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SUBJECT: Steady State Heat Transfer in ORR Irradiation Capsules, Part 2

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ABSTRACT

The mathematical model developed by Stiros et al.(8) for prediction of temperature profiles in ORR irradiation capsules was modified and a numerical solution obtained. A Fortran computer program was written to solve the generalized finite difference equations applied to a fixed lattice system superimposed on the capsule cross section. The Liebmann iterative method was employed. The solution accounts for changes in internal heat generation, thermal expansion, and thermal conductivity induced by both temperature and fluence. The computed temperatures deviated from actual experimental measurements in the fuel rods by less than 2.0%.

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1. SUMMARY

Stiros, Chao, and Michel (8) derived finite difference equations to describe conduction heat transfer in ORR irradiation test capsules. These equations were modified and completed to provide equations accounting for every possible type of finite difference node which could be generated with a cylindrical coordinate system lattice and the fuel capsule geometry. A computer program was written to solve the completed equations with the Liebmann iterative solution technique. To simplify program logic, the finite difference equations were reduced to a generalized form. The location and type of each node are determined and the appropriate finite difference equation for the temperature at that node is solved. Furthermore, the program accounts for fluence and temperature induced dimensional changes, for fission and gamma heat generation, and for fluence and temperature dependent thermal conductivities. The computer program was written and compiled on a PDP-10 computer and then modified for use on an IBM 360/91.

2. INTRODUCTION

2.1 Background

Prototype fuel rods for the High Temperature Gas-cooled Reactor (HTGR) have been tested under simulated HTGR conditions in the Oak Ridge Research Reactor (ORR) and the High Flux Isotope Reactor (HFIR) (4). A capsule assembly contains five fuel rods surrounded by a graphite moderator, housed inside two cylindrical stainless steel shells as shown in Fig. 1. The temperature profile at any position in the capsule changes during the irradiation period. Knowledge of this profile is necessary to investigate the rate of diffusion of fissile fuel inside the fuel rods.

The heat transfer equations which must be solved to compute the temperature profile are complex because the internal heat generation and material properties are dependent on temperature and fluence. The properties dependent on temperature and fluence include thermal conductivity and thermal expansion. The equations are further complicated by the non-linear boundary conditions resulting from radiative heat transfer. As a result, an analytical solution has not been obtained for the temperature profile, and a numerical method of solution is required.

2.2 Previous Work

Previous temperature profiles have been computed as a function of position at one fixed irradiation time interval by a general heat transfer computer program, HEATING3 (10). This program did not allow for temperature and fluence dependence of thermal conductivities and thermal expansion coefficients. Manual corrections for changes in the conductivities and

Regions, ○

- 2 - Central Fuel Rod
- 3 - Peripheral Fuel Rod
- 4 - Graphite Moderator
- 5 - Stainless Steel Cladding
- 6 - Stainless Steel Cladding

Gaps, ▽

- 0 - Cooling Water
- 1 - Thermocouple
- 2-5 - Sweep Gas
- 3 - Peripheral Fuel Rod

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1/8 SECTION OF ORR IRRADIATION CAPSULE

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FIG.
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material dimensions were necessary between successive runs of HEATING3. As a result, HEATING3 was inefficient for determining the capsule temperature profiles for numerous irradiation time intervals.

A previous MIT group (8) developed finite difference equations and boundary conditions for a fixed lattice system applied to a cross sectional segment of the capsule. A solution algorithm based on the Liebmann iterative method was suggested to solve these equations. No computer program for obtaining the solutions was developed.

The one-eighth section of the fuel capsule was divided into five homogeneous regions following the material boundaries. Figure 1 shows the regions and the region numbers which will be employed to identify each region. Two categories of regions result from the capsule geometry, as described in cylindrical coordinates with the origin at the capsule center. Regions with all boundaries parallel to the cylindrical coordinate system are referred to as normal. Special regions are defined as those regions with one boundary surface not parallel to the coordinate system.

When the fixed lattice system is applied to the capsule cross section, three basic types of regular lattice points are created. Figure 2 shows the two simple cases in both normal and special regions. A simple interior point has no boundary surfaces falling between it and the four lattice points around it. A finite difference equation can be written for the temperature of a simple interior point in terms of the temperature at the four surrounding lattice points. Appendix 9.1.1 gives the derivation of the equation for this case.

When a regular lattice point lies on a region boundary, the boundary point is termed simple. A Taylor series expansion composed of directional distance and surrounding temperature terms can be combined with the boundary conditions to obtain an expression for the boundary point temperature. This derivation is found in Appendix 9.1.2.

Non-simple interior lattice points result when a boundary line falls within one lattice increment distance, ΔR or $R\Delta\theta$, from the point. In a normal region only one irregular boundary point in the R-direction is created as the location of the fourth temperature in the central difference expansion. Two irregular boundary points may be required to locate the boundary temperatures adjacent to the non-simple interior point falling in a special region as shown in Fig. 2.

The incremental distances describing any irregular point position are defined as $a\Delta R$ in the radial direction and $bR\Delta\theta$ in the θ direction. The temperatures at the irregular points are referred to as $T_{i+a,j}$ and $T_{i,j+b}$ in the R and θ directions, respectively. Any regular lattice point temperature is labeled $T_{i,j}$.

Many different cases of these general point types were found by the previous MIT group. Figure 3 shows each different boundary in any region where the correct boundary conditions were applied. The varied positions of the boundaries relative to lattice points resulted in a total of 23

SIMPLE INTERIOR POINT

SIMPLE BOUNDARY POINT

NON-SIMPLE INTERIOR POINT

IRREGULAR BOUNDARY POINTS

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LIEBMANN LATTICE POINT TYPES

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FIG.
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DIFFERENT REGION BOUNDARIES

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finite difference equations. A complete table of these equations is found in Appendix 9.1.3.

2.3 Objectives and Method of Attack

To complete the task of obtaining theoretical temperature profiles:

- 1) The assumptions made by the previous MIT group were reviewed, and the possible sources of error identified. The equations were checked for mathematical accuracy. Additional equations were derived for lattice point cases not covered in the previous work.
- 2) A computer program was written to solve finite difference equations by the Liebmann method.
- 3) Computed results were compared with experimental results and with the computed profiles from HEATING3 to determine agreement between them.

3. FINITE DIFFERENCE EQUATION MODIFICATIONS

Stiros et al. (8) provided a set of finite difference equations to calculate the capsule temperature profile. However, the equations were incomplete. Heat generation terms had been neglected in all boundary point equations, and equations were not provided for three lattice point types.

3.1 Heat Generation Terms at Boundaries

According to the form of the original differential equation,

$$\frac{\partial^2 T}{\partial R^2} + \frac{1}{R} \frac{\partial T}{\partial R} + \frac{1}{R^2} \frac{\partial^2 T}{\partial \theta^2} = - \frac{S(Z,t)}{K(T)} \quad (1)$$

a heat generation term should be included in the finite difference approximations for each regular lattice point. However, no heat generation terms should be included in equations written for points not actually on the lattice, namely irregular boundary points. Because Stiros et al. neglected the heat generation terms in the regular boundary point cases, these terms were replaced in the proper finite difference equations (A2) through (A9) found in Appendix 9.1.3.

The heat generation terms are volumetric, so the actual heat generation calculated in each finite difference equation is the volumetric term multiplied by the finite difference volume. For a simple interior point, the volume is approximated by $\Delta R \cdot R \Delta \theta \cdot \Delta Z$ as shown in Fig. 4. For a simple boundary

SIMPLE INTERIOR POINT

SIMPLE BOUNDARY POINT

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VOLUMES ASSOCIATED WITH
SIMPLE LATTICE POINTS

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point in a normal region, the volume is one-half this quantity, as shown in Fig. 4. The equations for these points, Eqs. (1)-(9), account for the entire generation in the appropriate volume.

For non-simple points, however, the volume associated with the point is scaled down by the factors a and b which define the irregular boundary point locations. In normal regions, heat generation in a small rectangular volume element next to the boundary is neglected, as shown by Fig. 5. This case occurs at boundaries 3 and 4. In the special regions, the peripheral fuel rod boundaries are not parallel to the lattice coordinate system. The rectangular volume elements associated with non-simple interior points near these boundaries also neglect a part of the volume element, as shown in Fig. 5. Therefore, the actual heat generation at these non-simple interior points will not be the exact value for the entire volume element. To quantify this error, the heat generation term S/K was calculated for the worst case of the peripheral fuel rod at its maximum radial distance from the origin on boundary 9 near boundary 11. This number was compared in magnitude to the sum of the temperature terms in the finite-difference equation for the same case, Eq. (A18), in Appendix 9.1.3, with surrounding temperatures at the expected temperature of 830-840°C. The error was less than one percent when the heat generation term was neglected entirely; the approximation of the actual heat generation by the non-simple interior point equations in the special regions should be much less than one percent. This small error may be neglected because of the few points at which the approximation occurs.

In the case in which a regular lattice point falls on a special region boundary, 9, the heat generation term will be neglected for that point. Again, in this case, the inclusion of a heat generation term would not improve the solution, as the change in calculated temperature for this point type would be much less than one percent. Because there are very few boundary points of this type, the effect of omitting the heat generation term in Eqs. (A10) through (A17) is negligible.

3.2 Additional Finite Difference Equations

Three lattice point types were discovered for which Stiros et al. had provided no finite difference equations. One type, a non-simple boundary point, is shown in Fig. 6. This point is a special case of a simple boundary point in which the point is less than one lattice increment from a corner. Non-simple boundary points are found on boundaries 1 and 2 in both normal and special regions. Equations (A2.1) and (A2.2) were derived for non-simple points on B1, and Eqs. (A3.1) and (A3.2) were derived for non-simple points on boundary 2. As expected, these equations reduce to 2 and 3, respectively, for values of a_p or a_n of 1.0, representing simple boundary points.

The second lattice point type arose at an interior non-simple point in the peripheral fuel rod at the angle $(\gamma - \theta)$ or θ equal to $\pi/2$. In this case, shown in Fig. 7, there are no regular lattice points in the fuel rod on three sides of the non-simple point. To avoid generating three irregular boundary points for calculating the non-simple point temperature, Eq. (A19)

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VOLUMES ASSOCIATED WITH NON-SIMPLE
INTERIOR LATTICE POINTS

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FIG.
5

Irregular Corner
Point at Boundary 5

$T_{i,j-1}$

Non-Simple Boundary Point

$T_{i,j}$

Boundary 1

$a_n \Delta R$

ΔR

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NON-SIMPLE BOUNDARY POINT EXAMPLE

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FIG.
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X = Irregular Boundary Points

• = Regular Lattice Points

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LOCATION OF NON-SIMPLE
INTERIOR POINT FOR EQ. (A19)

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FIG.
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was written. Like Equations (A10) through (A17), Eq. (A19) replaces the four-way Taylor expansion of the central-difference approximation with a simplified one-dimensional expression. This expression is obtained by equating the energy flux from the neighboring simple interior point with the energy flux to the irregular boundary point which corresponds to the non-simple interior point. The derivative $(1/r)(\partial T/\partial \theta)$ is approximated by $\Delta T/r\Delta \theta$ to obtain Eq. (A19). Equation (A19) also avoids the problem of calculating $1/\cos(\gamma-\theta)$ as $\gamma-\theta$ approaches $\pi/2$.

The third point type is a regular lattice point on the peripheral fuel rod hole boundary of the graphite, at the angle θ equal to $\pi/2$. This location is shown in Fig. 8. In this case, there are interior lattice points on three sides of the boundary point, and the Taylor series expansion in the fourth direction is replaced with the boundary condition representing conduction and radiation heat transfer between the peripheral fuel rod and the graphite. Equation (A20) was written to solve for the temperature at this boundary point, completing the set of equations for all possible lattice points.

4. PROGRAM DESCRIPTION

4.1 General Overview

The program HOTSTF is written in Fortran for execution on either a Digital Equipment Corp. PDP-10 or an IBM-360 computer. The use of a PDP-10 offers teletype availability with immediate compilation and comprehensive surveying of the results during execution. This program is designed to accept input parameters from cards and to print the output on a line printer.

All arrays in the program are dimensioned and all other declarations are made in the initial statements of the program. The variable names are chosen as mnemonics for the calculated quantities appearing in the equations. There are five logical variables to simplify the execution of the program. IRREG is the logical variable to indicate that the lattice point is non-simple in the radial direction when a boundary exists less than a radial increment from the lattice point. FUNNY indicates that a boundary in the angular direction is less than an angular increment from the lattice point. WEIRD is the logical variable to indicate the presence of a non-simple point surrounded by irregular points in three directions. This is a special case appearing only in region 3 very near the line that passes through the origin and is tangent to the peripheral fuel rod. OUTER4 is used to designate that the lattice point is in special region 4 at a distance from the origin greater than that of the peripheral fuel rod hole center distance, R_p . ZEROIT is the variable to indicate the zeroth or initialization iteration.

The program is structured in several blocks: parameter input, thermal property calculation, region determination, lattice type determination with temperature solution of the finite difference equation, convergence calculation, and output. The parameter input and thermal property calculations

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LATTICE POINT ON RADIAL TANGENT LINE
AT PERIPHERAL ROD HOLE SURFACE

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FIG.
8

are described in Sect. 4.2. The region determination is presented in Sect. 4.3. Section 4.4 elucidates the procedure of lattice type determination. Section 4.5 describes the general form of the equations and the program development necessary to treat each specific equation. The convergence block is detailed in Sect. 4.6. The overall program flow chart is presented in Fig. 9.

4.2 Input

The input parameters determine the initial conditions for the temperature calculations, in addition to the variables defining the lattice. Also, the coefficients from which the power densities, thermal conductivities, thermal expansion coefficients, and neutron flux are computed are entered as input arrays. A total of twelve input card types are read by the program to enter the input parameters.

The first card contains the variable that indicates how the temperatures are to be initialized, i.e., as overall region average or as results from previous earlier runs; the limit on the number of iterations; and the two convergence criteria. This data card represents the beginning of a data set. The second card type contains the initial region temperature guess or results from earlier runs and the minimum and maximum radial dimensions of each region. There is one card of this type for each of the five regions.

One card each of types 3 through 5 is read. Card type 3 carries the dimensions of the special region. The fourth card type sets the lattice parameters. This card contains the number of radial and angular increments and the radius of the lattice edge. The axial location in the capsule cross section for which temperatures are being calculated is read from card type 5. The time limits and time increment for which temperatures are being calculated are entered on card type 6, which also contains the number of times the sweep gas composition changes.

The coefficients of the power density functions for each region are read from card types 7A and 7B. These coefficients are entered with each card corresponding to one of the five regions. Card type 7 contains time dependent fission heating coefficients while type 7B includes Z dependent gamma heating coefficients.

The equation for calculating fission power generation in the fuel rods is:

$$S_F = S_0 + S_1 t + S_2 t^2 \quad (2)$$

and the one for the graphite, stainless steel, and fuel rod gamma heating is:

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GENERAL MASTER FLOW CHART

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GENERAL MASTER FLOW CHART

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$$S_y = V_0 + V_1 Z + V_2 Z^2 \quad (3)$$

Card type 8 contains the helium mole fraction in the sweep gas, along with the time after which the mole fraction changes to a new value on the next card. The number of type 8 cards is determined from card type 6. Card type 9 enters the flux function coefficients for the equation

$$\theta = (F_0 + F_1 Z + F_2 Z^2 + F_3 Z^3) \quad (4)$$

There is only one card of this type.

The coefficients for calculating the thermal expansion coefficients are contained in card type 10. There are four cards for each of the three materials. For fuel rods and stainless steel, the equation is

$$\begin{aligned} \beta = & (B_{11} + B_{21}T + B_{31}T^2 + B_{41}T^3) + (B_{12} + B_{22}T + B_{32}T^2 + B_{42}T^3) \\ & \times (\theta t \times 10^{-21}) + (B_{13} + B_{23}T + B_{33}T^2 + B_{43}T^3)(\theta t \times 10^{-21})^2 \\ & + (B_{14} + B_{24}T + B_{34}T^2 + B_{44}T^3)(\theta t \times 10^{-21})^3 \end{aligned} \quad (5)$$

The hot dimension is calculated as

$$D = D_0 [1 + [\beta(T - 25^\circ\text{C})]] \quad (6)$$

For graphite, the equation for the natural strain value is of different form:

$$\begin{aligned} \ln\left(\frac{D_1}{D_0}\right) = N = & (N_{11} + N_{21}T + N_{31}T^2 + N_{41}T^3) + (N_{12} + N_{22}T \\ & + N_{32}T^2 + N_{42}T^3)(\theta t \times 10^{-21}) + (N_{13} + N_{23}T + N_{33}T^2 \\ & + N_{43}T^3)(\theta t \times 10^{-21})^2 + (N_{14} + N_{24}T + N_{34}T^2 + N_{44}T^3) \\ & \times (\theta t \times 10^{-21})^3 \end{aligned} \quad (7)$$

The natural strain value provides for graphite shrinkage caused by neutron irradiation at high temperatures. The complete graphite thermal expansion expression must also account for normal thermal expansion. Therefore, the exponential of the natural strain value is multiplied by an expansion term. This term also has a different form from Eq. (6) and presents the ratio of hot to reference dimension as a function of temperature.

$$\left(\frac{D}{D_1}\right) = (1 - 9.085 \times 10^{-5} + 3.87359 \times 10^{-6}T + 1.11176 \times 10^{-9}T^2) \quad (8)$$

By multiplying Eq. (7) by the exponential of the natural strain value, the final hot irradiated graphite dimension is obtained.

$$D = \left(\frac{D}{D_1}\right)\exp(N) \quad (9)$$

The thermal conductivities of stainless steel and fuel rods are calculated from the coefficients on card type 11. There are four cards of this type for each material. For stainless steel the thermal conductivity is calculated from

$$\begin{aligned} K_S = & 4.186[(C_{11} + C_{21}T + C_{31}T^2 + C_{41}T^3) + (C_{12} + C_{22}T + C_{32}T^2 \\ & + C_{42}T^3)(\phi t \times 10^{-21}) + (C_{13} + C_{23}T + C_{33}T^2 + C_{43}T^3) \\ & \times (\phi t \times 10^{-21})^2] \end{aligned} \quad (10)$$

For the fuel rods the fluence dependence is exponential.

$$\begin{aligned} K_f = & 4.186[(C_{11} + C_{21}T + C_{31}T^2 + C_{41}T^3) + (C_{12} + C_{22}T + C_{32}T^2 \\ & + C_{42}T^3) \times \exp[(C_{13} + C_{23}T + C_{33}T^2 + C_{43}T^3)(\phi t \times 10^{-21})]] \end{aligned} \quad (11)$$

For graphite, thermal conductivity is expressed as a function of temperature for a known constant fluence,

$$K_{m,1} = C_{11} + C_{21}T + C_{31}T^2 + C_{41}T^3 \text{ at } (\phi t)_1 \quad (12)$$

For fluence between $(\theta t)_i$ and $(\theta t)_{i+1}$, the thermal conductivity $K_m(\theta t)$ is calculated by a linear interpolation between $K_{m,i}$ and $K_{m,i+1}$. The temperature coefficients C_{1i} , C_{2i} , C_{3i} , and C_{4i} are entered with their corresponding fluence, $(\theta t)_i$, on card type 12.

The last card of the data set, type 13, contains the temperature of the water surrounding the fuel capsule and the overall heat transfer coefficient for heat transfer from the capsule to the water. These data determine the boundary conditions at the exterior surface of the capsule.

The exact description of each card, with the variables contained on each card type, may be found in Appendix 9.2. The variables are listed with their respective formats to simplify punching each data card. If more than one data set is entered, each set must contain the correct number of each type of card.

Tabular or graphical data for power density, flux, thermal expansion, and thermal conductivity were reduced to the functions explained above by a double-precision curve-fitting program, ANLE212S (1), available from Argonne National Laboratory. Data which were presented as functions of temperature and fluence were fit to a fluence polynomial or exponential equation at each temperature. The resulting sets of fluence coefficients were then fit to a temperature polynomial function, resulting in Eqs. (2) through (12). An exception to this method was fuel rod thermal conductivity, which was fit to temperature first and fluence second, resulting in Eq. (12).

