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Thermal-Hydraulic/Heat Transfer Code Development for Sphere-Pac-Fueled LMFBRs

David G. Morris

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for Sphere-Pac-Fueled LMFBRS

David G. Morris*

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*Engineering Technology Division.

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ABSTRACT

Sphere-pac fuel has received much attention recently in light of the development of proliferation-resistant fuel cycles for the Fast Breeder Reactor Program in the United States. However, for sphere-pac fuel to be a viable alternative to conventional pellet fuel, a means to analyze the thermal behavior of sphere-pac-fueled pin bundles is needed. To meet this need, a thermal-hydraulic/heat transfer computer code has been developed for sphere-pac-fueled fast breeder reactors. The code, COBRA-3SP, is a modified version of COBRA-3M incorporating a three-region sphere-pac fuel pin model which permits fuel restructuring. With COBRA-3SP, steady-state and transient analysis of sphere-pac-fueled pin bundles is possible. The validity of the sphere-pac fuel pin model has been verified using experimental results of irradiated sphere-pac fuel.

I. INTRODUCTION

The concepts associated with sphere-pac fuel for fast breeder reactors originated in the United States almost 20 years ago. Since then, sphere-pac fuel technology has been advanced through efforts in the United States, England, Germany, Italy, Switzerland, The Netherlands, and elsewhere. Today sphere-pac fuel is playing an important role in the development of proliferation-resistant fuel cycles for the fast breeder reactor program.

Basically, sphere-pac fuel consists of a discontinuous solid phase of closely packed fuel microspheres surrounded by a continuous gas phase. Two or three sizes of microspheres are generally used in fuel pins, the specific sizes depending on the smear density required. To arrange the fuel microspheres in a well-compacted homogeneous configuration, a low-energy vibration is applied to the pin. Figure 1 shows a conventional pellet fuel pin and a typical sphere-pac fuel pin.

The irradiation performance of sphere-pac fuel has exhibited some significant advantages over that of pellet fuel.¹ First, with sphere-pac fuel rods there is a reduction of the stress exerted on the clad by the fuel; second, the transport of fission products to the inner clad surface is not as rapid in sphere-pac fuel as in pellet fuel, and the fission products that do reach the clad tend to be less concentrated when sphere-pac fuel is used. These advantages are accounted for by the fact that, regardless of the power level used, an annulus of unsintered spheres always exists between the sintered fuel and the cladding when sphere-pac fuel is used. Sphere-pac fuel also has the significant advantage of lending itself much more readily to the remote fabrication of fuel elements.

Thus one can see that the sphere-pac fuel concept appears very attractive. However, a means to analyze the thermal-hydraulic/heat-transfer behavior of sphere-pac-fueled pin bundles is needed if sphere-pac fuel is to be available alternative to pellet fuel in LMFBRs. Since the only difference between sphere-pac and pellet-fueled cores is the form of the fuel material, it was possible to develop a code specifically designed for sphere-pac fuel by modifying the existing LMFBR thermal-hydraulic/heat-transfer computer code COBRA-3M² to incorporate a three-region restructuring

Fig. 1. Comparison of Pellet and Sphere-pac Fuel Pins.

fuel model in place of the single-region model in which no fuel restructuring was allowed. COBRA-3M was chosen because its flexibility and reasonable degree of complexity allowed its modification in a relatively short period of time. The modified version is called COBRA-3SP (SP denotes sphere-pac). Since much of COBRA-3M deals with behavior outside the fuel pin, a large portion of the code remains unchanged in COBRA-3SP (e.g. the fluid analysis models and duct wall model were untouched).

COBRA-3SP calculates the fuel structure at a user-prescribed steady-state power level. It then calculates the temperature distribution in the fuel at a second prescribed steady-state power level using the fuel structure determined in the previous calculation. (The same power level may be used for both the structure and temperature calculations.) Finally, COBRA-3SP can perform a transient calculation using the fuel structure

determined in the structure calculation if desired. As in the original version of COBRA-3M, duct wall and fluid calculations are made along with the fuel calculations.

Comparisons have been made between COBRA-3SP results and experimental results dealing with sphere-pac fuel under irradiation in order to verify the validity of the revised fuel pin model. Results indicate that agreement between code and experiment is within 5% for the cases examined here. Details of the cases studied can be found in the Sample Problems section.

II. SPHERE-PAC FUEL PIN MODEL

II.1. Development and Assumptions

The fuel portion of the sphere-pac fuel pin model (shown schematically in Fig. 2) consists of a central void surrounded by three concentric regions of structurally different fuel: a restructured region of high-density sintered fuel, a transition region of partially restructured fuel, and a region of unrestructured sphere-pac fuel. One can see these three distinct regions in the micrograph of a typical irradiated sphere-pac fuel element shown in Fig. 3.

The locations of the two interfaces separating the three fuel regions, as well as the sizes of these regions, are dependent on the amount of restructuring the fuel has undergone. Restructuring of the fuel occurs as voids (i.e., gas) travel up the temperature gradient. It has been observed that vaporization-condensation is the primary restructuring process in oxide fuels at temperatures above about 1700°C.³ It has been further observed that many factors influence fuel restructuring, including temperature, temperature gradient, time, fuel oxygen-to-metal ratio, fuel composition, fuel density, and hydrostatic stress. It should be noted that fuel temperature is a key factor in restructuring. In fact, restructuring proceeds exponentially with temperature; most of the restructuring of the spheres occurs early in the life of the fuel.⁴

Information pertaining to the correlation between temperature and locations of the interfaces separating the fuel regions can be obtained from micrographs of irradiated sphere-pac fuel. The micrograph in Fig. 4 shows that the fuel has restructured completely at temperatures above 1700°C, that

Fig. 2. Schematic Cross Section of a Sphere-pac Fuel Rod Showing the Void, Restructured, Transition, and Unrestructured Regions.

there is a region of partially restructured fuel between 1300°C and 1700°C , and that the fuel is essentially unrestructured below about 1300°C . Oxide sphere-pac fuel which has undergone any significant amount of radiation will generally exhibit these effects.⁵

In COBRA-3SP the user is required to supply the above mentioned interface temperatures, which are used in the determination of the fuel structure where it is assumed that restructuring depends on fuel temperature alone. That is, it is assumed that all of the fuel with temperatures higher than the sintered/transition interface temperature is completely restructured fuel. It is also assumed that the fuel below the transition/sphere-pac interface is completely unrestructured. Partially

Fig. 3. $(U_{0.8}Pu_{0.2})O_{1.98}$ Sphere-pac FBR Fuel Rod at 5.7 a/o Burnup Irradiated at 44.3 kW/m in EBR-II.

restructured fuel is assumed to exist between the two specified interface temperatures. In view of the scarcity of available information concerning the restructuring kinetics of sphere-pac fuel, this approach is quite reasonable.

The properties of restructured region fuel required by COBRA-3SP are readily available.^{6,7,8} These properties include thermal conductivity, specific heat, and density as a function of temperature. Some of

Fig. 4. Enlarged View of Transverse Microstructure of an EBR-II Fuel Pin at the Region of Maximum Linear Power, 46 kW/m (14 kW/ft). Fuel material is $(U,Pu)O_2$. The left figure is as polished, and the right figure is after etching. A temperature scale has been superimposed on the right figure.¹

the properties of the unrestructured region fuel are also easy to find. Properties such as specific heat and density can be found with no difficulty.^{6,7,8} On the other hand, the effective thermal conductivity of the sphere-gas mixture comprising the unrestructured fuel is difficult to find since few experiments have been performed to determine sphere-pac fuel conductivity. Thermal calculations with the code require that sphere-pac fuel conductivity be known. Therefore, an option has been built into the code whereby the sphere-pac fuel conductivity may be calculated with a theoretical conductivity correlation that has been incorporated into the code. Alternatively, the user may supply the effective thermal conductivity of the sphere-pac fuel.

There have been many attempts to derive theoretical expressions for the effective thermal conductivity of particle-gas mixtures.^{9,10,11} Many of these have been successful for a limited range of temperatures and/or particle-gas thermal conductivity ratios. In a number of correlations the effect of thermal radiation on heat transport is neglected. For the case of sphere-pac fuel, under normal operating conditions fuel temperatures are high, thereby requiring that thermal radiation effects be considered. After a careful review of the effective thermal conductivity correlations available in the literature, it is thought that sphere-pac fuel conductivity might best be described with an equation derived by Godbee.¹² This is presented below:

$$k_e = \frac{K_g^*}{\left[\frac{\frac{D_s}{X}}{\frac{K_g}{K_g^*} \left(1 - \frac{S}{X^2} \right) + \frac{K_d}{K_g^*} \left(\frac{S}{X^2} \right)} \right] + \left(1 - \frac{D_s}{X} \right)} + 4n_r^2 \sigma \epsilon \left(\frac{1}{V_d} - 1 \right) D_s T^3, \quad (1)$$

where

$$K_g^* = K_g \left(1 - \frac{S}{X^2} \right) + K_g^o \left(\frac{S}{X^2} \right), \quad (2)$$

$$K_g^o = \frac{K_g}{1 + Z \left(\frac{2-a}{a} \right) \left(\frac{\gamma}{1+\gamma} \right) \left(\frac{T}{Pd \psi^2 N_{Pr}} \right)}, \quad (3)$$

$$\frac{D_s}{X} = \left(\frac{V_d}{\alpha} \right)^{1/3}, \quad (4)$$

$$\alpha = \frac{S}{D_s^2}, \quad (5)$$

and where

K_e = Effective thermal conductivity of the two-phase system

K_d = Thermal conductivity of the discontinuous phase

K_g = Thermal conductivity of bulk gas

V_d = Volume fraction of discontinuous phase

a = Thermal accommodation coefficient for gas-solid surface

γ = Ratio of gas heat capacity at constant pressure to heat capacity at constant volume

C_{pg} = Gas heat capacity at constant pressure

C_{vg} = Gas heat capacity at constant volume

D_s = Mean sphere size

d = Distance between close parallel plates = $X - D_s$

T = Absolute temperature

P = Absolute pressure

ϕ = Molecular diameter of gas as determined from viscosity

$N_{Pr} = \frac{\eta C_{pg}}{K_g} = \text{Prandtl number}$

η = Viscosity of gas

Z = A constant = 1.26×10^{-19} for centimeter, gram, degree Kelvin units

n_r = Refractive index of media between surfaces

σ = Stefan-Boltzmann constant

ϵ = Emissivity.

Equations (1) through (5) have been shown by Godbee to be quite accurate in predicting particle-gas effective thermal conductivity.¹² These equations have been used elsewhere with good success in predicting the effective thermal conductivity of UO_2 powder in atmospheric air.¹³ Note that Eq. (1) has a thermal radiation term. The properties required by Eqs. (1) through (5) are available in the literature with the exception of the geometric property, α , the heat flow shape factor. By geometry-dependent it is meant that the shape factor is a function of the sizes of particles and how they are packed together. The heat flow shape factor determines what portion of the solid phase may be considered to be in parallel (in the heat flow sense) with the surrounding fluid and what portion may be considered to be in series. It is purely geometry-dependent and can be determined experimentally. Alternatively, the heat flow shape factor can be deduced for geometries of interest using Eqs. (1) through (5) to calculate effective thermal conductivity as a function of the shape factor which can be benchmarked with known values of conductivity. The value of the shape factor that results in the best agreement between calculated and known conductivities would thereby be obtained.

The properties of partially restructured sphere-pac fuel are not available. Properties for fuel in the partially restructured region are therefore deduced from completely restructured fuel properties and unrestructured fuel properties. In COBRA-3SP, all properties in the partially restructured region (i.e., thermal conductivity, specific heat, and density) are assumed to vary linearly with temperature throughout this region from the outer fuel interface to the inner interface. The property values at the outer fuel interface are assumed to be those of unrestructured sphere-pac fuel, whereas the property values at the inner fuel interface are those of completely restructured fuel.

Based on the fuel properties, fuel interface temperatures, and power level, COBRA-3SP is able to determine the fuel structure and temperature distribution throughout the pin. In the code, the structure of the fuel is assumed to be determined at some specific power level in the operating history. This power level will most often be the maximum power level achieved. The fuel structure thus determined is assumed to exist for all

later times, including the point in time where the temperature calculation of interest is to be performed. The code performs a discontinuous, two-point calculation where operating conditions are specified for both points. The point at which the fuel structure is determined may be the same as that at which the temperature distribution calculation is to be performed. It should be made clear that COBRA-3SP is not a kinetics code where operating conditions are stated for a sequence of time steps and restructuring occurs in a time-dependent fashion. In COBRA-3SP restructuring occurs "instantaneously" at some point in time based on user-specified power level, fuel densities, and fuel interface temperatures.

