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

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

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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

h	heat transfer coefficient
k	conductivity
R	radius
R_1, R_2, R_3, R_4	thermal resistances
$T_{i,j}$	temperature at node (i,j)

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ΔR	radial mesh size
$\Delta\phi$	circumferential mesh size
ε	relative error for terminating iterations
ε_O	emissivity of the outer surface
σ	Stefan Boltzman coefficient
ω	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 is 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

$$T_{i,j} = \frac{\dfrac{T_{i+1,j}}{R_1} + \dfrac{T_{i,j-1}}{R_2} + \dfrac{T_{i-1,j}}{R_3} + \dfrac{T_{i,j+1}}{R_4}}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \dfrac{1}{R_4}}$$

where

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

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

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

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

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

$$\frac{|T_{i,j}^{n} - T_{i,j}^{n-1}|}{T_{i,j}^{n}} > \varepsilon$$

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 ω for the geometry under consideration here is 1.9. This value of ω 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 that 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.

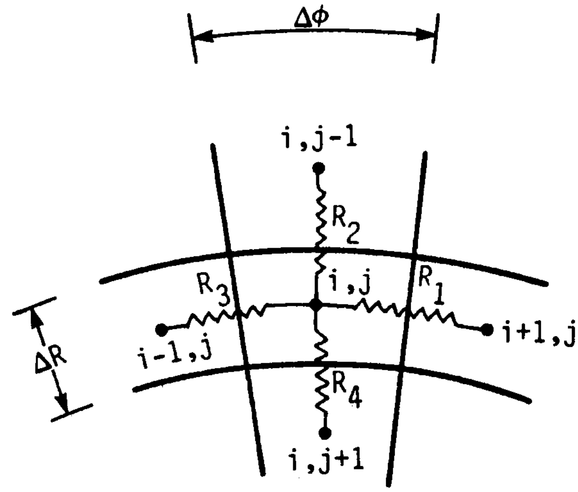
The output of the program includes a listing of the temperatures for each node, number of iterations, and the rate of heat transfer from the hot gas to the cooling channel. A sample output of the program is included in appendix B.

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



$$T_{i,j} = \frac{\dfrac{T_{i+1,j}}{R_1} + \dfrac{T_{i,j-1}}{R_2} + \dfrac{T_{i-1,j}}{R_3} + \dfrac{T_{i,j+1}}{R_4}}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \dfrac{1}{R_4}}$$

where

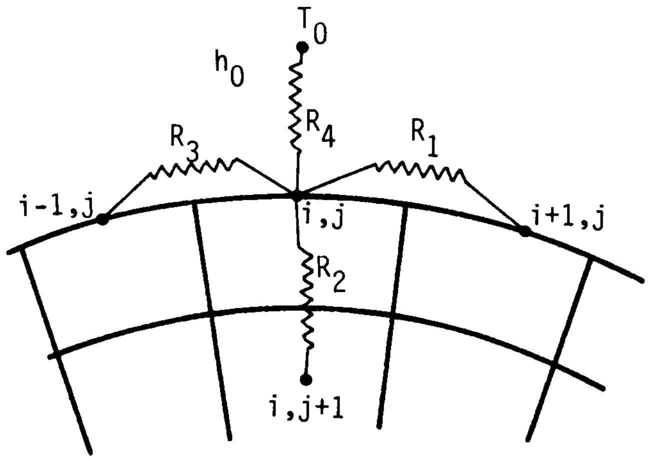
$$R_1 = \frac{R\ \Delta\phi}{2\ \Delta R}\left(\frac{1}{k_{i,j}} + \frac{1}{k_{i+1,j}}\right)$$

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

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

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

Upper boundary node



$$T_{i,j} = \frac{\dfrac{T_{i+1,j}}{R_1} + \dfrac{T_{i,j+1}}{R_2} + \dfrac{T_{i-1,j}}{R_3} + \dfrac{T_o}{R_4}}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \dfrac{1}{R_4}}$$

where

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

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

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

$$R_4 = \frac{1}{h_o R_o\ \Delta\phi}$$

For forced convection h_o is known

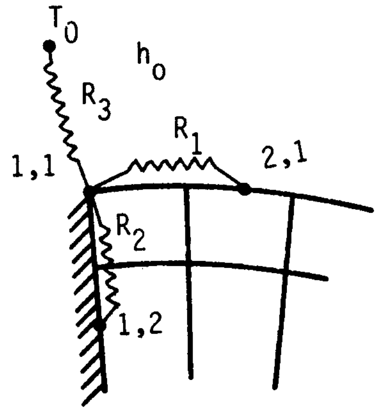
for free convection

$$h_o = \frac{0.53 h_{air}}{2R_o}\left[g|T_{i,j} - T_o|(2R_o)^3\ Pr\right]^{0.25}$$

for radiation to space

$$h_o = \varepsilon_o \sigma (T_{i,j}^3 + T_o T_{i,j}^2 + T_{i,j} T_o^2 + T_o^3)$$

Upper boundary (left corner)



$$T_{1,1} = \frac{\dfrac{T_{2,1}}{R_1} + \dfrac{T_{1,2}}{R_2} + \dfrac{T_o}{R_3}}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3}}$$

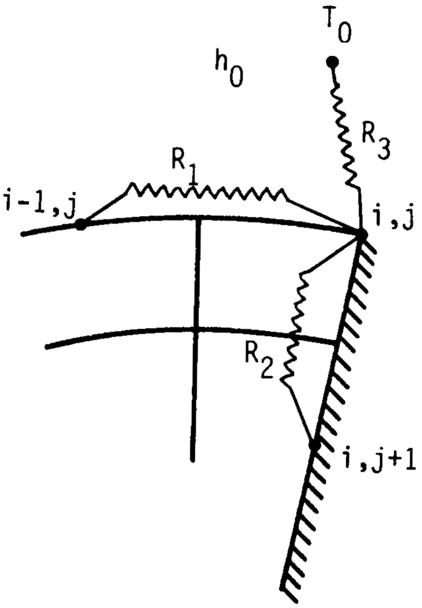
where

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

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

$$R_3 = \frac{2}{h_o R_o\ \Delta\phi}$$

upper boundary (right corner)



$$T_{i,j} = \frac{\dfrac{T_{i-1,j}}{R_1} + \dfrac{T_{i,j+1}}{R_2} + \dfrac{T_o}{R_3}}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3}}$$

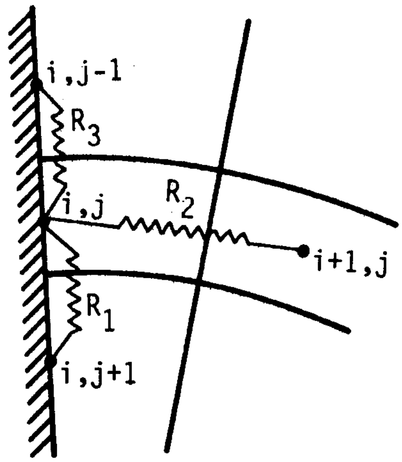
where

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

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

$$R_3 = \frac{2}{h_o R_o\ \Delta\phi}$$

Left boundary



$$T_{i,j} = \frac{\dfrac{T_{i,j+1}}{R_1} + \dfrac{T_{i+1,j}}{R_2} + \dfrac{T_{i,j-1}}{R_3}}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3}}$$

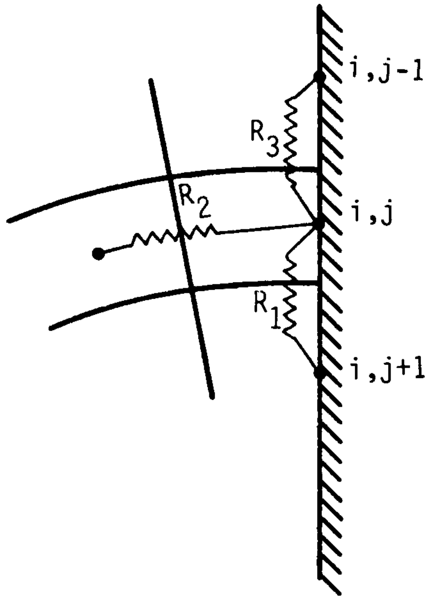
where

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

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

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

Right boundary



$$T_{i,j} = \frac{\dfrac{T_{i,j+1}}{R_1} + \dfrac{T_{i-1,j}}{R_2} + \dfrac{T_{i,j-1}}{R_3}}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3}}$$