Graphite thermal conductivity was fit to a polynomial function of temperature (Eq. 12) at constant fluence, as a poor fit was obtained for thermal conductivity as a function of fluence. Instead, the capsule temperature program performs a linear interpolation between thermal conductivities at different fluences to obtain an accurate value of K_m .

ANLE212S re-evaluates each original data point, allowing the fit quality to be evaluated. For all functions fit by ANLE212S, the worst error generated was 1.3% for the natural strain value of graphite at zero fluence and 1350°C.

4.3 Region Finding Logic

The logic for the determination of the region of a given lattice point is developed by considering the point position on a line at a fixed angle (constant θ) as shown in Fig. 10. The region in which the point is located is determined by successive comparison with the radial coordinates of the boundaries. The radial coordinate of the boundaries about the peripheral fuel rod are dependent on the angular coordinate θ . Above the angle θ corresponding to the tangent line to the semicircle, there is no boundary.

It is obvious from the diagram that any point on the line of constant θ be located on a boundary, between two boundaries, or on the outside of the capsule. The point is located by comparison with the following inequalities.

If

$$0 \leq R_i < R_{\min,2} \quad (13)$$

then the point is in the thermocouple hole, gap 1. If

$$R_{\min,2} \leq R_i \leq R_{\max,2} \quad (14)$$

then the point is in the central fuel rod, region 2. If

$$R_{\max,2} < R_i < R_{\min,4} \quad (15)$$

then the point is in the gap between the central fuel rod and the graphite moderator, gap 2. If the line of constant θ passes through the area of the peripheral fuel rod, it is necessary to compare the point with the location of these boundaries. This is necessarily the case if the theta coordinate of the point, θ_j , satisfies the inequality,

$$0 \leq \sin \theta_j \leq r_4/R_p \quad (16)$$

with R_p as the hypotenuse. If inequality (16) is not satisfied, there are no special boundaries for comparison, and if the inequality

$$R_{\min,4} \leq R_i \leq R_{\max,4} \quad (17)$$

is simultaneously satisfied, the point is in region 4.

When inequality (16) is satisfied, these further comparisons must be made. If

$$R_{\min,4} \leq R_i \leq \left[R_p - \sqrt{R_p^2 \cos^2 \theta - (R_p^2 - r_4^2)} \right] \quad (18)$$

then the point is located in the inner portion of the graphite moderator, region 4. If

$$\left[R_p - \sqrt{R_p^2 \cos^2 \theta - (R_p^2 - r_4^2)} \right] < R_i < \left[R_p - \sqrt{R_p^2 \cos^2 \theta - (R_p^2 - r_3^2)} \right] \quad (19)$$

then the point is located in the inner section of the gap between the peripheral fuel rod and the moderator, gap 3. If

$$\left[R_p - \sqrt{R_p^2 \cos^2 \theta - (R_p^2 - r_3^2)} \right] \leq R_i \leq \left[R_p + \sqrt{R_p^2 \cos^2 \theta - (R_p^2 - r_3^2)} \right] \quad (20)$$

then the point is located within the peripheral fuel rod, region 3. If

$$\left[R_p + \sqrt{R_p^2 \cos^2 \theta - (R_p^2 - r_3^2)} \right] < R_i < \left[R_p + \sqrt{R_p^2 \cos^2 \theta - (R_p^2 - r_4^2)} \right] \quad (21)$$

then the point is in the outer section of gap 3. If

$$\left[R_p + \sqrt{R_p^2 \cos^2 \theta - (R_p^2 - r_4^2)} \right] \leq R_i \leq R_{\max,4} \quad (22)$$

then the point is located in the outer portion of region 4. This locates the specific point of interest shown in Fig. 10.

If none of the equalities 13, 14, 15, 18-22 had been satisfied at this stage of testing, which is not the case for the example point shown, further comparison with the boundaries of the stainless steel cladding is needed. If

$$R_{\max,4} < R_i < R_{\min,5} \quad (23)$$

then the point is in the gap between the moderator and the inner stainless steel cladding, gap 4. If

$$R_{\min,5} \leq R_i \leq R_{\max,5} \quad (24)$$

then the point is in the stainless cladding, region 5. If

$$R_{\max,5} < R_i < R_{\min,6} \quad (25)$$

then the point is in gap 5. If

$$R_{\min,6} \leq R_i \leq R_{\max,6} \quad (26)$$

then the point is region 6. If none of these equalities (23) through (26) have been satisfied, the point must be located outside of the fuel rod in the media surrounding the capsule. This is designated gap 0.

After the region of interest has been established, the region on the opposite side of any gap is also determined. This information is needed for establishing the heat loss across a gap by conduction and by radiation.

4.4 Lattice Determination Logic

Once the region of a given lattice point has been established, it is necessary to establish the position of the point relative to the nearest boundaries more precisely. The complicated geometry of the special regions produces 23 possible relations between the lattice points of the cylindrical coordinate system and the boundaries of the fuel capsule in these coordinates. The normal region has 16 possible relations. Nine of these relations between the lattice points are shown in the enlargements of Fig. 11.

The nine enlargements shown in Fig. 11 correspond to the areas indicated on the diagram by the circle, square, and hexagon, respectively. Seven other relations occur along the line passing through the center of the peripheral fuel rod; line 0 of Fig. 10. Five relations along line Z of Fig. 10 are also established. The additional relations can be produced by drawing radial lines through the two points adjacent to each point of interest in Fig. 11: A, B, C, F, G, H, and I. These relations are not shown in Fig. 11.

To discuss the actual logic description here, it will be necessary to examine a constant θ line that produces the most relations. All lines, other than the two boundary lines 0 and Z (Fig. 10), that pass through the peripheral fuel rod hole can have any of the relations shown, depending upon the choice of lattice increments. A method analogous to that shown in the flow chart in Fig. 12 establishes the type of a lattice point in any other region. The region of the point is of course known from the previous region determination section. As an example for the explanation of Fig. 12, a point in region 3 having coordinates (R_i, θ_j) is chosen. The distances $R_{x,min,3}$ and $R_{x,max,3}$ are the minimum and maximum R coordinates of the boundaries, respectively, along the line $\theta = \theta_j$. From the geometrical development of Stiros et al.

$$R_{x,min,3} = R_p \cos \theta - \sqrt{(R_p \cos \theta)^2 - R_p^2 + r_{F3}^2} \quad (27)$$

$$R_{x,max,3} = R_p \cos \theta + \sqrt{(R_p \cos \theta)^2 - R_p^2 + r_{F4}^2} \quad (28)$$

Since the region of the point is known from the previous region determination block, it is necessary to examine the points only for relations occurring along the particular line of constant θ . Thus, the particular line of interest need not be examined for corner points which can only occur along lines O and Z of Fig. 10. For line O, it is not necessary to examine for simple or non-simple interior points; they do not occur along this boundary. The types of corner points that occur along line Z are mirror images of those on line O and thus are not considered along any other line.

For any line that does not intersect the boundaries of the gap produced by the peripheral fuel rod, or that passes more than one angular increment from the radial line tangent to the special region boundary at its closest approach, only five types of points may occur. These five types are: simple interior points (Fig. 11I), non-simple interior points that have irregular boundary points associated in either the negative or the positive r -direction (Figs. 11B and 11G, respectively), and regular boundary points (Figs. 11C and 11H). It is important to note that if a regular boundary occurs in a normal region, all of the boundary points for that particular region are parallel to the coordinate system, greatly simplifying the computational complexity.

For a line which passes less than an angular increment from the area indicated by the square on the diagram of Fig. 11, there is the possible occurrence of the situations shown in Figs. 11D and 11E, in addition to all of the other seven situations depicted. The seven situations, Figs. 11A, B, C, F, G, H, and I, can occur along any other line that intersects the boundaries associated with the peripheral fuel rod.

The particular example of Fig. 12 develops the logic used to determine precisely the type of point falling on a line of the most general case, specifically any line that passes through special region 3. The development for the boundary lines O and Z are analogous. For any line, the logic for point determination in a normal region is a subset of that shown in Fig. 12.

4.5 Temperature Solution

Once the lattice type has been determined, it is necessary to solve for the temperature at a given point using the surrounding temperatures and if necessary a set of boundary conditions. An equation for each specific point has been developed by the previous MIT group. These equations reduce to the general form of

$$T_{i,j} = \frac{x_A T_{i+a_p,j} + x_B T_{i-a_n,j} + x_C T_{i,j+b_p} + x_D T_{i,j-b_n} + x_Q \left(\frac{h_{gas}}{K} T_B + rod \right) + \frac{S}{K}}{x_A + x_B + x_C + x_D + x_Q \frac{h_{gas}}{K}} \quad (29)$$

A specific set of coefficients for each of the 23 different types of points are given in Appendix 9.1.3.

It was not possible to combine the temperature solution calculations into a subroutine because so many of the variables were different for each of the 23 types of points. This fact accounts for the actual size of the program.

If a point is non-simple in both the r and θ directions, it becomes necessary to create an irregular boundary point $T_{i,j+b}$ at the θ -direction and $T_{i+a,j}$ in the r -direction. The temperature at these points are solved using the appropriate equations; then $T_{i,j}$ is solved with the new values of $T_{i+a,j}$ and $T_{i,j+b}$. If a point is non-simple in one direction, a corresponding irregular boundary point is defined and $T_{i,j}$ solved by the use of this $T_{i+a,j}$ or $T_{i,j+b}$ in the appropriate equation. The coefficients for all the irregular boundary temperature equations are also found in Appendix 9.1.3.

4.6 Convergence Criteria

After a new temperature for each point in the lattice is established, the convergence section of the program is entered. The change in temperature between iterations is calculated for each point. If the change for the given point is greater than that for any other point in the lattice network, this difference is saved. Thus, when all new temperatures have been calculated, the largest change in temperature in the lattice is known. Simultaneously, the arithmetic average temperature of all the points in the lattice is computed.

Two convergence tests are made. First, the new system average temperature is subtracted from the old one and compared to the predetermined convergence criterion. If this criterion is not met, a second convergence test is made by comparing the largest change in temperature in the lattice to another criterion. When neither one is met, another iteration is started to obtain a better approximation for the profile.

5. RESULTS

A computed temperature profile was obtained for an axial position in the reactor of 9.875 in. at an irradiation time of 12 days. The convergence criteria for system average and worst point temperatures were set at 5×10^{-5} , and convergence was achieved after 174 iterations. The profile at the peripheral fuel rod centerline, i.e., $\theta=0$, is presented in Fig. 13.

A region map showing the location of each point in the system and the region number in which it lies is found on Fig. 14. The three lattice points, labeled 1, fell in gap 3 on the inner side of the peripheral fuel rod. The map represents each region shape as distorted by the change of coordinates necessary to accommodate the output format.

The shape of the centerline temperature profile is similar to the solutions obtained from HEATING3. The sharp breaks in the slope of the curve correspond to the large temperature differences across the gaps between regions.

When compared to experimental measurements in the fuel rods, the numerical solution deviated from them by less than 2.0%. The graphite thermocouple reading located between the rods was considerably too high. For this solution, an initial temperature guess of 700°C was used for the graphite, apparently a poor estimate.

6. CONCLUSIONS

1. A steady state model for heat transfer in ORR irradiation capsules has been completed, and a numerical solution obtained for one set of input parameters.

2. This program is more efficient than HEATING3 in obtaining a solution for this particular problem. Solutions for multiple time intervals can be obtained from one run, and no manual calculations are necessary, as was the case with HEATING3. The computation time per solution on the IBM 360-91 may be less than that for HEATING3, though no such run has yet been made.

7. RECOMMENDATIONS

Suggestions for further study are:

1. Experiment with different lattice sizes to determine their effect on solution accuracy.

2. Test different convergence criteria to optimize program efficiency with respect to accuracy and computation time.

3. Run with different sets of input data to insure that a universal solution is obtainable.

4. Modify the heat generation functions to account for the volumetric expansion of the materials.

8. ACKNOWLEDGMENTS

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9. APPENDIX

9.1 Finite Difference Equations

9.1.1 Determination of Finite Difference Equation for a Simple Interior Point

The equation for steady state heat conduction in R- θ coordinates is:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} = - \frac{S}{K(T)}$$

where S is the heat generation. The temperature at i, j from surrounding points is calculated with a Taylor series expansion.

$$T_{i+1,j} = T_{ij} + \Delta r \left. \frac{\partial T}{\partial r} \right|_{ij} + \frac{(\Delta r)^2}{2} \left. \frac{\partial^2 T}{\partial r^2} \right|_{ij} + \dots$$

$$T_{i-1,j} = T_{ij} - \Delta r \left. \frac{\partial T}{\partial r} \right|_{ij} + \frac{(\Delta r)^2}{2} \left. \frac{\partial^2 T}{\partial r^2} \right|_{ij}$$

$$T_{i,j+1} = T_{ij} + (r\Delta\theta) \left. \frac{\partial T}{r\partial\theta} \right|_{ij} + \frac{(r\Delta\theta)^2}{2} \left. \frac{\partial^2 T}{r^2\partial\theta^2} \right|_{ij}$$

$$T_{i,j-1} = T_{ij} - (r\Delta\theta) \left. \frac{\partial T}{r\partial\theta} \right|_{ij} + \frac{(r\Delta\theta)^2}{2} \left. \frac{\partial^2 T}{r^2\partial\theta^2} \right|_{ij}$$

Multiplying each equation by a constant and adding gives:

$$\begin{aligned}
 (A-B)\Delta r \left. \frac{\partial T}{\partial r} \right|_{ij} + (C-D)(r\Delta\theta) \left. \frac{\partial T}{r\partial\theta} \right|_{ij} + (A+B)\frac{(\Delta r)^2}{2} \left. \frac{\partial^2 T}{\partial r^2} \right|_{ij} \\
 + (C+D)\frac{(r\Delta\theta)^2}{2} \left. \frac{\partial^2 T}{r^2\partial\theta^2} \right|_{ij} = A(T_{i+1,j} - T_{ij}) + B(T_{i-1,j} - T_{ij}) \\
 + C(T_{i,j+1} - T_{ij}) + D(T_{i,j-1} - T_{ij})
 \end{aligned}$$

Equating the coefficients of the differential terms with those of the partial differential equation and solving for ABCD yields,

$$\begin{aligned}
 \left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} \right]_{ij} &= \frac{1}{(\Delta r)^2} \left[\left(1 - \frac{1}{2i}\right) T_{i-1,j} + \left(1 + \frac{1}{2i}\right) T_{i+1,j} \right. \\
 &\quad \left. - 2T_{ij} \right] + \frac{1}{i^2 (\Delta r \Delta \theta)^2} [T_{i,j-1} + T_{i,j+1} - 2T_{ij}] = -\frac{S}{K(T_{i,j})} \\
 i &= 1, 2, 3, \dots \dots \dots \quad j = 1, 2, 3, \dots \dots
 \end{aligned}$$

Solving for $T_{i,j}$ we obtain the result:

$$T_{ij} = \frac{\frac{1}{(\Delta r)^2} \left[\left(1 - \frac{1}{2i}\right) T_{i-1,j} + \left(1 + \frac{1}{2i}\right) T_{i+1,j} \right] + \frac{T_{i,j+1} + T_{i,j-1}}{i^2 (\Delta r \Delta \theta)^2} + \frac{S}{K(T_{i,j})}}{\frac{2}{(\Delta r)^2} + \frac{2}{i^2 (\Delta r \Delta \theta)^2}}$$

9.1.2 Determination of Finite Difference Equation for a Regular Corner Point

The equation for a regular corner point (Boundary 8) is:

$$k(T) \left[\frac{\partial^2 T}{\partial R^2} + \frac{1}{R} \frac{\partial T}{\partial R} + \frac{1}{R^2} \frac{\partial^2 T}{\partial \theta^2} \right] + S = 0$$

The Taylor expansions in terms of the surrounding temperatures are:

$$A \quad T_{i-1,j} = T_{i,j} - \Delta R \left. \frac{\partial T}{\partial R} \right|_{i,j} + \frac{(\Delta R)^2}{2} \left. \frac{\partial^2 T}{\partial R^2} \right|_{i,j} + \dots$$

$$B \quad T_{i,j-1} = T_{i,j} - R\Delta\theta \left. \frac{\partial T}{\partial \theta} \right|_{i,j} + \frac{(R\Delta\theta)^2}{2} \left. \frac{\partial^2 T}{\partial \theta^2} \right|_{i,j} + \dots$$

The boundary conditions are:

$$C \quad k \left. \frac{\partial T}{\partial R} \right|_{i,j} = \frac{k_g}{G}(T_B - T_{i,j}) + h_{\text{rad}}(T_B^4 - T_{i,j}^4)$$

$$D \quad \frac{k \partial T}{R \partial \theta} \Big|_{i,j} = 0$$

If each equation is multiplied by a constant A, B, C, or D and the partial terms are collected,

$$\begin{aligned} & (-A\Delta R + C) \left. \frac{\partial T}{\partial R} \right|_{i,j} + \frac{A(\Delta R)^2}{2} \left. \frac{\partial^2 T}{\partial R^2} \right|_{i,j} + (-BR\Delta\theta + D) \left. \frac{\partial T}{\partial \theta} \right|_{i,j} + \frac{B(R\Delta\theta)^2}{2} \left. \frac{\partial^2 T}{\partial \theta^2} \right|_{i,j} \\ & = A(T_{i-1,j} - T_{i,j}) + B(T_{i,j-1} - T_{i,j}) + C \left[\frac{k_g}{kG}(T_B - T_{i,j}) \right. \\ & \quad \left. + h_{\text{rad}}(T_B^4 - T_{i,j}^4) \right] \end{aligned}$$

Then solve for A, B, C, and D:

$$\begin{aligned} A &= [2/(\Delta R)^2] & B &= [2/i^2 \Delta R^2 \Delta \theta^2] \\ C &= [(1/i \Delta R) + (2/\Delta R)] & D &= [2/i \Delta R \Delta \theta] \end{aligned}$$

Finally,

$$\left. \frac{\partial^2 T}{\partial R^2} + \frac{1}{R} \frac{\partial T}{\partial R} + \frac{1}{R^2} \frac{\partial^2 T}{\partial \theta^2} \right|_{i,j} = \left(\frac{2}{\Delta R^2} \right) (T_{i-1,j} - T_{i,j}) + \left(\frac{2}{i^2 \Delta R^2 \Delta \theta^2} \right) \\ \times (T_{i,j-1} - T_{i,j}) - \left(\frac{1}{i \Delta R} + \frac{2}{\Delta R} \right) \left[\frac{kq}{kG} (T_B - T_{i,j}) + h_{rad} (T_B^4 - T_{i,j}^4) \right]$$

Finally, solve for a new $T_{i,j}$ with a value of $T_{i,j}$ from previous iteration in the radiation term.