The heat generation rate in each fuel pin can be made to vary radially in COBRA-3SP. Four options are available to the user:

- (1) The heat generation rate may be uniform with radius.
- (2) The user may specify peak-to-average power factors at certain radial positions (COBRA-3M and LIFE-I¹⁴ utilize this method).
- (3) It may be assumed that the heat generation rate will vary radially with the fuel density, which is a safe assumption for LMFBRs since the neutron flux is fairly flat radially across the fuel pin.
- (4) The user may vary the heat generation rate with power factors as in (2) and with fuel density as in (3) where these two methods are combined in such a way that the total heat generation rate in the fuel pin is conserved.

A number of the assumptions made in the fuel pin model development for COBRA-3SP have not been discussed as yet. Many of these assumptions are the same as those made in COBRA-3M. They include:²

- (1) Heat flow is one-dimensional, in the radial direction only. Axial and circumferential heat conductions are assumed to be insignificant.
- (2) A lumped-parameter approach is taken for both the fuel and cladding.
- (3) The centroid (node) of each radial zone is located at a radius $r^* = [0.5 (r_m^2 + r_{m+1}^2)]^{1/2}$ (see Fig. 5 for diagrams describing the nodal method as applied to the fuel pin).

Fig. 5. Thermal Model of Fuel Pin.²

- (4) For numerical reasons, Δr in the fuel is taken to be a constant at a given axial location. Note that the size of the Δr will depend on the degree to which the sphere-pac fuel restructures. The number of radial cuts at all axial locations will be a constant.
- (5) The inner surface of the first (innermost) radial zone is adiabatic.
- (6) Thermal expansion of the cladding is neglected.
- (7) Fuel is assumed not to heal following the restructure calculation.
- (8) Thermal conductivity, specific heat, and density of the fuel and cladding are temperature-dependent.
- (9) Heat generation in the fuel can be non-uniform, both radially and axially.

The nodal equations that describe the fuel pin model are presented in the following pages [Eqs. (6-8)]. These equations were taken directly from the COBRA-3M user's manual and are presented here for completeness.²

for the fuel (MF nodes)

$$\left. \begin{aligned}
 & \frac{T_2^* - T_1^*}{R_1} + q_1 - C_1 \frac{dT_1^*}{dt} = 0 \\
 & \vdots \\
 & \frac{T_{m-1}^* - T_m^*}{R_{m-1}} + \frac{T_{m+1}^* - T_m^*}{R_m} + q_m - C_m \frac{dT_m^*}{dt} = 0 \\
 & \vdots \\
 & \frac{T_{MF-1}^* - T_{MF}^*}{R_{MF-1}} + \frac{T_{MF+1}^* - T_{MF}^*}{R_{MF}} + q_{MF} - C_{MF} \frac{dT_{MF}^*}{dt} = 0
 \end{aligned} \right\} (6a)$$

and for the cladding [(MF-MF) nodes]

$$\left. \begin{aligned}
 & \frac{T_{MF}^* - T_{MF+1}^*}{R_{MF}} + \frac{T_{MF+2}^* - T_{MF+1}^*}{R_{MF+1}} - C_{MF+1} \frac{dT_{MF+1}^*}{dt} = 0 \\
 & \vdots \\
 & \frac{T_{ME-1}^* - T_{ME}^*}{R_{ME-1}} + \frac{T_i - T_{ME}^*}{R_{ME}} - C_{ME} \frac{dT_{ME}^*}{dt} = 0
 \end{aligned} \right\} (6b)$$

where

$$R_m = \frac{\ln(r_{m+1}/r_m^*)}{2\pi k_m \phi \Delta x} + \frac{\ln(r_{m+1}^*/r_{m+1})}{2\pi k_{m+1} \phi \Delta x}$$

$$R_{MF} = \frac{\ln(r_{MF+1}/r_{MF}^*)}{2\pi k_{MF} \phi \Delta x} + \frac{1}{h_{gap} A_{MF+1}} + \frac{\ln(r_{MF+1}^*/r_{MF+1})}{2\pi k_{MF+1} \phi \Delta x}$$

$$R_{ME} = \frac{\ln(r_o/r_{ME}^*)}{2\pi k_{ME} \phi \Delta x} + \frac{1}{h_i A_o}$$

h_i = heat-transfer coefficient between cladding outer surface and subchannel i

$$A_o = 2\pi r_o \phi \Delta x$$

$$q_m = q_m''' V_m$$

q_m''' = volumetric heat-generation rate in zone m

$$V_m = \pi(r_{m+1}^2 - r_m^2) \phi \Delta x$$

$$C_m = \rho_m V_m c_m$$

$$A_{MF+1} = 2\pi r_{MF+1} \phi \Delta x$$

Δx = axial increment

ϕ = fractional arc length over the outer cladding circumference.

By the use of a backward finite difference for the time derivative,
i.e.,

$$\frac{dT_m^*(t+\Delta t)}{dt} = \frac{T_m^*(t+\Delta t) - T_m^*(t)}{\Delta t}, \quad (7)$$

Eqs. 6a and 6b can be rearranged and combined into the form:

$$[G] \{T^*(t+\Delta t)\} = \{g\}, \quad (8)$$

where $[G]$ is a nonsymmetric square matrix whose elements are zero, except

$$G_{11} = 1 + \frac{\Delta t}{R_1 C_1}$$

$$G_{12} = \frac{\Delta t}{R_1 C_1}$$

$$G_{m,m-1} = -\frac{\Delta t}{R_{m-1} C_m}$$

$$G_{m,m} = \left[1 + \frac{\Delta t}{R_{m-1} C_m} \left(1 + \frac{R_{m-1}}{R_m} \right) \right]$$

$$G_{m,m+1} = -\frac{\Delta t}{R_m C_m}$$

$$\left. \begin{array}{l} G_{m,m-1} = -\frac{\Delta t}{R_{m-1} C_m} \\ G_{m,m} = \left[1 + \frac{\Delta t}{R_{m-1} C_m} \left(1 + \frac{R_{m-1}}{R_m} \right) \right] \\ G_{m,m+1} = -\frac{\Delta t}{R_m C_m} \end{array} \right\} 1 < m < ME$$

$$G_{ME,ME-1} = -\frac{\Delta t}{R_{ME-1} C_{ME}}$$

$$G_{ME,ME} = \left[1 + \frac{\Delta t}{R_{ME-1} C_{ME}} \left(1 + \frac{R_{ME-1}}{R_{ME}} \right) \right]$$

and the column vectors are:

$$\{g\} = \begin{Bmatrix} T_1^*(t) + \frac{\Delta t}{C_1} q_1 \\ \vdots \\ T_{MF}^*(t) + \frac{\Delta t}{C_{MF}} q_{MF} \\ T_{MF+1}^*(t) \\ \vdots \\ T_{ME}^*(t) + \frac{\Delta t}{R_{ME} C_{ME}} T_i(t+\Delta t) \end{Bmatrix}$$

and

$$\{T^*(t+\Delta t)\} = \begin{Bmatrix} T_1^*(t+\Delta t) \\ \vdots \\ T_{MF}^*(t+\Delta t) \\ \vdots \\ T_{ME}^*(t+\Delta t) \end{Bmatrix} .$$

II.2. Fuel-Clad Gap Conductance

At the fuel-clad interface there is a thermal resistance effect in sphere-pac fuel just as there is in pellet fuel. It has been found that the gap conductance for sphere-pac fuel is higher than for pellet fuel for equivalent smear densities.⁵ A gap conductance of $1.93 \text{ W cm}^{-2} (^{\circ}\text{C})^{-1}$ was deduced for sphere-pac fuel in the ORR thermal performance tests.⁵ This value of gap conductance is about 60% higher than that found for pellet fuel in these same tests. Transient tests with sphere-pac fuel indicate that the gap conductance for sphere-pac fuel may be as high as $3.4 \text{ W cm}^{-2} (^{\circ}\text{C})^{-1}$.¹⁵

In COBRA-3SP the user is required to supply two values of gap conductance for each fuel rod. One value is used in the fuel restructure calculation, while the other is used in the temperature distribution calculation. Two values of gap conductance are required because the inventory of fission gas in the pin, which increases with time, strongly affects gap conductance. Gap conductance data for sphere-pac fuel is available although there is not an abundance of sources.^{5,15} Additional experimental work combined with thermal analysis needs to be performed in order to improve the data base of gap conductance information for sphere-pac fuel.

III. METHOD OF SOLUTION

The general methodology of solution in COBRA-3SP closely follows that of COBRA-3M. Differences occur in calculations involving the inside of the fuel pin because COBRA-3SP has a fuel restructure model whereas COBRA-3M does not. Descriptions of the solution methods relating to the hydraulics or fluid flow analysis will not be given here, since that information is available in the COBRA-III¹⁶ and COBRA-3M² manuals. This section will focus on the solution methods relating to calculations involving the inside of the fuel pin.

In steady-state calculations with COBRA-3SP, as with COBRA-3M, a heat-balance calculation is performed. From this calculation coolant temperatures are determined which are then used to calculate fuel pin surface temperatures. The pin surface temperatures are calculated using the relation²

$$T_o = \frac{T_{ME}^* + (R_c/R_d)T_i}{1 + (R_c/R_f)}, \quad (9)$$

where

$$R_c = \frac{\ln(r_o/r_{ME}^*)}{2\pi K_{ME} \phi \Delta x},$$

$$R_d = \frac{1}{h_i A_o}.$$

The heat transfer coefficient is determined from the following correlation:²

$$Nu = f_1 + f_2 Pe^{f_3}, \quad (10)$$

where

Nu = Nusselt number = hDe/k ,

Pe = Peclet number = $RePr = Dv\rho c_p/k$

f_1, f_2, f_3 are input constants.

Fuel restructure and temperature calculations can be made using the fuel surface temperatures and the heat generation rate inside the pin.

Transient calculations with COBRA-3SP follow the same general method of solution used in the steady-state calculations, with the exception that coolant temperatures are not determined separately from fuel temperatures *a priori*. This difference is due to the fact that in transient calculations more or less heat reaches the coolant than is generated in the fuel, depending on how the enthalpy of the fuel changes during the transient. Thus, in transient calculations fuel and coolant temperatures are coupled and to determine them an iterative procedure is used.

When the restructuring of the fuel is considered, as is the case here with sphere-pac fuel, one is faced with solving a set of coupled nonlinear equations where one is interested in finding not only the temperature distribution but also the central void radius and the region sizes and interfaces. That is, the temperature distribution, the central void radius, and the region sizes and interfaces are related through a set of coupled nonlinear

equations. These nonlinear equations can be transformed into a form amenable to computer solutions using finite element theory, finite difference theory, or the nodal, lumped-parameter method mentioned previously. Once the equations are transformed, the successive substitution technique or a multidimensional version of the Newton-Raphson method¹⁷ can be used to find the solutions.

The transformation of the nonlinear equations using finite element or finite difference theory would provide a more accurate representation of the equations than the nodal, lumped-parameter method; however, the accuracy of the results obtained by using either of the former methods over the nodal lumped-parameter method is thought to be slight. In view of this and of the fact that the nodal, lumped-parameter method exists in COBRA-3M and is an accepted method in the field of heat transfer, the nodal, lumped-parameter method has been used.

With regard to dealing with the coupled nonlinear equations following transformation via the nodal, lumped-parameter method, the multi-dimensional Newton-Raphson method provides a simultaneous treatment of the transformed coupled system of equations. On the other hand, the successive substitution technique makes it possible to segregate the set of transformed equations and allows the solution to be found using iterative techniques. The successive substitution technique was chosen as the numerical approach because it can be combined with the nodal, lumped-parameter method and be made to work well with little difficulty. Also, it was thought that the multidimensional Newton-Raphson method would increase COBRA-3M's core space requirements significantly.

Using the nodal, lumped-parameter method along with the successive substitution technique, the temperature distribution and fuel restructure information can be found as follows:

To begin, assume a constant temperature distribution throughout the fuel pin with steady-state conditions such that no restructuring of the fuel occurs. This means that the fuel is entirely in the sphere-pac form. Property values for sphere-pac fuel at this temperature, which are either supplied by the user or calculated by the code, can then be used to calculate a revised temperature distribution in the fuel pin. Based on this

revised temperature distribution and the user-supplied minimum restructured region temperature and maximum sphere-pac region temperature, more appropriate property values can be found which can then be used to ascertain the central void radius and the sizes and interfaces of the three fuel regions. This determination of the fuel structure is accomplished by making a material balance on the fuel material in the pin. With the revised fuel structure and the updated fuel properties another calculation of the fuel temperature distribution can be made. This new fuel temperature distribution can in turn be used to determine a revised fuel structure. Fuel property values can be found from the previous temperature distribution calculation, which can be used in conjunction with the updated fuel structure to calculate a new fuel temperature distribution.

Thus, one can see how the iterative process of the successive substitution technique works. The iterative process would be continued until the fuel structure and temperature distribution do not change with additional iterations. It should be noted that with each iteration that results in a change in either the fuel structure or temperature distribution, the coefficients in the system of nodal equations which describe the fuel temperature distribution will change and thus have to be recalculated.

