X, 'DPHIC = ',F8.6, /10X, 'DPHIL = ',
9 FORMAT (/10X, 'DRCLO = ',F8.6, /10X, 'DRCHT = ',F8.6, /10X, 'DRCHB = '
1'T = (T + T0 + TC)/3.
500 CONTINUE
501 CONTINUE
ITER1 = 0
ITER2 = 0
4 DO 503 I2 = 1, NPHITOT
   DO 504 J2 = 1, NR
   T(I2, J2, 1) = T(I2, J2, 2)
504 CONTINUE
503 CONTINUE
ITER = 0
ITER1 = ITER1 + 1
1 IERR = 0
ITER = ITER + 1
ITER2 = ITER2 + 1
DO 1000 I = 1, NPHITOT
   DO 1001 J = 1, NR
      WRITE(6, 507) I, J
      WRITE(6, 507) 10X, 2( I3, 2X)
507 CONTINUE
   IF (J.LT.NR1) GO TO 508
   IF (J.GT.NR1 AND J.LT.NR2) GO TO 509
   IF (J.GT.NR2 AND J.LT.NR3) GO TO 510
   IF (J.GT.NR3 AND TCOAT.NE.0.0) GO TO 511
   IF (J.EQ.NR3 AND TCOAT.EQ.0.0) GO TO 510
   GO TO 506
505 R = RI - (J-NR3) * DRCOAT
   DR = DRCOAT
   GO TO 511
508 R = RO - (J-1) * DRCL
   DR = DRCL
   GO TO 511
509 R = RCO - (J-NR1) * DRCHT
   DR = DRCHT
   GO TO 511
510 IF (COOL.EQ.2) GOTO 508
   R = RCI - (J-NR2) * DRCHB
   DR = DRCHB
511 C1L = DR/(R'*DPHIL)
   C2L = (R-DR/2.)*DPHIL/DR
   C3L = (R+DR/2.)*DPHIL/DR
   IF (COOL.EQ.2) GOTO 515
   C1C = DR/(R'*DPHIC)
   C2C = (R-DR/2.)*DPHIC/DR
   C3C = (R+DR/2.)*DPHIC/DR
515 IF (I.GT.NPHIL) GOTO 513
   C1 = C1L
   C2 = C2L
   C3 = C3L
   DPHI = DPHIL
   GOTO 506
513 C1 = C1C
   C2 = C2C
   C3 = C3C
   DPHI = DPHIC
506 TT2 = T(I, J, 2)
IF (COOL .EQ. 2) GOTO 400
IF (I.EQ.NPHIL) GOTO 333
IF (I.EQ.1 .AND. J.EQ.1) GO TO 100
IF (I.EQ.NPHITOT .AND. J.EQ.1) GOTO 110
IF (J.EQ.1) GO TO 120
IF (I.EQ.1 .AND. J.EQ.NR) GO TO 130
IF (I.EQ.NPHITOT .AND. J.EQ.NR) GOTO 140
IF (J.EQ.NR) GOTO 150
IF (I.EQ.1 .AND. J.EQ.NR3) GO TO 135
IF (I.EQ.NPHITOT .AND. J.EQ.NR3) GOTO 145
IF (J.EQ.NR3) GOTO 155
IF (I.EQ.1) GO TO 160
IF (I.GT.NPHIL .AND. J.EQ.NR1) GO TO 180
IF (I.GT.NR1 .AND. J.LT.NR2) GO TO 190
GO TO 191

190 IF (I.GT.NPHIL) GOTO 210
191 IF (I.GT.NPHIL .AND. J.EQ.NR2) GOTO 230
IF (J.EQ.NR1) GOTO 240
IF (J.EQ.NR2) GO TO 260
IF (I.EQ.NPHITOT) GOTO 250
GOTO 192
333 IF (J.EQ.1) GOTO 300
IF (J.EQ.NR1) GOTO 170
IF (J.EQ.NR2) GOTO 220
IF (J.EQ.NR3) GOTO 320
IF (J.EQ.NR3) GOTO 310
IF (J.GT.NR1 .AND. (J.LT.NR2)) GOTO 200

C

MIDDLE NODE: CIRCUMFERENTIAL INTERFACE

C

TR1 = T(I,J,1)
TR2 = T(I+1,J,1)
TR3 = T(I,J-1,1)
TR4 = T(I-1,J,1)
TR5 = T(I,J+1,1)
IF (J.GT.NR3) GOTO 334
IF (J.GT.NR1) GOTO 335
CALL METAL (MTCLO, RK1, TR1)
CALL METAL (MTCLO, RK2, TR2)
CALL METAL (MTCLO, RK3, TR3)
CALL METAL (MTCLO, RK4, TR4)
CALL METAL (MTCLO, RK5, TR5)
GOTO 336
334 CALL METAL(MTCOAT, RK1, TR1)
CALL METAL(MTCOAT, RK2, TR2)
CALL METAL(MTCOAT, RK3, TR3)
CALL METAL(MTCOAT, RK4, TR4)
CALL METAL(MTCOAT, RK5, TR5)
GOTO 336
335 CALL METAL (MTCH, RK1, TR1)
CALL METAL (MTCH, RK2, TR2)
CALL METAL (MTCH, RK3, TR3)
CALL METAL (MTCH, RK4, TR4)
CALL METAL (MTCH, RK5, TR5)
336 CONTINUE
R1 = (1./RK1 + 1./RK2)/(2.*C1)
R2 = (1./RK1 + 1./RK3)*DR/(2.*DPH1B*(R+DR/2.))
R3 = (1./RK1 + 1./RK4)/(2.*C1)
R4 = (1./RK1 + 1./RK5)*DR/(2.*DPH1B*(R-DR/2.))
T(I,J,2) = ((T(I+1,J,2)/R1 + T(I,J-1,2)/R2 + T(I-1,J,2)/R3 +
1T(I,J+1,2)/R4)/(1./R1 + 1./R2 + 1./R3 + 1./R4)-T(I,J,2))*OMEGA + 2T(I,J,2)
ICH(I,J) = 50
GO TO 1002

C RADIATION COOLED DECISION SECTION
C
400 IF ((I.EQ.1).AND.(J.EQ.1)) GO TO 100
IF ((I.EQ.NPHITOT).AND.(J.EQ.1)) GO TO 110
IF (J.EQ.1) GO TO 120
IF ((I.EQ.1).AND.(J.EQ.NR)) GO TO 130
IF ((I.EQ.NPHITOT).AND.(J.EQ.NR)) GO TO 140
IF (J.EQ.NR) GO TO 150
IF ((I.EQ.1).AND.(J.EQ.NR3)) GO TO 135
IF ((I.EQ.NPHITOT).AND.(J.EQ.NR3)) GO TO 145
IF (J.EQ.NR3) GO TO 155
IF (I.EQ.1) GO TO 160
IF (I.EQ.NPHITOT) GO TO 250

C MIDDLE NODE
C
192 TR1 = T(I,J,1)
TR2 = T(I+1,J,1)
TR3 = T(I,J-1,1)
TR4 = T(I-1,J,1)
TR5 = T(I,J+1,1)
IF (J.GT.NR1 .AND. J.LT.NR3) GO TO 101
IF (J.GT.NR3) GO TO 109
CALL METAL (MTCOAT, RK1,TR1)
CALL METAL (MTCOAT, RK2,TR2)
CALL METAL (MTCOAT, RK3,TR3)
CALL METAL (MTCOAT, RK4,TR4)
CALL METAL (MTCOAT, RK5,TR5)
GO TO 102
101 CALL METAL (MTCH, RK1,TR1)
CALL METAL (MTCH, RK2,TR2)
CALL METAL (MTCH, RK3,TR3)
CALL METAL (MTCH, RK4,TR4)
CALL METAL (MTCH, RK5,TR5)
GO TO 102
109 CALL METAL (MTCOAT, RK1,TR1)
CALL METAL (MTCOAT, RK2,TR2)
CALL METAL (MTCOAT, RK3,TR3)
CALL METAL (MTCOAT, RK4,TR4)
CALL METAL (MTCOAT, RK5,TR5)
GO TO 102
102 R1 = 1./2.*C1*(1./RK1 + 1./RK2)
R2 = 1 ./2./C3*( 1 ./RK1 + 1 ./RK3)
R3 = 1 ./2./C1*( 1 ./RK1 + 1 ./RK4)
R4 = 1 ./2./C2*( 1 ./RK1 + 1 ./RK5)
T(I,J,2) = ((T(I + 1,J,2)/R1 + T(I,J-1,2)/R2 + T(I-1,J,2)/R3 +
1T(I,J + 1,2)/R4)/(1 ./R1 + 1 ./R2 + 1 ./R3 + 1 ./R4)-T(I,J,2))*OMEGA +
2T(I,J,2)
ICH(I,J) = 0
GO TO 1002