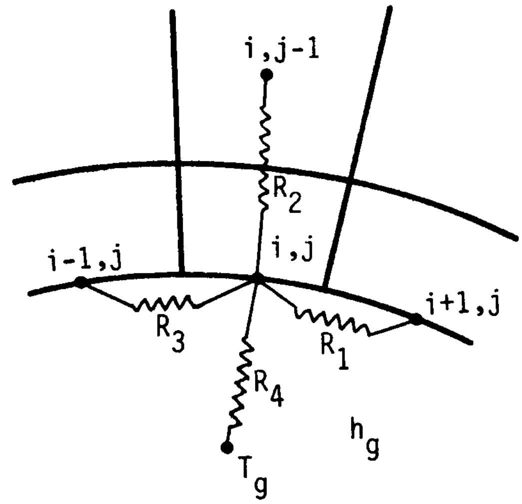
where

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

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

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

Lower boundary node



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

where

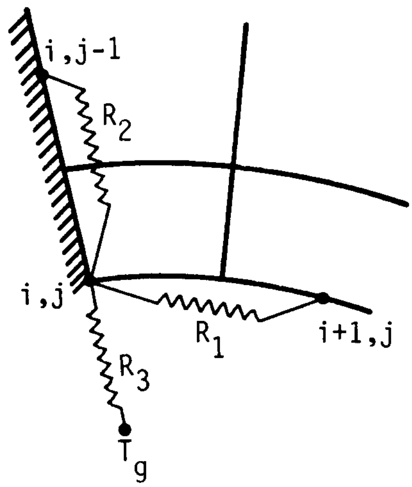
$$R_1 = \frac{R\,\Delta\phi}{\Delta R}\left(\frac{1}{k_{i,j}} + \frac{1}{k_{i+1,j}}\right)$$

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

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

$$R_4 = \frac{1}{h_g R_i\,\Delta\phi}$$

Lower left side boundary node



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

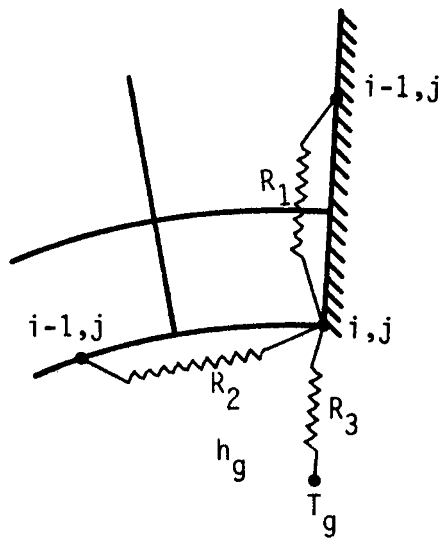
where

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

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

$$R_3 = \frac{2}{h_g R_i\ \Delta\phi}$$

Lower right side boundary node



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

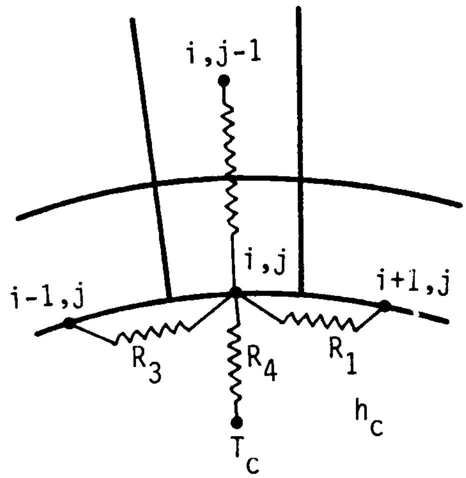
where

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

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

$$R_3 = \frac{2}{h_g R_i\ \Delta\phi}$$

Upper cooling channel wall



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

where

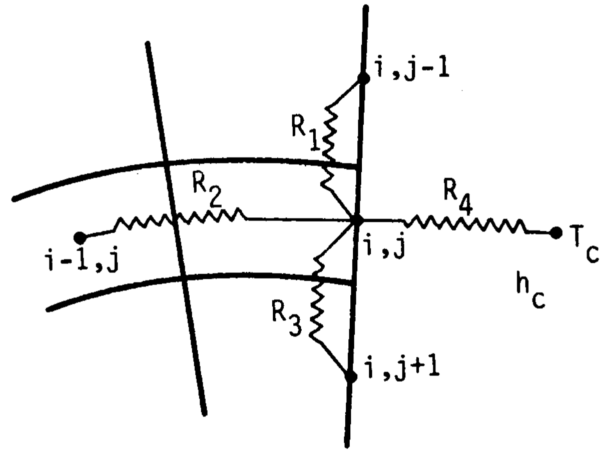
$$R_1 = \frac{R\,\Delta\phi}{\Delta R}\left(\frac{1}{k_{i,j}} + \frac{1}{k_{i+1,j}}\right)$$

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

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

$$R_4 = \frac{1}{h_c R\,\Delta\phi}$$

Cooling channel side wall



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

where

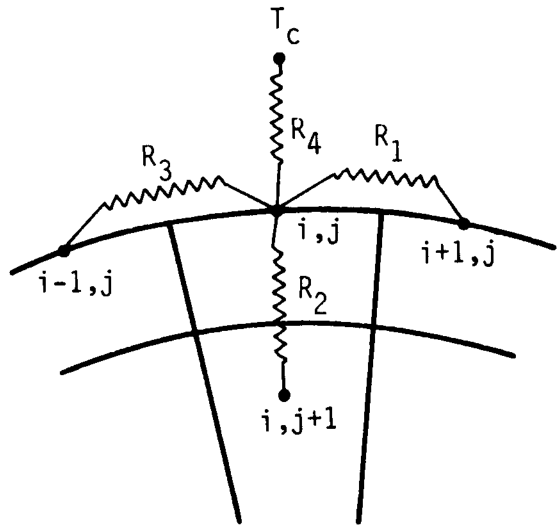
$$R_1 = \frac{\Delta R}{2(R + \Delta R/2)\Delta\phi}\left(\frac{1}{k_{i,j}} + \frac{1}{k_{i,j-1}}\right)$$

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

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

$$R_4 = \frac{1}{\Delta R h_c}$$

Cooling channel lower wall



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

where

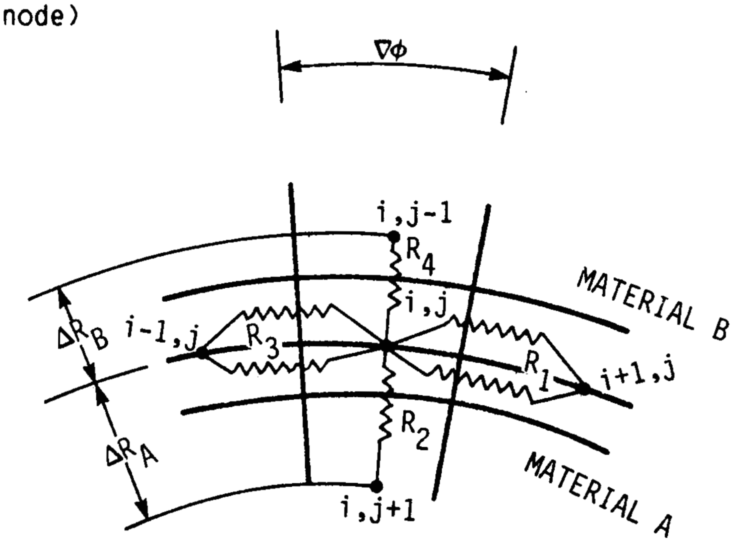
$$R_1 = \frac{R\ \Delta\phi}{\Delta R}\left(\frac{1}{k_{i,j}} + \frac{1}{k_{i+1,j}}\right)$$

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

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

$$R_4 = \frac{1}{R\ \Delta\phi\ h_c}$$

Interface between two materials (middle node)



$$T_{i,j} = \frac{\dfrac{T_{i+1,j}}{R_1} + \dfrac{T_{i,j+1}}{R_2} + \dfrac{T_{i-1,j}}{R_3} + \dfrac{T_{i,j-1}}{R_4}}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \dfrac{1}{R_4}}$$

where

$$R_{A_1} = \frac{R\ \Delta\phi}{\Delta R_A}\left(\frac{1}{k_{A_{i,j}}} + \frac{1}{k_{A_{i+1,j}}}\right)$$

$$R_{B_1} = \frac{R\ \Delta\phi}{\Delta R_B}\left(\frac{1}{k_{B_{i,j}}} + \frac{1}{k_{B_{i+1,j}}}\right)$$