If a steady-state temperature distribution calculation is desired at some time following the initial steady-state calculation under some different set of conditions but with the fuel structure determined in the previous steady-state calculation, such a calculation may be performed. The fuel temperature distribution would be found using the nodal, lumped-parameter method where no additional fuel restructuring would be allowed to occur. Following the steady-state calculation(s), a transient calculation may be performed if desired. In this calculation it is assumed that the structure of the fuel is that determined in the initial steady-state calculation over the entire time of the transient. This is a safe assumption if the transient occurs over a period of time that is short compared to the time required for significant restructuring to occur.

A flow diagram summarizing the method of solution used in determining the fuel structure and temperature distribution in a fuel pin can be found in Fig. 6.

Fig. 6. Flow Diagram for Determining the Fuel Structure and Temperature Distribution in a Fuel Pin.

IV. CODE MODIFICATIONS

While a sizable portion of COBRA-3M relates to behavior outside the fuel pin (i.e., fluid flow analysis or hydraulics), the COBRA-3M subroutine PINS performs calculations relating to behavior inside the fuel pin. PINS was modified extensively to permit the analysis of sphere-pac-fueled LMFBRs, but much of the basic code remains in its original form.

The matrix equation which describes the thermal model of the fuel pin is set up in PINS and was presented in Eq. (8) as:

$$[G] \cdot \{T^*(t + \Delta t)\} = \{g\}.$$

This equation is used to determine the temperature distribution inside the fuel pin. The elements of $[G]$ (see p. 14) are determined by both the physical properties (e.g. fuel density, thermal conductivity, specific heat) and the geometry or structure of the fuel material. Fuel restructuring is not permitted in COBRA-3M but is permitted in COBRA-3SP. Therefore the two versions use different means of determining the elements in $[G]$. The geometry is known initially via user input specifications in COBRA-3M, whereas it must be determined in COBRA-3SP along with the fuel temperature distribution. Thus, with COBRA-3SP the elements in $[G]$ change in the iteration process that determines the fuel structure and temperature distribution as both the physical properties and structure of the fuel change. This serves to complicate the procedure for determining the elements in $[G]$. A second factor which complicates the determination of these elements arises from the fact that a three-region fuel model is used in COBRA-3SP, while COBRA-3M has a one-region model. The three-region approach requires that fuel properties be determined at each node point according to the region in which it is located. For example, if a node point exists in the restructured region, sintered fuel properties would be used. If a node point exists in the partially restructured region, fuel properties would be determined using linear interpolation between sintered and sphere-pac fuel properties.

A number of modifications to PINS were made to incorporate program logic that would allow changing fuel pin structure as the temperature

distribution calculation is performed. Other logic changes were required to make possible the preliminary fuel structure calculation. Modifications in PINS also provide two alternative means of varying the heat generation rate in the fuel radially to that which exists in COBRA-3M.

A number of modifications were made in the MAIN program of COBRA-3M in order that it could supply PINS with the information it requires. The fuel property table in COBRA-3M was replaced with two fuel property tables, one for restructured fuel data and the other for sphere-pac fuel data. The properties contained in both tables are fuel density, thermal conductivity, and specific heat as a function of temperature. Recall that sphere-pac fuel thermal conductivity need not be supplied directly by the user. An option is available whereby sphere-pac fuel conductivity may be calculated in the code with a theoretical correlation (Eqs. 1-5) that has been incorporated into the code. It should be pointed out that fuel density is specified for each node point by the user in COBRA-3M, whereas it is treated as a temperature-dependent quantity in COBRA-3SP. It is required that fuel density be treated in this fashion if fuel restructuring is to be considered.

In order to determine inner (void) temperatures and locations of the interfaces separating the three fuel regions, a subroutine called CURFIT was added. (Recall that the central void temperature is not calculated in the nodal method; only an average temperature is calculated for the center-most node.) CURFIT performs the task of fitting a third-degree polynomial through the calculated fuel (nodal) temperatures to obtain a smooth temperature distribution function of radius in the fuel. Using the known inner void radii determined at each axial location in PINS, central void temperatures are found with the temperature function. With the Newton-Raphson method¹⁷ the locations of the fuel interfaces are determined using the temperature function and user-specified fuel interface temperatures. Three support subroutines, MINV, GMPRD, and GMTRA, were added to perform the matrix operations required by CURFIT.

The reader is referred to the program listings of COBRA-3SP and COBRA-3M for further details concerning changes made to COBRA-3M.

V. SAMPLE PROBLEMS

Two sample problems are examined in this chapter. In both sample problems COBRA-3SP is used to model the performance of sphere-pac fuel under irradiation. Comparisons of COBRA-3SP results and experimental results are made to determine the validity of the code for the thermal analysis of sphere-pac fuel.

V.1. Sample Problem 1: Oak Ridge Research Reactor Tests

In this sample problem COBRA-3SP is used to model a section of sphere-pac fuel contained in the SG-3 capsule of the ORR Thermal Performance Tests.⁵ This section of the SG-3 capsule was operated at a linear heat rate of 16 kw/ft, resulting in a fuel central temperature of 2000°C. The (U,Pu)O₂ fuel used in the experiment consisted of spheres of two sizes: <44 μm and 400 μm diameter. A diagram of the SG series capsule design is shown in Fig. 7.

The temperature distribution in the sphere-pac fuel found in the tests is shown in Fig. 8. This temperature distribution was computed with PROFIL¹⁸ from measured fuel centerline and cladding surface temperatures and heat generation rates using reported data¹⁹ on thermal conductivity of 82% dense (U,Pu)O₂ fuel. The central void temperature corresponds to a .0683-in. inner fuel radius.

COBRA-3SP results were obtained using nine fuel nodes and one axial node. In order to examine just the fuel behavior, it was necessary that the gap conductance, cladding thermal conductivity, and heat transfer coefficient between fuel pin surface and coolant be set equal to very large values so that essentially no temperature drop would occur from the coolant to the fuel surface. The fuel surface temperature found in the performance tests was then used as the inlet coolant temperature, and sphere-pac fuel thermal conductivity was calculated using the theoretical correlation in the code. The heat-flow shape factor, α , was taken to be .95, since this value has given best results for sphere-pac fuel packed as it was in these tests. It was assumed that the heat generation rate was radially uniform, which was a reasonable approximation since the fuel is radially thin, and the effects of thermal neutron flux depression and increased fuel density with decreasing radius tend to negate one another. Fuel restructuring was assumed to occur at the 16 kw/ft power level, which was the maximum level reached. Based on the temperature distributions shown in Fig. 8, the

Fig. 7. Diagram of SG Fuel Capsule Design.⁵

Fig. 8. Transverse Microstructure of Sphere-pac Fuel and Cladding in an SG-3 Fuel Capsule. Temperature distribution has been superimposed across the fuel.⁵

inner and outer interface temperatures were taken to be 1700⁰ and 1500⁰C, respectively. A listing of the input to COBRA-3SP for this problem can be found in Appendix B, and a portion of the output from the code can be found in Appendix C.

Temperature results obtained with COBRA-3SP and ORR test results are shown in Table 1. Agreement is within 4% at all radial points. The inner fuel radius of .0694 in. calculated with COBRA-3SP is 1.6% larger than the .0683-in. value found in the ORR tests. Agreement between calculated and test interface locations is equally good.

Table 1. Comparison of calculated and experimental temperature results

Distance from Center (in.)	Performance Test Temperatures (°C)	Calculated Temperature (°C)
0.0683*	2000.0	2024.0
0.0958	1900.0	1940.0
0.109	1800.0	1839.0
0.118	1700.0	1747.0
0.126	1600.0	1650.0
0.134	1500.0	1539.0
0.145	1300.0	1353.0
0.161	1000.0	1029.0
0.173	750.0	750.0

*Central void radius.

V.2. Sample Problem 2: Experimental Breeder Reactor-II Tests²⁰

COBRA-3SP is used in this sample problem to analyze a section of the sphere-pac fuel pin S-1-E which was encapsulated and irradiated in the Experimental Breeder Reactor II (EBR-II). The section of the fuel pin under consideration here was operated at a linear heat rate of 14 kw/ft. The $(U,Pu)O_2$ fuel contained in the pin consisted of spheres of two sizes, $< 44 \mu m$ and $400 \mu m$ diameter. A diagram of the capsule assembly and fuel pin is shown in Fig. 9.

The temperature distribution in the sphere-pac fuel section found in the tests is shown in Fig. 4. PROFIL¹⁸ was used to compute this temperature distribution with the aid of experimental information. A central void radius of .0272 in. was found in the tests.

As in Sample Problem 1, COBRA-3SP results were found using nine fuel nodes and one axial node. The behavior of the fuel was examined, without regard to cladding and coolant behavior, using the fuel-surface temperature obtained in the tests. Sphere-pac fuel thermal conductivity was calculated using the theoretical correlation in the code. A heat-flow shape factor, α , of .95 was used, and the heat generation rate was made to vary with fuel density. Fuel restructuring was assumed to occur at the 14 kw/ft power level, which was the maximum level reached. Based on the temperature distribution data shown in Fig. 4, the inner and outer interface temperatures were taken to be 1400° and $1700^{\circ}C$, respectively.

Temperature results obtained with COBRA-3SP are shown, along with EBR-II test results, in Table 2. Temperatures agree within 4.6% at all radial points. The inner fuel radius of .0277 in. calculated with the code is 1.8% larger than the .0272-in. value found in the tests. Good agreement was also found between calculated and tested interface locations.

VI. CONCLUSIONS AND RECOMMENDATIONS

As a result of this study, a thermal-hydraulic/heat transfer code has been developed specifically for sphere-pac-fueled LMFBRs. The code, COBRA-3SP, has been verified using experimental results from the irradiation of capsules containing sphere-pac fuel in the EBR-II and in the Oak Ridge Research Reactor. Agreement between code temperature results and experimental results is within 5% for the two cases examined. Fuel structure

Fig. 9. Capsule and Fuel Rod for EBR-II Tests.²⁰

Table 2. Comparison of calculated and EBR-II experimental temperature results

Radius (in.)	Performance Test Temperatures (°C)	Calculated Temperatures (°C)
0.0272*	2240.0	2137.0
0.0380	2200.0	2109.0
0.0489	2100.0	2030.0
0.0638	1900.0	1837.0
0.0727	1700.0	1679.0
0.0808	1500.0	1506.0
0.0883	1300.0	1320.0
0.0959	1100.0	1111.0
0.102	900.0	922.0
0.109	690.0	690.0

*Central void radius.

results agree within 2%. Thus, it appears that the solely temperature-dependent restructuring fuel pin model is satisfactory.

With COBRA-3SP supplying the groundwork, a number of things should be done in the future to improve the capability for thermal analysis of sphere-pac-fueled pin bundles:

(1) The effect of gap conductance at the fuel-wall interface in sphere-pac fuel conductivity measurements needs to be determined.²¹ Corrections need to be made for gap conductance effects, if these are significant, in order for measured conductivities to be useful in thermal analysis codes. In an effort to determine gap conductance effects, a gap conductance model could be developed and incorporated into COBRA-3SP. Gap conductance modeling for sphere-pac fuel may be possible using the Ross-Stoute gap conductance model,²¹ which was designed for pellet-type fuel but may be applicable to sphere-pac fuel.

(2) A time-dependent fuel restructuring model, where restructuring occurs over a user-specified power history, should be developed as soon as data is available to verify such a model. More explicit treatment of fission gas release in the fuel would be possible with this type of model. Fission gas release has a significant effect on sphere-pac fuel conductivity. Therefore, a fission gas release model which predicts gas release as a function of burnup, power history, and temperature is desirable; development of such a model will require experimental data concerning gas release.

(3) It is desirable to integrate the fuel pin models developed for sphere-pac fuel to form a code similar in stature to LIFE-III,²² which is the standard for thermal analysis in pellet-fueled LMFBRs.