C C C
UPPER LEFT SIDE CORNER BOUNDARY NODE

100 IF(IHOUT.EQ.1)HO(I) = HO1
   IF(IHOUT.EQ.2)HO(I) = 0.53*RKAIR/(2.*RO)* (GBROV*ABS(T(I,J,1)-TO)
   1*(2.*RO)**.3*PR)**.25
   IF(IHOUT.EQ.3)HO(I) = EM*SIGMA*(T(I,J,1)**3. + TO*T(I,J,1)**2. +
   1T(I,J,1)**TO**2. + TO**3.)
   TR1 = T(I,J,1)
   TR2 = T(I + 1,J,1)
   TR3 = T(I,J + 1,1)
   CALL METAL (MTCLO, RK1,TR1)
   CALL METAL (MTCLO, RK2,TR2)
   CALL METAL (MTCLO, RK3,TR3)
   R1 = 1 ./C1*( 1 ./RK1 + 1 ./RK2)
   R2 = 1 ./C2*( 1 ./RK1 + 1 ./RK3)
   IF(HO(I).EQ.0.)GO TO 103
   R3 = 2.*HO(I)/RO/DPHI
   GO TO 104
103 R3 = 10.*16
104 T(I,J,2) = ((T(I + 1,J,2)/R1 + T(I,J + 1,2)/R2 + TO/R3)/
1(1./R1 + 1./R2 + 1./R3)-T(I,J,2))*OMEGA + T(I,J,2)
ICH(I,J) = 100
GO TO 1002

C C C
UPPER RIGHT HAND SIDE CORNER BOUNDARY NODE

110 IF(IHOUT.EQ.1)HO(I) = HO1
   IF(IHOUT.EQ.2)HO(I) = 0.53*RKAIR/(2.*RO)* (GBROV*ABS(T(I,J,1)-TO)
   1*(2.*RO)**.3*PR)**.25
   IF(IHOUT.EQ.3)HO(I) = EM*SIGMA*(T(I,J,1)**3. + TO*T(I,J,1)**2. +
   1T(I,J,1)**TO**2. + TO**3.)
   TR1 = T(I,J,1)
   TR2 = T(I-1,J,1)
   TR3 = T(I,J + 1,1)
   CALL METAL (MTCLO, RK1,TR1)
   CALL METAL (MTCLO, RK2,TR2)
   CALL METAL (MTCLO, RK3,TR3)
   R1 = 1 ./C1*( 1 ./RK1 + 1 ./RK2)
   R2 = 1 ./C2*( 1 ./RK1 + 1 ./RK3)
   IF(HO(I).EQ.0.)GO TO 105
   R3 = 2.*HO(I)/RO/DPHI
   GO TO 106
105 R3 = 10.*16
106 T(I,J,2) = ((T(I-1,J,2)/R1 + T(I,J + 1,2)/R2 + TO/R3)/
1(1./R1 + 1./R2 + 1./R3)-T(I,J,2))*OMEGA + T(I,J,2)
ICH(I,J) = 110
GO TO 1002

C
UPPER BOUNDARY NODE
C
120 IF(IHOUT.EQ.1)HO(I) = HO1
   IF(IHOUT.EQ.2)HO(I) = 0.53*RKAIR/(2.*RO)*(GBROV*ABS(T(I,J,1)-TO)
      1.*(2.*RO)**3.*PR)**.025
   IF(IHOUT.EQ.3)HO(I) = EM*SIGMA*(T(I,J,1)**3.*TO**T(I,J,1)**2.*
      1*(2.*RO)**3.*PR)**.25
   TR1 = T(I,J,1)
   TR2 = T(I+1,J,1)
   TR3 = T(I,J+1,1)
   TR4 = T(I-1,J,1)
   CALL METAL (MTCLO, RK1,TR1)
   CALL METAL (MTCLO, RK2,TR2)
   CALL METAL (MTCLO, RK3,TR3)
   CALL METAL (MTCLO, RK4,TR4)
   R1 = 1./C1*(1./RK1 + 1./RK2)
   R2 = 1./C2*(1./RK1 + 1./RK3)
   R3 = 1./C1*(1./RK1 + 1./RK4)
   IF(HO(I).EQ.O.O)GO TO 107
   R4 = 1./HO(I)/RO/DPHI
   GO TO 108
107 R4 = 10.**16
108 T(I,J,2) = ((T(I+1,J,2)/R1 + T(I,J+1,2)/R2 + T(I-1,J,2)/R3 + TO/R4)
   1/(1./R1 + 1./R2 + 1./R3 + 1./R4)-T(I,J,2)*OMEGA + T(I,J,2)
ICH(I,J) = 120
GO TO 1002

C
UPPER BOUNDARY: CIRCUMFERENTIAL INTERFACE
C
300 IF(IHOUT.EQ.1)HO(I) = HO1
   IF(IHOUT.EQ.2)HO(I) = 0.53*RKAIR/(2.*RO)*(GBROV*ABS(T(I,J,1)-TO)
      1.*(2.*RO)**3.*PR)**.025
   IF(IHOUT.EQ.3)HO(I) = EM*SIGMA*(T(I,J,1)**3.*TO**T(I,J,1)**2.*
      1*(2.*RO)**3.*PR)**.25
   TR1 = T(I,J,1)
   TR2 = T(I+1,J,1)
   TR3 = T(I,J+1,1)
   TR4 = T(I-1,J,1)
   CALL METAL (MTCLO, RK1,TR1)
   CALL METAL (MTCLO, RK2,TR2)
   CALL METAL (MTCLO, RK3,TR3)
   CALL METAL (MTCLO, RK4,TR4)
   R1 = 1./C1*(1./RK1 + 1./RK2)/C1C
   R2 = 1./RK1 + 1./RK3)*DRCL0/2.*DPHIB*(RO-DRCL0/2.)
   R3 = 1./RK1 + 1./RK4/C1L
   IF(HO(I).EQ.O.O)GO TO 301
   R4 = 1./(HO(I)*RO*DPHIB)
   GO TO 302
301 R4 = 10.**16
302 T(I,J,2) = ((T(I+1,J,2)/R1 + T(I,J+1,2)/R2 + T(I-1,J,2)/R3 + TO/R4)
   1/(1./R1 + 1./R2 + 1./R3 + 1./R4)-T(I,J,2)*OMEGA + T(I,J,2)
ICH(I,J) = 300
GO TO 1002

LOWER LEFT SIDE BOUNDARY NODE

130 TR1 = T(I,J,1)
TR2 = T(I+1,J,1)
TR3 = T(I,J-1,1)
IF(TCOAT.EQ.0.0)GO TO 131
CALL METAL (MTCOAT, RK1,TR1)
CALL METAL (MTCOAT, RK2,TR2)
CALL METAL (MTCOAT, RK3,TR3)
GO TO 132
131 CALL METAL (MTCH, RK1,TR1)
CALL METAL (MTCH, RK2,TR2)
CALL METAL (MTCH, RK3,TR3)
R1 = 1./C1*(1./RK1 + 1./RK2)
R2 = 1./C3*(1./RK1 + 1./RK3)
R3 = 2./HI/R/DPHI
T(I,J,2) = (T(I+1,J,2)/R1 + T(I,J-1,2)/R2 + T(I,J)/R3)/
(1./R1 + 1./R2 + 1./R3) - T(I,J,2)*OMEGA + T(I,J,2)
ICH(I,J) = 130
GO TO 1002

INTERFACE BETWEEN COPPER AND COATING(LEFT BOUNDARY)