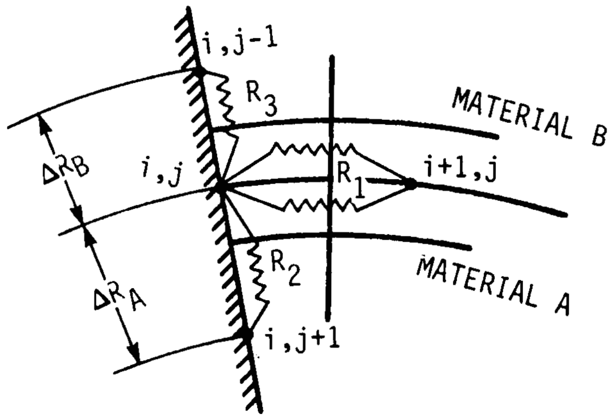
$$R_1 = \frac{R\ \Delta\phi}{\Delta R_A\Big/\left(1/k_{A_{i,j}} + 1/k_{A_{i+1,j}}\right) + \Delta R_B\Big/\left(1/k_{B_{i,j}} + 1/k_{B_{i+1,j}}\right)}$$

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

$$R_3 = \frac{R\ \Delta\phi}{\Delta R_A\Big/\left(1/k_{A_{i,j}} + 1/k_{A_{i-1,j}}\right) + \Delta R_B\Big/\left(1/k_{B_{i,j}} + 1/k_{B_{i-1,j}}\right)}$$

$$R_4 = \frac{\Delta R_B}{2(R + \Delta R_B/2)\Delta\phi}\left(\frac{1}{k_{B\ i,j}} + \frac{1}{k_{B\ i,j-1}}\right)$$

Interface between two materials (left boundary node)



$$T_{i,j} = \frac{\dfrac{T_{i+1,j}}{R_1} + \dfrac{T_{i,j+1}}{R_2} + \dfrac{T_{i,j-1}}{R_3}}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3}}$$

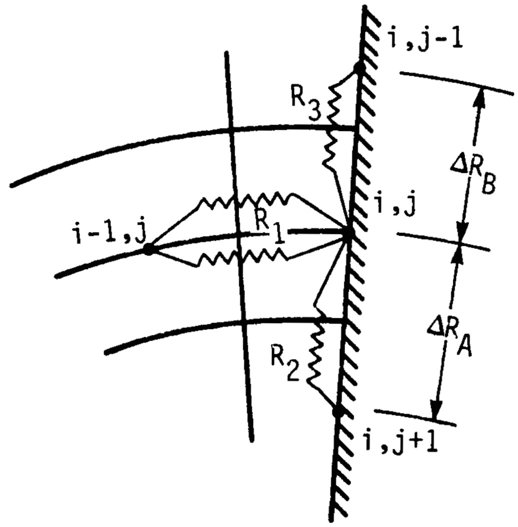
where

$$R_1 = \frac{R\ \Delta\phi}{\Delta R_A \Big/ \left(1/k_{A_{i,j}} + 1/k_{A_{i+1,j}}\right) + \Delta R_B \Big/ \left(1/k_{B_{i,j}} \quad 1/k_{B_{i+1,j}}\right)}$$

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

$$R_3 = \frac{\Delta R_B}{(R + \Delta R_B/2)\Delta\phi}\left(\frac{1}{k_{B_{i,j}}} + \frac{1}{k_{B_{i,j-1}}}\right)$$

Interface between two materials (right boundary node)



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

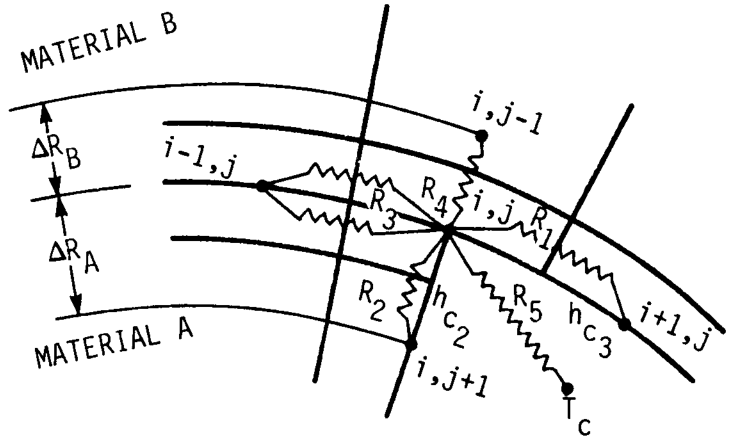
where

$$R_1 = \frac{R\ \Delta\phi}{\Delta R_A \Big/ \left(1/k_{A_{i,j}} + 1/k_{A_{i-1,j}}\right) + \Delta R_B \Big/ \left(1/k_{B_{i,j}} \quad 1/k_{B_{i-1,j}}\right)}$$

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

$$R_3 = \frac{\Delta R_B}{(R + \Delta R_B/2)\Delta\phi} \quad \frac{1}{k_{B_{i,j}}} + \frac{1}{k_{B_{i,j-1}}}$$

Interface between two materials (upper left side of the cooling channel)



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

where

$$R_1 = \frac{R\ \Delta\phi}{\Delta R_B}\left(\frac{1}{k_{B_{i,j}}} + \frac{1}{k_{B_{i+1,j}}}\right)$$

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

$$R_3 = \frac{R\ \Delta\phi}{\Delta R_A \Big/ \left(1/k_{A_{i,j}} + 1/k_{A_{i+1,j}}\right) + \Delta R_B \Big/ \left(1/k_{B_{i,j}} \quad 1/k_{B_{i+1,j}}\right)}$$

$$R_4 = \frac{\Delta R_B}{2(R + \Delta R_B/2)\Delta\phi}\left(\frac{1}{k_{B_{i,j}}} + \frac{1}{k_{B_{i,j-1}}}\right)$$