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APPENDIX A
INPUT INSTRUCTIONS

A number of changes were made to the input instructions for COBRA-3M to make them applicable to COBRA-3SP. Changes were made in card groups 8 and 9, and a new card group (Card Group 13) was added. A complete listing of the input instructions for COBRA-3SP can be found in this appendix. Note that much of this information was taken from the COBRA-3M program listing.²


```

C ***** COBRA-IIISP *****
C
C THIS PROGRAM COMPUTES THE STEADY STATE AND TRANSIENT FLOW AND ENTHALPY
C IN ROD BUNDLE NUCLEAR FUEL ELEMENT SUBCHANNELS DURING BOTH BOILING AND
C NONBOILING CONDITIONS. COBRA-IIISP IS A MODIFIED VERSION OF COBRA-IIIM.
C IT INCLUDES DETAILED THERMAL MODELS OF FUEL PIN AND DUCT WALL. THE CODE
C IS DESIGNED FOR USE WITH SPHERE-PAC FUEL ELEMENTS.
C
C REFERENCE DOCUMENTS -- BNWL-1229 AND BNWL-B-82 (COBRA-IIIB)
C                      -- ANL-8131 (COBRA-IIIM)
C                      -- ORNL/TM-7100 (COBRA-IIISP)
C
C ***** INPUT INSTRUCTIONS *****
C
C THE INPUT FOR A CASE REQUIRES A CASE CONTROL CARD FOLLOWED WITH UP
C TO 13 GROUPS OF INPUT INFORMATION. EACH OF THE 13 CARD GROUPS HAS A
C GROUP CONTROL CARD THAT IDENTIFIES THE GROUP NUMBER AND THE OPTIONS
C AVAILABLE FOR THAT GROUP.
C
C READ CASE CONTROL CARD, FORMAT(13,11,6X,11A6).
C   KASE = CASE NUMBER. IF KASE = 0, CALCULATION STOPS.
C   J1 = OPTION FOR DISPLAY OF INPUT. IF J1=0, PRINT ONLY NEW INPUT.
C   IF J1=1, PRINT ENTIRE INPUT. IF J1=2, PRINT ONLY OPERATING CONDITIONS.
C   TEXT = ALPHANUMERIC INFORMATION TO IDENTIFY CASE.
C
C READ GROUP CONTROL CARD, FORMAT(7I5)
C   NGR0UP = CARD GROUP NUMBER. IF NGR0UP=0, CALCULATION STARTS.
C   N1,N2,...,N11 =CARD GROUP OPTIONS. IF NOT SPECIFIED, THEY ARE BLANK.
C
C GO TO THE CARD GROUP SPECIFIED BY NGR0UP. IF THE DATA OF A CARD GROUP ARE
C THE SAME AS THE PREVIOUS CASE, THEN THAT CARD GROUP AND ITS CONTROL CARD
C MAY BE OMITTED.
C
C CARD GROUP 1, FLUID PROPERTY TABLE
C
C READ IN N1 CARDS OF FLUID PROPERTY DATA.
C EACH CARD CONTAINS -- SATURATION PRESSURE(P5IA), TEMPERATURE(DEG-F),
C LIQUID SPECIFIC VOLUME(CU-FT/LB), VAPOR SPECIFIC VOLUME(CU-FT/LB),
C LIQUID ENTHALPY(BTU/LB), VAPOR ENTHALPY(BTU/LB), LIQUID VISCOSITY
C (LB/FT-HR), LIQUID THERMAL CONDUCTIVITY(BTU/HR-FT-F) AND SURFACE
C TENSION(LB/FT), FORMAT(E5.2,F5.1,7F10.0). N1 MUST BE GREATER THAN
C ONE BUT NOT GREATER THAN THE PARAMETER MP.
C
C THIS PROPERTY TABLE MUST HAVE PRESSURE HIGHER THAN OPERATING PRESSURE
C AND LIQUID ENTHALPY LOWER THAN THE BUNDLE INLET ENTHALPY.

```

CARD GROUP 2, FLOW CORRELATIONS

READ IN UP TO FOUR SETS OF FRICTION FACTOR CORRELATION CONSTANTS THAT CORRESPOND TO THE SUBCHANNEL TYPES, FORMAT(12F5.3).

N1 IS THE SUBCOOLED VOID CORRELATION OPTION. N1=0, NO SUBCOOLED VOIDS. N1=1, LEVY SUBCOOLED VOID CORRELATION.

N2 IS THE BULK VOID CORRELATION OPTION. N2=0, HOMOGENEOUS MODEL. N2=1, MODIFIED ARMAND MODEL. N2=5, READ IN SLIP RATIO, FORMAT(5X,E10.5). N2=6, READ IN THE NUMBER OF TERMS AND COEFFICIENTS FOR UP TO A SIXTH ORDER POLYNOMIAL FUNCTION OF STEAM QUALITY, FORMAT(15,7E10.5).

N3 IS THE TWO-PHASE FRICTION GRADIENT MULTIPLIER OPTION. N3=0, HOMOGENEOUS. N3=1, ARMAND. N3=5, READ IN NUMBER OF TERMS AND COEFFICIENTS FOR UP TO A SIXTH ORDER POLYNOMIAL FUNCTION OF QUALITY, FORMAT(15,7E10.5).

CARD GROUP 3, AXIAL HEAT FLUX TABLE

READ IN N1 PAIR OF DATA FOR THE TABLE. EACH PAIR CONSISTS OF THE RELATIVE POSITION (X/L) AND THE CORRESPONDING RELATIVE HEAT FLUX (LOCAL FLUX/AVERAGE FLUX). EACH CARD ACCEPTS UP TO SIX PAIR OF DATA, FORMAT(12F5.3). N1 MUST BE GREATER THAN ONE BUT NOT GREATER THAN THE PARAMETER NP.

CARD GROUP 4, SUBCHANNEL LAYOUT AND DIMENSIONS

READ IN N1 CARDS OF SUBCHANNEL DATA CORRESPONDING TO THOSE SUBCHANNELS FOR WHICH DATA ARE BEING SUPPLIED. N2 IS THE TOTAL NUMBER OF SUBCHANNELS. FOR EACH OF THE N1 CARDS, READ IN THE SUBCHANNEL TYPE NUMBER (IF BLANK, IT IS ASSUMED TYPE 1), SUBCHANNEL IDENTIFICATION NUMBER, NOMINAL FLOW AREA(SQ-IN.), WETTED PERIMETER(IN.), HEATED PERIMETER(IN.) AND UP TO FOUR SETS OF ADJACENT SUBCHANNEL CONNECTION INFORMATION, FORMAT(11,14,3E5.2,4(15,2E5.2)). EACH SET OF CONNECTION INFORMATION INCLUDES THE ADJACENT SUBCHANNEL NUMBER(NEGATIVE IF A LINE OF SYMMETRY SPLITS A GAP AT A BOUNDARY), NOMINAL GAP SPACING(IN.) AND CENTROID-TO-CENTROID DISTANCE(IN.). IF SUBCHANNELS ARE INPUT IN ASCENDING ORDER, THEN ONLY HIGHER NUMBER SUBCHANNELS NEED TO BE IDENTIFIED AS CONNECTIONS. CENTROID DISTANCES ARE NOT REQUIRED IF THEY ARE NOT USED IN THE MIXING CORRELATIONS. N2 MUST BE GREATER THAN ONE BUT NOT GREATER THAN THE PARAMETER MC.

CARD GROUP 5, SUBCHANNEL AREA VARIATION TABLE

IF THERE ARE NO AREA VARIATIONS, OMIT THIS CARD GROUP.

READ N2 VALUES OF RELATIVE LOCATION(X/L) WHERE AREA FACTORS ARE GIVEN, FORMAT(12F5.3). N2 MUST BE GREATER THAN ONE BUT NOT GREATER THAN THE PARAMETER ML.

READ N1 SETS OF AREA VARIATION FACTORS(LOCAL AREA/NOMINAL AREA). EACH SET CONSISTS OF SUBCHANNEL NUMBER AND N2 AREA VARIATION FACTORS, FORMAT(15/(12F5.3)). N1 IS LIMITED BY THE PARAMETER MA. IF N1 IS ZERO, AREA VARIATIONS ARE DELETED FOR SUCCEEDING CASES.

C
 C CARD GROUP 6, GAP SPACING VARIATION TABLE
 C
 C IF THERE ARE NO GAP VARIATIONS, OMIT THIS CARD GROUP.
 C
 C READ N2 VALUES OF THE RELATIVE LOCATION(X/L) WHERE GAP FACTORS ARE
 C GIVEN, FORMAT(12F5.3). N2 MUST BE GREATER THAN ONE BUT NOT GREATER
 C THAN THE PARAMETER ML:
 C
 C READ N1 SETS OF GAP SPACING FACTORS(LOCAL GAP/NOMINAL GAP).
 C EACH SET CONSISTS OF THE ADJACENT SUBCHANNEL NUMBERS FOR THE GAP AND
 C N2 GAP VARIATION FACTORS, FORMAT(2I5/(12F5.3)). N1 IS LIMITED BY THE
 C PARAMETER MS. IF N1 IS ZERO, GAP VARIATIONS ARE DELETED FOR SUCCEEDING
 C CASES.
 C
 C
 C CARD GROUP 7, SPACER DATA AND DUCT WALL DATA
 C
 C IF N1=1, WIRE WRAP FORCED DIVERSION CROSSFLOW MIXING IS INCLUDED,
 C OTHERWISE, IT IS OMITTED.
 C
 C READ ONE CARD CONTAINING THE WIRE WRAP PITCH (IN.), PIN DIAMETER (IN.)
 C AND WIRE DIAMETER (IN.), FORMAT(8E10.5).
 C
 C FOR EACH GAP, READ A CARD CONTAINING THE GAP NUMBER, THE EFFECTIVE
 C FRACTION OF A PITCH FOR FORCING CROSSFLOW AND UP TO SIX RELATIVE
 C PITCH LENGTHS IDENTIFYING THE LOCATION OF WRAPS CROSSING THROUGH
 C A GAP USING A POSITIVE VALUE FOR WRAPS CROSSING FROM I TO J AND A
 C NEGATIVE VALUE FOR CROSSINGS FROM J TO I WHERE I IS LESS THAN J.
 C THE GAP NUMBERS ARE ASSIGNED IN THE ORDER THAT SUBCHANNEL PAIRS
 C ARE IDENTIFIED IN CARD GROUP 4.
 C
 C READ IN THE NUMBER OF WRAPS CONTAINED IN EACH SUBCHANNEL AT THE
 C START OF THE BUNDLE IN ASCENDING SUBCHANNEL ORDER, FORMAT(10I5).
 C USE ENOUGH CARDS TO SPECIFY ENTIRE WRAP INVENTORY.
 C
 C IF N1=2, SPACER PRESSURE LOSSES AND FORCED FLOW DIVERSION ARE INCLUDED,
 C OTHERWISE, THEY ARE OMITTED.
 C N2 IS THE TOTAL NUMBER OF SPACER LOCATIONS.
 C N3 IS THE NUMBER OF SPACER TYPES.
 C
 C READ N2 RELATIVE LOCATIONS(X/L) WHERE SPACERS ARE LOCATED AND THE
 C TYPE OF SPACER AT THAT LOCATION, FORMAT(6(F5.2,I5)).
 C IF N1=1, N2=NUMBER OF GAPS
 C
 C READ N3 SETS OF DATA CORRESPONDING TO EACH SPACER TYPE. EACH SET
 C CONSISTS OF A CARD FOR EVERY SUBCHANNEL. ON EACH CARD IS THE SUBCHANNEL
 C NUMBER, SPACER LOSS COEFFICIENT, CONNECTION NUMBER OF GAP THROUGH
 C WHICH FLOW IS FORCED, AND FRACTION OF FLOW DIVERTED, FORMAT(2(I5,E5.2)).
 C IF THE CONNECTION NUMBER IS ZERO AND THE FLOW FRACTION IS ZERO, THEN,
 C THERE IS NO FORCED FLOW DIVERSION. THE FORCED CROSSFLOW HAS THE SAME
 C SIGN AS THE FORCED FLOW FRACTION.
 C
 C IF N4=1, DUCT WALL TEMPERATURE CALCULATION IS INCLUDED, OTHERWISE
 C IT IS OMITTED.
 C N5=NUMBER OF DUCT WALL SECTIONS
 C READ ONE CARD CONTAINING NUMBER OF NODES, WALL THICKNESS(INCHES), DENSITY
 C (LB/CU-FT), HEAT TRANSFER COEFFICIENT TO BYPASS(BTU/HR-SQ-FT-F),
 C AVERAGE BYPASS TEMPERATURE(F), AND PRE-TRANSIENT VOLUMETRIC HEAT
 C GENERATION RATE IN DUCT WALL(BTU/HR-CU-FT). FORMAT(15,6E10.5)
 C