135 R = RI
TR1 = T(I,J,1)
TR2 = T(I+1,J,1)
TR3 = T(I,J+1,1)
TR5 = T(I,J-1,1)
CALL METAL (MTCH, RKCH1,TR1)
CALL METAL (MTCOA1, RKCH1,TR1)
CALL METAL (MTCH, RKCH2,TR2)
CALL METAL (MTCH, RKCH2,TR2)
CALL METAL (MTCH, RKCH3,TR3)
CALL METAL (MTCH, RKCH3,TR3)
R1 = R*DPHI/(DRCHB/(1./RKCH1 + 1./RKCH2) + DRCOA1/(1./RKCOA1 + 1./RKCOA2))
R2 = DRCOA1/(1./RKCH2 + 1./RKCH2) + DRCOA1/(1./RKCOA1 + 1./RKCOA3)
R4 = DRCHB/1./(R + DRCHB/2.) + DPHI*'(1./RKCH1 + 1./RKCH5)
T(I,J,2) = (1.*T(I+1,J,2)/R1 + T(I,J+1,2)/R2 + T(I,J-1,2)/R4)
(1./R1 + 1./R2 + 1./R4) - T(I,J,2)*OMEGA + T(I,J,2)
ICH(I,J) = 135
GO TO 1002

LOWER RIGHT SIDE BOUNDARY NODE

140 TR1 = T(I,J,1)
TR2 = T(I-1,J,1)
TR3 = T(I,J-1,1)
IF(TCOAT.EQ.0.0)GO TO 141
CALL METAL (MTCOAT, RK1,TR1)
CALL METAL (MTCOAT, RK2,TR2)
CALL METAL (MTCOAT, RK3,TR3)
GO TO 142
141 CALL METAL (MTCH, RK1,TR1)
     CALL METAL (MTCH, RK2,TR2)
     CALL METAL (MTCH, RK3,TR3)
142 R1 = 1./C1*(1./RK1 + 1./RK2)
     R2 = 1./C3*(1./RK1 + 1./RK3)
     R3 = 2./H1/R/DPHI
     T(I,J,2) = ((T(I-1,J,2)/R1 + T(I,J-1,2)/R2 + T(I,J,2))/R3)
     (1./R1 + 1./R2 + 1./R3)*OMEGA + T(I,J,2)
     ICH(I,J) = 140
     GO TO 1002
     GO TO 1002
     C
     INTERFACE BETWEEN COPPER AND COATING (RIGHT BOUNDARY)

145 R = RI
     TR1 = T(I,J,1)
     TR3 = T(I,J + 1,1)
     TR4 = T(I-1,J,1)
     TR5 = T(I-1,J-1,1)
     CALL METAL (MTCH, RK1, TR1)
     CALL METAL (MTCCOAT, RKCOAT1, TR1)
     CALL METAL (MTCCOAT, RKCOAT3, TR3)
     CALL METAL (MTCH, RK1, TR5)
     CALL METAL (MTCCOAT, RK1, TR4)
     CALL METAL (MTCCOAT, RKCOAT4, TR4)
     CALL METAL (MTCH, RKCH5, TR5)
     R2 = DRCCOAT1/(R-DRCOAT2)/DPHI*(1./RKCOAT1 + 1./RKCOAT3)
     R3 = R*DPHI/(R*DRCHB1/1./RKCH1 + 1./RKCH4) + DRCOAT/(1./RKCOAT1 + 1./RKCOAT4)
     R4 = DRCHB1/(R + DRCHB2)/DPHI*(1./RKCH1 + 1./RKCH5)
     T(I,J,2) = ((T(I-1,J,2)/R1 + T(I,J-1,2)/R3 + T(I,J,2))/R4)
     (1./R2 + 1./R3 + 1./R4)*OMEGA + T(I,J,2)
     ICH(I,J) = 145
     GO TO 1002

C
LOWER BOUNDARY NODES
C
150 TR1 = T(I,J,1)
     TR2 = T(I+1,J,1)
     TR3 = T(I,J-1,1)
     TR4 = T(I-1,J,1)
     IF(TCOAT.EQ.0.0)GO TO 151
     CALL METAL (MTCCOAT, RK1, TR1)
     CALL METAL (MTCCOAT, RK2, TR2)
     CALL METAL (MTCCOAT, RK3, TR3)
     CALL METAL (MTCCOAT, RK4, TR4)
     GO TO 152
151 CALL METAL (MTCH, RK1, TR1)
     CALL METAL (MTCH, RK2, TR2)
     CALL METAL (MTCH, RK3, TR3)
     CALL METAL (MTCH, RK4, TR4)
152 R1 = 1./C1*(1./RK1 + 1./RK2)
     R2 = 1./C3*(1./RK1 + 1./RK3)
     R3 = 1./C1*(1./RK1 + 1./RK4)
     R4 = 1./H1/R/DPHI
     T(I,J,2) = ((T(I+1,J,2)/R1 + T(I,J-1,2)/R2 + T(I-1,J,2)/R3 + T(I,J,2))/R4)
I(1./R1 + 1./R2 + 1./R3 + 1./R4)-T(I,J,2))*OMEGA + T(I,J,2)
ICH(I,J) = 150
GO TO 1002

LOWER BOUNDARY NODE: CIRCUMFERENTIAL INTERFACE

320 TR1 = T(I,J,1)
TR2 = T(I+1,J,1)
TR3 = T(I,J-1,1)
TR4 = T(I-1,J,1)
IF(TCOAT.EQ.0.0) GO TO 321
CALL METAL (MTCOAT, RK1,TR1)
CALL METAL (MTCOAT, RK2,TR2)
CALL METAL (MTCOAT, RK3,TR3)
CALL METAL (MTCOAT, RK4,TR4)
GO TO 322

321 CALL METAL (MTCH, RK1,TR1)
CALL METAL (MTCH, RK2,TR2)
CALL METAL (MTCH, RK3,TR3)
CALL METAL (MTCH, RK4,TR4)

322 R1 = (1./RK1 + 1./RK2)/CIC
R2 = (1./RK1 + 1./RK3)*DR/(2.*DPHIB*(R + DR/2.))
R3 = (1./RK1 + 1./RK4)/CIL
R4 = 1./(HI*R*DPHIB)
T(I,J,2) = (T(I+1,J,2)/R1 + T(I,J-1,2)/R2 + T(I-1,J,2)/R3 + T(I,J,2)/R4) /
1/(1./R1 + 1./R2 + 1./R3 + 1./R4)-T(I,J,2))*OMEGA + T(I,J,2)
ICH(I,J) = 320
GO TO 1002

INTERFACE BETWEEN COPPER AND COATING

155 R = R1
TR1 = T(I,J,1)
TR2 = T(I+1,J,1)
TR3 = T(I,J+1,1)
TR4 = T(I-1,J,1)
TR5 = T(I,J-1,1)
CALL METAL (MTCH, RKCH1,TR1)
CALL METAL (MTCOAT, RKCOA1,TR1)
CALL METAL (MTCH, RKCH2,TR2)
CALL METAL (MTCOAT, RKCOA2,TR2)
CALL METAL (MTCH, RKCOA3,TR3)
CALL METAL (MTCH, RKCH4,TR4)
CALL METAL (MTCOAT, RKCOA4,TR4)
CALL METAL (MTCH, RKCH5,TR5)

R1 = R*DPHI/(DRCHB/(1./RKCH1 + 1./RKCH2) + DRCOAT/(1./RKCOA1 + 1./RKCOA2))
R2 = DRCOAT/2/(R-DRCOAT/2.)/DPHIB*(1./RKCOA1 + 1./RKCOA3)
R3 = R*DPHI/(DRCHB/(1./RKCH1 + 1./RKCH4) + DRCOAT/(1./RKCOA1 + 1./RKCOA4))
R4 = DRCHB/2/(R+DRCHB/2.)/DPHI*(1./RKCH1 + 1./RKCH5)
T(I,J,2) = (T(I+1,J,2)/R1 + T(I,J+1,2)/R2 + T(I-1,J,2)/R3 + T(I,J-1,2) /
1/R4) / (1./R1 + 1./R2 + 1./R3 + 1./R4)-T(I,J,2))*OMEGA + T(I,J,2)
ICH(I,J) = 155
GO TO 1002