$$R_5 = \frac{2}{R\ \Delta\phi h_{c_2} + \Delta R h_{c_3}}$$

APPENDIX B

Computer Program Listing and Sample Output

```
      DATA CASE/'CASE'/,DIME/' SRB9 '/
C
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
C I   CCW      FULL COOLANT CHANNEL WIDTH (FEET)
C I   COOL     METHOD OF COOLING
C              =1  REGENERATIVE COOLING
C              =2  RADIATION COOLING
C     CW       RADIANS/FULL CELL WIDTH
C     DIFPHIC  RADIANS/CELL CHANNEL WIDTH
C     DIFPHIL  RADIANS/CELL LAND WIDTH
C     DPHIB    CIRCUMFERENTIAL INCREMENT AT CIRCUM INTERFACE(RADIANS)
C     DPHIC    CIRCUMFERENTIAL INCREMENT WITHIN CHANNEL (RADIANS)
C     DPHIL    CIRCUMFERENTIAL INCREMENT WITHIN LAND (RADIANS)
C I   EM       EMMISSIVITY OF CLOSE-OUT MATERIAL
C I   HC1      COOLANT HEAT TRANSFER COEFFICIENT(INNER WALL)
C I   HC2      COOLANT HEAT TRANSFER COEFFICIENT(SIDE WALL)
C I   HC3      COOLANT HEAT TRANSFER COEFFICIENT(OUTER WALL)
C I   HI       HOT GAS HEAT TRANSFER COEFFICIENT(BTU/FT**2*S*R)
C I   HO1      KNOWN OUTSIDE HEAT TRANSFER COEFFICIENT(BTU/FT**2*S*R)
C I   IFILE    FLAG TO MAKE CONTOURING FILE
C              =0  DO NOT CREATE FILE
C              =1  CREATE FILE
C I   IHOUT    TYPE OF HEAT TRANSFER AT OUTER BOUNDARY
C              =1  FOR KNOWN OUTSIDE HEAT TRANSFER COEFFICIENT
C              =2  FOR NATURAL CONVECTION AT THE OUTER BOUNDARY
C              =3  FOR RADIATION AT THE OUTER BOUNDARY
C I   MTCH     CHANNEL (TOP AND BOTTOM) MATERIAL
C I   MTCLO    CLOSE-OUT MATERIAL
C I   MTCOAT   COATING MATERIAL
C I   NCC      NUMBER OF COOLING CHANNELS
C I   NPHIC    NUMBER OF CIRCUM NODES WITHIN CHANNEL AREA
C I   NPHIL    NUMBER OF CIRCUM NODES IN LAND AREA (INC. CHANNEL WALL
C     NPHITOT  TOTAL NUMBER OF CIRCUMFERENTIAL NODES
C I   NRCHB    NUMBER OF RADIAL NODES IN CHANNEL (BOTTOM PORTION)
C I   NRCHT    NUMBER OF RADIAL NODES IN CHANNEL (TOP PORTION)
C I   NRCLO    NUMBER OF RADIAL NODES IN CLOSE-OUT
C I   NRCOAT   NUMBER OF RADIAL NODES IN THE COATING
C I   RCI      INNER CHANNEL RADIUS (FEET)
C I   RCO      OUTER CHANNEL RADIUS (FEET)
C I   RI       INNER RADIUS (FEET)
C I   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(1H1///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, MTCH MUST BE SAME AS MTCLO
      MTCH=1
      MTCOAT=3
      CCW=0.02/12.
      RO=1.945/12.
      RCO=1.925/12.
      RCI=1.76/12.
      RI=1.74/12.
      TCOAT=0.000/12.
      IF(TCOAT.EQ.0.0)NRCOAT=0
      NCC=100
      TO=530.
      EM=0.9
      TI=4748.
      HI=0.01419
      TC=90.
      HC1=0.71424
      HC2=1.0*0.75406
      HC3=1.0*0.77978
      HO1=0.0
      PI=3.1415
      CW=PI/NCC
      DIFPHIC=CCW/(2.*RCI)
      DIFPHIL=CW-DIFPHIC
      DPHIL=DIFPHIL/(NPHIL-1.)
      IF (NPHIC.EQ.99) GOTO 20
      DPHIC=DIFPHIC/NPHIC
      NPHITOT=NPHIC+NPHIL
      GOTO 25
   20 DPHIC=0.
      NPHITOT=NPHIL
   25 DPHIB=(DPHIC+DPHIL)/2.
      IF (COOL .EQ. 2) GOTO 15
      WRITE (6,5) NPHIL,NPHIC,CW,DIFPHIL,DIFPHIC,DPHIL,DPHIC,DPHIB
      WRITE(6,2)NRCLO,NRCHT,NRCHB,NRCOAT
      GOTO 10
```

```
   15 WRITE (6,8)NPHIL,CW,DPHIL
      WRITE (6,11)MTCLO,NRCLO
      WRITE (6,13)MTCOAT,NRCOAT
   10 CONTINUE
C
    2 FORMAT(///10X,'NRCLO=',I5,2X,'NRCHT=',I5,2X,'NRCHB=',I5,2X,
     1'NRCOAT=',I5)
    5 FORMAT (//10X,'NPHIL=',I4,3X,'NPHIC=',I4,3X,/10X,'CW=',F8.6,
     13X,'DIFPHIL=',F8.6,3X,'DIFPHIC=',F8.6,3X,/10X,'DPHIL=',F8.6,
     23X,'DPHIC=',F8.6,3X,'DPHIB=',F8.6)
    8 FORMAT (//10X,'NPHI=',I4,/10X,'CELL WIDTH=',F8.6,/10X,'DPHI=',
     1F8.6)
   11 FORMAT (//10X,'SUBSTRATE:  MATERIAL=',I3,6X,'NODES=',I3)
   13 FORMAT (/10X,'COATING:    MATERIAL=',I3,6X,'NODES=',I3)
C
      CALL COND(RI,RO,DPHIC,DPHIL,DPHIB,NRCLO,NRCHT,NRCHB,NRCOAT,
     1NPHIC,NPHIL,NPHITOT,RCI,RCO,TCOAT,TO,EM,TI,HI,TC,HC1,HC2,HC3,
     2MTCLO,MTCH,MTCOAT,COOL,IHOUT,HO1,IFILE,NCC)
      STOP
      END
C
      SUBROUTINE COND(RI,RO,DPHIC,DPHIL,DPHIB,NRCLO,NRCHT,NRCHB,NRCOAT,
     1NPHIC,NPHIL,NPHITOT,RCI,RCO,TCOAT,TO,EM,TI,HI,TC,HC1,HC2,HC3,
     2MTCLO,MTCH,MTCOAT,COOL,IHOUT,HO1,IFILE,NCC)
C
C     COOL    METHOD OF COOLING (FROM $MAIN)
C     C1-2-3  (L OR C) GIVES GEOMETRY TO RESISTANCES IN AREA/LENGTH
C     DOT     ARRAY WITH SCALING DATA FOR CONTOURING ROUTINE
C     DPHI       CIRCUMFERENTIAL INCREMENT (GIVEN C OR L VALUE)
C     DRCHB      RADIAL INCREMENT IN BOTTOM OF CHANNEL (FROM $MAIN)
C     DRCHT      RADIAL INCREMENT IN TOP OF CHANNEL (FROM $MAIN)
C     DRCLO      RADIAL INCREMENT IN CLOSE-OUT (FROM $MAIN)
C     DRCOAT     RADIAL INCREMENT IN COATING (FROM $MAIN)
C     EE      FRACTIONAL ERROR AT END OF CONDUCTIVITY ITERATION
C     EM      EMMISSIVITY OF CLOSE-OUT MATERIAL (FROM $MAIN)
C     ERR     FRACTIONAL ERROR WITHIN CONDUCTIVITY ITERATION
C     ERROR      RELATIVE ERROR FOR TERMINATING ITERATIONS
C     FC()    ARRAY WITH CONTOURING LEVELS FOR CONTOURING ROUTINE
C     GBROV      =G*BETA*ROU**2/VISC**2
C     HC1-2-3  COOLANT HEAT TRANSFER COEFFICIENT (FROM $MAIN)
C     HI      INSIDE HEAT TRANSFER COEFFICIENT (FROM $MAIN)
C     HO( )   OUTSIDE HEAT TRANSFER COEFFICIENT FOR EACH NODE
C     HOAVE   AVERAGE OUTSIDE HEAT TRANSFER COEFFICIENT
C     HO1     KNOWN OUTSIDE HEAT TRANSFER COEFFICIENT (FROM $MAIN)
C     ICH( , ) HOLDS TYPE OF POINT
C     IDASH   ARRAY WITH DATA FOR CONTOURING ROUTINE
C     IEE     ERROR COUNTER AT END OF CONDUCTIVITY ITERATION
C     IERR    ERROR COUNTER WITHING CONDUCTIVITY ITERATION
C     IFILE   FLAG TO MAKE CONTOURING FILE
C     IFLAG() ARRAY WITH DATA FOR CONTOURING ROUTINE
C     IHOUT   TYPE OF HEAT TRANSFER AT OUTER BOUNDARY (FROM $MAIN)
C     ITER    COUNTER WITHIN SINGLE CONDUCTIVITY ITERATION
C     ITER1   COUNTER: NUMBER OF CONDUCTIVITY ITERATIONS
C     ITER2   COUNTER FOR TOTAL NUMBER OF ITERATIONS
```

```
C     LOOP VARS:  I,I1,I2,I3,II,J,J1,J2,J3,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     OMEGA   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-I-O   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     TI      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)
      DIMENSION DOT(8),FC(20),IDASH(10)
C   IF NCON .LE. 0 THEN ALL PRINTED OUTPUT IS SUPPRESSED
      NCON=-15
      FC(1)=1300.
      FC(2)=1250.
      FC(3)=1200.
      FC(4)=1150.
      FC(5)=1100.
      FC(6)=1050.
      FC(7)=1000.
      FC(8)=950.
      FC(9)=900.
      FC(10)=850.
      FC(11)=800.
      FC(12)=750.
      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=',
     1F8.6,/10X,'DRCOAT=',F8.6,/10X,'DPHIC=',F8.6,/10X,'DPHIL=',
     2F8.6,/10X,'NR=',I5,2X,/10X,'NR1=',I5,2X,'NR2=',I5,2X,'NR3=',I5)
    9 FORMAT (//10X,'DRSUBSTRATE=',F8.6,/10X,'DRCOAT=',F8.6,/10X,
     1'NPHI=',I4,//10X,'NR1=',I4,5X,'NR=',I4)
      DO 500 I1=1,NPHITOT
      HO(I1)=HO1
      DO 501 J1=1,NR
      T(I1,J1,2)=(TI+TO+TC)/3.
  501 CONTINUE
  500 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
C      WRITE(6,507)I,J
  507 FORMAT(10X,2(I3,2X))
C
      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 505
      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.)*DRCLO
      DR=DRCLO
      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
C
  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)
C
```

```
      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)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.GT.NPHIL.AND.J.EQ.NR1)GO TO 180
      IF(J.GT.NR1.AND.J.LT.NR2)GO TO 190
      GO TO 191
C
  190 IF(I.GT.NPHIL)GO TO 210
  191 IF(I.GT.NPHIL.AND.J.EQ.NR2)GO TO 230
      IF(J.EQ.NR1)GO TO 240
      IF(J.EQ.NR2)GO TO 260
      IF(I.EQ.NPHITOT)GO TO 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. NR) GOTO 320
      IF (J .EQ. NR3) GOTO 310
      IF ((J .GT. NR1) .AND. (J .LT. NR2)) GOTO 200
C
C       MIDDLE NODE: CIRCUMFERENTIAL INTERFACE
C
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.*C1C)
      R2=(1./RK1+1./RK3)*DR/(2.*DPHIB*(R+DR/2.))
      R3=(1./RK1+1./RK4)/(2.*C1L)
      R4=(1./RK1+1./RK5)*DR/(2.*DPHIB*(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
C     RADIATION COOLED DECISION SECTION
C
  400 IF ((I.EQ.1).AND.(J.EQ.1)) GOTO 100
      IF ((I.EQ.NPHITOT).AND.(J.EQ.1)) GOTO 110
      IF (J.EQ.1) GOTO 120
      IF ((I.EQ.1).AND.(J.EQ.NR)) GOTO 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)) GOTO 135
      IF ((I.EQ.NPHITOT).AND.(J.EQ.NR3)) GOTO 145
      IF (J.EQ.NR3) GOTO 155
      IF (I.EQ.1) GOTO 160
      IF (I.EQ.NPHITOT) GOTO 250