9.1.3 Summary of Finite Difference Equations

All of the finite difference equations derived by Stiros *et al.* presented the nodal temperature $T_{i,j}$ as a function of the four nodal temperatures surrounding the node at i,j . Boundary point equations replaced one or two of these surrounding nodal temperatures with terms corresponding to the boundary condition(s). In addition, a heat generation term occurred in Eqs. (1) through (9) and (20) of the Stiros report. By defining the temperatures in the direction of increasing R as $T_{i+a_p,j}$, in the direction of decreasing R as $T_{i-a_n,j}$, and in the two θ -directions as $T_{i,j+b_p}$ and $T_{i,j-b_n}$, a general equation was developed. The values of a_p , a_n , b_p , and b_n are one for interior simple points, while up to three of these values could be between zero and one for the different types of interior non-simple points. For interior points, the boundary condition is absent, so the boundary term coefficient X_Q is zero. For boundary points, one or two of the surrounding nodal points are not included in the finite difference expansion, so the coefficients corresponding to these temperatures are zero and X_Q is non-zero. In this form for example, Eq. (A9)

$$T_{i,j} = \frac{\left[\frac{2}{(\Delta R)^2} \right] T_{i-1,j} + \left[\frac{2}{(i \Delta R \Delta \theta)^2} \right] T_{i,j-1} + \left[\frac{1+2i}{i \Delta R} \right] \left[\frac{kq}{Gk} T_B + \frac{\sigma f}{k} (e_1 T_B^4 - e_2 T_{i,j}^4) \right] + \frac{S}{K}}{\left[\frac{2}{(\Delta R)^2} \right] + \left[\frac{2}{(i \Delta R \Delta \theta)^2} \right] + \left[\frac{1+2i}{i \Delta R} \right] \left[\frac{kq}{Gk} \right]} \quad (30)$$

can be represented as

$$T_{i,j} = \frac{X_A T_{i+1,j} + X_B T_{i-1,j} + X_C T_{i,j+1} + X_D T_{i,j-1} + X_Q \left[\frac{h_{cond}}{K} T_B + q_{rad} \right] + \frac{S}{K}}{X_A + X_B + X_C + X_D + X_Q \left(\frac{h_{cond}}{K} \right)} \quad (31)$$

where:

$$x_A = 0$$

$$x_B = \frac{2}{(\Delta R)^2}$$

$$x_C = 0$$

$$x_D = \frac{2}{(i\Delta R\Delta\theta)^2}$$

$$x_Q = \frac{1 + 2i}{i\Delta R}$$

Table 1 presents the coefficient values for each type of point.

9.1.4 Derivation of Additional Finite Difference Equations

Equation (A19) applies to a special interior non-simple point in region 3 with three irregular boundary points (see Fig. 7). At $(\gamma - \theta) = 90^\circ$, the Taylor expansions for $T_{i+a,j}$ in Eqs. (A12) and (A13) will cause a computer overflow because they involve the calculation of $1/\cos(\gamma - \theta)$ as $\cos(\gamma - \theta)$ approaches zero. To prevent this situation, the equation is written by ignoring the flux from $T_{i,j}$ to the two $T_{i+a,j}$ points. Thus the flux from $T_{i,j}$ to $T_{i,j+b}$ equals the flux from $T_{i,j-1}$ to $T_{i,j}$. Let

$$\frac{\partial T}{R\Delta\theta} \approx \frac{\Delta T}{R\Delta\theta}$$

$$-k \frac{T_{i,j} - T_{i,j-1}}{R\Delta\theta} = -k \frac{T_{i,j+b} - T_{i,j}}{b_p R\Delta\theta}$$

or

$$T_{i,j} = \frac{T_{2i,j} - (T_{i,j-1})b_p}{1 + b_p}$$

Equation (A20) applies to a special simple boundary point at the tangent location on the graphite fuel rod hole (see Fig. 8). Standard expansions are applied in three directions, and the single boundary condition is applied in the negative θ direction:

$$T_{i+1,j} = T_{i,j} + \Delta R \frac{\partial T}{\partial R} + \frac{(\Delta R)^2}{2} \frac{\partial^2 T}{\partial R^2}$$

Table 1. Coefficients for Finite Difference Equations

A. Regular Lattice Point Equations

Equation No.	Boundary No. (See Fig. 3)	Conditions	I_A	I_B	I_C	I_D	I_Q	Heat Generation Term Present
A1	-	Interior Simple Point	$\frac{1}{(\Delta R)^2} \left(1 + \frac{1}{2\tau} \right)$	$\frac{1}{(\Delta R)^2} \left(1 - \frac{1}{2\tau} \right)$	$\frac{1}{(1 \pm R \pm \theta)^2}$	$\frac{1}{(1 \pm R \pm \theta)^2}$	0	yes
A2	1	Simple Boundary Point	$\frac{1}{(\Delta R)^2} \left(1 + \frac{1}{2\tau} \right)$	$\frac{1}{(\Delta R)^2} \left(1 - \frac{1}{2\tau} \right)$	$\frac{2}{(1 \pm R \pm \theta)^2}$	0	0	yes
A3	2	Simple Boundary Point	$\frac{1}{(\Delta R)^2} \left(1 + \frac{1}{2\tau} \right)$	$\frac{1}{(\Delta R)^2} \left(1 - \frac{1}{2\tau} \right)$	0	$\frac{2}{(1 \pm R \pm \theta)^2}$	0	yes
A4	3	Simple Boundary Point	$\frac{2}{(\Delta R)^2}$	0	$\frac{1}{(1 \pm R \pm \theta)^2}$	$\frac{1}{(1 \pm R \pm \theta)^2}$	$\frac{1+2\tau}{1 \pm R}$	yes
A5	4	Simple Boundary Point	0	$\frac{2}{(\Delta R)^2}$	$\frac{1}{(1 \pm R \pm \theta)^2}$	$\frac{1}{(1 \pm R \pm \theta)^2}$	$\frac{1+2\tau}{1 \pm R}$	yes
A6	5	Simple Boundary Point	$\frac{2}{(\Delta R)^2}$	0	$\frac{2}{(1 \pm R \pm \theta)^2}$	0	$\frac{2\tau-1}{1 \pm R}$	yes
A7	6	Simple Boundary Point	0	$\frac{2}{(\Delta R)^2}$	$\frac{2}{(1 \pm R \pm \theta)^2}$	0	$\frac{1+2\tau}{1 \pm R}$	yes
A8	7	Simple Boundary Point	$\frac{2}{(\Delta R)^2}$	0	0	$\frac{2}{(1 \pm R \pm \theta)^2}$	$\frac{2\tau-1}{1 \pm R}$	yes
A9	8	Simple Boundary Point	0	$\frac{2}{(\Delta R)^2}$	0	$\frac{2}{(1 \pm R \pm \theta)^2}$	$\frac{1+2\tau}{1 \pm R}$	yes
A10	9, 11	Simple Boundary Sector 1, Graphite	$\frac{1}{\Delta R \cos \theta}$	0	0	0	1	no
A11	9, 10	Simple Boundary Sector 2, Graphite	0	$\frac{-1}{\Delta R \cos \theta}$	0	0	1	no
A12	9, 10	Simple Boundary Sector 3, Peripheral Fuel Rod	$\frac{-1}{\Delta R \cos \theta}$	0	0	0	1	no
A13	9, 11	Simple Boundary Sector 4, Peripheral Fuel Rod	0	$\frac{1}{\Delta R \cos \theta}$	0	0	1	no
A18	-	Interior Non-Simple Point General Equation	$\left[\frac{a_n^2}{a_n a_p + a_p^2} \right] \left[\frac{2}{(a_n \Delta R)^2} - \frac{a_p}{a_n^2 (\Delta R)^2} \right] - \frac{a_p}{a_n^2 (1 \pm R)^2} + \left[\frac{1}{a_p (1 \pm R)^2} \right]$	$\left[\frac{2}{(a_n \Delta R)^2} - \frac{a_p}{a_n^2 (\Delta R)^2} \right] + \left[\frac{a_n}{a_n + a_p} \right]$	$\frac{2(b_n/b_p)}{[b_n(1 \pm R \pm \theta)]^2} + (1 \pm R \pm \theta)^2$	$\frac{2}{[b_p(1 \pm R \pm \theta)]^2} + (1 \pm R \pm \theta)^2$	0	yes
A19	9	Special Interior Non-Simple Point Near Region 3 Tangent	-	-	1	b_p	-	no
A2.1	1	Non-Simple Near 5	$\frac{2\tau + a_n}{(a_n + 1)(\Delta R)^2}$	$\frac{2\tau - 1}{(a_n + 1)(\Delta R)^2}$	$\frac{2}{(1 \pm R \pm \theta)^2}$	0	0	yes
A2.2	1	Non-Simple Near 6	$\frac{2\tau + 1}{(a_p(a_p + 1)(\Delta R)^2)}$	$\frac{2\tau - a_p}{(a_p + 1)(\Delta R)^2}$	$\frac{2}{(1 \pm R \pm \theta)^2}$	0	0	yes
A3.1	2	Non-Simple Near 7	$\frac{2\tau + a_n}{(a_n + 1)(\Delta R)^2}$	$\frac{2\tau - 1}{(a_n + 1)(\Delta R)^2}$	0	$\frac{2}{(1 \pm R \pm \theta)^2}$	0	yes
A3.2	2	Non-Simple Near 8	$\frac{2\tau + 1}{(a_p(a_p + 1)(\Delta R)^2)}$	$\frac{2\tau - a_p}{(a_p + 1)(\Delta R)^2}$	0	$\frac{2}{(1 \pm R \pm \theta)^2}$	0	yes
A20	9	Simple Boundary at Tangent Point to Fuel Rod Hole, Region 4	$\frac{1}{(\Delta R)^2} \left(1 + \frac{1}{2\tau} \right)$	$\frac{1}{(\Delta R)^2} \left(1 - \frac{1}{2\tau} \right)$	$\frac{2}{(1 \pm R \pm \theta)^2}$	-	$\frac{2}{1 \pm R \pm \theta}$	yes

Table 1. Coefficients for Finite Difference Equations (continued)

B. Normal Region Irregular Boundary Point Temperature $\{T_{1,j}\}$ - Equation Coefficients								
Equation No.	Boundary No. (See Fig. 3)	Conditions	I_{1A}	I_{1B}	I_{1C}	I_{1D}	I_{1E}	Heat Generation Term Present
A4	3	positive R direction	$2(a_n - R)^2$	-	$1/(1-R\sin\theta)^2$	$1/(1-R\cos\theta)^2$	$1/(1-R) + 2/a_n \cdot R$	no
A5	4	positive R direction	-	$2(a_p - R)^2$	$1/(1-R\sin\theta)^2$	$1/(1-R\cos\theta)^2$	$1/(1-R) + 2/a_p \cdot R$	no
A6	5	corner point	$2/a_p \cdot R^2$	-	$2/(1-R\sin\theta)^2$	-	$1/(1-R) + 2/a_p \cdot R$	no
A7	6	corner point	-	$2/a_p \cdot R^2$	$2/(1-R\sin\theta)^2$	-	$1/(1-R) + 2/a_p \cdot R$	no
A8	7	corner point	$2/(a_n - R)^2$	-	-	$2/(1-R\cos\theta)^2$	$1/(1-R) + 2/a_n \cdot R$	no
A9	8	corner point	-	$2/(a_p - R)^2$	-	$2/(1-R\cos\theta)^2$	$1/(1-R) + 2/a_p \cdot R$	no
C. Special Region Irregular Boundary Point Temperature $\{T_{1,j}\}$ - Equation Coefficients								
A10	9, 11	sector 1	-	$1/a_n \cdot R \cos\theta$	-	-	1.0	no
A11	9, 10	sector 2	$-1/a_p \cdot R \cos\theta$	-	-	-	1.0	no
A12	9, 10	sector 3	-	$-1/a_n \cdot R \cos\theta$	-	-	1.0	no
A13	9, 11	sector 4	$1/a_p \cdot R \cos\theta$	-	-	-	1.0	no
D. Special Region Irregular Boundary Point Temperature $\{T_{2,j}\}$ - Equation Coefficients								
A14			I_{2A}	I_{2B}	I_{2C}	I_{2D}	I_{2E}	no
A14	9	sector 1	-	-	$1/(1-R\sin\theta)$	-	1.0	no
A15	identical equations	sector 2						
A16		sector 3						
A17		sector 4						
		where $b = b_p$ or b_n						
A17	9	special case on region 3 radial tangent point where $\theta = \pi/2$	-	-	-	$1/(1-R\sin\theta)$	1.0	no
						[$R\sin\theta = 1.0$]		

$$T_{i-1,j} = T_{i,j} - \Delta R \frac{\partial T}{\partial R} + \frac{(\Delta R)^2}{2} \frac{\partial^2 T}{\partial R^2}$$

$$T_{i,j+1} = T_{i,j} + R\Delta\theta \frac{\partial T}{\partial \theta} + \frac{(R\Delta\theta)^2}{2} \frac{\partial^2 T}{\partial \theta^2}$$

and

$$-\frac{\partial T}{\partial \theta} = \frac{kg}{Gk}(T_B - T_{i,j}) + \frac{\sigma F}{k}(e_1 T_B^4 - e_2 T_{i,j}^4)$$

Multiply each by a constant; then add:

$$\begin{aligned} A(T_{i+1,j} - T_{i,j}) + B(T_{i-1,j}) + C(T_{i,j+1} - T_{i,j}) + Q\left[\frac{kg}{Gk}(T_B - T_{i,j})\right. \\ \left. + \frac{\sigma F}{k}(e_1 T_B^4 - e_2 T_{i,j}^4)\right] = (A\Delta R - B\Delta R) \frac{\partial T}{\partial R} + (A + B) \frac{\Delta R^2}{2} \frac{\partial^2 T}{\partial R^2} \\ + (CR\Delta\theta - Q) \frac{\partial T}{\partial \theta} + \frac{(\Delta R)^2}{2} (C) \frac{\partial^2 T}{\partial \theta^2} \end{aligned}$$

Solve for the constants by equating coefficients with the Laplacian:

$$A - B = \frac{1}{R\Delta R}$$

$$A + B = \frac{2}{\Delta R^2}$$

$$A = \left(1 + \frac{1}{2i}\right) \frac{1}{\Delta R^2}$$

$$C = \frac{2}{(i\Delta R\Delta\theta)^2}$$

$$B = \left(1 + \frac{1}{2i}\right) \left(\frac{1}{\Delta R^2}\right) - \left(\frac{1}{i\Delta R^2}\right) = \left(1 - \frac{1}{2i}\right) \frac{1}{\Delta R^2}$$

$$Q = \frac{2}{i\Delta R\Delta\theta}$$

Finally, solving for $T_{i,j}$:

$$T_{i,j} = \frac{1}{(\Delta r)^2} \left(1 + \frac{1}{2i}\right) T_{i+1,j} + \frac{1}{(\Delta r)^2} \left(1 - \frac{1}{2i}\right) T_{i-1,j} +$$

$$\frac{\frac{2}{(i\Delta r\Delta\theta)^2} T_{i,j+1} + \frac{2}{i\Delta r\Delta\theta} [\text{boundary condition}] + \frac{S}{K}}{\frac{2}{(\Delta r)^2} + \frac{2}{(i\Delta r\Delta\theta)^2} + \frac{2}{i\Delta r\Delta\theta} \left(\frac{k_g}{Gk}\right)}$$

Equations (A2.1), (A2.2), (A3.1), and (A3.2) were necessary to treat non-simple boundary points falling within one lattice increment from any of the four types of corner points, boundaries 5, 6, 7, and 8 as shown in Fig. 6. Taylor series expansions can be applied for the two regular lattice temperatures and the single irregular point temperature values. The boundary condition in the θ direction is then included, and an expression for $T_{i,j}$ is derived.

Equation (A2.1) is for a point on boundary 1 near corner 5. The Taylor series expansions are:

$$T_{i,j+1} = T_{i,j} + r\Delta\theta \frac{\partial T}{r\partial\theta} + \frac{(r\Delta\theta)^2}{2} \frac{\partial^2 T}{r^2 \partial\theta^2}$$

$$T_{i,j-1} = T_{i-a,j} = T_{i,j} - a\Delta r \frac{\partial T}{\partial r} + \frac{(a\Delta r)^2}{2} \frac{\partial^2 T}{\partial r^2}$$

$$T_{i+1,j} = T_{i,j} + \Delta r \frac{\partial T}{\partial r} + \frac{(\Delta r)^2}{2} \frac{\partial^2 T}{\partial r^2}$$

Invoke the boundary condition,

$$\frac{\partial T}{r\partial\theta} = 0$$

Multiply each expression by a constant:

$$\begin{aligned}
& A(T_{i,j+1} - T_{i,j}) + B(T_{i-a,j} - T_{i,j}) + C(T_{i+1,j} - T_{i,j}) \\
& = (Ar\Delta\theta + D) \frac{\partial T}{r\partial\theta} + A \frac{(r\Delta\theta)^2}{2} \frac{\partial^2 T}{r^2 \partial\theta^2} + (C\Delta r - Ba\Delta r) \frac{\partial T}{\partial r} \\
& + \left[B \frac{(a\Delta r)^2}{2} + C \frac{(\Delta r)^2}{2} \right] \frac{\partial^2 T}{\partial r^2} = -\frac{S}{K}
\end{aligned}$$

Solve for the constants by comparing coefficients:

$$Ar\Delta\theta + D = 0 \qquad A \frac{(r\Delta\theta)^2}{2} = 1$$

$$D = \frac{-2}{r\Delta\theta} \qquad A = \frac{2}{(r\Delta\theta)^2}$$

$$B \frac{(a\Delta r)^2}{2} + C \frac{(\Delta r)^2}{2} = 1 \qquad (C - Ba)\Delta r = \frac{1}{r}$$

$$C - Ba = \frac{1}{r\Delta r}$$

$$C + Ba^2 = \frac{2}{(\Delta r)^2}$$

$$B(a^2 + a) = \frac{2}{(\Delta r)^2} - \frac{1}{(r\Delta r)}$$

$$B = \frac{1}{a(a+1)(\Delta r)^2} \left(2 - \frac{1}{i}\right) = \frac{2i-1}{ia(a+1)(\Delta r)^2}$$

$$C = \frac{2i-1}{i(a+1)(\Delta r)^2} + \frac{1}{r\Delta r}$$

$$C = \frac{(2i-1) + (a+1)}{i(a+1)(\Delta r)^2} = \frac{2i+a}{i(a+1)(\Delta r)^2}$$

Solving for $T_{i,j}$,

$$T_{i,j} = \frac{\frac{2T_{i,j+1}}{(i\Delta r\Delta\theta)^2} + \frac{(2i-1)T_{i-a,j}}{ia(a+1)(\Delta r)^2} + \frac{(2i+a)T_{i+1,j}}{i(a+1)(\Delta r)^2} + \frac{S}{K}}{\frac{2}{(i\Delta r\Delta\theta)^2} + \frac{2i-1}{ia(a+1)(\Delta r)^2} + \frac{2i+a}{i(a+1)(\Delta r)^2}}$$

Equation (A2.2) is for a point on boundary 1 near corner 6. The Taylor series expansions in three directions are:

$$T_{i,j+1} = T_{i,j} + r\Delta\theta \frac{\partial T}{\partial\theta} + \frac{(r\Delta\theta)^2}{2} \frac{\partial^2 T}{\partial\theta^2}$$

$$T_{i-1,j} = T_{i,j} - \Delta r \frac{\partial T}{\partial r} + \frac{(\Delta r)^2}{2} \frac{\partial^2 T}{\partial r^2}$$

$$T_{i+a,j} = T_{i,j} + a\Delta r \frac{\partial T}{\partial r} + \frac{(a\Delta r)^2}{2} \frac{\partial^2 T}{\partial r^2}$$

Invoke the single boundary condition:

$$\frac{\partial T}{\partial\theta} = 0$$

Factoring out $T_{i,j}$,

$$T_{i,j} = \frac{AT_{i,j+1} + BT_{i-1,j} + CT_{i+a,j} + \frac{S}{K}}{A + B + C}$$

Equate coefficients with the Laplacian and solve:

$$Ar\Delta\theta + D = 0$$

$$A \frac{(r\Delta\theta)^2}{2} = 1$$

$$D = \frac{-2}{r\Delta\theta}$$

$$A = \frac{2}{(r\Delta\theta)^2}$$

$$B \frac{(\Delta r)^2}{2} + C \frac{(a\Delta r)^2}{2} = 1$$

$$(Ca - B)\Delta r = \frac{1}{r}$$

$$(B + Ca^2) = \frac{2}{(\Delta r)^2}$$

$$Ca - B = \frac{1}{r\Delta r}$$

$$C(a^2 + a) = \frac{1}{i(\Delta r)^2} + \frac{2}{(\Delta r)^2} = \frac{1 + 2i}{i(\Delta r)^2} \quad C = \frac{1 + 2i}{ia(a + 1)(\Delta r)^2}$$

$$B = \frac{1 + 2i}{(a + 1)i(\Delta r)^2} - \frac{1}{i(\Delta r)^2} = \frac{2i - a}{i(a + 1)(\Delta r)^2}$$

Finally,

$$T_{i,j} = \frac{\frac{2T_{i,j+1}}{(i\Delta r\Delta\theta)^2} + \frac{(2i - a)T_{i-1,j}}{i(a + 1)(\Delta r)^2} + \frac{(1 + 2i)T_{i+a,j}}{ia(a + 1)(\Delta r)^2} + \frac{S}{K}}{\frac{2}{(i\Delta r\Delta\theta)^2} + \frac{2i - a}{i(a + 1)(\Delta r)^2} + \frac{2i + 1}{ia(a + 1)(\Delta r)^2}}$$

Equation (A3.1) is for a point on boundary 2 near corner 7. The only difference between this and Eq. (A2.1) is $(D - Ar\Delta\theta) = 0$. Thus,

$$A = \frac{2}{(i\Delta r\Delta\theta)^2} = D$$

$$B = \frac{2i - 1}{ia(a + 1)(\Delta r)^2} \quad C = \frac{2i + a}{i(a + 1)(\Delta r)^2}$$

Solving,

$$T_{i,j} = \frac{\frac{2T_{i,j-1}}{(i\Delta r\Delta\theta)^2} + \frac{(2i - 1)T_{i-a,j}}{ia(a + 1)(\Delta r)^2} + \frac{(2i + a)T_{i+1,j}}{i(a + 1)(\Delta r)^2} + \frac{S}{K}}{\frac{2}{(i\Delta r\Delta\theta)^2} + \frac{2i - 1}{ia(a + 1)(\Delta r)^2} + \frac{2i + a}{i(a + 1)(\Delta r)^2}}$$

Equation (A3.2) is for a point on boundary 2 near corner 8. The only difference between Eq. (A2.2) and (A3.2) is $(D - Ar\Delta\theta) = 0$. Then

$$A = \frac{2}{(i\Delta r\Delta\theta)^2}$$

$$D = \frac{+2}{(i\Delta r\Delta\theta)^2}$$

$$B = \frac{2i - a}{i(a + 1)(\Delta r)^2}$$

$$C = \frac{i + 2i}{ia(a + 1)(\Delta r)^2}$$

Finally,

$$T_{i,j} = \frac{\frac{2T_{i,j-1}}{(i\Delta r\Delta\theta)^2} + \frac{2i - a}{i(a + 1)(\Delta r)^2} T_{i-1,j} + \frac{1 + 2i}{ia(a + 1)(\Delta r)^2} T_{i+a,j} + \frac{S}{K}}{\frac{2}{(i\Delta r\Delta\theta)^2} + \frac{2i - a}{i(a + 1)(\Delta r)^2} + \frac{2i + 1}{ia(a + 1)(\Delta r)^2}}$$

9.2 Input Information

The following card types are required as program input and are listed in the order in which they must appear in the data deck. The input variable names are also listed.