C IF N7 IS LESS THAN OR EQUAL TO ZERO, BYPASS TEMPERATURE IS A CONSTANT.
 C OTHERWISE N7 IS THE NUMBER OF ENTRY POINTS IN THE TEMPERATURE
 C VARIATION TABLE. READ TIME AND BYPASS TEMPERATURE, FORMAT(12E5.0).
 C MAXIMUM NUMBER OF ENTRIES IS 10.
 C
 C READ N5 SETS OF DATA CORRESPONDING TO EACH WALL SECTION. EACH SET
 C CONSISTS OF A CARD FOR EACH WALL SECTION. ON EACH CARD IS THE SECTION
 C NUMBER, SUBCHANNEL NUMBER IN CONTACT, WETTED(CONTACT) LENGTH(IN.).
 C FORMAT (2I5,F5.4)
 C
 C N6 IS A PARAMETER FOR GRADUALLY INCREASING THE VALUE OF DUR(K),
 C THE EFFECTIVE FRACTION OF A PITCH FOR FORCING CROSSFLOW.
 C IF N6.LT.2 DUR(K) ASSUMES THE FULL VALUE (DUM) IN THE FIRST ITERATION.
 C THE VALUE OF N6 IS THE NUMBER OF ITERATIONS OVER WHICH DUR(K) IS
 C INCREASED LINEARLY FROM 0 TO 100 PERCENT OF THE FULL VALUE.
 C
 C
 C CARD GROUP 8, ROD LAYOUT, DIMENSIONS AND POWER FACTORS
 C
 C READ IN N1 CARDS OF ROD LAYOUT DATA CORRESPONDING TO THOSE RODS FOR
 C WHICH DATA ARE BEING SUPPLIED. N2 IS THE TOTAL NUMBER OF RODS.
 C FOR EACH OF THE N1 CARDS, READ IN THE ROD NUMBER, DIAMETER(IN.),
 C RELATIVE ROD POWER(ROD POWER/AVERAGE ROD POWER) AND UP TO SIX SETS
 C DATA FOR ROD-TO-SUBCHANNEL CONNECTIONS, FORMAT(5(I5,2E5.2)/2(I5,2E5.2)).
 C EACH SET OF CONNECTION INFORMATION INCLUDES THE ADJACENT SUBCHANNEL
 C NUMBER, FRACTION OF THE ROD POWER TO THAT SUBCHANNEL AND FRACTION OF
 C ARC LENGTH. N2 IS LIMITED BY THE PARAMETER NR.
 C
 C IF N3=1, FUEL ELEMENT THERMAL MODEL IS INCLUDED, OTHERWISE IT IS OMITTED.
 C READ ONE CARD CONTAINING TOTAL NUMBER OF RADIAL ZONES IN FUEL ELEMENT, ME,
 C NUMBER OF RADIAL ZONES IN FUEL ONLY, MF, NUMBER OF CARDS OF SINTERED FUEL
 C PROPERTY DATA, NFT, NUMBER OF CARDS OF SPHERE-PAC FUEL PROPERTY DATA,
 C NFTSP, NUMBER OF CARDS OF CLADDING PROPERTY DATA, NCT,
 C FILM COEFFICIENT CORRELATION CONSTANTS, FILM1, FILM2, AND FILM3,
 C WHERE $NU = FILM1 + FILM2 * PE * FILM3$, DEFAULT: FILM1=7.0, FILM2=0.025,
 C FILM3=0.8, FUEL MASS IN EACH PIN, FUELS(LB), AND THE INITIAL
 C FUEL RADIUS, RADINI(IN.). FORMAT(5I5,5E5.0)
 C
 C READ N2 CARDS OF FUEL-CLAD GAP CONDUCTANCE DATA. EACH CARD
 C CONTAINS THE ROD NUMBER, AND GAP CONDUCTANCE(BTU/HR-FT²-F).
 C FORMAT(15,E10.3)
 C
 C READ GAP-CONDUCTANCE INDEX AS A FUNCTION OF RELATIVE AXIAL LOCATION (X/L).
 C THE SAME VALUES OF (X/L) IN CARD GROUP 3 FOR THE AXIAL HEAT FLUX
 C TABLE ARE ASSUMED. FORMAT(12E5.0). NO HEAT TRANSFER OCCURS
 C BETWEEN CLADDING AND FUEL IF INDEX IS LESS THAN OR EQUAL TO ZERO.
 C A GAS PLENUM CAN BE CONSIDERED AS CONSISTING OF A CLADDING AND A
 C DUMMY FUEL WITH NO HEAT TRANSFER BETWEEN THEM.
 C
 C READ ME MINUS MF CARDS OF CLADDING RADIAL ZONE INFORMATION. EACH CARD
 C CONTAINS ZONE NO., INNER RADIUS(IN.) AND AVERAGE DENSITY(LB/CU-FT) OF THAT
 C ZONE. FORMAT(15,2E10.0)
 C
 C READ IN NFT CARDS OF SINTERED FUEL PROPERTY DATA.
 C EACH CARD CONTAINS--TEMPERATURE(DEG-F), SPECIFIC HEAT(BTU/LB-F),
 C DENSITY(LB/CU-FT), AND THERMAL CONDUCTIVITY(BTU/HR-FT-F). FORMAT(4E10.0)

C N4 IS THE SPHERE-PAC FUEL THERMAL CONDUCTIVITY OPTION. IF N4=0,
 C USER SUPPLIES EFFECTIVE THERMAL CONDUCTIVITY OF THE SPHERE-GAS
 C MIXTURE. IF N4=1, USER SUPPLIES DATA TO CALCULATE EFFECTIVE
 C THERMAL CONDUCTIVITY VIA EQUATION. IF N4=0, READ IN NTSF CARDS OF
 C SPHERE-PAC FUEL PROPERTY DATA. EACH CARD CONTAINS--TEMPERATURE
 C (DEG-F), SPECIFIC HEAT(BTU/LB-F), DENSITY(LB/CU-FT), AND EFFECTIVE
 C THERMAL CONDUCTIVITY(BTU/HR-FT-F). FORMAT(4E10.0). IF N4=1, READ
 C IN A CARD CONTAINING -- MEAN SPHERE DIAMETER(MICRONS), VOLUME
 C FRACTION OF THE SPHERES, HEAT FLOW SHAPE FACTOR, AND
 C ABSOLUTE PRESSURE (LB/FT2). FORMAT(4E10.0). NEXT, READ IN NTSF
 C PAIRS OF CARDS CONTAINING TEMPERATURE(DEG-F), THERMAL CONDUCTIVITY
 C OF THE SPHERES(BTU/HR-FT-F), THERMAL CONDUCTIVITY OF THE FILLING
 C GAS(BTU/HR-FT-F), THERMAL ACCOMMODATION COEFFICIENT FOR SPHERE-GAS
 C SURFACE, RATIO OF GAS HEAT CAPACITY AT CONSTANT PRESSURE TO HEAT
 C CAPACITY AT CONSTANT VOLUME, AND GAS HEAT CAPACITY AT CONSTANT
 C PRESSURE(BTU/LB-F), FORMAT(6E10.0)- AND, MOLECULAR DIAMETER OF GAS AS
 C DETERMINED FROM VISCOSITY(FT), REFRACTIVE INDEX OF MEDIA BETWEEN
 C SURFACES, EMISSIVITY, VISCOSITY OF THE GAS(LB/HR-FT), SPHERE
 C DENSITY (LB/CU-FT), AND SPECIFIC HEAT OF THE SPHERES(BTU/LB-F),
 C FORMAT(6E10.0).
 C
 C READ IN NCT CARDS OF CLADDING PROPERTY DATA. EACH CARD CONTAINS--
 C TEMPERATURE(DEG-F), SPECIFIC HEAT(BTU/LB-F), AND THERMAL CONDUCTIVITY
 C (BTU/HR-FT-F). FORMAT(3E10.0)
 C
 C IF N5=1, 2, OR 3, NONUNIFORM HEAT GENERATION IS ASSUMED. IF N5=1, FOR EACH
 C ROD READ IN UP TO 6 CARDS. EACH CARD CONTAINS THE ROD NUMBER,
 C ROD-TO-SUBCHANNEL CONNECTION NUMBER(1 TO 6), AND RELATIVE POWER FACTOR FOR
 C RADIAL FUEL ZONES. FORMAT(2I5,14F5.4). THE ROD-TO-SUBCHANNEL CONNECTION
 C NUMBERS SHOULD BE IN THE SAME ORDER AS THOSE IN THE ROD LAYOUT DATA. IF
 C N5=2, CODE WILL GENERATE RELATIVE POWER FACTORS BASED ON THE RELATIVE
 C DENSITY OF THE FUEL IN EACH ZONE. IF N5=3, PROVIDE INFORMATION AS IF N5=1
 C TO BE USED WITH CODE GENERATED RELATIVE POWER FACTORS. FORMAT(2I5,14F5.4).
 C
 C
 C CARD GROUP 9, CALCULATION VARIABLES
 C
 C READ IN DIVERSION CROSSFLOW RESISTANCE FACTOR, TURBULENT MOMENTUM
 C FACTOR, BUNDLE LENGTH(IN.), POSITION FROM VERTICAL(DEGREES), NUMBER
 C OF AXIAL NODES, NUMBER OF TIME STEPS, TOTAL TRANSIENT TIME(SECONDS),
 C MAXIMUM NUMBER OF ITERATIONS FOR STEADY STATE CALCULATIONS, THE
 C ALLOWABLE ERROR IN CROSSFLOW CONVERGENCE DURING ITERATION, THE
 C ALLOWABLE ERROR IN SODIUM TEMPERATURE CONVERGENCE DURING ITERATION,
 C THE RELATIVE ALLOWABLE ERROR IN FUEL TEMPERATURE CONVERGENCE,
 C THE RELATIVE ALLOWABLE ERROR IN FUEL STRUCTURE CONVERGENCE,
 C NUMBER OF TIME STEPS IN FIRST SECTION OF TRANSIENT, AND TOTAL
 C TIME IN FIRST SECTION OF TRANSIENT. (BOTH OF THE PREVIOUS TWO
 C VALUES MUST BE ZERO IF DELTA T IS TO BE CONSTANT). FORMAT(4E5.2,
 C 2I5,E5.2,I5,4E5.2,I5,E5.2) IF THE ALLOWABLE ERRORS AND NUMBER OF
 C ITERATIONS ARE BLANK, THE PROGRAM ASSUMES 20, .01 LB/SEC-FT, .1 DEG F,
 C .005, AND .005, RESPECTIVELY.
 C
 C READ IN THE MAXIMUM SPHERE-PAC REGION TEMPERATURE(F) AND THE MINIMUM
 C RESTRUCTURED REGION TEMPERATURE(F). FORMAT(2F10.3).
 C

N1 IS AN OPTION GIVING THE SPATIAL PRINTING INCREMENT. IF N1=1, EVERY STEP IS PRINTED. IF N1=2, EVERY OTHER STEP IS PRINTED, ETC. IF N1 IS ZERO OR BLANK, THE PROGRAM SETS N1=1.

N2 IS AN OPTION GIVING THE TIME PRINTING INCREMENT AND IS SET UP THE SAME AS N1 ABOVE.

N3 IS A DEBUG PRINT OPTION. IF N3=0, NO DEBUG INFORMATION IS PRINTED. IF N3=1 A DEBUG PRINT IS MADE FOR EACH STEP OF THE CALCULATION. THIS CAN GENERATE A LOT OF PAPER SO IT IS NOT NORMALLY USED.

CARD GROUP 10, TURBULENT MIXING CORRELATIONS

N1 IS THE OPTION FOR SUBCOOLED MIXING CORRELATIONS. REFER TO SUBROUTINE MIX FOR THE CORRELATION FORMS. FOR ANY VALUE OF N1, READ IN THE CORRELATION CONSTANTS, FORMAT(2F5.3).

N2 IS THE OPTION FOR TWO-PHASE MIXING. IF N2=1, TWO-PHASE MIXING IS THE SAME AS FOR SUBCOOLED CONDITIONS. IF N2 IS GREATER THAN ONE, READ IN N2 PAIR OF DATA FOR A TABLE OF TWO-PHASE MIXING DATA. EACH PAIR CONSISTS OF THE STEAM QUALITY AND THE CORRESPONDING VALUE OF BETA. N2 IS LIMITED BY THE PARAMETER NP.

N3 IS THE OPTION FOR THERMAL CONDUCTION MIXING. IF N3=0, NO THERMAL CONDUCTION. IF N3=1, READ IN THE THERMAL CONDUCTION GEOMETRY FACTOR, FORMAT(F5.3).

CARD GROUP 11, OPERATING CONDITIONS

READ IN THE OPERATING PRESSURE(P51A), INLET ENTHALPY(BTU/LB) OR INLET TEMPERATURE(DEG-F), MASS VELOCITY(M-LB/HR-SQ-FT) AND AVERAGE HEAT FLUX(M-BTU/HR-SQ-FT). FORMAT(6E10.3)

N1 IS THE INLET ENTHALPY OPTION. IF N1=0, INLET ENTHALPY IS GIVEN. IF N1=1, INLET TEMPERATURE IS GIVEN. IF N1=2, READ IN THE INDIVIDUAL SUBCHANNEL INLET ENTHALPIES, FORMAT(12E5.0). IF N1=3, READ IN THE INDIVIDUAL SUBCHANNEL INLET TEMPERATURES, FORMAT(12E5.0).

N2 IS THE INLET FLOW DISTRIBUTION OPTION. IF N2=0, THE SUBCHANNELS ARE GIVEN THE SAME MASS VELOCITY. IF N2=1, THE INLET FLOW IS DIVIDED TO GIVE EQUAL PRESSURE GRADIENT IN THE SUBCHANNELS. IF N2=2, READ IN FRACTION OF TOTAL FLOW ADMITTED TO EACH SUBCHANNEL, FORMAT(12E5.0).

N3, N4, N5 AND N6 ARE OPTIONS FOR TRANSIENT FORCING FUNCTIONS. IF ANY OF THESE OPTION NUMBERS ARE ZERO OR BLANK, THE CORRESPONDING FORCING DATA IS NOT READ AND IS EXCLUDED FROM THE CALCULATIONS. EACH OF THESE NUMBERS GIVE THE NUMBER OF PAIRS OF TABULAR DATA TO BE READ FOR EACH FUNCTION. ALL DATA IS READ IN PAIRS OF TIME(SECONDS) AND RELATIVE VALUE, FORMAT(12E5.0)

N3 IS THE OPTION FOR REFERENCE PRESSURE VERSUS TIME.