C
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 (MTCLO, RK1,TR1)
      CALL METAL (MTCLO, RK2,TR2)
      CALL METAL (MTCLO, RK3,TR3)
      CALL METAL (MTCLO, RK4,TR4)
      CALL METAL (MTCLO, 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)
  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     UPPER LEFT SIDE CORNER BOUNDARY NODE
C
  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)**0.25
      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     UPPER RIGHT HAND SIDE CORNER BOUNDARY NODE
C
  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)**0.25
      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
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)**0.25
      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)
      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./2./C2*(1./RK1+1./RK3)
      R3=1./C1*(1./RK1+1./RK4)
      IF(HO(I).EQ.0.0)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
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)**0.25
      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)
      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./RK1+1./RK2)/C1C
      R2=(1./RK1+1./RK3)*DRCLO/(2.*DPHIB*(RO-DRCLO/2.))
      R3=(1./RK1+1./RK4)/C1L
      IF(HO(I).EQ.0.0)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
C
C     LOWER LEFT SIDE BOUNDARY NODE
C
  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)
  132 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+TI/R3)/
     1(1./R1+1./R2+1./R3)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=130
      GO TO 1002
C
C     INTERFACE BETWEEN COPPER AND COATING(LEFT BOUNDARY)
C
  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 (MTCOAT, RKCOA1,TR1)
      CALL METAL (MTCH, RKCH2,TR2)
      CALL METAL (MTCOAT, RKCOA2,TR2)
      CALL METAL (MTCOAT, RKCOA3,TR3)
      CALL METAL (MTCH, RKCH5,TR5)
      R1=R*DPHI/(DRCHB/(1./RKCH1+1./RKCH2)+DRCOAT/(1./RKCOA1+1./RKCOA2))
      R2=DRCOAT/1./(R-DRCOAT/2.)/DPHI*(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)/(1./R1+1./R2+1./R4)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=135
      GO TO 1002
C
C     LOWER RIGHT SIDE BOUNDARY NODE
C
  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./HI/R/DPHI
      T(I,J,2)=((T(I-1,J,2)/R1+T(I,J-1,2)/R2+TI/R3)/
     1(1./R1+1./R2+1./R3)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=140
      GO TO 1002
C
C     INTERFACE BETWEEN COPPER AND COATING(RIGHT BOUNDARY)
C
  145 R=RI
      TR1=T(I,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 (MTCOAT, RKCOA3,TR3)
      CALL METAL (MTCH, RKCH4,TR4)
      CALL METAL (MTCOAT, RKCOA4,TR4)
      CALL METAL (MTCH, RKCH5,TR5)
      R2=DRCOAT/1./(R-DRCOAT/2.)/DPHI*(1./RKCOA1+1./RKCOA3)
      R3=R*DPHI/(DRCHB/(1./RKCH1+1./RKCH4)+DRCOAT/(1./RKCOA1+1./RKCOA4))
      R4=DRCHB/1./(R+DRCHB/2.)/DPHI*(1./RKCH1+1./RKCH5)
      T(I,J,2)=((T(I,J+1,2)/R2+1.*T(I-1,J,2)/R3+T(I,J-1,2)/R4
     1)/(1./R2+1./R3+1./R4)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=145
      GO TO 1002
C
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 (MTCOAT, RK1,TR1)
      CALL METAL (MTCOAT, RK2,TR2)
      CALL METAL (MTCOAT, RK3,TR3)
      CALL METAL (MTCOAT, 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./2./C3*(1./RK1+1./RK3)
      R3=1./C1*(1./RK1+1./RK4)
      R4=1./HI/R/DPHI
      T(I,J,2)=((T(I+1,J,2)/R1+T(I,J-1,2)/R2+T(I-1,J,2)/R3+TI/R4)/
```

```
     1(1./R1+1./R2+1./R3+1./R4)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=150
      GO TO 1002
C
C       LOWER BOUNDARY NODE: CIRCUMFERENTIAL INTERFACE
C
  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)/C1C
      R2=(1./RK1+1./RK3)*DR/(2.*DPHIB*(R+DR/2.))
      R3=(1./RK1+1./RK4)/C1L
      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+TI/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
C
C
C     INTERFACE BETWEEN COPPER AND COATING
C
  155 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./RKCOA1+1./RKCOA2))
      R2=DRCOAT/2./(R-DRCOAT/2.)/DPHI*(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
C
C     CHANNEL-COATING INTERFACE: CIRCUMFERENTIAL INTERFACE
C
  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*DPHIC/(DRCHB/(1./RKCH1+1./RKCH2)+DRCOAT/
     1(1./RKCOA1+1./RKCOA2))
      R2=DRCOAT/(2.*(R-DRCOAT/2.)*DPHIB)*(1./RKCOA1+1./RKCOA3)
      R3=R*DPHIL/(DRCHB/(1./RKCH1+1./RKCH4)+
     1DRCOAT/(1./RKCOA1+1./RKCOA4))
      R4=DRCHB/(2.*(R+DRCHB/2.)*DPHIB)*(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
C
C     LEFT BOUNDARY NODES
C
  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 (MTCLO, RK1,TR1)
      CALL METAL (MTCLO, RK2,TR2)
      CALL METAL (MTCLO, RK3,TR3)
      CALL METAL (MTCLO, 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=1./2./C1*(1./RK1+1./RK3)
      R3=1./C3*(1./RK1+1./RK4)
      T(I,J,2)=((T(I,J+1,2)/R1+T(I+1,J,2)/R2+T(I,J-1,2)/R3)/
     1(1./R1+1./R2+1./R3)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=160
      GO TO 1002
C
C   CHANNEL, UPPER LEFT SIDE CORNER NODE
C   (ITERFACE BETWEEN COPPER AND NICKEL): ALSO CIRCUM INTERFACE
C
  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*DPHIC/DRCLO*(1./RKCLO1+1./RKCLO2)
      R2=DRCHT/(R-DRCHT/2.)/DPHIL*(1./RKCH1+1./RKCH3)
      R3=R*DPHIL/(DRCLO/(1./RKCLO1+1./RKCLO4)+DRCHT/(1./RKCH1+1./RKCH4))
      R4=DRCLO/(2.*(R+DRCLO/2.)*DPHIB)*(1./RKCLO1+1./RKCLO5)
      R5=2./((R*DPHIC*HC3)+(DRCHT*HC2))
      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)/R4
     1+TC/R5)/(1./R1+1./R2+1./R3+1./R4+1./R5)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=170
      GO TO 1002
C
C   UPPER CHANNEL WALL
C
  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=DRCLO/2./(R+DRCLO/2.)/DPHI*(1./RK1+1./RK3)
      R3=R*DPHI/DRCLO*(1./RK1+1./RK4)
      R4=1./HC3/R/DPHI
      IF(I.EQ.NPHITOT)GO TO 185
      TR2=T(I+1,J,1)
      CALL METAL (MTCLO, RK2,TR2)
      R1=R*DPHI/DRCLO*(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)/
     1(1./R1+1./R2+1./R3+1./R4)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=180
      GO TO 1002
C   CENTERLINE OF TOP OF CHANNEL
```

```
  185 R2=2.*R2
      R4=2.*R4
      T(I,J,2)=((T(I,J-1,2)/R2+1.*T(I-1,J,2)/R3+TC/R4)/
     1(1./R2+1./R3+1./R4)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=185
      GO TO 1002
C
C     CHANNEL SIDE WALL: ALSO A CIRCUMFERENTIAL INTERFACE
C
  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./2./C1L*(1./RK1+1./RK3)
      R3=1./C2L*(1./RK1+1./RK4)
      R4=1./DR/HC2
      T(I,J,2)=((T(I,J-1,2)/R1+T(I-1,J,2)/R2+T(I,J+1,2)/R3+TC/R4)/
     1(1./R1+1./R2+1./R3+1./R4)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=200
      GO TO 1002
C               WITHIN CHANNEL
  210 T(I,J,2)=TC
      ICH(I,J)=210
      GO TO 1002
C
C       CHANNEL, LOWER LEFT SIDE CORNER NODE:
C               ALSO CIRCUMFERENTIAL INTERFACE
C
  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)=((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))*OMEGA+T(I,J,2)
      ICH(I,J)=220
      GO TO 1002
C
```

```
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/2./(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)/
    1(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,J+1,2)/R2+1.*T(I-1,J,2)/R3+TC/R4)/
    1(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)
 252 R1=1./C2*(1./RK1+1./RK2)
     R2=1./2./C1*(1./RK1+1./RK3)
     R3=1./C3*(1./RK1+1./RK4)
     T(I,J,2)=((T(I,J+1,2)/R1+T(I-1,J,2)/R2+T(I,J-1,2)/R3)/
```

```
     1(1./R1+1./R2+1./R3)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=250
      GO TO 1002
C
C     INTERFACE BETWEEN COPPER AND NICKEL
C
  240 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 (MTCH, RKCH2,TR2)
      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*DPHI/(DRCLO/(1./RKCLO1+1./RKCLO2)+DRCHT/(1./RKCH1+1./RKCH2))
      R2=DRCHT/2./(R-DRCHT/2.)/DPHI*(1./RKCH1+1./RKCH3)
      R3=R*DPHI/(DRCLO/(1./RKCLO1+1./RKCLO4)+DRCHT/(1./RKCH1+1./RKCH4))
      R4=DRCLO/2./(R+DRCLO/2.)/DPHI*(1./RKCLO1+1./RKCLO5)
      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)=240
      GO TO 1002
C
C      LEFT SIDE NODE (INTERFACE BETWEEN COPPER AND NIKEL)
C
  245 R=RCO
      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 (MTCLO, RKCLO1,TR1)
      CALL METAL (MTCH, RKCH2,TR2)
      CALL METAL (MTCLO, RKCLO2,TR2)
      CALL METAL (MTCH, RKCH3,TR3)
      CALL METAL (MTCLO, RKCLO5,TR5)