<u>Card type (quantity)</u>	<u>Columns</u>	<u>Format</u>	<u>Label and Description</u>
1(1)			<u>Program Control Information</u>
	1 - 2	(I2)	NCASE = number of data sets to be entered
	8 - 10	(I3)	MAXIT = upper limit of number of iterations through the entire lattice
	11 - 20	(E10.0)	CCR1 = lattice point temperature convergence criterion
	21 - 30	(E10.0)	CCR2 = average capsule temperature convergence criterion

Card types 2 and 6 must be read in order of region number NREG where,

<u>Card No.</u>	<u>NREG</u>	<u>Region</u>
1	2	Central fuel rod
2	3	Peripheral fuel rod
3	4	Graphite
4	5	Interior stainless steel cladding
5	6	Exterior stainless steel cladding

No card should be read for a gap where NREG is 1.

<u>Card Type (Quantity)</u>	<u>Columns</u>	<u>Format</u>	<u>Label and Description</u>
2(5)			
	10	(I1)	MATR(NREG) material number for each region. 1 = fuel rod, 2 = stainless steel, 3 = graphite
	11 - 20	(F10.0)	TIN(NREG) = initial temperature guess for each region, °C
	21 - 30	(F10.0)	RMIN(NREG) = minimum radial dimension, in., at 25°C for each region. No number must be entered for peripheral fuel rod.
	31 - 40		RMAX(NREG) = maximum radial dimension, in., at 25°C for each region. No number must be entered for peripheral fuel rod.
			<u>Special Region Dimensions</u>
3(1)	1 - 10	(F10.0)	RPO = distance from capsule center to center of peripheral fuel rod, in.
	11 - 20	(F10.0)	RF#3 = radius of peripheral fuel rod at 25°C, in.
	21 - 30	(F10.0)	RF#4 = radius of peripheral fuel rod hole at 25°C, in.
4(1)			<u>Lattice Information</u>
	1 - 10	(F10.0)	RLMAX = maximum radial dimension of lattice, in. RLMAX should be greater than radius of capsule at hot temperature of exterior stainless steel cladding.
	18 - 20	(I3)	NRDL = number of lattice points along any line of constant angle.
	28 - 30	(I3)	THRDL = number of lattice points along any line of constant radial distance from origin.
5(1)			<u>Axial Position of Cross-Section</u>
	1 - 10	(F10.0)	ZPOS = axial position of fuel capsule cross section relative to reactor end, in.

<u>Card Type (quantity)</u>	<u>Columns</u>	<u>Format</u>	<u>Label and Description</u>
6(1)			Time information
	1 - 10	(F10.0)	TMIN = first time for which temperature profile must be calculated, days
	11 - 20	(F10.0)	TMAX = last time for which temperature profile must be calculated, days
	21 - 30	(F10.0)	DT = time increment from TMIN to TMAX, days
	39 - 40	(I2)	NHE = number of time intervals with different sweep gas compositions
7a(2)			Fuel Rods - Fission Power Density Coefficients
	1 - 10	(F10.0)	C0(L) = zeroth order t coefficient
	11 - 20	(F10.0)	C1(L) = first order t coefficient
	21 - 30	(F10.0)	C2(L) = third order t coefficient
			where L = 2 central fuel rod L = 3 peripheral fuel rod
7b(5)			Power Density Coefficients - Gamma Heating
	1 - 10	(F10.0)	C0(L) = zeroth order z coefficient
	11 - 20	(F10.0)	C1(L) = first order z coefficient
	21 - 30	(F10.0)	C2(L) = second order z coefficient
			where L = 1 fuel rods L = 4 graphite L = 5 stainless steel L = 6 stainless steel

The type 7 data cards must be read in order L = 1, 2, 3, 4, 5, 6.

8 (NHE)			<u>Sweep Gas Composition</u>
	1 - 10	(F10.0)	HE = mole fraction of helium in sweep gas
	11 - 20	(F10.0)	HTIME = final time, days, corresponding to HE value

<u>Card Type (quantity)</u>	<u>Columns</u>	<u>Format</u>	<u>Label and Description</u>
9(1)			<u>Flux Coefficients</u>
	1 - 10	(F10.0)	FF0 = zeroth order coefficient
	11 - 20	(F10.0)	FF1 = first order coefficient
	21 - 30	(F10.0)	FF2 = second order coefficient
	31 - 40	(F10.0)	FF3 = third order coefficient

Card types 11 and 12 should be read in the following order, based on material number NMAT.

<u>NMAT</u>	<u>M</u>	<u>Material</u>
1	1	fuel rods
	2	fuel rods
	3	fuel rods
	4	fuel rods
2	1	stainless steel
	2	stainless steel
	3	stainless steel
	4	stainless steel
3	1	graphite
	2	graphite
	3	graphite
	4	graphite

<u>Card Type (quantity)</u>	<u>Columns</u>	<u>Format</u>	<u>Label and Description</u>
10(12)			<u>Coefficients to compute Thermal Expansion Coefficient</u>
	1 - 15	(E15.0)	BETACO(NMAT,M,1) = (M-1) st order coefficient of temperature to compute zeroth order coefficient of fluence. If no coefficient, enter 0.

<u>Card Type (quantity)</u>	<u>Columns</u>	<u>Format</u>	<u>Label and Description</u>
	16 - 30	(E15.0)	BETACO(NMAT,M,2) = (M - 1) st order coefficient of temperature to compute first order coefficient of fluence. If no coefficient, enter 0.
	31 - 45	(E15.0)	BETACO(NMAT,M,3) = (M-1) st order coefficient of temperature to compute second order coefficient of fluence. If no coefficient, enter 0.
	46 - 60	(E15.0)	BETACO(NMAT,M,4) = (M-1) st order coefficient of temperature to compute third order coefficient of fluence. If no coefficient, enter 0.
11(12)			Coefficients to compute fuel rod and stainless steel <u>thermal conductivities</u>
	1 - 15	(E15.0)	KCO(NMAT, M, 1) + (M - 1) st order coefficient of temperature to compute zeroth order coefficient of fluence. If no coefficient, enter 0.
	16 - 30	(E15.0)	KCO(NMAT,M,2) = (M-1) st order coefficient of temperature to compute first order coefficient of fluence. If no coefficient, enter 0.
	31 - 45	(E15.0)	KCO(NMAT,M,3) = (M-1) st order coefficient of temperature to compute second order coefficient of fluence. If no coefficient, enter 0.
i2(7)			Coefficients to compute graphite <u>thermal conductivity</u>
	1 - 15	(E15.0)	GKCO(L,1) = zeroth order temperature coefficient
	16 - 30	(E15.0)	GKCO(L,2) = first order temperature coefficient
	31 - 45	(E15.0)	GKCO(L,3) = second order temperature coefficient
	46 - 60	(E15.0)	GKCO(L,4) = third order temperature coefficient

<u>Card type (quantity)</u>	<u>Columns</u>	<u>Format</u>	<u>Label and Description</u>
	61 - 75	(E15.0)	FKCO(L) = fluence associated with values of thermal conductivity from which the above coefficients were obtained in (10^{21} n/cm^2)
13(1)			<u>Capsule Exterior Conditions</u>
	1 - 10	(F10.0)	TWATER = temperature of water surrounding capsule, °C
	11 - 20	(F10.0)	HWATER = heat transfer coefficient from capsule to water, watts/cm-°C

9.3 Program Listing

```

C      HOTSTEP: A PROGRAM TO GENERATE TEMPERATURE PROFILES
C      IN ORR IRRADIATION TEST CAPSULES.
C
C      BY S.L. MICHAELS, R.C. MICHEL, AND G.R. WILKES
C      MIT PRACTICE SCHOOL, ORNL, APRIL 1976.
C
C      REQUESTED IN PACE
C
C      DIMENSIONS AND INITIALIZATIONS
C
REAL KCO(2,4,3)
REAL I2,K,NPD(6)
INTEGER REG(52,30)
LOGICAL IHREG,FUNNY,WE,PD,CUTER,ZERO,T
DIMENSION SUMT(6),KT(6)
DIMENSION C(6),C1(6),C2(6)
DIMENSION MATP(6),TIN(6),RMIN2(6),RMAX0(6)
DIMENSION AVT(6),RX(6),RMAX(6),RMIN(6)
DIMENSION HE(20),HTIME(20)
DIMENSION FKCO(7)
DIMENSION R(52),TH(30),RF(4)
DIMENSION E(6,2)
DIMENSION T(5,30),T1(50,30),T2(20,30)
DIMENSION NRUSE(20),NRUSE1(20)
DIMENSION GKCO(4,7)
DIMENSION BETACO(3,4,4)
DIMENSION NBOUN1(4),NBOUN2(4)
DIMENSION IBOUN1(4,100),IBOUN2(4,100)
DIMENSION JBOUN1(4,100),JBOUN2(4,100)

```

```

      I1 = 5
      IOUT=6
      PI = 3.1415926535
      ACUNT = 1
      E(1,1)=0.
      E(1,2)=0.
      F(2,1)=0
      E(2,2)=.9
      F(3,1)=.9
      F(3,2)=.9
      E(4,1)=.9
      E(4,2)=.9
      E(5,1)=0.75
      F(5,2)=0.5
      F(6,1)=0.5
      E(6,2)=0.

CC
C      INPUT DATA
C
C
C      PROGRAM CONTROL INFORMATION
1000 READ(IIN,1075) NCASE,MAXIT,CCR1,CCR2
1005 FORMAT(12,5X,13,2E1,2,50X)
      IF(NCASE.EQ.0) GO TO 9999
C
C      INITIAL REGION INFORMATION FOR FIVE REGIONS
C
      DO 1210 L=2,6
      READ(IIN,1015) MATR(L),TIN(L),RMING(L),RMAX0(L)
      RMING(L)=RMING(L)*2.54
1210  RMAX2(L)=RMAX2(L)*2.54
1015  FORMAT(9X,I1,4F12.7,30X)
C
C      SPECIAL REGION DIMENSIONS
C
      READ(IIN,1020) RP2,RF23,RF24
      RP2=RP2*2.54
      RF23=RF23*2.54
      RF24=RF24*2.54
1020  FORMAT (3F10.0,30X)
C
C      LATTICE INFORMATION
C
      READ(IIN,1030) PLMAX,NRDL,NTHDL
      PLMAX=PLMAX*2.54
1030  FORMAT (F10.0,2(7X,I3),70X)
C
C      2 POSITION
C

```



```

      READ (IIN,1235) ZPOS
1235 FORMAT (F12.7)
C
C      TIME INFORMATION
C
      READ(IIN,1242) ITMIN,ITMAX,DT,NHE
1242 FORMAT(3F12.7,2X,I2.4X)
C
C      POWER DENSITY COEFFICIENTS
C
      DO 1252 L=1,6
1252 READ(IIN,1227) C1(L),C2(L),C3(L)
C
C      SKEW GAS COMPOSITION
C
      DO 1262 L=1,NHE
1262 READ (IIN,1224) HE(L),YTIME(L)
C
C      FLUX COEFFICIENTS
C
      READ (IIN,1265) FF0,FF1,FF2,FF3
1265 FORMAT(4F12.6)
C
C      THERMAL EXPANSION COEFFICIENTS FOR FLUENCE AND
C      TEMPERATURE DEPENDENCY
C
      DO 1272 L=1,3
      DO 1273 M=1,4
1272 READ(IIN,1282) (SETACO(L,M,N), N=1,4)
1282 FORMAT (4E15.7,20X)
C
C      THERMAL CONDUCTIVITY COEFFICIENTS FOR FLUENCE AND
C      TEMPERATURE DEPENDENCY
C
      DO 1292 L=1,2
      DO 1293 M=1,4
1292 READ (IIN,1291) (KCO(L,M,N), N=1,3)
1291 FORMAT(3E15.7)
      DO 1292 L=1,7
1292 READ(IIN,1295) GKCO(1,L),GKCO(2,L),GKCO(3,L),
      AGKCO(4,L),FKCO(L)
1295 FORMAT(5E15.8,2X)
C      WATER TEMPERATURE AND HEAT TRANSFER COEFFICIENT
C
      READ(IIN,1112) TWATER, HWATER
1112 FORMAT(2F12.2)
C
C

```

```

RDL = RLMAX/NRDL
THDL = PI/4/NTHDL
RDL2 = RDL * RDL
THDL2 = THDL * THDL
RTHDL = RDL * THDL
RTHDL2 = RDL2 * THDL2
WRDL2 = 2./RDL2
ZEROIT = .TRUE.
JMAX = NTHDL*1

```

C
C
C
C
C
C
C
C

START OF ALGORITHM

FIX TIME

```

TIME = TTMIN
2002 DO 2005 IHE=2, NHE
    IF (TIME, LT, HTIME(IHE)) GO TO 2006
2005 CONTINUE
2006 NHEPER=NHE(IHE-1)

```

C
C
C

CALCULATE HEAT GENERATION

```

VAR = ZPOS * 3.4375
NPD(1) = CG(1) * C1(1) * VAR + C2(1) * VAR * VAR
NPD(2) = CG(2) * C1(2) * TIME + C2(2) * TIME * TIME
NPD(3) = CG(3) * C1(3) * TIME + C2(3) * TIME * TIME
NPD(4) = CG(4) * C1(4) * VAR + C2(4) * VAR * VAR
NPD(5) = CG(5) * C1(5) * VAR + C2(5) * VAR * VAR
NPD(6) = CG(6) * C1(6) * VAR + C2(6) * VAR * VAR
NPD(2) = NPD(1) * NPD(2)
NPD(3) = NPD(1) * NPD(3)

```

C
C
C

CALCULATE FLUX AND FLUENCE

```

Z = ZPOS * 3.4375
FLUX = FF0 + FF102 + FF20202 + 1/2 * FF3020202
FLU = FLUX * TIME * 0.64E-03

```

C
C
C

INITIALIZE REGION AVERAGE TEMPERATURES

```

DO 2032 L = 2, 6
2032 AVT(L) = TIN(L)
TC3AV = AVT(3)
TC4AV = AVT(4)
TC3CIF = 0.
TC4CIF = 0.

```

AA3=F.
AA4=2.