N4 IS THE OPTION FOR INLET ENTHALPY VERSUS TIME.

N5 IS THE OPTION FOR INLET FLOW VERSUS TIME.

N6 IS THE OPTION FOR POWER VERSUS TIME.

C
 C CARD GROUP 12, OUTPUT DISPLAY OPTIONS
 C
 C N1 IS AN OPTION FOR PRINTING ANSWERS. IF N1=0, SUBCHANNEL DATA IS
 C PRINTED. IF N1=1, SUBCHANNEL DATA AND DIVERSION CROSSFLOWS ARE
 C PRINTED.
 C
 C N2 IS AN OPTION FOR SUBCHANNEL DATA PRINTOUT. IF N2=0, ALL SUBCHANNEL
 C DATA ARE PRINTED, IF IT IS CALLED FOR BY N1. FOR N2 GREATER THAN ZERO,
 C READ IN N2 SUBCHANNEL NUMBERS FOR WHICH RESULTS ARE TO BE PRINTED.
 C FORMAT(3612).
 C
 C N3 IS AN OPTION FOR PRINTING OUT ITERATIVE RESULTS BEFORE STEADY
 C STATE CONDITIONS ARE ATTAINED. IF N3=0, NO ITERATIVE RESULTS ARE
 C PRINTED. IF N3=1, RESULTS ARE PRINTED OUT AFTER EACH ITERATION.
 C
 C N4 AND N5 ARE OPTIONS FOR PUNCHED OUTPUT. IF N4>0, PUNCH SUBCHANNEL DATA
 C AS SPECIFIED BY N2. IF N5>0, PUNCH RADIAL DATA SETS. READ IN N5 AXIAL
 C LEVELS WHERE RADIAL TEMPERATURES ARE DESIRED (AXIAL LEVEL=1 AT INLET).
 C
 C N6, N7, N8, AND N9 ARE OPTIONS FOR CALCOMP PLOTS.
 C
 C IF N6>0, AXIAL PLOTS ARE SPECIFIED. READ IN NUMBER OF PLOTS CONTAINING
 C ONE, TWO, THREE, AND FOUR SUBCHANNELS (415). IF THE FIRST VALUE IS
 C NEGATIVE, THE SUBCHANNELS TO BE PLOTTED ARE SPECIFIED BY
 C N2 AND EACH AXIAL PLOT WILL CONTAIN ONLY ONE SUBCHANNEL. IT IS NOT
 C SET UP TO GRAPH MORE THAN FOUR SUBCHANNELS ON A SINGLE AXIAL PLOT.
 C THEN READ IN UP TO FOUR GROUPS OF CARDS CONSISTING OF THE SUBCHANNEL
 C NUMBERS (1615). THE FIRST GROUP ARE THE SUBCHANNELS WHICH WILL BE
 C GRAPHED SINGLY, THE SECOND GROUP CONSIST OF PAIRS OF SUBCHANNELS WHICH
 C WILL BE GRAPHED TOGETHER IN ONE PLOT, ETC. OMIT THAT GROUP FOR WHICH
 C NO PLOTS ARE SPECIFIED.
 C
 C IF N7>0, RADIAL PLOTS ARE SPECIFIED. N7 IS THE NUMBER OF RADIAL PLOTS.
 C FOR EACH RADIAL PLOT, READ IN THE AXIAL LEVEL AND THE NUMBER OF GRAPHS
 C PER PLOT (215). THIS IS FOLLOWED BY THE FOLLOWING INFORMATION FOR EACH
 C GRAPH: THE NUMBER OF SUBCHANNELS IN THE GRAPH AND PAIRS OF NUMBERS FOR
 C EACH SUBCHANNEL CONSISTING OF THE RELATIVE POSITION ON THE ABSCISSA
 C (1 TO 20) AND THE SUBCHANNEL NUMBER. FORMAT(1115)
 C
 C IF N8>0, EXPERIMENTAL DATA POINTS ARE TO BE PLOTTED WITH THE ANALYTICAL
 C RESULTS. N8 IS THE TOTAL NUMBER OF EXPERIMENTAL POINTS. FOR EACH POINT,
 C READ IN THE SUBCHANNEL NUMBER, AXIAL LEVEL, AND TEMPERATURE (215,F5.0).
 C
 C IF N9=0, T-INLET IS PLOTTED. IF N9>0, T IS PLOTTED.
 C
 C N10 IS AN OPTION FOR DUCT WALL DATA PRINTOUT. IF N10=0, ALL SECTIONS
 C ARE PRINTED. FOR N10 GREATER THAN ZERO, READ IN N10 WALL SECTION NUMBERS
 C FOR WHICH RESULTS ARE TO BE PRINTED. FORMAT(3612)
 C
 C N11 IS AN OPTION FOR FUEL PIN DATA PRINTOUT. IF N11=0, NO FUEL PIN DATA
 C IS PRINTED. FOR N11 GREATER THAN ZERO, READ IN N11 SETS OF ROD
 C NUMBER/SUBCHANNEL NUMBER IN CONTACT FOR WHICH RESULTS ARE TO BE PRINTED.
 C FORMAT(3612)
 C

CARD GROUP 13, FUEL RESTRUCTURE DATA

IF FUEL ELEMENT THERMAL MODEL IS NOT INCLUDED OR FUEL RESTRUCTURING PRIOR TO THE TEMPERATURE CALCULATION IS NOT DESIRED, OMIT THIS CARD GROUP.

READ IN N1 PAIR OF DATA FOR THE AXIAL HEAT FLUX TABLE. EACH PAIR CONSISTS OF THE RELATIVE POSITION (X/L) AND THE CORRESPONDING RELATIVE HEAT FLUX (LOCAL FLUX/AVERAGE FLUX). EACH CARD ACCEPTS UP TO SIX PAIR OF DATA, FORMAT(12F5.3). N1 MUST BE GREATER THAN ONE BUT NOT GREATER THAN THE PARAMETER MP.

IF A DUCT WALL TEMPERATURE CALCULATION IS TO BE PERFORMED, READ IN ONE CARD CONTAINING HEAT TRANSFER COEFFICIENT TO BYPASS(BTU/HR-SQ-FT-F), AVERAGE BYPASS TEMPERATURE(F), AND PRE-TRANSIENT VOLUMETRIC HEAT GENERATION RATE IN DUCT WALL(BTU/HR-CU-FT). FORMAT(3E10.5)

FOR EACH ROD, READ IN ROD NUMBER AND RELATIVE ROD POWER(ROD POWER/AVERAGE ROD POWER). FORMAT(7(15,E5.2)).

FOR THE FUEL RESTRUCTURE CALCULATION, READ IN THE NUMBER OF CARDS OF SINTERED FUEL PROPERTY DATA, NFTS, AND THE NUMBER OF CARDS OF SPHERE-PAC FUEL PROPERTY DATA, NFTSPS. FORMAT(2I5).

READ IN NFTS CARDS OF SINTERED FUEL PROPERTY DATA.

EACH CARD CONTAINS--TEMPERATURE(DEG-F), SPECIFIC HEAT(BTU/LB-F), DENSITY(LB/CU-FT), AND THERMAL CONDUCTIVITY(BTU/HR-FT-F). FORMAT(4E10.0)

N2 IS THE SPHERE-PAC FUEL THERMAL CONDUCTIVITY OPTION. IF N2=0,

USER SUPPLIES EFFECTIVE THERMAL CONDUCTIVITY OF THE SPHERE-GAS

MIXTURE. IF N2=1, USER SUPPLIES DATA TO CALCULATE EFFECTIVE

THERMAL CONDUCTIVITY VIA EQUATION. IF N2=0, READ IN NFTSP CARDS OF

SPHERE-PAC FUEL PROPERTY DATA. EACH CARD CONTAINS--TEMPERATURE

(DEG-F), SPECIFIC HEAT(BTU/LB-F), DENSITY(LB/CU-FT), AND EFFECTIVE

THERMAL CONDUCTIVITY(BTU/HR-FT-F). FORMAT(4E10.0). IF N2=1, READ

IN A CARD CONTAINING -- MEAN SPHERE DIAMETER(MICRONS), VOLUME

FRACTION OF THE SPHERES, HEAT FLOW SHAPE FACTOR, AND

ABSOLUTE PRESSURE (LB/FT²). FORMAT(4E10.0). NEXT, READ IN NFTSP

PAIRS OF CARDS CONTAINING TEMPERATURE(DEG-F), THERMAL CONDUCTIVITY

OF THE SPHERES(BTU/HR-FT-F), THERMAL CONDUCTIVITY OF THE FILLING

GAS(BTU/HR-FT-F), THERMAL ACCOMMODATION COEFFICIENT FOR SPHERE-GAS

SURFACE, RATIO OF GAS HEAT CAPACITY AT CONSTANT PRESSURE TO HEAT

CAPACITY AT CONSTANT VOLUME, AND GAS HEAT CAPACITY AT CONSTANT

PRESSURE(BTU/LB-F), FORMAT(6E10.0)- AND, MOLECULAR DIAMETER OF GAS AS

DETERMINED FROM VISCOSITY(FT), REFRACTIVE INDEX OF MEDIA BETWEEN

SURFACES, EMISSIVITY, VISCOSITY OF THE GAS(LB/HR-FT), SPHERE

DENSITY (LB/CU-FT), AND SPECIFIC HEAT OF THE SPHERES(BTU/LB-F),

FORMAT(6E10.0).

READ IN ONE CARD OF FUEL-CLAD GAP CONDUCTANCE DATA FOR EACH ROD. EACH CARD CONTAINS THE ROD NUMBER, AND GAP CONDUCTANCE(BTU/HR-FT²-F).

FORMAT(15,E10.3)

READ GAP-CONDUCTANCE INDEX AS A FUNCTION OF RELATIVE AXIAL LOCATION (X/L).

THE SAME VALUES OF (X/L) FOR THE AXIAL HEAT FLUX TABLE ABOVE ARE

ASSUMED. FORMAT(12E5.0). NO HEAT TRANSFER OCCURS

BETWEEN CLADDING AND FUEL IF INDEX IS LESS THAN OR EQUAL TO ZERO.

A GAS PLENUM CAN BE CONSIDERED AS CONSISTING OF A CLADDING AND A

DUMMY FUEL WITH NO HEAT TRANSFER BETWEEN THEM.

C IF N3=1, 2, OR 3, NONUNIFORM HEAT GENERATION IS ASSUMED. IF N3=1, FOR EACH
 C ROD READ IN UP TO 6 CARDS. EACH CARD CONTAINS THE ROD NUMBER,
 C ROD-TO-SUBCHANNEL CONNECTION NUMBER(1 TO 6), AND RELATIVE POWER FACTOR FOR
 C RADIAL FUEL ZONES. FORMAT(2I5,14F5.4). THE ROD-TO-SUBCHANNEL CONNECTION
 C NUMBERS SHOULD BE IN THE SAME ORDER AS THOSE IN THE ROD LAYOUT DATA. IF
 C N3=2, CODE WILL GENERATE RELATIVE POWER FACTORS BASED ON THE RELATIVE
 C DENSITY OF THE FUEL IN EACH ZONE. IF N3=3, PROVIDE INFORMATION AS IF N3=1
 C TO BE USED WITH CODE GENERATED RELATIVE POWER FACTORS. FORMAT(2I5,14F5.4).
 C
 C READ IN MAXIMUM SPHERE-PAC REGION TEMPERATURE(F) AND THE MINIMUM
 C RESTRUCTURED REGION TEMPERATURE(F). FORMAT(2F10.3).
 C
 C READ IN THE OPERATING PRESSURE(Psia), INLET ENTHALPY(BTU/LB)
 C OR INLET TEMPERATURE(DEG-F), MASS VELOCITY(M-LB/HR-SQ-FT) AND
 C AVERAGE HEAT FLUX(M-BTU/HR-SQ-FT). FORMAT(6E10.3)
 C N4 IS THE INLET ENTHALPY OPTION. IF N4=0, INLET ENTHALPY IS
 C GIVEN. IF N4=1, INLET TEMPERATURE IS GIVEN. IF N4=2, READ IN THE
 C INDIVIDUAL SUBCHANNEL INLET ENTHALPIES, FORMAT(12E5.0). IF N4=3,
 C READ IN THE INDIVIDUAL SUBCHANNEL INLET TEMPERATURES, FORMAT(12E5.0).
 C N5 IS THE INLET FLOW DISTRIBUTION OPTION. IF N5=0, THE SUBCHANNELS
 C ARE GIVEN THE SAME MASS VELOCITY. IF N5=1, THE INLET FLOW IS DIVIDED
 C TO GIVE EQUAL PRESSURE GRADIENT IN THE SUBCHANNELS. IF N5=2, READ IN
 C FRACTION OF TOTAL FLOW ADMITTED TO EACH SUBCHANNEL, FORMAT(12E5.0).
 C
 C
 C TO START A CALCULATION, READ A BLANK GROUP CONTROL CARD.
 C
 C TO STOP THE CALCULATIONS, AFTER FINISHING A CASE, READ A BLANK CASE CARD.
 C
 C * * * * END OF INPUT INSTRUCTIONS * * * *