CHANNEL-COATING INTERFACE: CIRCUMFERENTIAL INTERFACE

310 R = RI
TR1 = T(I, J, 1)
TR2 = T(I + 1, J, 1)
TR3 = T(I, J + 1, 1)
TR4 = T(I - 1, J, 1)
TR5 = T(I, J - 1, 1)
CALL METAL (MTCH, RKCH1, TR1)
CALL METAL (MTCOAT, RKCOA1, TR1)
CALL METAL (MTCH, RKCH2, TR2)
CALL METAL (MTCOAT, RKCOA2, TR2)
CALL METAL (MTCOAT, RKCOA3, TR3)
CALL METAL (MTCH, RKCH4, TR4)
CALL METAL (MTCOAT, RKCOA4, TR4)
CALL METAL (MTCH, RKCH5, TR5)
R1 = R*DPHI/(DRCHB/(1./RKCH1 + 1./RKCH2) + DRCOAT/
1/(1./RKCOA1 + 1./RKCOA2))
R2 = DRCOAT/(2.*(R-DRCOAT/2.)*DPHI/(1./RKCOA1 + 1./RKCOA3)
R3 = R*DPHI/(DRCHB/(1./RKCH1 + 1./RKCH4) +
1/DRCOAT/(1./RKCOA1 + 1./RKCOA4))
R4 = DRCHB/(2.*(R + DRCHB/2.)*DPHI/(1./RKCH1 + 1./RKCH5)
T(I, J, 2) = (T(I + 1, J, 2)/R1 + T(I, J + 1, 2)/R2 + T(I - 1, J, 2)/R3 + T(I, J - 1, 2)
1/R4)/(1./R1 + 1./R2 + 1./R3 + 1./R4) - T(I, J, 2)*OMEGA + T(I, J, 2)
ICH(I, J) = 310
GO TO 1002

LEFT BOUNDARY NODES

160 IF(J.EQ.NR1) GO TO 245
IF(J.EQ.NR2) GO TO 265
TR1 = T(I, J, 1)
TR2 = T(I, J + 1, 1)
TR3 = T(I + 1, J, 1)
TR4 = T(I, J - 1, 1)
IF(J .GT. NR1.AND.J.LT.NR3) GO TO 161
IF(J .GT. NR3) GO TO 163
CALL METAL (MTCOAT, RK1, TR1)
CALL METAL (MTCOAT, RK2, TR2)
CALL METAL (MTCOAT, RK3, TR3)
CALL METAL (MTCOAT, RK4, TR4)
GO TO 162
161 CALL METAL (MTCH, RK1, TR1)
CALL METAL (MTCH, RK2, TR2)
CALL METAL (MTCH, RK3, TR3)
CALL METAL (MTCH, RK4, TR4)
GO TO 162
163 CALL METAL (MTCOAT, RK1, TR1)
CALL METAL (MTCOAT, RK2, TR2)
CALL METAL (MTCOAT, RK3, TR3)
CALL METAL (MTCOAT, RK4, TR4)
162 R1 = 1./C2*(1./RK1 + 1./RK2)
\[ R2 = \frac{1}{2}C_1^* (\frac{1}{R K1} + \frac{1}{R K3}) \]
\[ R3 = \frac{1}{2}C_3^* (\frac{1}{R K1} + \frac{1}{R K4}) \]
\[ T(I,J,2) = \frac{(T(I,J+1,2)/R1 + T(I+1,J,2)/R2 + T(I-1,J-2)/R3)}{(1/R1 + 1/R2 + 1/R3)} - T(I,J,2) + T(I,J,2) \]
\[ ICH(I,J) = 160 \]
\[ GO \ TO \ 1002 \]

**CHANNEL, UPPER LEFT SIDE CORNER NODE**

**ITERFACE BETWEEN COPPER AND NICKEL**: ALSO CIRCUM INTERFACE

170 
\[ R = RCO \]
\[ TR1 = T(I,J,1) \]
\[ TR2 = T(I+1,J,1) \]
\[ TR3 = T(I,J+1,1) \]
\[ TR4 = T(I-1,J,1) \]
\[ TR5 = T(I,J-1,1) \]
\[ CALL \ METAL \ (MTCH, \ RKCH1, TR1) \]
\[ CALL \ METAL \ (MTCLO, \ RKCLO1, TR1) \]
\[ CALL \ METAL \ (MTCLO, \ RKCLO2, TR2) \]
\[ CALL \ METAL \ (MTCH, \ RKCH3, TR3) \]
\[ CALL \ METAL \ (MTCH, \ RKCH4, TR4) \]
\[ CALL \ METAL \ (MTCLO, \ RKCLO4, TR4) \]
\[ CALL \ METAL \ (MTCLO, \ RKCLO5, TR5) \]
\[ R1 = R^* \frac{D\Phi_i}{DRCLO}(1/RKCLO1 + 1/RKCLO2) \]
\[ R2 = \frac{DRCHT}{(R-DRCHT/2)}^*D\Phi_i(1/RKCH1 + 1/RKCH3) \]
\[ R3 = R^* \frac{D\Phi_i}{DRCLO}(1/RKCLO1 + 1/RKCLO4) + DRCHT(1/RKCH1 + 1/RKCH4) \]
\[ R4 = \frac{DRCLO}{(2R + DRCLO/2)^*D\Phi_i(1/RKCLO1 + 1/RKCLO5)} \]
\[ R5 = \frac{2}{((R^* D\Phi_i \cdot HC3) + (DRCHT \cdot HC2))} \]
\[ T(I,J,2) = \frac{(T(I+1,J,2)/R1 + T(I,J+1,2)/R2 + T(I-1,J-2)/R3 + T(I,J-1,2)/R4)}{(1+TC/R5)(1/R1 + 1/R2 + 1/R3 + 1/R4 + 1/R5)} - T(I,J,2) + T(I,J,2) \]
\[ ICH(I,J) = 170 \]
\[ GO \ TO \ 1002 \]

**UPPER CHANNEL WALL**

180 
\[ R = RCO \]
\[ TR1 = T(I,J,1) \]
\[ TR3 = T(I,J-1,1) \]
\[ TR4 = T(I-1,J,1) \]
\[ CALL \ METAL \ (MTCLO, \ RK1, TR1) \]
\[ CALL \ METAL \ (MTCLO, \ RK3, TR3) \]
\[ CALL \ METAL \ (MTCLO, \ RK4, TR4) \]
\[ R2 = \frac{DRCLO}{(R + DRCLO/2)^*D\Phi_i(1/RK1 + 1/RK3)} \]
\[ R3 = R^* \frac{D\Phi_i}{DRCLO}(1/RK1 + 1/RK4) \]
\[ R4 = \frac{1}{HC3/R\cdot D\Phi_i} \]
\[ IF(1EQ.NPHITOT) \ GO \ TO \ 185 \]
\[ TR2 = T(I+1,J,1) \]
\[ CALL \ METAL \ (MTCLO, \ RK2, TR2) \]
\[ R1 = R^* \frac{D\Phi_i}{DRCLO}(1/RK1 + 1/RK2) \]
\[ T(I,J,2) = \frac{(T(I+1,J,2)/R1 + T(I,J-1,2)/R2 + T(I-1,J,2)/R3 + TC/R4)}{(1/R1 + 1/R2 + 1/R3 + 1/R4)} - T(I,J,2) + T(I,J,2) \]
\[ ICH(I,J) = 180 \]
\[ GO \ TO \ 1002 \]

**CENTERLINE OF TOP OF CHANNEL**

35
185 \( R2 = 2 \cdot R2 \)
\( R4 = 2 \cdot R4 \)
\[
T(I,J,2) = \frac{((T(I,J-1,2)/R2 + 1 \cdot T(I-1,J,2)/R3 + TC/R4)/\left(1/R2 + 1/R3 + 1/R4\right) - T(I,J,2)) \cdot OMEGA + T(I,J,2)}{185} = ICH(I,J)
\]
GO TO 1002

CHANNEL SIDE WALL: ALSO A CIRCUMFERENTIAL INTERFACE

200 TR1 = T(I,J,1)
TR2 = T(I,J-1,1)
TR3 = T(I-1,J,1)
TR4 = T(I,J+1,1)
CALL METAL (MTCH, RK1,TR1)
CALL METAL (MTCH, RK2,TR2)
CALL METAL (MTCH, RK3,TR3)
CALL METAL (MTCH, RK4,TR4)
R1 = 1/C3L*(1/RK1 + 1/RK2)
R2 = 1/C1L*(1/RK1 + 1/RK3)
R3 = 1/C2L*(1/RK1 + 1/RK4)
R4 = 1/DR/HC2
\[
T(I,J,2) = \frac{((T(I,J-1,2)/R1 + T(I-1,J,2)/R2 + T(I,J+1,2)/R3 + TC/R4)/\left(1/R1 + 1/R2 + 1/R3 + 1/R4\right) - T(I,J,2)) \cdot OMEGA + T(I,J,2)}{200}
\]
ICH(I,J) = 200
GO TO 1002