C
C
C
C
C
C

START LIEBHART METHOD

CALCULATE THERMAL EXPANSION COEFFICIENTS

2040 DO 2060 L = 2,5
NMAT=MATN(L)
TCHG=AVT(L)-25.
TEQN=AVT(L)
IF(NMAT,LE,2) GO TO 2050
TCHG=1.8*TCHG
TEQN=1.8*TEQN+32.
2050 COEXF=F.
DO 2070 N=1,4
COEXT=2.
DO 2060 N=1,4
2060 COEXT=BETACG(NMAT,N,M)*TEQN**((N-1)+COEXT)
2070 COEXF=COEXT*FL**((N-1)+COEXF)
IF(NMAT,GE,3) GO TO 2075
RHOT=-9.385E-05+1.+3.87359E-06*TEQN+1.11170E-09*TEQN*TEQN
RX(L)=RHOT*EXP(COEXF/100.)
GO TO 2080
2075 RX(L)=COEXF*TCHG+1.
2080 CONTINUE

C
C
C

CALCULATE DIMENSIONS

DO 2100 L = 2,5
RMIN(L) = RMIN(L) + BX(L)
2100 RMAX(L) = RMAX(L) + BX(L)
INOLE=RMIN(2)/-DL+1.
RF3 = RF03 + BA(3)
RF4 = RF04 + BA(4)
RP = RPO
RCHIN4=RP-RF4
RCHIN3=RP-RF3
RCHIX3=RP+RF3
RCHIX4=RP+RF4
THTAN3=ASIN(RF3/RP)
THTAN4=ASIN(RF4/RP)
JTAN=THTAN4/THTAN3 + 2.
RF(3)=RF3
RF(4)=RF4

C
C
C
C

INITIALIZE ITERATION COUNTERS

```

      IMAX = RMAX(4)/RDL + 1.
      NSOUN1(3)=1
      NSOUN2(3)=2
      NSOUN1(4)=3
      NSOUN2(4)=2
2122 ITER=(KOUNT+1)/2
      KOUNT = KJUNT + 1

C
C      START LATTICE POINT ITERATION
C
C      J-LOOP
C
      DO 6062 J = 1, JMAX
      J1=J
      IF(MOD(KOUNT,2).EQ. )GO TO 2202
      IF(MOD(J1,2).EQ.3)GO TO 2192
2152 IMIN = 1
      GO TO 2222
2192 IMIN = 2
      GO TO 2222
2202 IF(MOD(J1,2).EQ.3)GO TO 2182
      GO TO 2192

C
C
C      I - LOOP
C
2222 DO 7022 I = IMIN, IMAX, 2
      I1=I
      I2=I+1

C
C      COMPUTE R , THETA COORDINATES
C
      R(I) = I * RDL
      TH(J)=(J-1)*THDL

C
C      REGION DETERMINATION
C
      NGAP=0
      OUTER=FALSE.
      IF(R(I),GE,RMIN,(2))GO TO 2342
      NGAP=1
      GAP=RMIN(2)
2332 REG(I,J)=1
      GO TO 2462
2342 IF(R(I),GT,RMAX(2)) GO TO 2345
      REG(I,J)=2
      GO TO 2462
2345 IF(R(I),GE,RMIN(4))GO TO 2332

```

```

NGAP=2
GAP=RMIN(4)-RMAX(2)
GO TO 2332
2352 IF(J.LT.(J+1))GO TO 236F
IF(R(I).GT.RMAX(4))GO TO 2420
IF(R(I).GT.RP) OUTER4=.TRUE.
2355 REG(I,J)=4
GO TO 2466
2362 RCOSTH=RF*CGR(TM(J))
RANGLE=RCOSTH*CGSTH=RP*RP
BILL3=RANGLE*RF3*RF3
BILL4=RANGLE*RF4*RF4
IF(BILL4.LT.2.AND.BILL3.LT.0) GO TO 2410
IF(BILL4.GE.2.AND.BILL3.LT.2) GO TO 2370
R3DISC = SURT(BILL3)
RXMIN3=RCOSTH-R3DISC
RXMAX3=RCOSTH+R3DISC
2372 R4DISC=SURT(BILL4)
RXMIN4=RCOSTH-R4DISC
RXMAX4=RCOSTH+R4DISC
IF (R(I).GT.RXMIN4)GO TO 2380
GO TO 2352
2382 IF(R(I).GE.RXMIN3)GO TO 2390
NGAP=3
GAP=RCMIN3-RCMIN4
GO TO 2332
2392 IF(R(I).GT.RXMAX3)GO TO 2400
REG(I,J)=3
GO TO 2466
2402 IF(R(I).GE.RXMAX4)GO TO 2410
NGAP=3
GAP=RCMAX4-RCMAX3
GO TO 2332
2412 IF(R(I).GT.RMAX(4))GO TO 2420
IF(R(I).GE.RP) OUTER4=.TRUE.
GO TO 2352
2422 IF(R(I).GE.RMI(5))GO TO 2430
NGAP=4
GAP=RMIN(5)-RMAX(4)
GO TO 2332
2432 IF(R(I).GT.RMAX(5))GO TO 2440
REG(I,J)=5
GO TO 2466
2442 IF(R(I).GE.RMIN(6))GO TO 2450
NGAP=5
GAP=RMIN(6)-RMAX(5)
GO TO 2332
2452 IF(R(I).GT.RMAX(6))GO TO 2332
REG(I,J)=6
2462 NREG=NREG(I,J)
GO TO (2702,2501,2503,2504,2502,2502),NREG

```

```

2501 NREGN=1
    NGAPN=1
    GAPN=RMIN(2)
    GO TO 2600
2502 NREGBN=NREG-1
    NGAPN=NREG-1
    GAPN=RMIN(NREG)-RMAX(NREGBN)
    GO TO 2600
2503 NREGBN=4
    NGAPN=3
    GAPN=RCMIN3-RCMIN4
    GO TO 2600
2504 IF(OUTER4)GO TO 2505
    NREGBN=2
    NGAPN=2
    GAPN=RMIN(4)-RMAX(2)
    GO TO 2600
2505 NREGBN=3
    NGAPN=3
    GAPN=RCMAX4-RCMAX3
2600 GO TO (9999,2501,2602,2603,2604,2606),NREG
2601 NREGBN=4
    NGAPN=4
    GAPN=RMIN(4)-RMAX(2)
    GO TO 2650
2602 NREGBN=4
    NGAPN=3
    GAPN=RCMAX4-RCMAX3
    GO TO 2650
2603 IF(OUTER4)GO TO 2604
    NREGBN=3
    NGAPN=3
    GAPN=RCMIN3-RCMIN4
    GO TO 2650
2604 NREGBN=5
    NGAPN=4
    GAPN=RMIN(5)-RMAX(4)
    GO TO 2650
2605 NREGBN=6
    NGAPN=5
    GAPN=RMIN(6)-RMAX(5)
    GO TO 2650
2606 NREGBN=1
2652 RMAX(3)=RXMAX3
    RMIN(3)=RXMIN3
2702 IF(ZEROIT) GO TO 33

```

C
C
C

THERMAL CONDUCTIVITY EVALUATION

```

      SIGMA = 5.006E+12
      IF(NREG,EJ,1) GO TO 2020
      NMAT=PMAT(NREG)
      TTTT=TT(I,J)
      IF(NMAT,EJ,1) K=CONDF(KC0,TTTT,FLU)
      IF(NMAT,EJ,2) K=CO'D(KC0,TTTT,FLU,2)
      IF(NMAT,EJ,3) K=CONDM(GKC0,KKC0,TTTT,FLU)
      K=K/SIGMA/K
298.  IREG=FALSE.
      PUNY=FALSE.
      LEINC=FALSE.

C
C      LATTICE POINT DETERMINATION AND TEMPERATURE SOLUTION
C
      IF(NREG,EJ,1) GO TO 347F
      IF(L,GT,1) GO TO 317F

C
C      BOUNDARY POINTS AT THETA=2
C
      300.  300.  300.
      DELTAR=MIN(NREG)
      IF(OUTER4) DELTAR=MIN(NMAX4
307.  IF (DELTAR,EJ,1) GO TO 3217
      IF (DELTAR,EJ,2) GO TO 3220

C
C      IRREGULAR BOUNDARY POINT 05 OR 010
C
      IREG=TRUE.
      JONN=5
      A=DELTAR/ROL
      A2=A*A
      IF(OUTER4,OR,NREG,EJ,3) GO TO 3100
      NEJ1=0
      X1A=2./A2/ROL2
      T11APJOT(1,1)
      X1C=2./A2/ROL2/12
      T11JEPOT(1,1)
      NFEGB=NREGDM
      IF(NREG,EJ,2) GO TO 3027
302.  T2=T1(1,1)
      T10LO=T1(1,1)
      X1A=1./((1/ROL)+(2/A/ROL)
      GRAD=GRAD*(E(NFEGB,2)*(T2-273.15)**4-E(NREG,1)*(T10LO-273.15)**4)
      GAP=GAPN
      AVGT=(T2+T10LO)/2.
      GCOND=CONDG(HEPER,AVGT)
      KCOND=GCOND/K/GAP
      JCOND=KCOND*T2
      QGAP=QCOND*GRAD
      GO TO 3020

```

```

3027 2GAP=0
X12=0

```

```

C
C      EQUATION 6 FOR IRREGULAR CORNER POINT
C

```

```

3028 T1NUM=X1A+T1IAPJ+X1C+T1IJB+X1G+2GAP
DENOM1=X1A+X1C+X1G+2CONO
T1VEN=T1NUM/DENOM1

```

```

3029 IF (NREG.EQ.3) TCHINS=T1VEN
IF (NREG.EQ.4.AND.OJTER4) TCHMAX4=11VEN

```

```

C
C      EQUATION 15 FOR NON-SIMPLE (BOTH R AND THETA) BOUNDARY POINT
C

```

```

IF (NREG.NE.3) GO TO 3029
IF (REG(I,2).EQ.3) GO TO 3029
PUNY = .TRUE.
NE2 = 10
TVEN = (A*(I+1,1)+T1VEN)/(A+1.)
GO TO 3026

```

```

C
C      EQUATION 2.1 FOR NON-SIMPLE (R ONLY) BOUNDARY POINT
C

```

```

3029 NE2=2
AIRDL2=(A+1.)*RDL2
XA=(A+2*I)/AIRDL2
T1APJ=T(I+1,1)
XB=(2*I-1)/A/AIRDL2
T1ANJ=T1VEN
XC=X1C
T1JB=T(I,1)
XD=0
T1JBN=0
XE=0
2GAP=0
DENOM=XA+XB+XC
GO TO 3022

```

```

C
C      REGULAR R-MINIMUM CORNER POINT, B5 OR B10
C

```

```

3011 IF (NREG.NE.3) GO TO 3011
NCRN=10
XA=1./RDL
T1APJ=T(I+1,J)
TOLD=TCHINS
T2=TCHIN4
NE2=12
XB=2
T1ANJ=0
XC=0
T1JB=0
XD=0
T1JBN=0

```



```

GRADONRAD=(E(4,1)*(TB+273.16)***E(3,1)*(TOLD+273.16)***4)
AVGT=(TB+TOLD)/2.
CCOND=CONDUC(TEMPER,AVGT)
GAP=RCM*(43-RCMIN4)
HCOND=CCOND/4/3AP
SCOND=HCOND*TB
TGAP=CCOND*GAP
X2=1
GO TO 3214
3211 NCCORN=5
IF(OUTER4) NCCORN=11
NE=0
XARMHOL2
TIANJ=T(1,1)
X2=1
TIANJ=2
KC=2./RTHOL2/12
TJBP=T(1,1)
X2=7
TJBP=0
IF(NREG,EO,2)GO TO 3212
NREG=NREG+1
T2=T1(1,1)
TOLD=T(1,1)
X2=(-1+2*1)/(1+KOL)
GRADONRAD=((TB+273.16)***E(NREG,2)-E(NREG,1)*(TOLD+273.16)***4)
AVGT=(TB+TOLD)/2.
CCOND=CONDUC(TEMPER,AVGT)
GAP=GAP*
HCOND=CCOND/4/3AP
SCOND=HCOND*TB
CGAP=CCOND*GAP
GO TO 3214
3212 CGAP=0
X2=7
3214 DENOM=XA+XC+XU+HCOND
GO TO 3222
3220 DELTANORMAX(NREG)-R(1)
IF(NREG,EO,4)A D..NOT.OUTER4)DELTAR=RCMIN4-R(1)
IF(DELTAR,EO,7)GO TO 3232
IF(DELTAR,GE,HOL)GO TO 3242
C
C
C
C
NOV-SIMPLE BOUNDARY POINT NEAR 86
IPREG=,TRUE,
NCCORN=5
A=DELTAR/MUL
A2=AA*

```

```

IF(NREG, EQ. 4, A=0..NOT.OUTER4) GO TO 31229
IF(NREG, EQ. 3) GO TO 31205
NEQ1=7
X12=NRDL2/A2
T1IANJ=T(1,1)
X1C=2./((12+RTM)DL2)
T1IJBP=T1(1,1)
X13=1./((1+RDL)+2./A/RDL)
IF(NREG, EQ. 6) GO TO 3027
NREG8=NREG6P
T9=T1(1+1,1)
T1OLD=T1(1,1)
THAD=THAD+(E(NREG,1)*(TB-273.16)+4-E(NREG,2)*(T1OLD-273.16)+4)
CAP=CAPP
A/ST=(TB-T1OLD)/2.
SCOND=CONOG(MEPEP,AVGT)
MCOND=GCOND/K/CAP
SCOND=MCOND+TB
CSAP=GCOND+QRA3
GO TO 3020
3027 MCOND=MWATER/K
CSAP=MCOND+TWATER
C
C      EQUATION 7 FOR IRREGULAR CURNER POINT
C
3026 T1NUM=X1B+T1IANJ+X1C+T1IJBP+X10+CGAP
DENOM=X1D+X1C+X10+MCOND
T1NEW=T1NUM/DENOM1
30201 IF(NREG, EQ. 3) TCHAX3=T1NEW
IF(NREG, EQ. 4, A=0..NOT.OUTER4) ICTIN4=T1NEW
C
C      EQUATION 19 FOR NON-SIMPLE (BOTH R AND THETA) BOUNDARY POINT
C
IF(NREG, EQ. 3) GO TO 3029
IF(NREG(1,2), EQ. 3) GO TO 3029
FUNNY=.TRUE.
NEQ=19
TNEW=(A*T(1-1,1)+T1NEW)/(A+1.)
GO TO 3020
C
C      EQUATION 2.2 FOR NON-SIMPLE (R-ONLY) BOUNDARY POINTS
C
3029 NEQ=2
A/RDL2=(A+1.)+RDL2
XA=(1+2*1)/A/RDL2
T1APJ=T1NEW
XB=(2+1-A)/A/RDL2
T1ANJ=T(1-1,1)

```

```

XC=XIC
TJUBP=T(I,1)
XJ=0
TJUBN=0
XJ=0
OGAP=0
CEMON=XI-XI-XC
GO TO 3953

```

C
C
C

REGULAR R-MAXIMUM CORRECTION POINT, 06 OR 011

3332 IF(NREG,4,3) GO TO 3031

```

XCTK=11
XC=13
XJ=0
TJAPJ=0
XJ=1/RDL
TIANJ=T(I-1,1)
XJ=0
TJUBP=0
XJ=0
TJUBN=0
TOLC=TCMAX3
TS=TCMAX4
CRADONRAD=(E(4,2)*(TB+273.16)**4-E(3,1)*(TOLD+273.16)**4)
AVGT=(TB+TOLD)/2.
GCCNG=CONJG(E**E,AVGT)
CAP=RCFAH4-RCFAH3
HCCNG=GCCNG/H/CAP
GCCNG=CONJG(TB
OGAP=LCUP.3+OGA
XJ=1
GO TO 3034

```

3031

```

NCCRN=0
IF(NREG,4,4) AND(.NOT.OUTER4) NCCRN=10
XJ=0
XJ=0
TJAPJ=0
XJ=NRDL2
TIANJ=T(I-1,1)
XJ=2/(12*NRDL2)
TJUBP=T(I,1)
XJ=0
TJUBN=0
XJ=(1+2*I)/(1+DL)
IF(NREG,4,6) GO TO 3332
TS=T1(I+1,2)
TOLD=T(I,1)
NREGB=NREGBP
CRADONRAD=(E(NREG,1)*(TB+273.16)**4-E(NREG,2)*(TOLD+273.16)**4)

```

```

      GAP=GAPP
      AVGT=(TB+TOLD)/2.
      GCOND=CONDG(MLPER,AVGT)
      HCOND=GCOND/K/GAP
      QCOND=HCOND*TB
      OGAP=QCOND*QMA?
      GO TO 3034
3032 HCOND=H*WATER/K
      OGAP=HCOND*TWATER
3034 DENOM=XB+XC+XU+HCOND
      GO TO 3500

C
C
C      REGULAR THETA=0 BOUNDARY POINT, B1
C
3242 NEG=2
      XA=(1.+0.5/I)/RDL2
      TIANJ=T(I+1,1)
      XB=(1.-0.5/I)/RDL2
      TIANJ=T(I-1,1)
      XC=2./((2+RTWDL2)
      TIJBP=T(I,1)
      XQ=2
      TIJBN=2
      YQ=2
      OGAP=2
      DENOM=XA+XB+XC
      GO TO 3300

C
C.....
C      INTERIOR AND R-BOUNDARY POINTS
C
C
C
3102 IF(J.GE,JMAX)GO TO 3200
      DELTAR(I)-RMIN(NREG)
      IF(J.EQ,JTAN) GO TO 3101
3100 IF(NREG.EQ,3,AND,R3DISC.LT,RDL)GO TO 3101
      IF(OUTER4.AND,J.LT,JTAN)DELTAR(I)-RXMAX4
      IF(DELTAR.EQ,2)GO TO 3110
      IF(DELTAR.GE,RDL)GO TO 3120
      IF(J.GE,(JTAN+1))GO TO 3101
      GO TO (99999,3111,31001,31001,3101,3101),NREG

C
C
C      SPECIAL REGION
C      NEAR BOUNDARY POINT, B9
C      REGION 3 SECTOR(QUADRANT ) 3
C      REGION 4 SECTOR(QUADRANT) 1

```

```

C
31001 IFREG=.TRUE.
      NSOUND=9
      A=DELTA/R/NOL
      IF(NREG.EQ.3,A=U.REG(I,J+1),NE.9)GO TO 31002
      IF(NREG.EQ.4,A=U.REG(I,J-1),NE.9)GO TO 31002
      IF(NREG.EQ.4,A=U..NOT.OUTER4) GO TO 31001
      A2=A*A

```

```

C
C      NON-SIMPLE (R-ONLY) INTERIOR POINT
C      SOLVE FOR TIJ1 ONLY
C

```

```

      R=1.
      IF(NREG.EQ.3) T2NEW=T(I,J+1)
      IF(NREG.EQ.4) T2NEW=T(I,J-1)
      GO TO 31005

```

```

C
C      NON-SIMPLE (BOTH R AND THETA) INTERIOR POINT
C      EQUATION 14 FOR TIJ2
C

```

```

31002 IF(A.GE.1) GO TO 31002
      FUNNY=.TRUE.
      NEQ2=14
      TH2=ACOS((H(I)*R(I)+RP*RP-RF(NREG)*RF(NREG))/(2.*R(I)*HP))
      B=ABS((TH2-TH(J))/THDL)
      IF(NREG.EQ.3) GAMMA2=PI-ACOS((RP*HP+RF3*RF3-R(I)*R(I))
A/(2.*RP*RF3))
      IF(NREG.EQ.4) GAMMA2=PI-ACOS((RP*HP+RF4*RF4-R(I)*R(I))
A/(2.*RP*RF4))
      PHI2=GAMMA2-TH(J)
      X2=1./(1+RDL*B+THDL*SIN(PHI2))
      T2IJ=T(I,J)
      GAMMAP=GAMMA2
      IF(GAMMA2.GT.PI/2.) GAMMAP=PI-GAMMA2
      TB3=TC3AV-TC3U*IF*ICOS(GAMMA2)+AA3*GAMMAP
      TB4=TC4AV-TC4U*IF*ICOS(GAMMA2)+AA4*GAMMAP
      IF(NREG.EQ.4)GO TO 31003
      NREGB=4
      TB=TB4
      T2OLD=TB3
      GO TO 31004
31003 NREGB=3
      TB=TB3

```

```

T2OLD=TB4
31824 QRAD=MRAD*(E(NREG,1)*(TB+273.15)**4-E(NREG,1)*(T2OLD+273.15)**4)
AVGT=(TB+T2OLD)/2.
GCOND=CONDG(HEPER,AVGT)
GAP=RCMAX4-RCMAX3
MCOND=GCOND/K/GAP
SCOND=MCOND*TB
CGAP=SCOND*QRA2
T2NUM=X2+T2J*CGAP
DENUM=X2+MCOND
T2NE=T2NUM/DE*OM2
NRJUN2(NREG)=NRJUN2(NREG)+1
NRJUN2=NRJUN2(NREG)
JUN2(NREG,NRJUN2)=I
JUN2(NREG,NRJUN2)=J

```

```

C
C      EQUATION 12 FOR TIJ1 IN REGION 3
C      EQUATION 1 FOR TIJ1 IN REGION 4
C

```

```

31825 TH1=TH(J)
IF(NREG,EQ.3,AND(J,NE.1)GAMMA1=PI-ACOS((RPF3+QF3)/RPF3)
A=RXM1*(EX4[43]/(2.*RPF3))
IF(NREG,EQ.4,AND(J,NE.1)GAMMA1=PI-ACOS((RPF4+QF4)/RPF4)
A=RXMAX4*(EX4[44]/(2.*RPF4))
IF(NREG,EQ.3,AND(J,EQ.1) GAMMA1=PI
IF(NREG,EQ.4,AND(J,EQ.1) GAMMA1=0.
PH1=GAMMA1-TH(J)
X1A = 1./((A*RU)*COS(PH1))
IF(NREG,EQ.3)X1A=-1.*X1A
T1APJ=T(1,J)
GAMMAP=GAMMA1
IF(GAMMA1.GT.PI/2.) GAMMAP=PI-GAMMA1
T3=TC3AV-TC3D[F*cos(GAMMA1)+AA3]*GAMMAP
T4=TC4AV-TC4D[F*cos(GAMMA1)+AA4]*GAMMAP
IF(NREG,EQ.4)GO TO 31826
NREGB=4
TB=TB4
T1OLD=TB3
NE1=12
GO TO 31827
31826 NREGB=3
TB=TB3
NE1=12
T1OLD=TB4