APPENDIX B

INPUT DATA FOR SAMPLE PROBLEM 1

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11      ORR EXPERIMENT MORRIS ORNL JUN 1979
1      30
52E-4500.0 .01801 999999. 303.76 2204.83 .9235 45.43 .01238
17E-4550.0 .01801 999998. 319.44 2212.94 .8591 44.60 .0121
48E-3600.0 .01828 999997. 335.01 2220.52 .8038 43.79 .01200
12E-2650.0 .01842 409866. 350.49 2227.58 .7558 42.98 .011813
30E-2700.0 .01856 178122. 365.88 2234.13 .7138 42.18 .011623
66E-2750.0 .01870 83102. 381.19 2240.18 .6767 41.39 .011432
14E-1800.0 .01885 41266. 396.43 2245.77 .6437 40.62 .01124
24E-1840.0 .01897 24533. 408.58 2249.94 .6198 40.00 .011089
40E-1880.0 .01909 15060. 420.69 2253.87 .5980 39.39 .01093
65E-1920.0 .01921 9519. 432.77 2257.57 .5778 38.79 .01078
82E-1940.0 .01927 7645. 438.80 2259.35 .5683 38.50 .01070
10E+0960.0 .01933 6180. 444.83 2261.09 .5592 38.20 .010632
13E+0980.0 .01940 5026. 450.85 2262.78 .5504 37.91 .01055
16E+01000. .01946 4111. 456.86 2264.44 .5419 37.61 .010480
20E+01020. .01952 3382. 462.87 2266.06 .5338 37.42 .010403
24E+01040. .01959 2798. 468.88 2267.65 .5259 37.03 .010327
29E+01060. .01965 2326. 474.88 2269.22 .5183 36.74 .01025
35E+01080. .01971 1944. 480.88 2270.75 .5110 36.46 .010175
47E+01100. .01978 1632. 486.88 2272.27 .5004 36.03 .010060
54E+01120. .01985 1376. 492.87 2273.76 .4970 35.89 .010022
61E+01140. .01991 1166. 498.87 2275.24 .4904 35.61 .009946
72E+01160. .01998 992.0 504.86 2276.70 .4840 35.33 .00987
85E+01180. .02005 847.5 510.86 2278.15 .4778 35.05 .009794
10E+11200. .02011 726.9 516.85 2279.60 .4717 34.78 .009718
21E+11300. .02046 356.3 546.85 2286.72 .4442 33.42 .009337
42E+11400. .02082 189.1 576.95 2293.86 .4204 32.11 .00895
78E+11500. .02119 107.4 607.21 2301.10 .3995 30.84 .008575
14E+21600. .02157 64.63 637.70 2306.47 .3811 29.61 .00819
15E+21619. .02165 59.34 643.40 2310.19 .3779 29.38 .008123
12E+32145. .02388 8.52153 810.92 2351.67 .3094 23.64 .006119
2      0      0      0
.316 .25
3      2
0.0 1.0 1.0 1.0
4      6
1 1.0098.4340.1204 2.0637.1360 6.0637.1360
1 2.0098.4340.1204 1.0637.1360 3.0637.1360
1 3.0098.4340.1204 2.0637.1360 4.0637.1360
1 4.0098.4340.1204 3.0637.1360 5.0637.1360
1 5.0098.4340.1204 4.0637.1360 6.0637.1360
1 6.0098.4340.1204 1.0637.1360 5.0637.1360
7      0      0      0      0      0      0
8      1      1      1      1      0
1 .375 1.0 1.1667.1667 2.1667.1667 3.1667.1667 4.1667.1667
5.1667.1667 6.1667.1667
10 9 20 20 201.E100.025 0.8.0241.0625
1 1.E10
1.0 1.0
10 .173 490.
80.33 7.64E-02549.37 1.91
800.33 7.64E-02549.37 1.91
980.33 7.67E-02549.37 1.87
1160.33 7.76E-02549.37 1.75
1340.33 7.85E-02549.37 1.65
1520.33 7.94E-02549.37 1.58
1700.33 8.03E-02549.37 1.51
1880.33 8.11E-02549.37 1.47
2060.33 8.18E-02549.37 1.43
2240.33 8.24E-02549.37 1.41
2600.33 8.36E-02549.37 1.39
2960.33 8.41E-02549.37 1.35
3140.33 8.41E-02549.37 1.35
3500.33 8.41E-02549.37 1.37
3860.33 8.41E-02549.37 1.43
4220.33 8.41E-02549.37 1.52
4580.33 8.41E-02549.37 1.72
4940.33 8.41E-02549.37 1.80
5300.33 8.41E-02549.37 1.87
9000.00 8.41E-02549.37 1.87

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290.	.82	.95	2113.3		
80.33	2.12	.0866	.9	1.658	1.240
6.234E-10	1.5	.9	4.812E-02624.28		7.64E-02
800.33	2.12	.161	.9	1.658	1.240
6.234E-10	1.5	.9	8.504E-02624.28		7.64E-02
980.33	2.12	.177	.9	1.658	1.240
6.234E-10	1.5	.9	9.393E-02624.28		7.67E-02
1160.33	1.95	.194	.9	1.658	1.240
6.234E-10	1.5	.9	9.997E-02624.28		7.76E-02
1340.33	1.84	.210	.9	1.658	1.240
6.234E-10	1.5	.9	1.089E-01624.28		7.85E-02
1520.33	1.75	.225	.9	1.658	1.240
6.234E-10	1.5	.9	1.161E-01624.28		7.94E-02
1700.33	1.68	.240	.9	1.658	1.240
6.234E-10	1.5	.9	1.229E-01624.28		8.03E-02
1880.33	1.63	.256	.9	1.658	1.240
6.234E-10	1.5	.9	1.294E-01624.28		8.11E-02
2060.33	1.59	.271	.9	1.658	1.240
6.234E-10	1.5	.9	1.357E-01624.28		8.18E-02
2240.33	1.57	.286	.9	1.658	1.240
6.234E-10	1.5	.9	1.417E-01624.28		8.24E-02
2400.33	1.54	.313	.9	1.658	1.240
6.234E-10	1.5	.9	1.533E-01624.28		8.36E-02
2960.33	1.50	.345	.9	1.658	1.240
6.234E-10	1.5	.9	1.642E-01624.28		8.41E-02
3140.33	1.50	.358	.9	1.658	1.240
6.234E-10	1.5	.9	1.693E-01624.28		8.41E-02
3500.33	1.52	.387	.9	1.658	1.240
6.234E-10	1.5	.9	1.795E-01624.28		8.41E-02
3860.33	1.50	.414	.9	1.658	1.240
6.234E-10	1.5	.9	1.894E-01624.28		8.41E-02
4220.33	1.49	.440	.9	1.658	1.240
6.234E-10	1.5	.9	1.894E-01624.28		8.41E-02
4580.33	1.82	.466	.9	1.658	1.240
6.234E-10	1.5	.9	1.894E-01624.28		8.41E-02
4940.33	2.01	.492	.9	1.658	1.240
6.234E-10	1.5	.9	1.894E-01624.28		8.41E-02
5300.33	2.08	.517	.9	1.658	1.240
6.234E-10	1.5	.9	1.894E-01624.28		8.41E-02
9000.00	2.08	.735	.9	1.658	1.240
6.234E-10	1.5	.9	1.894E-01624.28		8.41E-02
271.	9.1E-02	1.0E10			
374.	9.1E-02	1.0E10			
410.	9.1E-02	1.0E10			
462.	9.2E-02	1.0E10			
482.	9.2E-02	1.0E10			
502.	9.2E-02	1.0E10			
526.	9.2E-02	1.0E10			
591.	9.3E-02	1.0E10			
620.	9.3E-02	1.0E10			
646.	9.3E-02	1.0E10			
688.	9.4E-02	1.0E10			
747.	9.4E-02	1.0E10			
762.	9.5E-02	1.0E10			
791.	9.5E-02	1.0E10			
904.	9.6E-02	1.0E10			
932.	9.7E-02	1.0E10			
1051.	9.95E-02	1.0E10			
1168.	1.03E-01	1.0E10			
1355.	1.08E-01	1.0E10			
3000.	1.00E-01	1.0E10			
9	5				
.5	1.	1	25	28.	.5 .001 .001 20 8.
3822.	3092.				
.10	0	0	1		
.025					
2.					
11	1		4		
60.	1382.	3.106	.5562		
0.0	1.0	3.0	1.5	4.0	1.5 28. 1.5
12	1	1			
1 1 1 2 1 3 1 4 1 5 1 6					6

APPENDIX C

PORTION OF OUTPUT DATA OF SAMPLE PROBLEM 1

INPUT FOR CASE 1 ORR EXPERIMENT MORRIS ORNL JUN 1979

DATE

TIME

FLUID PROPERTY TABLE

P	T	WF	VG	HF	HG	VISC.	KF	SIGMA
0.0	500.00	0.01801	999999.0000	303.76	2204.83	0.92350	45.43000	0.01233
0.0	550.00	0.01801	999998.0000	319.44	2212.94	0.85910	44.60000	0.01210
0.0	600.00	0.01828	999997.0000	335.01	2220.52	0.80380	43.79000	0.01203
0.0	650.00	0.01842	405866.0000	350.49	2227.58	0.75580	42.98000	0.01181
0.0	700.00	0.01856	178122.0000	365.88	2234.13	0.71380	42.18000	0.01162
0.0	750.00	0.01870	83102.0000	381.19	2240.18	0.67670	41.39000	0.01143
0.0	800.00	0.01885	41266.0000	396.43	2245.77	0.64370	40.62000	0.01124
0.0	840.00	0.01897	24533.0000	408.58	2249.94	0.61980	40.00000	0.01109
0.0	880.00	0.01909	15060.0000	420.69	2253.87	0.59800	39.39000	0.01093
0.1	920.00	0.01921	9519.0000	432.77	2257.57	0.57780	38.79000	0.01078
0.1	940.00	0.01927	7645.0000	438.80	2259.35	0.56830	38.50000	0.01070
0.1	960.00	0.01933	6180.0000	444.83	2261.09	0.55920	38.20000	0.01063
0.1	980.00	0.01940	5026.0000	450.85	2262.78	0.55040	37.91000	0.01055
0.2	1000.00	0.01946	4111.0000	456.86	2264.44	0.54190	37.61000	0.01048
0.2	1020.00	0.01952	3382.0000	462.87	2266.06	0.53380	37.42000	0.01040
0.2	1040.00	0.01959	2798.0000	468.88	2267.65	0.52590	37.03000	0.01033
0.3	1060.00	0.01965	2326.0000	474.88	2269.22	0.51830	36.74000	0.01025
0.4	1080.00	0.01971	1944.0000	480.88	2270.75	0.51100	36.46000	0.01018
0.5	1100.00	0.01978	1632.0000	486.88	2272.27	0.50040	36.03000	0.01006
0.5	1120.00	0.01985	1376.0000	492.87	2273.76	0.49700	35.89000	0.01002
0.6	1140.00	0.01991	1166.0000	498.87	2275.24	0.49040	35.61000	0.00995
0.7	1160.00	0.01998	992.0000	504.86	2276.70	0.48400	35.33000	0.00987
0.9	1180.00	0.02005	847.5300	510.86	2278.15	0.47780	35.05000	0.00979
1.0	1200.00	0.02011	726.9000	516.85	2279.60	0.47170	34.78000	0.00972
2.1	1200.00	0.02046	356.3000	546.85	2286.72	0.44420	33.42000	0.00934
4.2	1400.00	0.02082	189.1000	576.95	2293.86	0.42040	32.11000	0.00895
7.8	1500.00	0.02119	107.4000	607.21	2301.10	0.39950	30.84000	0.00858
14.0	1600.00	0.02157	64.6300	637.70	2308.47	0.38110	29.61000	0.00819
15.0	1619.00	0.02165	59.3400	643.40	2310.19	0.37790	29.38000	0.00812
120.0	2145.00	0.02388	8.5215	810.92	2351.67	0.30940	23.64000	0.00612

FRICTION FACTOR CORRELATION

CHANNEL TYPE 1 FRIC1 = 0.316*RE**(-.250) + 0.0

TWO-PHASE FLOW CORRELATIONS

NO SUBCOOLED VOID CORRELATION

HOMOGENEOUS BULK VOID MODEL

HOMOGENEOUS MODEL FRICTION MULTIPLIER

HEAT FLUX DISTRIBUTION

X/L	RELATIVE FLUX	GAP CONDUCTANCE INDEX
0.0	1.000	1.00000
1.000	1.000	1.00000

SUBCHANNEL INPUT DATA

CHANNEL NO.	TYPE	AREA (SQ-IN)	WETTED PERIM. (IN)	HEATED PERIM. (IN)	HYDRAULIC DIAMETER (IN)	(ADJACENT CHANNEL NO., SPACING, CENTROID DISTANCE)							
1	1	0.005600	0.434000	0.120400	0.090323	(2.0.064.0.136)(	6.0.064.0.136)(	0.0.0	.0.0	((0.0.0	.0.0	)	
2	1	0.009800	0.434000	0.120400	0.090323	(1.0.064.0.136)(	3.0.064.0.135)(	0.0.0	.0.0	((0.0.0	.0.0	)	