      R1=R*DPHI/(DRCLO/(1./RKCLO1+1./RKCLO2)+DRCHT/(1./RKCH1+1./RKCH2))
      R2=DRCHT/1./(R-DRCHT/2.)/DPHI*(1./RKCH1+1./RKCH3)
      R4=DRCLO/1./(R+DRCLO/2.)/DPHI*(1./RKCLO1+1./RKCLO5)
      T(I,J,2)=((1.*T(I+1,J,2)/R1+T(I,J+1,2)/R2+T(I,J-1,2)/R4)
     1/(1./R1+1./R2+1./R4)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=245
      GO TO 1002
C
C       INTERFACE BETWEEN TWO LAYERS WITH DIFFERENT
C            RADIAL INCREMENTS (CHANNEL REGION)
C
  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)
      CALL METAL (MTCH, RKCH1,TR1)
      CALL METAL (MTCH, RKCH2,TR2)
      CALL METAL (MTCH, RKCH3,TR3)
      CALL METAL (MTCH, RKCH4,TR4)
      CALL METAL (MTCH, RKCH5,TR5)
      R1=R*DPHI/(DRCHT+DRCHB)*(1./RKCH1+1./RKCH2)
      R2=DRCHB/2./(R-DRCHB/2.)/DPHI*(1./RKCH1+1./RKCH3)
      R3=R*DPHI/(DRCHT+DRCHB)*(1./RKCH1+1./RKCH4)
      R4=DRCHT/2./(R+DRCHT/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)=260
      GO TO 1002
C
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)
      CALL METAL (MTCH, RKCH1,TR1)
      CALL METAL (MTCH, RKCH2,TR2)
      CALL METAL (MTCH, RKCH3,TR3)
      CALL METAL (MTCH, RKCH5,TR5)
      R1=R*DPHI/(DRCHT+DRCHB)*(1./RKCH1+1./RKCH2)
      R2=DRCHB/1./(R-DRCHB/2.)/DPHI*(1./RKCH1+1./RKCH3)
      R4=DRCHT/1./(R+DRCHT/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(1./R1+1./R2+1./R4)-T(I,J,2))*OMEGA+T(I,J,2)
      ICH(I,J)=265
C
 1002 RADP(I,J)=12.*R
      IF(T(I,J,2).EQ.0.)GO TO 1003
      ERR=ABS((TT2-T(I,J,2))/T(I,J,2))
      GO TO 1005
 1003 ERR=ABS(T(I,J,2)-TT2)
 1005 IF(ERR.GT.ERROR)IERR=IERR+1
 1001 CONTINUE
 1000 CONTINUE
C  END OF CELL LOOP
C     WRITE(6,1006)ITER,IERR
 1006 FORMAT(10X,'ITERATION NUMBER=',I6,3X,'IERR=',I6)
C     DO 1007 KM=1,NR
C     WRITE(6,2006)(T(MM,KM,2),MM=1,NPHITOT)
C     IF(ITER1.EQ.1)WRITE(6,2003)(ICH(MM,KM),MM=1,NPHITOT)
C1007 CONTINUE
 2006 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)=',I5/5X,
     2'CONDUCTIVITY ITERATIONS(ITER1)=',I5,/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)
C2000 CONTINUE
C      DO 2111 K=1,NR
C      WRITE(6,2001)RADP(1,K),(T(M,K,2),M=1,NPHITOT)
C2111 CONTINUE
      IEE=0
C          TO CHECK FOR CONVERGENCE BETWEEN DIFFERENT CONDUCTIVITIES
      DO 4100 I3=1,NPHITOT
      DO 4101 J3=1,NR
      EE=ABS((T(I3,J3,2)-T(I3,J3,1))/T(I3,J3,2))
      IF(EE.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)
      WRITE (6,2007) (DPHIC*NPHIC+DPHIL*NPHIL-DPHIL*JJ,JJ=1,NPHIL),
     1(DPHIC*NPHIC-DPHIC*II,II=1,NPHIC)
      GOTO 4600
 4700 WRITE (6,2008)
 4600 CONTINUE
C                  PRINTING THE RESULTS
      DO 2002 II=1,NR
      WRITE(6,2001)RADP(1,II),(T(JJ,II,1),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)
C2222 CONTINUE
C
C      DO 2010 MM=1,NR
C      WRITE(6,2011)(RADP(NN,MM),NN=1,NPHITOT)
C2010 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,I2)
        IF (NCON .LE. 0)NCON=-1*NCON
        DO 5500 I=1,NCON
          WRITE (9,5600) FC(I)
 5500   CONTINUE
 5600 FORMAT (3X,F7.1)
        DO 5700 II=1,NPHITOT
          DO 5800 JJ=1,NR
            NI=II
            NJ=JJ
C
            IF (T(II,JJ,1).NE.TC) GOTO 5010
C   TOP WALL OF CHANNEL
              IF (JJ.NE.NR1+1) GOTO 5020
                NJ=NR1
                NI=NPHIL
                GOTO 5010
 5020           CONTINUE
C   BOTTOM WALL OF CHANNEL
              IF (JJ.NE.NR2-1) GOTO 5030
                NJ=NR2
                NI=NPHIL
                GOTO 5010
 5030           CONTINUE
C   SIDE WALL AND INTERIOR OF CHANNEL
              NI=NPHIL
C
 5010         CONTINUE
C
            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
            ZI=RADP(NI,NJ)*SIN(PSI)
            ZJ=RADP(NI,NJ)*COS(PSI)
C
            WRITE (9,5900) ZI,ZJ,T(NI,NJ,1)
C
C
C
 5900 FORMAT (3X,2(F7.4,2X),F8.2)
```

```
5800    CONTINUE
5700  CONTINUE
C
5555 CONTINUE
C
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(ICH(I,J).EQ.320)GO TO 3700
      IF(ICH(I,J).EQ.300)GO TO 3750
      IF(ICH(I,J).EQ.230)GO TO 3100
      IF(ICH(I,J).EQ.180)GO TO 3150
      IF(ICH(I,J).EQ.235)GO TO 3200
      IF(ICH(I,J).EQ.185)GO TO 3250
      IF(ICH(I,J).EQ.200)GO TO 3300
      IF(ICH(I,J).EQ.220)GO TO 3400
      IF(ICH(I,J).EQ.170)GO TO 3450
      IF(ICH(I,J).EQ.120)GO TO 3500
      IF(ICH(I,J).EQ.100.OR.ICH(I,J).EQ.110)GO TO 3550
      IF(ICH(I,J).EQ.150)GO TO 3600
      IF(ICH(I,J).EQ.130.OR.ICH(I,J).EQ.140)GO TO 3650
      GO TO 3001
3100 QC1=QC1+2.*RCI*DPHI*HC1*(T(I,J,2)-TC)*1.
      GO TO 3001
3150 QC3=QC3+2.*RCO*DPHI*HC3*(T(I,J,2)-TC)*1.
      GO TO 3001
3200 QC1=QC1+RCI*DPHIC*HC1*(T(I,J,2)-TC)*1.
      GO TO 3001
3250 QC3=QC3+RCO*DPHIC*HC3*(T(I,J,2)-TC)*1.
      GO TO 3001
3300 QC2=QC2+2.*DRCHT*HC2*(T(I,J,2)-TC)*1.
      GO TO 3001
3400 QC1=QC1+(RCI*DPHIC*HC1)*(T(I,J,2)-TC)*1.
      QC2=QC2+(DRCHT*HC2)*(T(I,J,2)-TC)*1.
      GO TO 3001
3450 QC3=QC3+(RCO*DPHIC*HC3)*(T(I,J,2)-TC)*1.
      QC2=QC2+(DRCHT*HC2)*(T(I,J,2)-TC)*1.
      GO TO 3001
3500 QO=QO+2.*RO*DPHI*HO(I)*(T(I,J,2)-TO)*1.
      GO TO 3001
3550 QO=QO+RO*DPHI*HO(I)*(T(I,J,2)-TO)*1.
      GO TO 3001
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)*DPHIB*HI*(T(I,J,2)-TI)*1.
      GO TO 3001
 3750 QO=QO+2.*RO*DPHIB*HO(I)*(T(I,J,2)-TO)*1.
 3001 CONTINUE
 3000 CONTINUE
      QC=QC1+QC2+QC3
      Q=QC+QO+QI
      HOAVE=HOAVE/NPHITOT
      WRITE(6,3002)QC,QC1,QC2,QC3,QO,QI,Q
 3002 FORMAT(1H1/10X,'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)
C  CALCULATING THE AVERAGE FLUXES FOR DIFFERENT WALL SECTIONS
C    THESE ARE IN BTU/IN¬2-S)
      QO=QO*NCC/(2.*3.1415*RO)/144.
      QI=QI*NCC/(2.*3.1415*(RI-TCOAT))/144.
      IF (COOL .EQ. 2) GOTO 3010
        QC1=QC1/(2.*DPHIC*NPHIC*RCI)/144.
        QC2=QC2/(2.*(RCO-RCI))/144.
        QC3=QC3/(2.*DPHIC*NPHIC*RCO)/144.
        QC=QC/(2.*(DPHIC*NPHIC*(RCI+RCO)+(RCO-RCI)))/144.
 3010 CONTINUE
C
      WRITE(6,3005)QI,QC,QC1,QC2,QC3,QO
 3005 FORMAT(////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(///10X,'OUTSIDE HEAT TRANSFER COEFFICIENT (BTU/FT¬2-)=',
     1F10.5/10X,'CONDUCTIVITY ITERATIONS(ITER1)=',I5/10X,
     2'TOTAL NUMBER OF ITERATIONS=',I5)
      RETURN
      END
C
      SUBROUTINE COPPER(RKC,TC)
C
C      SUBROUTINE FOR EVALUATION OF COPPER THERMAL CONDUCTIVITY
C
C     NINT        NUMBER OF INTERVALS
C     RK          CONDUCTIVITY
C     T           TEMPERATURE
C
      DIMENSION RK(10),T(10)
      NINT=2
```

```
      RK(1)=53.*10.**(-4)*12.
      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
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
      RK(1)=26.*10.**(-4.)*12.
      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
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
      RK(1)=7.*10.**(-6)*12.
      T(1)=100.
      RK(2)=7.*10.**(-6)*12.
      T(2)=2000.
      CALL INTER(RK,T,NINT,TC,RKC)
      RETURN
      END
C
```

```
      SUBROUTINE NARLOYZ(RKC,TC)
C
C        SUBROUTINE FOR EVALUATION OF NARLOY-Z CONDUCTIVITY
C
C     NINT       NUMBER OF INTERVALS
C     RK         CONDUCTIVITY
C     T          TEMPERATURE
C
      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
C
C
      SUBROUTINE RSR995(RKC,TC)
C
C        SUBROUTINE FOR EVALUATION OF RSR 995-AE CONDUCTIVITY
C
C     NINT       NUMBER OF INTERVALS
C     RK         CONDUCTIVITY
C     T          TEMPERATURE
C
      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
C
      SUBROUTINE COLUMB(RKC,TC)
C
C        SUBROUTINE FOR EVALUATION OF COLUMBIUM CONDUCTIVITY
C
C     NINT       NUMBER OF INTERVALS
C     RK         CONDUCTIVITY
C     T          TEMPERATURE
C
      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
C
C
      SUBROUTINE INTER(RK,T,NINT,TC,RKC)
C
C        SUBROUTINE FOR INTERPOLATION
C
      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
   20 RKC=RK(M)+(RK(M+1)-RK(M))*(TC-T(M))/(T(M+1)-T(M))
      GO TO 40
   30 IF(TC.LT.T(1))RKC=RK(1)+(RK(2)-RK(1))*(TC-T(1))
     1/(T(2)-T(1))
      IF(TC.GT.T(NINT+1))RKC=RK(NINT)+(RK(NINT+1)-RK(NINT))*
     1(TC-T(NINT))/(T(NINT+1)-T(NINT))
   40 RETURN
      END
C
      SUBROUTINE METAL (M,RK,T)
C     THIS SUBROUTINE ALLOWS THE TRIAL OF MANY DIFFERENT MATERIALS FOR
C     THE DIFFERENT REGIONS.  TO ADD A NEW MATERIAL, ADD A NEW NUMBER IN
C     THE GOTO LIST, THE SUBROUTINE TO FIGURE CONDUCTIVITY AND THE CALL
C     TO THAT ROUTINE.  MAKE SURE TO CHANGE THE MATERIAL NUMBER.
C
      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
```