```

```

31827 QRAD=MRAD*(E(NREG,1)*(TB+273.15)**4-E(NREG,1)*(T1OLD+273.15)**4)
AVGT=(TB+T1OLD)/2.
GCOND=CONDG(HEPER,AVGT)
GAP=RCMIN3-RCMIN4
MCOND=GCOND/K/GAP
SCOND=MCOND*TB
CGAP=SCOND*QRA2
T1NUM=X1A+T1APJ*CGAP
DENOM=X1A+MCOND
T1NE=T1NUM/DE*OM1
NRJUN1(NREG)=NRJUN1(NREG)+1
NRJUN1=NRJUN1(NREG)
JUN1(NREG,NRJUN1)=I
JUN1(NREG,NRJUN1)=J
IF(J,EQ.1)GO TO 31828
IF(.NOT.FUNNY) GO TO 31829

```

C
C
C

EQUATION 1 FOR NON-SIMPLE INTERIOR POINT

```

R1RDL2=(E+1.)*I2ORTHDL2
NEJ=1
XA=(A2/(A+1.))*(WRDL2/A2-1./(A2*I0RDL2))+1./(I0RDL2)
TIAPJ=T(I+1,J)
XB=(WRDL2/A2-1./(A2*I0RDL2))*(A/(A+1.))
TIANJ=T1NEJ
IF(NREC,EQ.4) GO TO 3188
XC=2./B/B1RDL2
T1JBP=T2NEJ
XD=2./B1RDL2
T1JBN=T(I,J-1)
GO TO 3188V
3188V XC=2./B1RDL2
T1JBP=T(I,J+1)
XD=2./B/B1RDL2
T1JBN=T2NEJ
31889 XD=0
GAP=0
DENOM=XA+XB+XC+XD
GO TO 3584

```

C
C
C

NON-SIMPLE (R-ONLY) INTERIOR POINT NEAR B3

```

3181 IREG=,TRUE.
N3JUND=3
A0DELTA/RHDL
A2=404
NEJ104
X1A=WRDL2/A2
T1IAPJ=T(I,J)
X1C=1./(I2ORTHDL2)
T1IJBPT1(I,J+1)
X1D=X1C
T1IJBNT1(I,J-1)
IF(NREC,EQ.2) GO TO 3187
NREG=NREG+1
TB=T1(I+1,J)
T1OLD=T1(I,J)
X1Q=1./(I0RDL)+2./(A0RDL)
GAP=GAP+1
HCOND=COND/K/GAP
GRAD=GRAD+(E(NREG,2)*(TB+273.15)**4-E(NREG,1)*(T1OLD+273.15)**4)
AVGT=(TB+T1OLD)/2.
COND=COND*(HEP2,AVGT)
HCOND=HCOND*TB
GAP=COND/HCOND
GO TO 3186
3187 GCAP=0
X1Q=0

```

C
C
C

EQUATION 4 FOR IRREGULAR R-MIN. BOUNDARY B3

```

3189 T1NUM=X1A*T1IAPJ+X1C*T1IJBPT1+X1D*T1IJBNT1+X1Q*GCAP
DENOM1=X1A+X1C+X1D+X1Q*HCOND
T1NEW=T1NUM/DENOM1

```

C
C

EQUATION 1 FOR NON-SIMPLE INTERIOR POINT

```

C
3109 NE=1
XAO=(A2/(A+1.))*(RDL2/A2-1./(A2*(RDL2)))+1./(1.RDL2)
YIAPJ=Y(I+1,J)
XBO=(RDL2/A2-1./(A2*(RDL2)))*(A/(A+1.))
YIANJ=YIAEJ
XC=XIC
YIJB=Y(I,J+1)
XD=XIC
YIJBH=Y(I,J-1)
Y30F
ZCAP=0
ZEYOM=XAO*XB+XC+XJ
GO TO 3520

C
C      REGULAR BOUNDARY POINT ON 03 OR 09 FACING ORIGIN
C
C      EQUATION 4 FOR NORMAL REGION
C      EQUATION 12 FOR REGION 3
C      EQUATION 12 FOR REGION 4
C
3112 GO TO (00009,3114,3111,3111,3112,3114),NREG
3111 K30U=000
IF(NREG,EQ.4,A 0.000000000)GO TO 3114
GAMMA=ASIN(R(I)/RF(NREG))*S(V(TH(J)))
IF(NREG,EQ.3) GAMMA=PI-ACOS((RP*RP+RF3*RF3-RXN[N3]*RXN[N3])
A/(2.*RP*RF3))
IF(NREG,EQ.4) GAMMA=PI-ACOS((RP*RP+RF4*RF4-RXN[N4]*RXN[N4])
A/(2.*RP*RF4))
P4=GAMMA-TH(J)
XAO1./(RLOC75(P4))
IF(NREG,EQ.3) XAO=1.0XA
X30F
YIJBH=Y
XC=X
YIJB=Y
XD=X
YIJBH=Y
X30F
GAMMA=0.678A
IF(GAMMA,GT,PI/2.) GAMMA=PI-GAMMA
T3J=TC3AV-TC3JIF(COS(GAMMA)*AA3*GAMMA
T64=TC4AV-TC4JIF(COS(GAMMA)*AA4*GAMMA
IF(NREG,EQ.4)GO TO 3112
NREG=4
T3=TB4
NEQ=12
YIAPJ=Y(I+1,J)
TCLD=TB3
GO TO 3110
3112 NREG=3
NEQ=12
YIAPJ=Y(I+1,J)
T3=TB3
TCLD=TB4
3113 JRAO=HRAO*(E(L-EGO,1)*(TB+273.15)**4-E(NREG,1)*(TCLD+273.15)**4)
GO TO 3110
3114 NBOUND=3
NEQ=4
XAO=RDL2

```



```

      T1APJ=T(1,J)
      X2=2
      T1ANJ=2
      XC=1/(12*RTNDL2)
      T1JBP=T(1,J+1)
      X2=XC
      T1JBN=T(1,J-1)
      IF(NREG,EQ.2)GJ TO 3117
      T1NT1 (1-1,J)
      TOLDET(1,J)
      X2=(1-2*1)/(1-OL)
      GRADIENTAP=(EIN-EG9.2)*(TB+273.16)**4-E(NREG,1)*(TOL0+273.16)**4)
3115 GAP=GAP+
      AVGT=(TB+TOL0)/2.
      GCONC=CO*OG(NPER,AVGT)
      MC7ND=GCONC/K/TAP
      GCONC=MC7ND*TB
      GCAP=GCONC*GRAD
      GJ TO 3116
3117 GCAP=0
      X2=2
3118 DECONC=X2*XC*XD*X2*HCONC
      GJ TO 3520
3120 DELTANORMAX(NREG)-R(1)
      IF(NREG,EQ.4,A=D.10T.0UTE+4,ANY,J.LT.JTAN) DELTANORMAX=N4-R(1)
      IF (DELTAR,EQ.1)GJ TO 3130
      IF (DELTAR,GE.OL)GJ TO 3142
C
C
C      NO-SIMPLE INTERIOR POINT LEAN 24 OR 29
C
C      GJ TO (95009,3121,3122,3123,3124,3125),NREG
C
C
C      SPECIAL REGION
C      NEAR 99 QUADRANT POINT
C      REGION 3 SECTOR(QUADRANT)4
C      REGION 4 SECTOR(QUADRANT)2
C
31201 INREG=.TRUE.
      A2TUMD=0
      A=DELTAR/HUL
      A2=A*A
      IF(OUTER4)GJ TO 3121
      IF(NREG,EQ.3,A=D.NREG(1,J+1),NE.2)GJ TO 3122
      IF(NREG,EQ.4,A=D.NREG(1,J-1),NE.2)GJ TO 3122
C
C
C      NO-SIMPLE(N-ONLY) INTERIOR POINT
C      SOLVE FOR T1J1 ONLY
C
      B01.
      IF(NREG,EQ.3) T2NEW=T(1,J+1)
      IF(NREG,EQ.4) T2NEW=T(1,J-1)
      GJ TO 31202
C
C
C      NON-SIMPLE (BOTH R AND THETA) INTERIOR POINT
C
C      EQUATION 14 FOR T1J2
31202 FUNNY=.TRUE.

```

```

NEJ2=14
TH2=ACOS((19(1)-H(1)-RP-PP-RF(NREG),RF(NREG))/(2.0R(1)+RP))
B=ABS((TH2-TH(J))/THDL)
GAMMA2=PI-ACOS((PP-PP-RF(NREG)-RF(NREG)-R(1)+R(1))
A/(2.0R(1)+RP))
PH12=GAMMA2-TH(J)
X2=1./((1+JLON+THJL+5I):(PH12))
T21J=PI(1,J)
GAMMA2=GAMMA2
IF(GAMMA2-PI,PI/2.) GAMMA2=PI-GAMMA2
T23=TC3AV-TC3UIF=COS(GAMMA2)+AA30GAMMA2
T34=TC4AV-TC4UIF=COS(GAMMA2)+AA40GAMMA2
IF(NREG,EO.4) GO TO 31233
NREG=4
T2=124
T27LJ=T23
GO TO 31244
31233 NREG=3
T2=123
T27LJ=T24
31234 JAUON7AC=(E(NREG,2)-(T2+273.12)+4-E(NREG,1)-(T27LJ+273.12)+4)
AVGT=(T2+T27LJ)/2.
GCONJ=CONJG(NEPER,AVGT)
GAP=RCX(XJ-RCX)114
GCONJ=CONJG/XJAP
GCONJ=PCONDOTG
JGAP=CONJG-394
T27UM=X2+T21J+GAP
JEION2=X2+4021
T27E=27UM/JEION2
H30U42(NREG)ONJOUN2(NREG)+1
H30U42=H30U42(NREG)
I30U42(NREG,XB30U42)=I
J47U42(NREG,XB30U42)=J
C
C      EQUATION 13 FOR T1J1 IN REGION 3
C      EQUATION 11 FOR T1J1 IN REGION 4
C
31235 T41=TH(J)
IF(NREG,EO.3,A+D,J,NE.1) GAMMA1=PI-ACOS((PP-PP-RP3-PP3)
A-2XMAX3+PPX1AX3)/(2.0R(PP3))
IF(NREG,EO.4,A+D,J,NE.1) GAMMA1=PI-ACOS((PP-PP-RP4-PP4)
A-2XMAX4+PPX1AX4)/(2.0R(PP4))
IF(NREG,EO.3,A+D,J,EO.1) GAMMA1=0.
IF(NREG,EO.4,A+D,J,EO.1) GAMMA1=PI
PH11=GAMMA1-TH(J)
X13=1./((A+RPLCOS(PH11))
IF(NREG,EO.3)X13=1.0X13
T11J=PI(1,J)
GAMMA1=GAMMA1
IF(GAMMA1-PI,PI/2.) GAMMA1=PI-GAMMA1
T43=TC3AV-TC3UIF=COS(GAMMA1)+AA30GAMMA1
T44=TC4AV-TC4UIF=COS(GAMMA1)+AA40GAMMA1
IF(NREG,EO.4) GO TO 31238
NREG=4
T2=124
T10LD=T23
NEJ1=13
GO TO 31244
31238 NREG=3

```

```

T9=TB3
T2=TL0+T94
31209 ORAD=HRAC*(E(H-LG9,1)*(T9+273.15)**4-E(HREG,1)*(T10L0+273.15)**4)
AVST=(T9+T10L0)/2.
SCON=CONJG(WPER,AVST)
CAP=RC*(N3-RCN)*R4
KCON=GCOUN/K/CAP
CCON=CONJG(TB
JCAP=GCOUN+QRA
T1=UNH15+T11A-J0CAP
DEYON10X10+MCO-U
T1NEN=T1NU*/DE-UM1
H3OUN1(HREG)*E=QU11(HREG)*1
H3OUN10H=UUN1(HREG)
I2OUN1(HREG,KH=U11)=I
J2OUN1(HREG,KH=U11)=J
IF(J.E.,1)GO TO 31201
IF(.NOT.FUNNY)TO TO 3129

```

C
C
C

EQUATION 1 FOR NON-SIMPLE INTERIOR POINT

```

R1=DL2*(5+1.)+I2=RTMOL2
DE=1
X1=1./(A+AZ)*(RDL2-1/(1+RDL2))*1./(A+1+RDL2)
T1APJ=T11LH
X2=(RDL2-1/(1+RDL2))/(A+1.)
T1ANJ=T11LJ
IF(HREG,63.4)GO TO 31219
X1=2./4+RDL2
T1JMP=T21LH
X2=2./R1+RDL2
T1JBN=T11LJ-1
GO TO 31211
31219 X1=2./R1+RDL2
T1JMP=T11LJ-1
X2=2./R1+RDL2
T1JBN=T21LH
31211 X1=X2,
JCAP=3
DEYON10X10+MCO-XC=XJ
GO TO 3509

```

C
C
C

NON-SIMPLE (Q-ONLY) INTERIOR POINT NEAR B4

```

3121 H3OUN1004
A2=ELTAR/MOL
A2=A0A
H271=5
X19=HRDL2/A2
T11ANJ=T11LJ
X1C=1/(I2=RTMOL2)
T11JBN=T11LJ-1
X1J=X1C
T11JBN=T11LJ-1
X1J=1./(1+RDL)*2./A+RDL
IF(HREG,63.4)GO TO 3127
T11LJ=T11LJ
T11LJ=T11LJ
H3OUN1004
ORAD=HRAD*(E(HREG,1)*(T2+273.15)**4-E(HREG,2)*(T10L0+273.15)**4)

```

```

CAP=CAPP
AVST=(T3+T10L0)/2.
CCOND=COND6(NEPE3,AVST)
MCOND=COND/4/CAP
CCOND=MCOND*Y
ZCAP=COND*QRA
GO TO 3126
3127 MCOND=LATER/K
CCAP=MCOND*WATER
C
EQUATION 5 FOR IRREGULAR BOUNDARY POINT
C
3128 T1JUN=X1F+T1IA-J*X1C+T1JBP+X1D+T1JBN+X1G+QCAP
CCOND=X1B+X1C+X1D+X1G+MCOND
T1YEM=T1JUN/7E-04
C
EQUATION 1 FOR NON-SIMPLE INTERIOR POINT
NORMAL REGION
C
3129 ME7=1
XAB=(1./(A+A2)).*(RDL2-1/(1+DUL2))+1/(A+1+RDL2)
T1APJ=T1JEN
X3=(XJL2-A/(1+DUL2))/(1+A)
T1ANJ=T(1-1,J)
X2=X1C
T1JBP=T(1-J+1)
X3=X1C
T1JBN=T(1-J-1)
X2=
QCAP=
CCOND=XAB+X3+XC+XJ
GO TO 3126
C
REGULAR BOUNDARY POINT ON B2 OR B3
C
EQUATION 5 FOR NORMAL REGION
EQUATION 13 FOR REGION 3
EQUATION 11 FOR REGION 4
C
3130 GO TO (3349V,3134,3131,3131,3134,3134),NREG
C
SPECIAL REGION E13 OR E11
C
3131 MCOND = V
IF(OUTER) GO TO 3134
IF(NREG,E0,3) GAMMA=1-ACOS((RPP*RP3+RFP3-RXN*Y3+MXX*Y3)
A/(2.*RPP*RP3))
IF(NREG,EJ,4) GAMMA=1-ACOS((RPP*RP4+RFP4-RXN*Y4+MXX*Y4)
A/(2.*RPP*RP4))
PHI=GAMMA-TM(J)
XAB=
T1APJ=
IF(NREG,E0,4) X3=1./RDL*COB(PHI)
IF(NREG,E0,3) X3=1./RDL*COB(PHI)
T1ANJ=T(1-1,J)
XC=
T1JBP=
X3=
X3=1
GAMMA=GAMMA

```

```

IF (GAMMA,GT,P1/2.) GAMMAP=P1-GAMMA
T33=TC3AV-TC3DIF=CS(S(GAMMA)+AA3*GAMMAP
T94=TC4AV-TC4DIF=CS(S(GAMMA)+AA4*GAMMAP
IF (NREG,EO,4) GO TO 3132
NREG=4
T3=TB4
TJLD=TB3
NE=1
GO TO 3133
3132 NREG=3
T3=TB3
TJLD=TB4
NE=11
3133 TAD=AD*(E(N-EG,1)*(TB+273,12)+E(NREG,1)*(TJLD+273,16)+4)
GO TO 3134
3134 NCON=0
NE=5
NAC=7
TAPJ=2

NCONDL2
TAPJ=T(I-1,J)
NC=1/(12*THL2)
TJDP=T(I,J+1)
XJ=XE
TJDN=T(I,J-1)
N3=(1-2*1)/(1+2*1)
IF (NREG,EO,6) GO TO 3137
T3=TB(I+1,J)
TJLD=T(I,J)
NREG=NREG+1
TAD=AD*(E(N-EG,1)*(TB+273,12)+E(NREG,2)*(TJLD+273,16)+4)
3136 CAP=CAP
AVGT=(TB+TJLD)/2.
CCONJ=CONJ*(NEPER,AVGT)
NCON=CCONJ/N/2*AD
NCON=NCON+TB
TAPJ=CCONJ+CAP
GO TO 3138
3137 NCON=NCON+TATER/N
CAP=CCONJ/TATER
3138 OETON=KA*NB*NC*N3*TB+NCON
GO TO 3137

C
C      INTERIOR SIMPLE POINT
C
3148 NREG=FALSE,
IF (NREG,EO,3,AND,REG(I,J+1),NE,0) GO TO 3149
IF (NREG,EO,4,AND,REG(I,J-1),NE,0) GO TO 3149
NE=1
N3=(1+2*1)/(1+2*1)
TAPJ=T(I+1,J)
N3=(1+2*1)/(1+2*1)
TJDN=T(I-1,J)
NC=1/(12*THL2)
TJDP=T(I,J+1)
N3=XE
TJDN=T(I,J-1)
N3=0.
CAP=0.