WITHIN CHANNEL

210 T(I,J,2) = TC
ICH(I,J) = 210
GO TO 1002

CHANNEL, LOWER LEFT SIDE CORNER NODE:
ALSO CIRCUMFERENTIAL INTERFACE

220 R = RCI
TR1 = T(I,J,1)
TR2 = T(I+1,J,1)
TR3 = T(I,J+1,1)
TR4 = T(I-1,J,1)
TR5 = T(I,J-1,1)
CALL METAL (MTCH, RK1,TR1)
CALL METAL (MTCH, RK2,TR2)
CALL METAL (MTCH, RK3,TR3)
CALL METAL (MTCH, RK4,TR4)
CALL METAL (MTCH, RK5,TR5)
R1 = R*DPHIC/DRCHB*(1/RK1 + 1/RK2)
R2 = DRCHB/(2*(R-DRCHB/2)*DPHIB)*(1/RK1 + 1/RK3)
R3 = R*DPHIL/(DRCHT + DRCHB)*(1/RK1 + 1/RK4)
R4 = DRCHT/(R + DRCHT/2)*DPHIL*(1/RK1 + 1/RK5)
R5 = 2/(R*DPHIC+HC1) + (DRCHT+HC2)
\[
T(I,J,2) = \frac{((T(I,J+1,2)/R1 + T(I,J+1,2)/R2 + T(I+1,J,2)/R3 + T(I,J-1,2)/R4 + TC/R5)/(1/R1 + 1/R2 + 1/R3 + 1/R4 + 1/R5) - T(I,J,2)) \cdot OMEGA + T(I,J,2)}{220}
\]
ICH(I,J) = 220
GO TO 1002
C LOWER CHANNEL WALL
C
230 R = RCI
   TR1 = T(I,J,2)
   TR3 = T(I,J + 1,2)
   TR4 = T(I-1,J,2)
   CALL METAL (MTCH, RK1, TR1)
   CALL METAL (MTCH, RK3, TR3)
   CALL METAL (MTCH, RK4, TR4)
   R2 = DRCHB/(R-DRCHB/2.)/DPHI*(1./RK1 + 1./RK3)
   R3 = R"DPHI/DRCHB"*(1./RK1 + 1./RK4)
   R4 = 1./HC1/R/DPHI
   IF(I.EQ.NPHITOT)GO TO 235
   TR2 = T(I + 1,J,2)
   CALL METAL (MTCH, RK2, TR2)
   R1 = R"DPHI/DRCHB"*(1./RK1 + 1./RK2)
   T(I,J,2) = ((T(I + 1,J,2)/R1 + T(I,J + 1,2)/R2 + T(I-1,J,2)/R3 + TC/R4)/
   3(1./R1 + 1./R2 + 1./R3 + 1./R4)-T(I,J,2))"OMEGA + T(I,J,2)
   ICH(I,J) = 230
   GO TO 1002
C BOTTOM CENTERLINE OF CHANNEL
235 R2 = 2."R2
   R4 = 2."R4
   T(I,J,2) = ((T(I + 1,J,2)/R2 + T(I,J + 1,2)/R3 + TC/R4)/
   3(1./R2 + 1./R3 + 1./R4)-T(I,J,2))"OMEGA + T(I,J,2)
   ICH(I,J) = 235
   GO TO 1002
C C RIGHT BOUNDARY NODES
C
250 TR1 = T(I,J,1)
   TR2 = T(I,J + 1,1)
   TR3 = T(I-1,J,1)
   TR4 = T(I,J-1,1)
   IF(J.GT.NR1.AND.J.LT.NR3)GO TO 251
   IF(J.GT.NR3)GO TO 253
   CALL METAL (MTCLO, RK1, TR1)
   CALL METAL (MTCLO, RK2, TR2)
   CALL METAL (MTCLO, RK3, TR3)
   CALL METAL (MTCLO, RK4, TR4)
   GO TO 252
251 CALL METAL (MTCH, RK1, TR1)
   CALL METAL (MTCH, RK2, TR2)
   CALL METAL (MTCH, RK3, TR3)
   CALL METAL (MTCH, RK4, TR4)
   GO TO 252
253 CALL METAL (MTCOAT, RK1, TR1)
   CALL METAL (MTCOAT, RK2, TR2)
   CALL METAL (MTCOAT, RK3, TR3)
   CALL METAL (MTCOAT, RK4, TR4)
   GO TO 252
252 R1 = 1./C2*(1./RK1 + 1./RK2)
   R2 = 1./C1*(1./RK1 + 1./RK3)
   R3 = 1./C3*(1./RK1 + 1./RK4)
   T(I,J,2) = ((T(I,J + 1,2)/R1 + T(I,J,2)/R2 + T(I,J-1,2)/R3+TC/R4)/
\[
1 \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) - T(I,J,2) \cdot \omega + T(I,J,2)
\]

ICH(I,J) = 250
GO TO 1002

INTERFACE BETWEEN COPPER AND NICKEL

240 R = RCO
TR1 = T(I,J,1)
TR2 = T(I+1,J,1)
TR3 = T(I+1,J,1)
TR4 = T(I-1,J,1)
TR5 = T(I,J-1,1)
call metal (MTCH, RKCH1, TR1)
call metal (MTCL, RKCO1, TR1)
call metal (MTCH, RKCH2, TR2)
call metal (MTCL, RKCO2, TR2)
call metal (MTCH, RKCH3, TR3)
call metal (MTCL, RKCO3, TR3)
call metal (MTCL, RKCO, TR4)
call metal (MTCL, RKCO4, TR4)
call metal (MTCL, RKCO5, TR5)
R1 = R'DPHI/(RDKL/1./RKCO1 + 1./RKCO2 + DRCHT/(1./RKCH1 + 1./RKCH2))
R2 = DRCHT/(R - DRCHT/2.)/DPHI*(1./RKCH1 + 1./RKCH3)
R3 = R'DPHI/(RDKL/1./RKCO1 + 1./RKCO4 + DRCHT/(1./RKCH1 + 1./RKCH4))
R4 = RDKL/2./(R + RDKL/2.)/DPHI*(1./RKCL01 + 1./RKCL05)
T(I,J,2) = \left( \frac{T(I+1,J,2)}{R1} + \frac{T(I,J+1,2)}{R2} + \frac{T(I,J-1,2)}{R4} \right) \cdot \omega + T(I,J,2)
ICH(I,J) = 240
GO TO 1002

LEFT SIDE NODE (INTERFACE BETWEEN COPPER AND NIKEL)

245 R = RCO
TR1 = T(I,J,1)
TR2 = T(I+1,J,1)
TR3 = T(I+1,J,1)
TR5 = T(I,J-1,1)
call metal (MTCH, RKCH1, TR1)
call metal (MTCL, RKCO1, TR1)
call metal (MTCH, RKCH2, TR2)
call metal (MTCL, RKCO2, TR2)
call metal (MTCH, RKCH3, TR3)
call metal (MTCL, RKCO3, TR3)
call metal (MTCL, RKCO, TR4)
call metal (MTCL, RKCL01, TR4)
call metal (MTCL, RKCO5, TR5)
R1 = R'DPHI/(RDKL/1./RKCO1 + 1./RKCO2 + DRCHT/(1./RKCH1 + 1./RKCH2))
R2 = DRCHT/(R - DRCHT/2.)/DPHI*(1./RKCH1 + 1./RKCH3)
R4 = RDKL/2./(R + RDKL/2.)/DPHI*(1./RKCL01 + 1./RKCL05)
T(I,J,2) = \left( \frac{T(I+1,J,2)}{R1} + \frac{T(I,J+1,2)}{R2} + \frac{T(I,J-1,2)}{R4} \right) \cdot \omega + T(I,J,2)
ICH(I,J) = 245
GO TO 1002

INTERFACE BETWEEN TWO LAYERS WITH DIFFERENT RADIAL INCREMENTS (CHANNEL REGION)