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

1

TEMPERATURE DISTRIBUTION

RADIANS FROM CENTERLINE OF CHANNEL

	0.03141	0.02284	0.01426	0.00568	0.00379	0.00189	0.00000
1.9450	113.48	113.42	113.26	113.03	113.00	112.98	112.97
1.9400	113.48	113.43	113.26	113.02	112.99	112.96	112.95
1.9350	113.50	113.44	113.27	113.00	112.95	112.92	112.91
1.9300	113.52	113.46	113.28	112.98	112.89	112.83	112.81
1.9250	113.56	113.49	113.31	112.98	112.77	112.67	112.64
1.8920	113.94	113.88	113.70	113.39	90.00	90.00	90.00
1.8590	114.83	114.77	114.59	114.28	90.00	90.00	90.00
1.8260	116.26	116.20	116.02	115.71	90.00	90.00	90.00
1.7930	118.27	118.22	118.05	117.75	90.00	90.00	90.00
1.7600	120.81	120.80	120.76	120.71	121.00	121.13	121.17
1.7550	121.21	121.20	121.18	121.21	121.31	121.37	121.39
1.7500	121.61	121.61	121.60	121.65	121.68	121.71	121.72
1.7450	122.02	122.02	122.02	122.06	122.08	122.09	122.10
1.7400	122.43	122.42	122.43	122.47	122.48	122.49	122.50

1

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/IN ¬ 2-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/FT ¬ 2-) = 0.00048
CONDUCTIVITY ITERATIONS(ITER1) = 4

REFERENCES

1. Ozisik, M.M.: Heat Conduction, John Wiley & Sons, 1980.

2. Carnahan, B.; Luther, H.A.; and Wilkes, J.O.: Applied Numerical Methods. John Wily & sons, Inc., 1969.

3. Touloukian, Y.S., ed.: Thermophysical Properties of High Temperature Solid Materials. Thermophysical Properties Research Center, Purdue University, 1967.