```

DEMON=XA+XB+XC+XD
GO TO 3988

C
C
C

SPECIAL POINT IN REGIONS 3 OR 4--EQUATION 10

```

3159 IREG=.TRUE.
      FUNNY=.TRUE.
      WEIRD=.TRUE.
      NE2=10
      TH2=TH7ALJ
      B=(TH2-TH(1))/TH3L
      GAMMA2P1=ACOS((NDORP.NF(NREG)ORP(NREG)-B(1)OR(1))
      A/(2.0RPOBF(NREG)))
      T23=TC3AV-TC3DIFOCOS(GAMMA2)AA3OGAMMA
      T4E=(B+Y(1,J-1)+T23)/(B+1.)
      GO TO 3988
31621 IF(NREG,EG,4,AND,NREG(1,J-1),NE,2) GO TO 31982
      GO TO 31688
31622 IREG=.FALSE.
      FUNNY=.TRUE.
      WE2=14
      TH2=ACOS((B(1),B(1)+NDORP.NF(NREG),NF(NREG))/(2.0B(1),NDP))
      B=ABS((TH2-TH(J))/THDL)
      GAMMA2OP1=ACOS((NDORP+NF(NREG)ORP(NREG)-B(1)OR(1))
      A/(2.0RPOBF(NREG)))
      PH2OGAMMA2-TH(J)
      IF(B,EG,2) GO TO 31623
      X2=1./((NDL+D+THDL+5)N(PH2))
      T21JOT(1,J)
31623 GAMMA2OGAMMA2
      IF(GAMMA2.GT.PI/2.) GAMMA2OP1-GAMMA2
      T23=TC3AV-TC3DIFOCOS(GAMMA2)AA3OGAMMA2P
      T34=TC4AV-TC4DIFOCOS(GAMMA2)AA3OGAMMA2P
      IF(NREG,EG,4) GO TO 31625
      T4=TB4
      T23LD=TB3
      GO TO 31626
31625 T4=TB3
      T23LD=TB4
31626 GAMMA2AD=(E(3,1)+(TB+273.16)+E(4,1)+(T23LD+273.16)+E(4,1))
      AVST=(TB+T23LD)/2.
      ZC3ND=CONOC(NEPE,AVST)
      GAP=RCNAX4-RCNAX3
      MC3ND=CC3ND/N/3AP
      CC3ND=4CC3ND+TB
      ZCAP=OC3ND+GMA
      IF(B,EG,2) GO TO 31624
      T2YUN=Z2+T21J+ZCAP
      NEVCN2=X2+MC3ND
      T2YE=(T2YUN/NEVCN2)
31624 X2YUN2(4)=X2YUN-2(4)+1
      X2YUN2(4,X2YUN2(4))
      J2YUN2(4,X2YUN2(4))

```

C
C
C

EQUATION 1 FOR NON-SIMPLE POINT

B19DL2=(B+1.)+I2+RTNOL2
NE2=1

```

      XA=(1.0,5/1)/NDL2
      T1APJ=T(I-1,J)
      XB=(1.0,5/1)/NDL2
      T1ANJ=T(I-1,J)
      XC=2./J/NDL2
      IF(MREG,ED,4) GO TO 3167
      T1JBP=T2HEW
      T1JBX=T(I,J-1)
      GO TO 3168
3167 T1JBP=T(I,J-1)
      T1JBX=T2HEW
3168 IF(B.E.C) GO TO 3161
      XD=2./B/NDL2
      XC=C
      OCAP=8
      DECOM=XA+XB+XC+XD
      GO TO 3500

C
C      EQUATION 2V FOR REGULAR TANGENT REGION 4 BOUNDARY
C
3161 FJTRY=.FALSE.
      IF(MREG,ED,4) GO TO 3162
      XD=XC
      XC=C
      T1JBP=C
      GO TO 3163
3162 XD=C
      T1JBX=C
3163 XD=2./(|)NDL2
      DECOM=XA+XB+XC+XD+XD+XD+XD
      GO TO 3500

C
C.....
C      BOUNDARY POINTS AT THETA =PI/2
C
3201 JBOUND=2
      DELTAN(I)=MIN(MREG)
      IF(DELTAN,ED,8) GO TO 3210
      IF (DELTAN,EG,NDL) GO TO 3220

C
C      NEAR IRREGULAR R-MINIMUM CORNER POINT, B7
C
C      NO-SIMPLE BOUNDARY POINT NEAR B7
C      NORMAL REGION. (E 3.1)
C
      IIRREG=.TRUE.
      MCOM=7
      A=DELTAN/NDL
      A2=A*A
      ME91=8
      X1A=MNDL2/A2
      T1APJ=T(I,JMAX)
      X10=2./MNDL2/12
      T1JBX=T(I,JMAX)
      IF(MREG,ED,2) GO TO 3222
      MREG=4MREG
      T10L0=T1(I,JMAX)
      X12=2./A/NDL=1./(|)NDL
      GRADOMRAD=(E(MREG,2)*(TB=273.12)+C(MREG,1)*(T10L0=273.16)+C4)

```

```

GAP=GAPn
AVGT=(T0+T10)/2.
GCOND=CONDG(MEPLR,AVGT)
MCOND=GCOND/K/7AP
GCOND=MCOND*7n
GAP=GCOND*QRA0
GO TO 3224

```

```

3222 GAPP=2
X17=0

```

```

C      EQUATION 3 FOR IRREGULAR CORNER POINT
C      NORMAL REGION (E 3.1)
C

```

```

3224 T1JUN=X1A+T1IAPJ=X1D+T1JUN=X1D+GAP
DETON=X1A+X1D+MCOND
T1JUN=T1JUN/DETON

```

```

C      EQUATION 3.1 FOR NON-SIMPLE BOUNDARY POINT
C      NORMAL REGION
C

```

```

N=3
A1NCL2=1/(A+1.)+DL2
XN=(A+2)/A/1NCL2
T1APJ=T1I+1,JMAX
XN=(2+1)/A/1NCL2
T1ANJ=T1XN
XC=7
T1JBP=7
XN=X1D
T1JBN=T1I,JMAX=1
XN=0
GAPP=0
DETON=X1A+X1D+XN
GO TO 3222

```

```

C      REGULAR MINIMUM CORNER POINT.07
C

```

```

3212 INREG=.FALSE.
MCOND=7
N=0
XN=DL2
T1APJ=T1I+1,JMAX
XN=7
T1ANJ=2
XC=7
T1JBP=7
XN=2/(1+1NCL2)
T1JBN=T1I,JMAX=1
IF(MNCL2,0.2) GO TO 3212
MCOND=MCOND
T1JBN=T1I,JMAX
XN=(2+1)/(1+DL)
GAPP=MCOND*(E(N-1,3,1)*(T0+273.15)+4-E(MNCL2,1)*(T0+273.15)+4)
GAP=GAPP
AVGT=(T0+T10)/2.
GCOND=CONDG(MEPLR,AVGT)
MCOND=GCOND/K/7AP
GCOND=MCOND*7n
GAP=GCOND*QRA0
GO TO 3214

```



```

3212 0CAP=0
      X0=0
3214 DENOM=XA-X0+XU*HCOND
      GO TO 3300
3222 DELTAR=MAX(MREG)-R(1)
      IF (DELTAR.EQ.0) GO TO 3230
      IF (DELTAR.GE.-DL) GO TO 3240

```

C
C
C
C

NON-SIMPLE BOUNDARY POINT NEAR 00

```

      IREG=TRUE.
      MCON=0
      A=DELTAR/DL
      A2=A*A
      REG=0
      K13=MREG/2/A2
      T1A=J*(1,MAX)
      K12=2./(12+MREG/2)
      T1J=J*(1,MAX-1)
      K11=1./(12+MREG/2)+2/(A+DL)
      IF (MREG.EQ.0) GO TO 3222
      T1=J*(1,MAX)
      T1LD=T1(1,MAX)
      MREG=MREG*0.5
      MREG=MAX(1, (T1-273.15)*0.4-E(MREG,2)*(T1LD-273.15)*0.4)
      SA=CAP
      AVGT=(T1-T1LD)/2.
      GCOND=COND*0.06(MPEER,AVGT)
      HCOND=GCOND/H/7AP
      QCOND=MCON*H/7AP
      0CAP=QCOND*0.00045
      GO TO 3224
3222 MCON=MCON+H/7AP
      0CAP=QCOND*0.00045

```

C
C
C
C

EQUATION 4 FOR IRREGULAR CORNER POINT
NORMAL REGION

```

3224 T1J=J*(1,MAX)+T1A-J*K11*D*T1J+T10*0.5AP
      DENOM=X10-X1D+X13+HCOND
      T1HE=T1J*H/DENOM

```

C
C
C
C

EQUATION 3 FOR NON-SIMPLE BOUNDARY POINT
NORMAL REGION (E 3.2)

```

      MREG=0
      A1DL2=(A+1.)*DL2
      K12=(1+2*A)/A/4/NDL2
      T1AP=J*(1,MAX)
      K11=(2+A)/A/4/NDL2
      T1A=J*(1,MAX-1)
      K10=0
      T1J=J*(1,MAX)
      K10=2./(12+MREG/2)
      T1J=J*(1,MAX-1)
      K10=0
      0CAP=0
      DENOM=XA-X0+XU
      GO TO 3300

```

C
C
C

REGULAR R-MAXIMUM CORNER POINT. 00

```

3232 4CORN=0
      4EJ=9
      4A=2
      7IAPJ=7
      4R=HDL2
      7IANJ=7(I-1,JMAX)
      4C=1
      7IJB=7
      4H=2./((12*HDL2)
      7IJB=7(I,JMAX-1)
      4B=(1+2*1)/(1+DL)
      IF(4REG,4,6) GO TO 3232
      7A=7(I+1,JMAX)
      7OLD=7(I,JMAX)
      4REG=4REG+1
      4RANDOM=4C*(4EJ-1)*(79+273.15)**4-4*(4REG,2)*(7OLD+273.15)**4)
      4GAP=4GAP
      4VGT=(7A+7OLD)/2.
      4COND=4COND*(4VGT,4VGT)
      4COND=4COND/4GAP
      4COND=4COND*4VGT
      4GAP=4COND*4GAP
      GO TO 3234
3232 4COND=4H*4VGT/4GAP
      4GAP=4COND*4VGT
3234 7ENOM=4A+4B+4C+4COND
      GO TO 3236

```

C
C
C

REGULAR THETA=PI/4 BOUNDARY POINT 02

```

3241 4EJ=3
      4A=(1+3,5/1)/HDL2
      7IAPJ=7(I+1,JMAX)
      4B=(1+3,5/1)/HDL2
      7IANJ=7(I-1,JMAX)
      4C=2
      7IJB=7
      4H=2./((12*HDL2)
      7IJB=7(I,JMAX-1)
      4C=7
      4GAP=7
      7ENOM=4A+4B+4C
      GO TO 3243

```

C
C
C

TEMPERATURE INITIALIZATION ON ZEROth ITERATION

```

3300 IF(4REG,4,6) GO TO 3306
      IF(4GAP,4,6) GO TO 3306
      GO TO (3301,3302,3303,3306,3308),4GAP
3301 7ENOM=4VGT(2)
      GO TO 3304
3302 DELTAR(1)=4H*4VGT(2)
      7ENOM=(4VGT(2)*(4GAP-DELTAR)+4VGT(4)*DELTAR)/4GAP
      GO TO 3304
3303 4SIN(7ENOM(1))=4SIN(7ENOM(1))

```

```

      R(COSJWR(1)+COS(TH(J))
      DELTAX=RCOSJ-CP
      IF(DELTA)3384,3385,3386
3384 GAMMA=P*-ATAN(-NS/INTH/DELTA)
      GO TO 3387
3385 GAMMA=P/2.
      GO TO 3387
3386 GAMMA=ATAN(NS/INTH/DELTA)
3387 RRCOORD = SORT(NS/INTH/NS/INTH*DELTA+DELTA)
      DELTAR=RRCOORD-REF
      TB3=AVT(3)
      TB4=AVT(4)
      TNEW=(TB3*(GAP+DELTA)+TB4*DELTA)/GAP
      GO TO 3343
3388 DELTAR=1)-MAX(NGAP)
      TNEW=(AVT(NGAP)*(GAP+DELTA)+AVT(NGAP+1)*DELTA)/GAP
      GO TO 3340
3389 TNEW=TWATER
      GO TO 3340
3390 TNEW=AVT(NRES)
      GO TO 3340

```

C
C TEMPERATURES OF POINTS IN GAPS

```

C
3400 IF(NGAP,EG.7) GO TO 3409
      GO TO (3401,3402,3403,3404,3405,3406),NGAP
3401 TNEW=T1(MOLE,J)
      GO TO 3401
3402 DELTAR=1)-MAX(NGAP)
      TNEW=T1(1-1,J)*(GAP+DELTA)+T1(1+1,J)*DELTA)/GAP
      GO TO 3401
3403 NS/INTH=RC(1)+S*(TH(J))
      R(COSJWR(1)+COS(TH(J))
      DELTAX=RCOSJ-CP
      IF(DELTA)3424,3425,3426
3424 GAMMA=P*-ATAN(-NS/INTH/DELTA)
      GO TO 3427
3425 GAMMA=P/2.
      GO TO 3427
3426 GAMMA=ATAN(NS/INTH/DELTA)
3427 RRCOORD=SORT(NS/INTH/NS/INTH*DELTA+DELTA)
      DELTAR=RRCOORD-REF
      GAMMAPOGAMMA
      IF(GAMMA,LT,P/2.) GAMMAPO=P-GAMMA
      TB3=TC3AV-TC3DIF(COS(GAMMA)+AA3*GAMMA
      TB4=TC4AV-TC4DIF(COS(GAMMA)+AA4*GAMMA
      TNEW=(TB3*(GAP+DELTA)+TB4*DELTA)/GAP
      GO TO 3401
3409 TNEW=TWATER
      GO TO 3401

```

C
C CONVERGENCE INFORMATION

```

C
3502 IF(.NOT.WEIRD) GO TO 3510
      NWEIRD=NWEIRD+1
      TOLDOT(I,J)
      T(I,J)=TNEW
      GO TO 3400
3510 TOLDOT(I,J)
      SOURCE=NP0(NRES)/K

```

```

      IF (NEG.GT.9) SOURCE=0.
      T.CEN=(XA+TIAPJ+XB+TIANJ+XC+TIJBP+XD+TIJBP
      A.XQ=QGAP.SOURCE)/DENOM
      IF (.NOT.FUNNY) GO TO 3522
      T2(I,J)=T2NEW
      *FUNNY=NFUNNY+1
      K5OUN2 (HNEG)=NOUN2(HNEG)+1
      K5OUN2=NBOUN2(HNEG)
      I5OUN2(HNEG,K5OUN2)=I
      J5OUN2(HNEG,K5OUN2)=J
      IF (.NOT.HNEG) GO TO 3531
      GO TO 3521
3522 IF (.NOT.HNEG) GO TO 3530
      T2(I,J)=T2NEW
3521 T1(I,J)=T1NEW
      IF (HNEG.EQ.3.AND.HNEG.NE.4) GO TO 3522
      K5OUN1(HNEG)=NOUN1(HNEG)+1
      K5OUN1=NBOUN1(HNEG)
      I5OUN1(HNEG,K5OUN1)=I
      J5OUN1(HNEG,K5OUN1)=J
3522 K5USE1(HNEG)=N5USE1(HNEG)+1
      T(I,J)=T.CEN
      K5USE(HNEG)=N5USE(HNEG)+1
      GO TO 3602
3530 T2(I,J)=T2NEW
3531 T1(I,J)=T1NEW
      T(I,J)=T2NEW
      IF (HNEG.EQ.3.AND.HCORN.EQ.10) T5MIN3=T2NEW
      IF (HNEG.EQ.3.AND.HCORN.EQ.11) T5MAX3=T2NEW
      IF (HNEG.EQ.4.AND.HCORN.EQ.10) T5MIN4=T2NEW
      IF (HNEG.EQ.4.AND.HCORN.EQ.11) T5MAX4=T2NEW
      GO TO 3602
3540 *LTHAXON.
      T1(I,J)=T2NEW
      T(I,J)=T2NEW
      T2(I,J)=T2NEW
      GO TO 3601
3601 DELTAT=ABS(TNEW-TOLD)
      IF (DELTAT.LE.DLTMAX) GO TO 3601
      DLTMAX=DELTAT
      I3AD=I
      J3AD=J
3601 SUMT(HNEG)=SUMT(HNEG)+TNEW
      KT(HNEG)=KT(HNEG)+1
      GO TO 6022
6022 CONTINUE
7022 CONTINUE
8022 CONTINUE
C
C          CONVERGENCE TEST
C
      IF (MOD(KOUNT,2).EQ.1) GO TO 2120
      SAVTQ=AVTQ
      AVTQ=2
      DO 8012 HNEG=1,8
      AVT(HNEG)=SUMT(HNEG)/KT(HNEG)
      SUMT(HNEG)=0.
      KT(HNEG)=0
8012 AVTQ=AVTQ+AVT(HNEG)
      IF (KOUNT.EQ.1) ZEROIT=.FALSE.

```

```

IF (ITER.EQ.3) GO TO 2948
CC2TES=ABS(AVTT0-DAVTT0)/AVTT0
IF(CC2TES.LE.CCN2)GO TO 9888
CC1TES=DLTMAX/T(I8AD,J8AD)
IF(CC1TES.LE.CCR1) GO TO 9888
IF(ITER.LT.MAXIT)GO TO 883F
WRITE(IOUT,883E)MAXIT
9838 FORMAT('CONVERGENCE NOT OBTAINED AFTER',I3,'ITERATIONS')
WRITE(IOUT,883I)I8AD,J8AD
8831 FORMAT('WORST POINT AT',I3,',',I3,',',I3,',')
WRITE(IOUT,8832)CC1TES,CC2TES
8832 FORMAT('CALCULATED CONVERGENCE RATIOS: INDIVIDUAL ',
A'TEMPERATURE = ',E14.9,' IAVG TEMPERATURE = ',E14.9)
CALL REGMAP(TIME,2,IMAX,JMAX,REG)
CALL TENTAB(IMAX,JMAX,TIME,2,RC4,IMOL,T)
GO TO 99999
8852 DCLTMX=DLTMAX
TC3AV=(TCMIN3+TCMAX3)/2.
TC3DIF=(TCMIN3-TCMAX3)/2.
TC4AV=(TCMIN4+TCMAX4)/2.
TC4DIF=(TCMIN4-TCMAX4)/2.

```

C
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C

DETERMINATION OF AA'S FOR NEXT ITERATION

```

SUMAA3=0.
KAA3=0.
L3JUND=NBOUN1(3)
DO 8851 KJUND=1,LBOUND
I19OU1=SUMH1(3,KJUND)
JJ9OU1=JFOUN1(3,KJUND)
TH1=TH(JJ9OU1)
IF(R(I19OU1),GT,RP) GAMMA1=PI-ACOS((RP-RP-RF3-RF3)
A-RXMAX3+RXMAX3)/(2.*RP-RF3))
IF(R(I19OU1),LE,RP) GAMMA1=PI-ACOS((RP-RP-RF3-RF3)
A-RXMIN3+RXMIN3)/(2.*RP-RF3))
GAMMAPOGAMMA1
IF(GAMMA1.GT,PI/2.) GAMMAPOPI-GAMMA1
AA3=(T2(I19OU1,JJ9OU1)-TC3AV+TC3DIF+COS(GAMMA1))/GAMMAPO
SUMAA3=SUMAA3+AA3
KAA3=KAA3+1
8851 CONTINUE
L3JUND=NBOUN2(3)
DO 8852 KJUND=1,LBOUND
I19OU2=NBOUN2(3,KJUND)
TH2=ACOS((R(I19OU2)+R(I19OU2)+RP-RP-RF3-RF3)/
A(2+R(I19OU2)+RP))
GAMMA2=PI-ACOS((RP-RP-RF3-RF3-R(I19OU2)+R(I19OU2))
A/(2.*RP-RF3))
GAMMAPOGAMMA2
IF(GAMMA2.GT,PI/2.) GAMMAPOPI-GAMMA2
AA3=(T2(I19OU2,JJ9OU2)-TC3AV+TC3DIF+COS(GAMMA2))/GAMMAPO
SUMAA3=SUMAA3+AA3
KAA3=KAA3+1
8852 CONTINUE
SUMAA4=0.
KAA4=0.
LBOUND=NBOUN1(4)
DO 8853 KJUND=1,LBOUND
I19OU1=NBOUN1(4,KJUND)

```

C

```

JJOU1=JOU1(4,KOUN2)
TN1=TN(JJOU1)
IF(R(IJOU1),GT,RP) GAMMA1=P1-ACOS((RP-RP-RF4-RF4
A-RXN14-RXN14)/(2.*RP-RF4))
IF(R(IJOU1),LE,RP) GAMMA1=P1-ACOS((RP-RP-RF4-RF4
A-RXN14-RXN14)/(2.*RP-RF4))
GAMMA1=GAMMA1
IF(GAMMA1.GT,P1/2.) GAMMA1=P1-GAMMA1
AA4=(7.1(IJOU1,JJOU1)-TC4AV-TC5BIF*COS(GAMMA1))/GAMMA1
SUMAA4=SUMAA4+AA4
KAA4=KAA4+1
0053 CONTINUE
LBOUND=KOUN2(4)
DO 0055 KOUN2=1,LBOUND
IJOU2=KOUN2(4,KOUN2)
TN2=ACOS((R(IJOU2)*R(IJOU2)+RP-RP-RF4-RF4)/
A(2*R(IJOU2)*RP))
GAMMA2=P1-ACOS((RP-RP-RF4-RF4-R(IJOU2)*R(IJOU2))
A/(2.*RP-RF4))
GAMMA2=GAMMA2
IF(GAMMA2.GT,P1/2.) GAMMA2=P1-GAMMA2
AA4=(7.2(IJOU1,JJOU1)-TC3AV-TC5BIF*COS(GAMMA2))/GAMMA2
SUMAA4=SUMAA4+AA4
KAA4=KAA4+1
0055 CONTINUE
AA3=SUMAA3/KAA3
AA4=SUMAA4/KAA4
GO TO 2048