260 R = RCI
\[ TR1 = T(I, J, 1) \]
\[ TR2 = T(I + 1, J, 1) \]
\[ TR3 = T(I, J + 1, 1) \]
\[ TR4 = T(I - 1, J, 1) \]
\[ TR5 = T(I, J - 1, 1) \]

\[ \text{CALL METAL (MTCH, RKCH1, TR1)} \]
\[ \text{CALL METAL (MTCH, RKCH2, TR2)} \]
\[ \text{CALL METAL (MTCH, RKCH3, TR3)} \]
\[ \text{CALL METAL (MTCH, RKCH4, TR4)} \]
\[ \text{CALL METAL (MTCH, RKCH5, TR5)} \]

\[ R1 = R^{\Delta \phi} / (\Delta \rho T + \Delta \rho B) * (1 /RKCH1 + 1 /RKCH2) \]
\[ R2 = \Delta \rho T / 2 \cdot (\Delta \rho \rho T / 2) / \Delta \phi * (1 /RKCH1 + 1 /RKCH2) \]
\[ R3 = \Delta \rho B / 2 \cdot (\Delta \rho \rho B / 2) / \Delta \phi * (1 /RKCH1 + 1 /RKCH2) \]
\[ T(I, J, 2) = \left( T(I + 1, J, 2) / R1 + T(I, J + 1, 2) / R2 + T(I, J - 1, 2) / R3 + T(I, J, 1, 2) / R4 \right) / (1/R1 + 1/R2 + 1/R3 + 1/R4) - T(I, J, 2) \]
\[ \text{ICH(I, J) = 260} \]

GO TO 1002

C LEFT BOUNDARY: CHANNEL Top/BOTTOM INTERFACE

C (DIFFERENT RADIAL INCREMENTS)

265 \[ R = RCI \]
\[ TR1 = T(I, J, 1) \]
\[ TR2 = T(I + 1, J, 1) \]
\[ TR3 = T(I, J + 1, 1) \]
\[ TR5 = T(I, J - 1, 1) \]

\[ \text{CALL METAL (MTCH, RKCH1, TR1)} \]
\[ \text{CALL METAL (MTCH, RKCH2, TR2)} \]
\[ \text{CALL METAL (MTCH, RKCH3, TR3)} \]
\[ \text{CALL METAL (MTCH, RKCH5, TR5)} \]

\[ R1 = R^{\Delta \phi} / (\Delta \rho T + \Delta \rho B) * (1 /RKCH1 + 1 /RKCH2) \]
\[ R2 = \Delta \rho T / 2 \cdot (\Delta \rho \rho T / 2) / \Delta \phi * (1 /RKCH1 + 1 /RKCH2) \]
\[ R3 = \Delta \rho B / 2 \cdot (\Delta \rho \rho B / 2) / \Delta \phi * (1 /RKCH1 + 1 /RKCH2) \]
\[ T(I, J, 2) = \left( T(I + 1, J, 2) / R1 + T(I, J + 1, 2) / R2 + T(I, J - 1, 2) / R3 + T(I, J - 1, 2) / R4 \right) / (1/R1 + 1/R2 + 1/R3 + 1/R4) - T(I, J, 2) \]
\[ \text{ICH(I, J) = 265} \]

C 1002 \[ \text{RADP(I, J) = 12.*R} \]
\[ \text{IF(T(I, J, 2) EQ 0.) GO TO 1003} \]
\[ \text{ERR = ABS(TT2 - T(I, J, 2))} \]
\[ \text{GO TO 1005} \]

1003 \[ \text{ERR = ABS(T(I, J, 2) - TT2)} \]

1005 \[ \text{IF(ERRI GT ERROR) IERR = IERR + 1} \]

1001 \text{CONTINUE} 

1000 \text{CONTINUE} 

C END OF CELL LOOP

C \text{WRITE(6,1006)(ITER, IERR)} 

1006 \text{FORMAT(10X,'ITERATION NUMBER = ',16,3X,'IERR = ',16)} 

C DO 1007 KM = 1, NR 
C WRITE(6,2006)(T(MM,KM,2),MM = 1,NPHITOT) 
C IF(ITER.EQ.1)WRITE(6,2003)(ICH(MM,KM),MM = 1,NPHITOT) 
C 1007 \text{CONTINUE} 

2006 \text{FORMAT(5X,11(F8.2,2X))}
IF (IERR GT 0) GO TO 1
C WRITE(6,2004) ITER, ITER1
2004 FORMAT (/10X,'TEMPERATURE DISTRIBUTION',5X,
 1 'NUMBER OF ITERATIONS(ITER) = ',15/5X,
 2 'CONDUCTIVITY ITERATIONS(ITER1) = ',15/5X,'RADIUS')
C PRINT STATEMENTS TO CHECK PROCESS OF CONVERGENCE
C DO 2000 K = 1,NR
C WRITE(6,2001) RADP(1,K), (T(M,K,1), M = 1,NPHITOT)
C 2000 CONTINUE
C DO 2111 K = 1,NR
C WRITE(6,2001) RADP(1,K),(T(M,K,2), M = 1,NPHITOT)
C 2111 CONTINUE
IEE = 0
C TO CHECK FOR CONVERGENCE BETWEEN DIFFERENT CONDUCTIVITIES
DO 4100 I3 = 1,NPHITOT
DO 4101 J3 = 1,NR
IEE = ABS((T(I3,J3,2)-T(I3,J3,1))T(I3,J3,2))
IF (IEE GT ERROR) IEE = IEE + 1
4101 CONTINUE
4100 CONTINUE
C IF (ITER1 GT 50) GO TO 5
IF (IEE GT 0) GO TO 4
2001 FORMAT (5X,F7.4,2X,11 (F8.2,1X))
5 WRITE(6,3)
IF (COOL .EQ. 2) GOTO 4700
WRITE(6,2005)
5 WRITE(6,2005)
WRITE (6,2007) (DPHIC'N PHIC + DPHIL'NPHIL-DPHIL'II,II = 1,NPHIC)
GOTO 4600
4700 WRITE (6,2008)
4600 CONTINUE
C PRINTING THE RESULTS
DO 2002 II = 1,NR
WRITE(6,2003) (ICH(JJ,II), JJ = 1,NPHITOT)
C WRITE(6,2003) (ICH(JJ,II), JJ = 1,NPHITOT)
2002 CONTINUE
C DO 2222 II = 1,NR
C WRITE(6,2001) RADP(1,II),(T(JJ,II,2), JJ = 1,NPHITOT)
C 2222 CONTINUE
C DO 2010 MM = 1,NR
C WRITE(6,2011)(RADP(NN,MM),NN = 1,NPHITOT)
C 2010 CONTINUE
C 3 FORMAT(///)
2003 FORMAT (10X,11(I3,2X))
2005 FORMAT (1H1///30X,'TEMPERATURE DISTRIBUTION'//24X,
 1 'RADIANS FROM CENTERLINE OF CHANNEL')
2007 FORMAT (14X,11(F8.5,1X)/5X,'RADIUS')
2008 FORMAT (1H1///30X,'TEMPERATURE DISTRIBUTION'//)
2011 FORMAT (/5X,11(F8.5,2X))
C
C WRITING TEMPERATURES TO A FILE FOR CONTOURING PACKAGE
C
IF (IFILE .EQ. 0) GOTO 5555
WRITE (9,5100) NPHITOT,NR,NCON
5100 FORMAT (3X,3(I3,2X))
WRITE (9,5200) (IFLAG(I),I = 1,7)
5200 FORMAT (3X,7(I3,2X))
WRITE (9,5300) (DOT(I),I = 1,8)
5300 FORMAT (3X,8(F7.3,2X))
WRITE (9,5400) IDASH(1)
5400 FORMAT (3X,12)
DO 5500 I = 1,NCON
IF (NCON .LE. 0)NCON = -1*NCON
WRITE (9,5600) FC(I)
CONTINUE
DO 5700 J = 1,NPHITOT
DO 5800 JJ = 1,NR
NI = J
NJ = JJ
5010 CONTINUE
IF (NI.GT.NPHIL) GOTO 5040
PSI = (NI-1)*DPHIL
5040 CONTINUE
IF (NI.LT.NPHIL+1) GOTO 5050
PSI = (NPHIL-1)*DPHIL + DPHIC*(NI-NPHIL)
5050 CONTINUE
C SIDE WALL AND INTERIOR OF CHANNEL
NI = NPHIL
C
5010 CONTINUE
C
5010 CONTINUE
C
5010 CONTINUE
C
ZI = RADP(NI,NJ)*SIN(PSI)
ZJ = RADP(NI,NJ)*COS(PSI)
C
WRITE (9,5900) ZI,ZJ,T(NI,NJ,1)
C
5900 FORMAT (3X,2(F7.4,2X),F8.2)
C CALCULATE HEAT TRANSFER RATES
C THESE ARE BULK RATES FOR EACH CHANNEL USING FEET
QO = 0.
QC = 0.
QC1 = 0.
QC2 = 0.
QC3 = 0.
QI = 0.
HOAVE = 0.