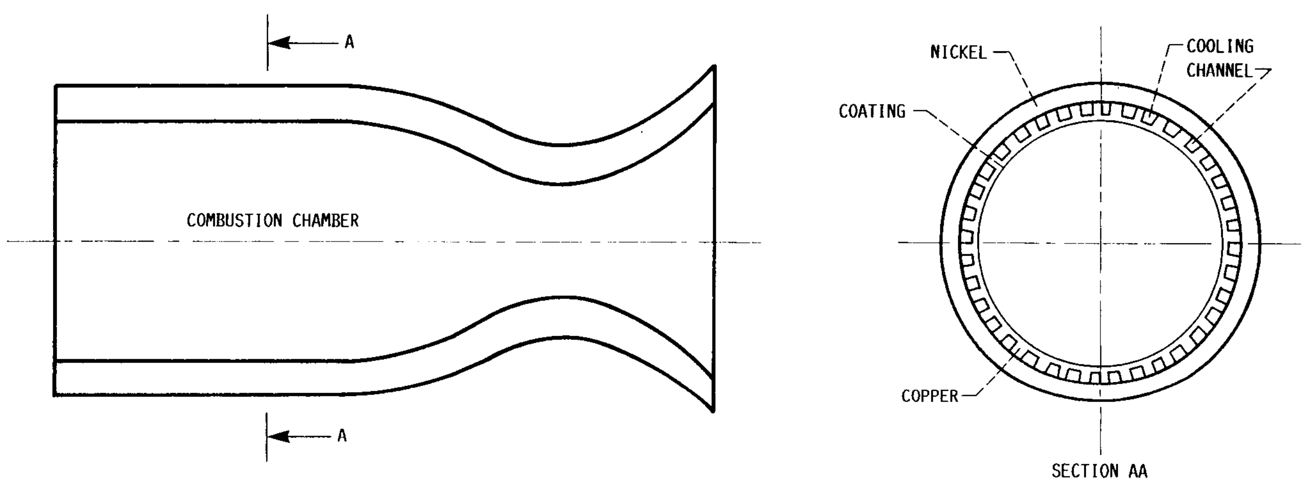


FIGURE 1. - A ROCKET (SPACECRAFT) THRUST CHAMBER.

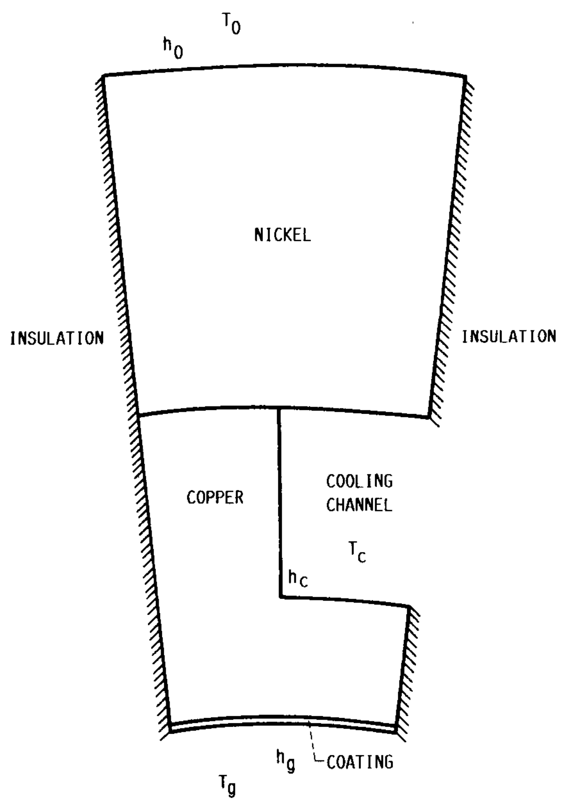


FIGURE 2. - A HALF COOLING CHANNEL CELL.

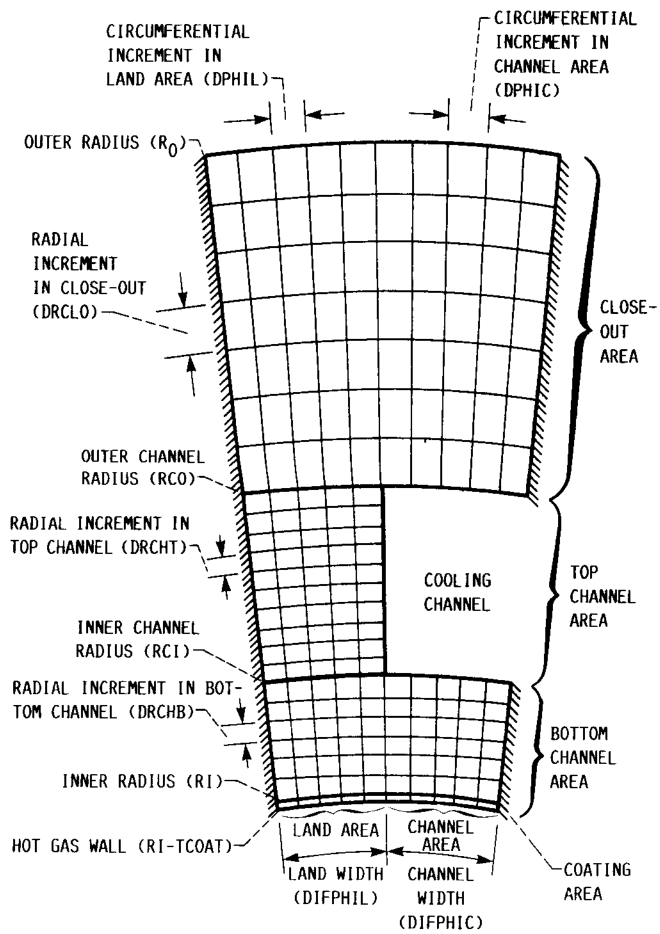


FIGURE 3. - FINITE DIFFERENCE GRIDS SUPERIMPOSED ON THE HALF COOLING CHANNEL CELL (SEE THE COMPUTER PROGRAM LISTING IN APPENDIX B FOR NOTATION).

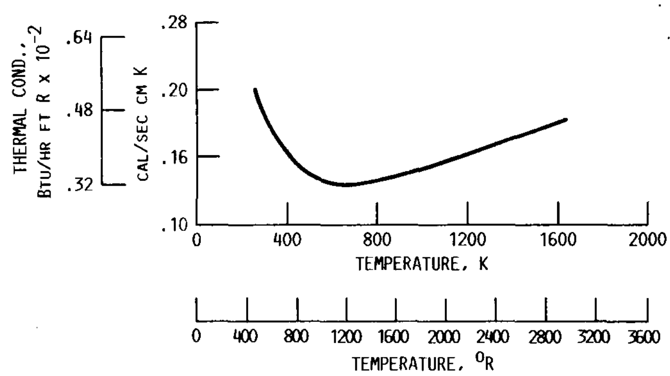


FIGURE 4. - THERMAL CONDUCTIVITY OF NICKEL (FROM REF. 3).

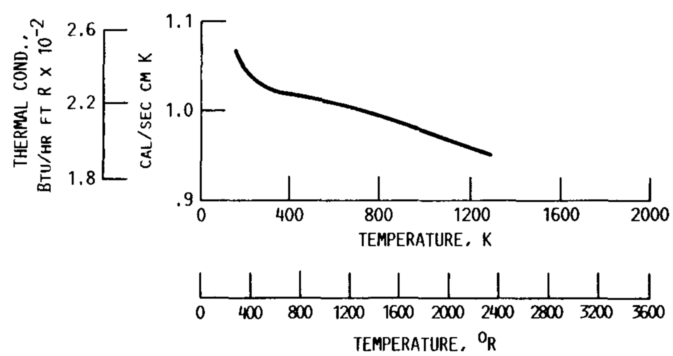


FIGURE 5. - THERMAL CONDUCTIVITY OF COPPER (FROM REF. 3).

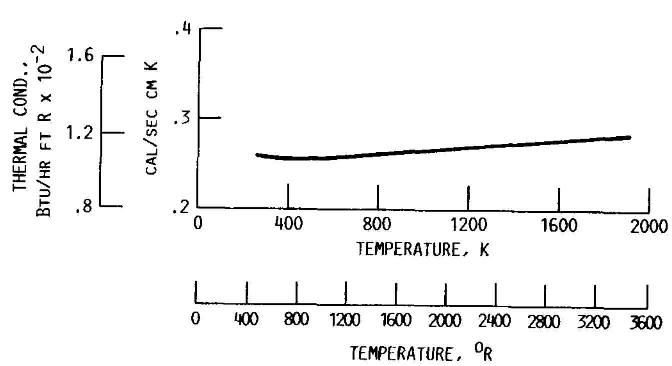


FIGURE 6. - THERMAL CONDUCTIVITY OF COLUMBIUM (FROM REF. 3).

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15. Supplementary Notes

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16. Abstract

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.

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