```

C
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C

OUTPUT INFORMATION

```

0000 WRITE(1OUT,9010)ITER
9010 FORMAT('1 CONVERGENCE OBTAINED AFTER',I3,'ITERATIONS')
WRITE(1OUT,9031) IDAD,JBAD
CALL REGCAP(TIME,2,IMAX,JMAX,REY)
CALL TENTAB(IMAX,JMAX,TIME,2,NEL,TNOL,T)
TIME=TTMIN+DT
IF(TIME.GT,TTMIN+GO TO 1000
GO TO 2000
99990 FORMAT('1END OF ORFCAP RUNS')
99999 WRITE(1OUT,99990)
STOP
END

```

```

FUNCTION COND(KCO,T,PLU,MAT)
REAL KCO(2,4,3)

```

C
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C

COMPUTES THERMAL CONDUCTIVITY OF
STAINLESS STEEL IN WATTS/CM-DEG.C. AS FUNCTION
OF TEMPERATURE T IN DEGREE C. AND FLUENCE PLU
(100021 N/CM002) WITH COEFFICIENTS KCO(3,4,3).
MAT IS THE MATERIAL NUMBER=0
2 FOR STAINLESS STEEL

```

COND2=0,
DO 7000 L1=1,3
COND1=0,
LM=L1-1

```

```

      DO 6000 L2=1,4
      L1=L2-1
6000 COND1=KCO(MAT,L2,L1)*T=LL*COND1
7000 COND2=COND1*FLU=LL*COND2
      COND=4.186*COND2
      RETURN
      END

```

```

      FUNCTION CONDF(KCO,T,FLU)
      REAL KCO(2,4,3)
      DIMENSION CONDF(3)

```

```

C      COMPUTES THERMAL CONDUCTIVITY OF FUEL RODS
C      IN WATTS/CM-DEG.C. AS FUNCTION OF TEMPERATURE T
C      IN DEGREES C. AND FLUENCE, FLU, IN (1021 n/cm2)
C      FROM POLYNOMIAL COEFFICIENTS KCO(3,4,4).
C

```

```

      DO 7100 L1=1,3
7100 CONDF(L1)=0.
      DO 7200 L2=1,3
      DO 7200 L3=1,4
7200 CONDF(L2)=KCO(1,L3,L2)*T=(L3-1)*CONDF(L3)
      COND=4.186*(CONDF(1)+CONDF(2)+EXP(CONDF(3)*FLU))
      RETURN
      END

```

```

      FUNCTION CONDC(ME,TG)
      REAL MECON

```

```

C      COMPUTES THERMAL CONDUCTIVITY OF SNEEP GAS
C      IN WATTS/CM-DEG.C. AS FUNCTION
C      OF HELIUM MOLE FRACTION ME AND AVERAGE GAS
C      TEMPERATURE TG IN DEGREES C.
C

```

```

      MECON=4.8697E-14+9.7869E-07*TG-1.0231E-10*TG*TG
      MECON=1.31E-03+3.78E-06*TG-5.05E-10*TG*TG
      CONDC=0.5*(ME*MECON+(1.-ME)*MECON)+0.5/((1.-ME)/MECON+
      A(ME/MECON))
      RETURN
      END

```

```

      SUBROUTINE TENTAB(IMAX,JMAX,TIME,d,RDL,TNOL,T)

```

```

C      TEMPERATURE TABLE OUTPUT
C      GIVES LATTICE COORDINATES I,J AND
C      CAPSULE COORDINATES R, THETA
C      WITH CORRESPONDING TEMPERATURE IN DEGREES C.
C

```

```

      DIMENSION T(92,30)
      IOUT=0
      TNOLD=57.29577991*TNOL
      NMAX=((JMAX-1)/3)+1
      DO 6000 NPAGE=1,NMAX
      J1=NPAGE*3-2
      WRITE(IOUT,6000) TIME,B
6000 FORMAT('1',40X,'TIME=',F4.1,1X,'DAYS',10X,'S-POSITION',
      A7.5,1X,'INCHES')
      WRITE(IOUT,6010)
6010 FORMAT(1X,3(7X,'LATTICE POINT TEMPERATURES',7X))
      WRITE(IOUT,6020)

```

```

6020 FORMAT(1X,3(3X,'I',3X,'J',5X,'R',5X,'THETA',2X,
A'TEMPERATURE',3X))
WRITE(IGOUT,6030)
6030 FORMAT(1X,3(3X,'INCHES',4X,'DEG',6X,'DEG.C',6X))
DO 6040 I=1,IMAX
  J0=J1-1
  J2=J1-1
  J3=J1-2
  THETA2=J1*THDLJ
  THETA3=J2*THDLJ
  R0=RDL/2.54
  THETA10=J0*THDLJ
  WRITE(IGOUT,6040) I,J0,R,THETA1,[(I,J1),I,J1,R,THETA2
A,T(I,J2),I,J2,R,THETA3,T(I,J3)]
6040 FORMAT(1X,3(2X,12,2X,12,2X,F7.9,2X,F6.3,2X,F6.3,6X))
6050 CONTINUE
RETURN
END

```

```

SUBROUTINE REGMAP(TIME,Z,IMAX,JMAX,REG)
INTEGER REG(50,50)
DIMENSION IREG(50),L(50)

```

```

C
C      REGION MAP OUTPUT ROUTINE
C

```

```

  IGOUT=
  WRITE(IGOUT,100) TIME,Z
100 FORMAT('8',25X,'REGION MAP AT TIME= ',F4.1,1X,
A'DAYS AND Z-POSITION= ',F7.9,1X,'INCHES/')
  WRITE(IGOUT,200)
200 FORMAT(2X,'J',35X,'I')
  DO 300 K=1,IMAX
    L(K)=MOD(K,10)
    WRITE(IGOUT,400) L
400 FORMAT('8',3X,5'I1/')
    DO 700 J=1,JMAX
      J0=JMAX-J5+1
      J1=J-1
      DO 500 I=1,IMAX
600 IREG(I)=REG(I,J)
      WRITE(IGOUT,600) J1,IREG
600 FORMAT(1X,12,1X,12'I1)
700 CONTINUE
      RETURN
    END
  FUNCTION CONDH(GKCO,FKCO,TEMP,FLU)
  DIMENSION GKCO(4,7),FKCO(7)

```

```

C
C      COMPUTES GRAPHITE THERMAL CONDUCTIVITY
C      IN WATTS/CM-DEG.C, AS FUNCTION OF FLUENCE
C      (150021 N/CM002) AND TEMPERATURE (DEG.C.)
C

```

```

  NC 100 LF=1.7
  IF(FLU,LE,FKCO(LF)) LK=LF
100 CONTINUE
  TK1=0.
  TK2=0.
  DO 200 L1=1,4
    TK1=GKCO(L1,LK=1)*TEMP00(L1=1)*TK1
200 TK2=GKCO(L1,LK)*TEMP00(L1=1)*TK2

```


CONVERGENCE OBTAINED AFTER 274 ITERATIONS

WORST POINT AT(51, 0)

REGION MAP AT TIME= 12.0 DAYS AND Z-POSITION= 9.87500 INCHES

[illegible]

TIME-DATE				POSITIONS 0.07500 INCHES				LATTICE POINT TEMPERATURES				TEMPERATURES			
I	J	INCHES	DEG. C	I	J	INCHES	DEG. C	I	J	INCHES	DEG. C	I	J	INCHES	DEG. C
1	10	.02000	43.920	1	10	.02000	43.920	1	20	.02000	43.900	1	20	.02000	43.900
2	10	.05000	48.930	2	10	.05000	48.930	2	20	.05000	48.930	2	20	.05000	48.930
3	10	.08000	53.940	3	10	.08000	53.940	3	20	.08000	53.940	3	20	.08000	53.940
4	10	.11000	58.950	4	10	.11000	58.950	4	20	.11000	58.950	4	20	.11000	58.950
5	10	.14000	63.960	5	10	.14000	63.960	5	20	.14000	63.960	5	20	.14000	63.960
6	10	.17000	68.970	6	10	.17000	68.970	6	20	.17000	68.970	6	20	.17000	68.970
7	10	.20000	73.980	7	10	.20000	73.980	7	20	.20000	73.980	7	20	.20000	73.980
8	10	.23000	78.990	8	10	.23000	78.990	8	20	.23000	78.990	8	20	.23000	78.990
9	10	.26000	83.000	9	10	.26000	83.000	9	20	.26000	83.000	9	20	.26000	83.000
10	10	.29000	88.010	10	10	.29000	88.010	10	20	.29000	88.010	10	20	.29000	88.010
11	10	.32000	93.020	11	10	.32000	93.020	11	20	.32000	93.020	11	20	.32000	93.020
12	10	.35000	98.030	12	10	.35000	98.030	12	20	.35000	98.030	12	20	.35000	98.030
13	10	.38000	103.040	13	10	.38000	103.040	13	20	.38000	103.040	13	20	.38000	103.040
14	10	.41000	108.050	14	10	.41000	108.050	14	20	.41000	108.050	14	20	.41000	108.050
15	10	.44000	113.060	15	10	.44000	113.060	15	20	.44000	113.060	15	20	.44000	113.060
16	10	.47000	118.070	16	10	.47000	118.070	16	20	.47000	118.070	16	20	.47000	118.070
17	10	.50000	123.080	17	10	.50000	123.080	17	20	.50000	123.080	17	20	.50000	123.080
18	10	.53000	128.090	18	10	.53000	128.090	18	20	.53000	128.090	18	20	.53000	128.090
19	10	.56000	133.100	19	10	.56000	133.100	19	20	.56000	133.100	19	20	.56000	133.100
20	10	.59000	138.110	20	10	.59000	138.110	20	20	.59000	138.110	20	20	.59000	138.110
21	10	.62000	143.120	21	10	.62000	143.120	21	20	.62000	143.120	21	20	.62000	143.120
22	10	.65000	148.130	22	10	.65000	148.130	22	20	.65000	148.130	22	20	.65000	148.130
23	10	.68000	153.140	23	10	.68000	153.140	23	20	.68000	153.140	23	20	.68000	153.140
24	10	.71000	158.150	24	10	.71000	158.150	24	20	.71000	158.150	24	20	.71000	158.150
25	10	.74000	163.160	25	10	.74000	163.160	25	20	.74000	163.160	25	20	.74000	163.160
26	10	.77000	168.170	26	10	.77000	168.170	26	20	.77000	168.170	26	20	.77000	168.170
27	10	.80000	173.180	27	10	.80000	173.180	27	20	.80000	173.180	27	20	.80000	173.180
28	10	.83000	178.190	28	10	.83000	178.190	28	20	.83000	178.190	28	20	.83000	178.190
29	10	.86000	183.200	29	10	.86000	183.200	29	20	.86000	183.200	29	20	.86000	183.200
30	10	.89000	188.210	30	10	.89000	188.210	30	20	.89000	188.210	30	20	.89000	188.210
31	10	.92000	193.220	31	10	.92000	193.220	31	20	.92000	193.220	31	20	.92000	193.220
32	10	.95000	198.230	32	10	.95000	198.230	32	20	.95000	198.230	32	20	.95000	198.230
33	10	.98000	203.240	33	10	.98000	203.240	33	20	.98000	203.240	33	20	.98000	203.240
34	10	1.01000	208.250	34	10	1.01000	208.250	34	20	1.01000	208.250	34	20	1.01000	208.250
35	10	1.04000	213.260	35	10	1.04000	213.260	35	20	1.04000	213.260	35	20	1.04000	213.260
36	10	1.07000	218.270	36	10	1.07000	218.270	36	20	1.07000	218.270	36	20	1.07000	218.270
37	10	1.10000	223.280	37	10	1.10000	223.280	37	20	1.10000	223.280	37	20	1.10000	223.280
38	10	1.13000	228.290	38	10	1.13000	228.290	38	20	1.13000	228.290	38	20	1.13000	228.290
39	10	1.16000	233.300	39	10	1.16000	233.300	39	20	1.16000	233.300	39	20	1.16000	233.300
40	10	1.19000	238.310	40	10	1.19000	238.310	40	20	1.19000	238.310	40	20	1.19000	238.310
41	10	1.22000	243.320	41	10	1.22000	243.320	41	20	1.22000	243.320	41	20	1.22000	243.320
42	10	1.25000	248.330	42	10	1.25000	248.330	42	20	1.25000	248.330	42	20	1.25000	248.330
43	10	1.28000	253.340	43	10	1.28000	253.340	43	20	1.28000	253.340	43	20	1.28000	253.340
44	10	1.31000	258.350	44	10	1.31000	258.350	44	20	1.31000	258.350	44	20	1.31000	258.350
45	10	1.34000	263.360	45	10	1.34000	263.360	45	20	1.34000	263.360	45	20	1.34000	263.360
46	10	1.37000	268.370	46	10	1.37000	268.370	46	20	1.37000	268.370	46	20	1.37000	268.370
47	10	1.40000	273.380	47	10	1.40000	273.380	47	20	1.40000	273.380	47	20	1.40000	273.380
48	10	1.43000	278.390	48	10	1.43000	278.390	48	20	1.43000	278.390	48	20	1.43000	278.390
49	10	1.46000	283.400	49	10	1.46000	283.400	49	20	1.46000	283.400	49	20	1.46000	283.400
50	10	1.49000	288.410	50	10	1.49000	288.410	50	20	1.49000	288.410	50	20	1.49000	288.410
51	10	1.52000	293.420	51	10	1.52000	293.420	51	20	1.52000	293.420	51	20	1.52000	293.420
52	10	1.55000	298.430	52	10	1.55000	298.430	52	20	1.55000	298.430	52	20	1.55000	298.430
53	10	1.58000	303.440	53	10	1.58000	303.440	53	20	1.58000	303.440	53	20	1.58000	303.440
54	10	1.61000	308.450	54	10	1.61000	308.450	54	20	1.61000	308.450	54	20	1.61000	308.450
55	10	1.64000	313.460	55	10	1.64000	313.460	55	20	1.64000	313.460	55	20	1.64000	313.460
56	10	1.67000	318.470	56	10	1.67000	318.470	56	20	1.67000	318.470	56	20	1.67000	318.470
57	10	1.70000	323.480	57	10	1.70000	323.480	57	20	1.70000	323.480	57	20	1.70000	323.480
58	10	1.73000	328.490	58	10	1.73000	328.490	58	20	1.73000	328.490	58	20	1.73000	328.490
59	10	1.76000	333.500	59	10	1.76000	333.500	59	20	1.76000	333.500	59	20	1.76000	333.500
60	10	1.79000	338.510	60	10	1.79000	338.510	60	20	1.79000	338.510	60	20	1.79000	338.510

9.5 Nomenclature

A_3, A_4	correction factors for gamma dependence of special region boundary temperatures in regions 3 and 4, respectively
a_p, a_n	fraction of distance ΔR in the positive and negative R direction for irregular boundary points, dimensionless
b_p, b_n	fraction of distance $R\Delta\theta$ in the positive and negative θ direction for irregular boundary points, dimensionless
$B_{n,m}$	thermal expansion function polynomial coefficients for temperature dependence $(^\circ\text{C}^{-n})(10^{21} \text{ N/cm}^2)^{-m}$ added together to form fluence dependence coefficients
$C_{n,m}$	thermal conductivity function polynomial coefficients for fluence and temperature dependence $(^\circ\text{C}^{-n})(10^{21} \text{ N/cm}^2)^{-m}$ to be added together to form fluence dependence coefficients
D	thermally expanded dimension at temperature T
D_0	reference dimension for expansion evaluated at 25°C, cm
D_1	intermediate graphite irradiated dimension calculated from natural strain value, cm
e_1, e_2	emissivities of boundary surfaces, dimensionless
F_n	flux function polynomial coefficients for axial position dependency $(\text{cm}^{-n})(\text{N/day})$ multiplied by $(10^{14} \text{ n/cm}^2/\text{sec})(86,400 \text{ sec/day})$
G	gap width, cm
h_{cond}	conduction heat transfer coefficient in gap, $\text{Kg/G, w/cm}^2\text{-}^\circ\text{C}$
K	thermal conductivity of material, $\text{w/cm-}^\circ\text{C}$
K_g	thermal conductivity of sweep gas, $\text{w/cm-}^\circ\text{C}$
$N_{n,m}$	natural strain value polynomial coefficients for temperature and fluence dependence, $(^\circ\text{C})^{n-1}(\text{n/cm}^2)^{m-1}$
q_{rad}	modified radiation heat transfer term in gap $= \frac{\sigma}{K}(e_1 T_B^4 - e_2 T_{ij}^4)$, $^\circ\text{C/cm}$
R_i	radial position coordinate of lattice point, cm
R_p	distance from origin of peripheral fuel rod and hole center, cm
$R_{\text{min},n}$	minimum R boundary radial coordinate in region $N = 2, 4, 5, 6$, cm

$R_{\max,n}$	maximum R boundary radial coordinate in region $N = 2, 4, 5, 6$, cm
$R_{x,\min,3}$	minimum R boundary radial coordinate in peripheral fuel rod where $\gamma > 90^\circ$, cm
$R_{x,\min,4}$	minimum special R boundary radial coordinate in peripheral fuel rod hole where $\gamma > 90^\circ$, cm
$R_{x,\max,3}$	maximum R boundary radial coordinate in peripheral fuel rod where $\gamma < 90^\circ$, cm
$R_{x,\max,4}$	maximum special R boundary radial coordinate in peripheral fuel rod hole where $\gamma < 90^\circ$, cm
$R_{x,\max}$	$P_{x,\min}$ at $\gamma = 90^\circ$
ΔR	lattice radial increment, cm
r_3	radius of peripheral fuel rod with origin at R_p , cm
r_4	radius of peripheral fuel rod hole with origin at R_p , cm
S_F	fission heat generation term of fuel rod, t dependent, w/cm^3
S_n	nth order polynomial fission heat generation function coefficient, $(\text{sec})^{-n}(w/cm^3)$
S_γ	gamma heating term of each material, z dependent, w/cm^3
T_B	boundary temperature across the gap from boundary point to be evaluated, $^\circ\text{C}$
$T_{i,j}$	regular lattice point temperature value, $^\circ\text{C}$
$T_{1i,j}$	irregular boundary point temperature associated with regular i, j lattice point, $^\circ\text{C}$
$T_{2i,j}$	irregular boundary point temperature associated with regular i, j lattice point along a line of constant R, $^\circ\text{C}$
t	irradiation time, sec
$t_{\min}$	shortest irradiation time of interest, sec
$t_{\max}$	longest irradiation time of interest, sec
Δt	time increment, sec
V_n	nth order polynomial gamma heating function coefficients, $(\text{cm})^{-n}(w/cm^3)$
$X_{\text{He}}, X_{\text{Ne}}$	mole fractions of helium and neon in sweep gas

X_A	coefficient for general finite difference equation temperature expansion term in positive R direction
X_B	coefficient for temperature term in negative R direction
X_C	coefficient for temperature term in positive θ direction
X_D	coefficient for temperature term in negative θ direction
X_Q	coefficient for boundary heat transfer term in any direction
$X_{1A}, X_{1B}, X_{1C}, X_{1D}, X_{1Q}, X_{2A}, X_{2B}, X_{2C}, X_{2D}, X_{2Q}$	coefficients for corresponding terms in equations for $T_{1i,j}$ and $T_{2i,j}$
Z	axial position in capsule, cm

Greek Symbols

β	thermal expansion coefficient, dimensionless
γ	position angle of point on peripheral fuel rod or hole surfaces, centered at R_p , radians
ϕ	neutron flux, N/cm^2 -day
θ	angle difference, $\gamma - \theta$, radians
ρ_{FR}	density of fuel rod, g/cm^3
ρ_{GR}	density of graphite, g/cm^3
ρ_{SS}	density of 304 stainless steel, g/cm^3
σ	Stefan-Boltzmann constant, 5.886×10^{-12} , $w/cm^2 \cdot ^\circ K^4$
θ_j	angular position coordinate of regular lattice point, radians
$\Delta\theta$	lattice angular increment, radians

9.6 Literature References

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