DO 3000 I = 1, NPHITOT
HOAVE = HOAVE + HO(I)
DO 3001 J = 1, NR
IF (I.LT.NPHIL) DPHI = DPHIL
IF (I.GT.NPHIL) DPHI = DPHIC
IF(I(I,J).EQ.320) GO TO 3700
IF(I(I,J).EQ.300) GO TO 3750
IF(I(I,J).EQ.230) GO TO 3100
IF(I(I,J).EQ.180) GO TO 3150
IF(I(I,J).EQ.235) GO TO 3200
IF(I(I,J).EQ.185) GO TO 3250
IF(I(I,J).EQ.200) GO TO 3300
IF(I(I,J).EQ.220) GO TO 3400
IF(I(I,J).EQ.170) GO TO 3450
IF(I(I,J).EQ.120) GO TO 3500
IF(I(I,J).EQ.100.OR.I(I,J).EQ.110) GO TO 3550
IF(I(I,J).EQ.150) GO TO 3600
IF(I(I,J).EQ.130.OR.I(I,J).EQ.140) GO TO 3650
GO TO 3001

3100 QC1 = QC1 + 2.*RCl*DPHI*HC1*(T(I,J,2)-TC)*1.
3150 QC3 = QC3 + 2.*RCO*DPHI*HC3*(T(I,J,2)-TC)*1.
3200 QC1 = QC1 + RCl*DPHIC*HC1*(T(I,J,2)-TC)*1.
3250 QC3 = QC3 + RCO*DPHIC*HC3*(T(I,J,2)-TC)*1.
3300 QC2 = QC2 + 2.*DRCHT*HC2*(T(I,J,2)-TC)*1.
3400 QC1 = QC1 + (RCl*DPHIC*HC1)*(T(I,J,2)-TC)*1.
3450 QC3 = QC3 + (RCO*DPHIC*HC3)*(T(I,J,2)-TC)*1.
3500 QO = QO + 2.*RO*DPHI*HO(I)*(T(I,J,2)-TC)*1.
3550 QO = QO + RO*DPHI*HO(I)*(T(I,J,2)-TC)*1.
3600 QI = QI + 2.*(RI-TCOAT)*DPHI*HI*(T(I,J,2)-TI)*1.
GO TO 3001
3650 QI = QI + (RI-TCOAT)*DPHI*HI*(T(I,J,2)-TI)*1.
GO TO 3001
3700 QI = QI + 2.*RI-TCOAT)*DPHI*HI*(T(I,J,2)-TI)*1.
GO TO 3001
3750 QQ = QQ + 2.*RO*DPHI*HO(I)*(T(I,J,2)-TO)*1.
3001 CONTINUE
3000 CONTINUE
QI = QC1 + QC2 + QC3
Q = QC + QQ + QI
HOAVE = HOAVE/NPHITOT
WRITE(6,3002)QC,QC1,QC2,QC3,QQ,QI,Q
3002 FORMAT(IHI/IOX,'HEAT RATE PER CHANNEL IN BTU/S PER FT LENGTH'
1/10X,'COOLING CHANNEL = ',F13.2/10X,'INNER WALL = ',F13.2,2X,
2'SIDE WALL = ',F13.2,2X,'OUTER WALL = ',F13.2/10X,
3'HEAT TRANSFER TO OUTSIDE = ',F13.2
4/10X,'HEAT TRANSFER FROM HOT GAS WALL = ',F13.2
5/10X,'SUM OF ALL BULK HEAT TRANSFERS = ',F13.2)
WRITE(6,3)
CALCULATING THE AVERAGE FLUXES FOR DIFFERENT WALL SECTIONS
THESE ARE IN BTU/IN -2-S,
QI = QI*NCC/(2.*3.1415*(RI-TCOAT))/144.
QO = QO*NCC/(2.*3.1415*RO)/144.
IF (COOL .EQ. 2) GOT0 3010
QC1 = QC1/(2.*DPHI*NPHIC*RCI)/144.
QC2 = QC2/(2.*(RCO-RCI))/144.
QC3 = QC3/(2.*DPHI*NPHIC*RCO)/144.
QC = QC/(2.*DPHI*NPHIC*(RCI+RCO)+(RCO-RCI))/144.
3010 CONTINUE
WRITE(6,3005)QI,QC,QC1,QC2,QC3,QQ
3005 FORMAT(IHI/10X,'HEAT FLUXES AT THIS STATION IN BTU/IN -2-S'
1/10X,'GAS WALL = ',F13.2/10X,'AVERAGE COOLANT CHANNEL = ',F13.2
2/10X,'INNER WALL = ',F13.2,2X,'SIDE WALL = ',F13.2,2X,
3'OUTER WALL = ',F13.2/10X,'CLOSE-OUT = ',F13.2)
C
WRITE(6,3)
WRITE(6,4500)HOAVE,ITER1,ITER2
4500 FORMAT(IHI/10X,'OUTSIDE HEAT TRANSFER COEFFICIENT (BTU/FT -2-S) = '
1F10.5/10X,'CONDUCTIVITY ITERATIONS(ITER1) = ',15/10X,
2'TOTAL NUMBER OF ITERATIONS = ',15)
RETURN
END
C
SUBROUTINE COPPER(RKC,TC)
SUBROUTINE FOR EVALUATION OF COPPER THERMAL CONDUCTIVITY
C
NINT NUMBER OF INTERVALS
RK CONDUCTIVITY
T TEMPERATURE
DIMENSION RK(10),T(10)
NINT = 2
C
43
T(1) = 400.
RK(2) = 52. *10. **(-4)*12.
T(2) = 500.
RK(3) = 46.6 *10. **(-4)*12.
T(3) = 1650.
CALL INTER(RK,T,NINT,TC,RKC)
RETURN
END
C
SUBROUTINE NICKEL(RKC,TC)
C
SUBROUTINE FOR EVALUATION OF NICKEL THERMAL CONDUCTIVITY
C
C NINT NUMBER OF INTERVALS
C RK CONDUCTIVITY
C T TEMPERATURE
C
DIMENSION RK(10),T(10)
NINT = 5
T(1) = 130.
RK(2) = 15. *10. **(-4)*12.
T(2) = 300.
RK(3) = 9.5 *10. **(-4)*12.
T(3) = 500.
RK(4) = 7.2 *10. **(-4)*12.
T(4) = 800.
RK(5) = 6.2 *10. **(-4)*12.
T(5) = 1200.
RK(6) = 7.2 *10. **(-4)*12.
T(6) = 1800.
CALL INTER(RK,T,NINT,TC,RKC)
RETURN
END
C
SUBROUTINE SOOT(RKC,TC)
C
SUBROUTINE FOR EVALUATION OF SOOT CONDUCTIVITY
C
C NINT NUMBER OF INTERVALS
C RK CONDUCTIVITY
C T TEMPERATURE
C
DIMENSION RK(20),T(20)
NINT = 1
T(1) = 100.
T(2) = 2000.
CALL INTER(RK,T,NINT,TC,RKC)
RETURN
END
C
SUBROUTINE NARLOYZ(RKC,TC)

SUBROUTINE FOR EVALUATION OF NARLOY-Z CONDUCTIVITY

NINT NUMBER OF INTERVALS
RK CONDUCTIVITY
T TEMPERATURE

DIMENSION RK(20),T(20)
NINT = 1
RK(1) = 4.0375*10.**(-3.)*12.
T(1) = 500.
RK(2) = 4.305*10.**(-3.)*12.
T(2) = 1000.
CALL INTER(RK,T,NINT,TC,RKC)
RETURN
END

SUBROUTINE RSR995(RKC,TC)

SUBROUTINE FOR EVALUATION OF RSR 995-AE CONDUCTIVITY

NINT NUMBER OF INTERVALS
RK CONDUCTIVITY
T TEMPERATURE

DIMENSION RK(20),T(20)
NINT = 4
RK(1) = 4.95*10.**(-3.)*12.
T(1) = 100.
RK(2) = 4.95*10.**(-3.)*12.
T(2) = 300.
RK(3) = 4.86*10.**(-3.)*12.
T(3) = 500.
RK(4) = 4.699*10.**(-3.)*12.
T(4) = 1000.
RK(5) = 4.37*10.**(-3.)*12.
T(5) = 1500.
CALL INTER(RK,T,NINT,TC,RKC)
RETURN
END

SUBROUTINE COLUMB(RKC,TC)

SUBROUTINE FOR EVALUATION OF COLUMBIUM CONDUCTIVITY

NINT NUMBER OF INTERVALS
RK CONDUCTIVITY
T TEMPERATURE

DIMENSION RK(20),T(20)
NINT = 1
RK(1) = 4.5*10.**(-4)*12.
T(1) = 100.
RK(2) = 4.5*10.**(-4)*12.
T(2) = 2000.
CALL INTER(RK,T,NINT,TC,RKC)
RETURN
END

SUBROUTINE INTER(RK,T,NINT,TC,RKC)

SUBROUTINE FOR INTERPOLATION

DIMENSION RK(10),T(10)
DO 10 I = 1,NINT
M = I
IF(TC.GE.T(I).AND.TC.LE.T(I + 1))GO TO 20
10 CONTINUE
GO TO 30
GO TO 40
1/(T(2)-T(1))
IF(TC.GT.T(NINT + 1))RKC = RK(NINT) + (RK(NINT+1)-RK(NINT))*(TC-T(NINT))/(T(NINT+1)-T(NINT))
30 IF(TC.LT.T(I))RKC = RK(1) + (RK(2)-RK(I))*(TC-T(I))/(T(I+1)-T(I))
40 RETURN
END

SUBROUTINE METAL (M,RK,T)

THIS SUBROUTINE ALLOWS THE TRIAL OF MANY DIFFERENT MATERIALS FOR
THE DIFFERENT REGIONS. TO ADD A NEW MATERIAL, ADD A NEW NUMBER IN
THE GOTO LIST, THE SUBROUTINE TO FIGURE CONDUCTIVITY AND THE CALL
TO THAT ROUTINE. MAKE SURE TO CHANGE THE MATERIAL NUMBER.

GOTO (1,2,3,4,5,6), M
1 CALL COPPER(RK,T)
RETURN
2 CALL NICKEL(RK,T)
RETURN
3 CALL SOOT(RK,T)
RETURN
4 CALL NARLOYZ(RK,T)
RETURN
5 CALL RSR995(RK,T)
RETURN
6 CALL COLUMB(RK,T)
RETURN
END
/EOF

46
Sample Output

CASE SRB

NPHIL = 4  NPHIC = 3
CW = 0.031415  DIFPHIL = 0.025733  DIFPHIC = 0.005682
DPHIL = 0.008578  DPHIC = 0.001894  DPHIB = 0.005236

NRCLO = 5  NRCHT = 5  NRCHB = 4  NRCOAT = 0

DRCLO = 0.000417
DRCHT = 0.002750
DRCHB = 0.000417
DRCOAT = 0.000000
DPHIC = 0.001894
DPHIL = 0.008578
NR = 14
NR1 = 5  NR2 = 10  NR3 = 14

TEMPERATURE DISTRIBUTION

<table>
<thead>
<tr>
<th>Radian from Centerline of Channel</th>
<th>Channel 1</th>
<th>Channel 2</th>
<th>Channel 3</th>
<th>Channel 4</th>
<th>Channel 5</th>
<th>Channel 6</th>
<th>Channel 7</th>
<th>Channel 8</th>
<th>Channel 9</th>
<th>Channel 10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.9450</td>
<td>1.9400</td>
<td>1.9350</td>
<td>1.9300</td>
<td>1.9250</td>
<td>1.8920</td>
<td>1.8590</td>
<td>1.8260</td>
<td>1.7930</td>
<td>1.7600</td>
</tr>
<tr>
<td></td>
<td>113.48</td>
<td>113.48</td>
<td>113.50</td>
<td>113.52</td>
<td>113.56</td>
<td>113.94</td>
<td>114.83</td>
<td>116.26</td>
<td>118.27</td>
<td>120.81</td>
</tr>
<tr>
<td></td>
<td>113.42</td>
<td>113.43</td>
<td>113.44</td>
<td>113.46</td>
<td>113.49</td>
<td>113.88</td>
<td>114.77</td>
<td>116.20</td>
<td>118.22</td>
<td>120.80</td>
</tr>
<tr>
<td></td>
<td>113.26</td>
<td>113.26</td>
<td>113.27</td>
<td>113.28</td>
<td>113.31</td>
<td>113.70</td>
<td>114.59</td>
<td>116.02</td>
<td>118.05</td>
<td>120.76</td>
</tr>
<tr>
<td></td>
<td>113.03</td>
<td>113.02</td>
<td>113.00</td>
<td>112.98</td>
<td>112.98</td>
<td>113.39</td>
<td>114.28</td>
<td>115.71</td>
<td>117.75</td>
<td>120.71</td>
</tr>
<tr>
<td></td>
<td>113.00</td>
<td>112.99</td>
<td>112.95</td>
<td>112.89</td>
<td>112.87</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.00</td>
</tr>
<tr>
<td></td>
<td>112.98</td>
<td>112.96</td>
<td>112.92</td>
<td>112.83</td>
<td>112.87</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.13</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.91</td>
<td>112.81</td>
<td>112.67</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
<tr>
<td></td>
<td>112.97</td>
<td>112.95</td>
<td>112.81</td>
<td>112.81</td>
<td>112.64</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>121.17</td>
</tr>
</tbody>
</table>

HEAT RATE PER CHANNEL IN BTU/S PER FT LENGTH
COOLING CHANNEL = 0.60
INNER WALL = 0.04  SIDE WALL = 0.53  OUTER WALL = 0.03
HEAT TRANSFER TO OUTSIDE = 0.00
HEAT TRANSFER FROM HOT GAS WALL = -0.60
SUM OF ALL BULK HEAT TRANSFERS = 0.00

HEAT FLUXES AT THIS STATION IN BTU/IN²-S
GAS WALL = -0.46
AVERAGE COOLANT CHANNEL = 0.13
INNER WALL = 0.15  SIDE WALL = 0.13  OUTER WALL = 0.12
CLOSE-OUT = 0.00

OUTSIDE HEAT TRANSFER COEFFICIENT (BTU/FT²-S) = 0.00048
CONDUCTIVITY ITERATIONS(ITER1) = 4
REFERENCES


FIGURE 1. - A ROCKET (SPACECRAFT) THRUST CHAMBER.
CIRCUMFERENTIAL INCREMENT IN LAND AREA (DPHIL)

CIRCUMFERENTIAL INCREMENT IN CHANNEL AREA (DPHIC)

FIGURE 2. - A HALF COOLING CHANNEL CELL.

FIGURE 3. - FINE DIFFERENCE GRIDS SUPERIMPOSED ON THE HALF COOLING CHANNEL CELL (SEE THE COMPUTER PROGRAM LISTING IN APPENDIX B FOR NOTATION).
FIGURE 4. - THERMAL CONDUCTIVITY OF NICKEL (FROM REF. 3).

FIGURE 5. - THERMAL CONDUCTIVITY OF COPPER (FROM REF. 3).

FIGURE 6. - THERMAL CONDUCTIVITY OF COLUMBIUM (FROM REF. 3).
A two-dimensional finite difference computer model for thermal analysis of rocket thrust chambers has been developed. The model uses an iterative scheme for calculating the temperature distribution within the chamber wall and implements a successive overrelaxation formula for a quick convergence. The inputs of the model are the dimensions of the thrust chamber wall, types of materials used, heat transfer coefficients and temperatures of the hot gas and the coolant. The resulting output of the program consists of the nodal temperature distribution, heat transfer to the coolant and heat transfer from the hot gas.