3	1	0.005800	0.434000	0.120400	0.090323	(2.0.064,0.136)(4.0.064,0.136)(0.0.0 .0.0)(0.0.0 .0.0)
4	1	0.009800	0.434000	0.120400	0.090323	(3.0.064,0.136)(5.0.064,0.136)(0.0.0 .0.0)(0.0.0 .0.0)
5	1	0.009600	0.434000	0.120400	0.090323	(4.0.064,0.136)(6.0.064,0.136)(0.0.0 .0.0)(0.0.0 .0.0)
6	1	0.009800	0.434000	0.120400	0.090323	(1.0.064,0.136)(5.0.064,0.136)(0.0.0 .0.0)(0.0.0 .0.0)

ROD INPUT DATA

ROD NO.	DIAMETER (IN)	RADIAL POWER FACTOR	FRACTION OF POWER TO ADJACENT CHANNELS (ADJ. CHANNEL NO.)						MASS IN FUEL PIN(LB)
1	0.3750	1.0000	0.1667(1)	0.1667(2)	0.1667(3)	0.1667(4)	0.1667(5)	0.1667(6)	0.024

CLADDING DATA FOR FUEL ELEMENT THERMAL MODEL

RADIAL ZONE NO.	INNER RADIUS(IN)	CENTROID(IN)	AVERAGE DENSITY
10	0.1730	0.1804	490.0000

SINTERED FUEL PROPERTY TABLE

T	THERMAL CONDUCTIVITY	SPECIFIC HEAT	DENSITY
80.33	1.9100	0.0764	549.3700
800.33	1.9100	0.0764	549.3700
980.33	1.8700	0.0767	549.3700
1160.33	1.7500	0.0776	549.3700
1340.33	1.6500	0.0785	549.3700
1520.33	1.5800	0.0794	549.3700
1700.33	1.5100	0.0803	549.3700
1880.33	1.4700	0.0811	549.3700
2060.33	1.4300	0.0818	549.3700
2240.33	1.4100	0.0824	549.3700
2600.33	1.3900	0.0836	549.3700
2960.33	1.3500	0.0841	549.3700
3140.33	1.3500	0.0841	549.3700
3500.33	1.3700	0.0841	549.3700
3860.33	1.4300	0.0841	549.3700
4220.33	1.5200	0.0841	549.3700
4580.33	1.7200	0.0841	549.3700
4940.33	1.8000	0.0841	549.3700
5300.33	1.8700	0.0841	549.3700
9660.60	1.8700	0.0841	549.3700

SPHERE-PAC FUEL PROPERTY TABLE

T	THERMAL CONDUCTIVITY	SPECIFIC HEAT	SPHERE DENSITY
80.33	0.9041	0.0764	624.2800
800.33	1.1699	0.0764	624.2800
980.33	1.2085	0.0767	624.2800
1160.33	1.1809	0.0776	624.2800
1340.33	1.1666	0.0785	624.2800
1520.33	1.1525	0.0794	624.2800
1700.33	1.1436	0.0803	624.2800
1880.33	1.1428	0.0811	624.2800
2060.33	1.1447	0.0818	624.2800
2240.33	1.1562	0.0824	624.2800
2600.33	1.1852	0.0836	624.2800
2960.33	1.2129	0.0841	624.2800
3140.33	1.2383	0.0841	624.2800
3500.33	1.3074	0.0841	624.2800
3860.33	1.4061	0.0841	624.2800

4220.33	1.5363	0.0841	624.2800
4580.33	1.6858	0.0841	624.2800
4940.33	1.8747	0.0841	624.2800
5300.33	2.0117	0.0841	624.2800
5600.00	3.9380	0.0841	624.2800

CLADDING PROPERTY TABLE

T	THERMAL CONDUCTIVITY	SPECIFIC HEAT
271.00	*****	0.0910
374.00	*****	0.0910
410.00	*****	0.0910
462.00	*****	0.0920
482.00	*****	0.0920
502.00	*****	0.0920
526.00	*****	0.0920
591.00	*****	0.0930
620.00	*****	0.0930
646.00	*****	0.0930
688.00	*****	0.0940
747.00	*****	0.0940
762.00	*****	0.0950
791.00	*****	0.0950
904.00	*****	0.0965
932.00	*****	0.0970
1051.00	*****	0.0995
1168.00	*****	0.1030
1355.00	*****	0.1080
3000.00	*****	0.1080

FILM COEFFICIENT CORRELATION

NU=*****0.025**C.800

RED NO. 1

GAP CONDUCTANCE =***** BTU/HR-SQ-FT-F

CALCULATION PARAMETERS

CROSSFLOW RESISTANCE .5000+00
 MOMENTUM TURBULENT FACTOR 0.0
 CHANNEL LENGTH 1.00 INCHES
 CHANNEL ORIENTATION 0.0 DEGREES
 NUMBER OF AXIAL NODES 1
 NODE LENGTH 1.000 INCHES
 TOTAL NUMBER OF TIME STEPS 0
 TOTAL TRANSIENT TIME 0.0 SECONDS
 NUMBER OF TIME STEPS IN FIRST SECTION OF TRANSIENT 0
 TOTAL FIRST SECTION TRANSIENT TIME 0.0 SECONDS
 ERROR CRITERION IN CROSSFLOW 0.1000-01 LB/SEC
 ERROR CRITERION IN SODIUM TEMPERATURE 0.5000+00 F
 RELATIVE ERROR CRITERION IN FUEL TEMPERATURE = 0.1000-01
 RELATIVE ERROR CRITERION IN FUEL STRUCTURE = 0.1000-01
 MAXIMUM SPHERE-FAC REGION TEMPERATURE= 2822.000 F
 MINIMUM RESTRICTURED REGION TEMPERATURE= 3092.000 F

MIXING CORRELATIONS

SUBCOOLED MIXING, $\beta = 0.0250$
 BOILING MIXING, β IS ASSUMED SAME AS SUBCOOLED
 CONDUCTION MIXING, GEOMETRY FACTOR = 2.0000

OPERATING CONDITIONS

SYSTEM PRESSURE = 60.0 PSIA
 INLET ENTHALPY = 571.5 BTU/LB
 AVG. MASS VELOCITY = 3.106 MILLION LB/(HR-SQFT)
 INLET TEMPERATURE = 1382.0 DEGREES F
 AVG. HEAT FLUX = 0.55620 MILLION BTU/(HR-SQFT)

FUEL-PIN RESULTS

TIME= 0.0 SECONDS. DATA FOR ROD NO. 1 (IN CONTACT WITH SUBCHANNEL NO. 1)

AXIAL DISTANCE FEET	CENTRAL VOID		SINTERED/TRANSITION REGIONS INTERFACE		SPHERE-PAC/TRANSITION REGIONS INTERFACE		NODE POINTS			
	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)
0.0	3675.9	0.0694	3092.0	0.1223	2822.0	0.1332	3674.1	0.0753	3613.4	0.0868
0.083	3689.4	0.0694		0.1229		0.1337	3687.8	0.0754	3627.0	0.0869
AXIAL DISTANCE FEET	CENTRAL VOID		SINTERED/TRANSITION REGIONS INTERFACE		SPHERE-PAC/TRANSITION REGIONS INTERFACE		NODE POINTS (CONTINUED)			
	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)
0.0	3497.7	0.0983	3330.4	0.1098	3114.6	0.1213	2838.0	0.1328	2493.3	0.1443
0.083	3511.1	0.0984	3343.5	0.1098	3127.3	0.1213	2850.8	0.1328	2506.3	0.1443
AXIAL DISTANCE FEET	CENTRAL VOID		SINTERED/TRANSITION REGIONS INTERFACE		SPHERE-PAC/TRANSITION REGIONS INTERFACE		CLAD SURFACE			
	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)	T DEGREE F	RADIAL DIST(IN)
0.0	2090.1	0.1558	1633.7	0.1673	1382.0	0.1804	1382.0	0.1875		
0.083	2102.8	0.1558	1645.9	0.1673	1393.9	0.1804	1393.9	0.1875		

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APPENDIX D

NOMENCLATURE FOR CODE VARIABLES

A list of the important code variables appearing in COBRA-3SP along with their definitions is presented in this appendix. Many of the variables presented were taken from the variable list in COBRA-3M.² These variables are presented again for completeness.

<u>CODE VARIABLE</u>	<u>DEFINITION</u>
A	Coefficient matrix in Equation 8.
AFLUX	Average heat flux at the fuel pin surface.
ARC	Fractional arc length over the outer cladding circumference.
AREA	Duct wall heat transfer area.
AXIAL	Axial power factor array.
B	Column vector in Equation 8.
C	Heat capacity of duct wall.
CAP	Heat capacity of fuel pin.
CONST	Axial increment multiplied by 2π .
CTC	Specific heat array for cladding/duct wall property table.
CTK	Thermal conductivity array for cladding/duct wall property table.
CTT	Temperature array for cladding/duct wall property table.
DR	Fuel pin diameter.
DT	Time increment.
DUCT, DUCTL	Thickness of duct wall.
DUCTC	Specific heat of duct wall.
DUCTD	Average density of duct wall.
DUCTK	Thermal conductivity of duct wall.
DUCTQ	Volumetric heat-generation rate in duct walls.
DX	Axial increment.
DY	Spatial increment in duct wall.
FAX	Axial power factor.

<u>CODE VARIABLE</u>	<u>DEFINITION</u>
FILM1,FILM2,FILM3	Film-coefficient correlation constants defined by Equation 10.
FQS	Transient power factor.
FSERR	Relative allowable error in fuel structure.
FTC	Specific heat array for sintered fuel property table.
FTD	Density array for sintered fuel property table.
FTK	Thermal conductivity array for sintered fuel property table.
FTT	Temperature array for sintered fuel property table.
FUELMS	Fuel mass in fuel pin.
HBP	Heat transfer coefficient from duct wall to bypass.
HFILM,HTC	Heat transfer coefficient between surfaces and subchannels.
HGAP	Gap conductance between fuel and cladding.
HGC	Gap conductance index array.
MD	Number of spatial increments in duct wall.
ME	Total number of radial zones in fuel pin including cladding.
MF	Total number of radial zones in the fuel.
NCHANL	Number of subchannels.
NCT	Number of elements in arrays for cladding/duct wall property table.
ND	Number of duct wall sections.
NDT	Total number of time steps.
NDT1	Number of time steps in first section transient.
NDX	Number of axial nodes.
NFT	Number of elements in arrays for sintered fuel property table.
NFTSP	Number of elements in arrays for sphere-pac fuel property table.
NROD	Number of fuel pins.
NTYPE	Coolant subchannel type number: NTYPE=1 for central subchannels and >1 for edge and corner subchannels.
PHI	Fraction of rod power to a particular subchannel.

<u>CODE VARIABLE</u>	<u>DEFINITION</u>
PINC	Specific heat of fuel pin.
PIND	Density of fuel pin.
PINK	Thermal conductivity of fuel pin.
Q	Volumetric heat generation rate in the fuel.
QAV	Average volumetric heat generation rate in the fuel.
QF	Power factor for each radial zone in fuel.
R,RA,RB	Heat transfer resistance in duct wall.
RAD	Node inner boundary radius.
RADIAL	Fuel rod power factor.
RADINT	Initial inner fuel radius.
RADS	Radius of centroid for each radial zone in fuel pin.
RC	Inner cladding radius.
RF	Fuel outer radius.
RPIN,R1,R2	Heat transfer resistance in fuel pin.
SPFTC	Specific heat array for sphere-pac property table.
SPFTD	Density array for sphere-pac fuel property table.
SPFTK	Thermal conductivity array for sphere-pac fuel property table.
SPFTT	Temperature array for sphere-pac fuel property table.
SSDEN	Fuel density established in steady-state fuel structure calculation.
SSRAD1	Inner fuel radius established in steady-state fuel structure calculation.
TDUCS	Temperature of duct wall surface, assumed to be the same as that of its first node.
TDUCT	Duct wall node temperature.
TFERR	Relative allowable error in fuel temperature.
FPIN	Fuel pin node temperature.
TRESTC	Minimum restructured fuel temperature.
TSP	Maximum unrestructured fuel temperature.
TTIME	Total transient time.

CODE VARIABLEDEFINITION

TTIME1	Total time in first section of transient.
VDFRC	Void fraction in sphere-pac fuel.
VOL	Fuel zone volume.
WET	Contact length between subchannel and wall section.
X	Distance axially in the rod from the bottom of the rod.
Y	Axial distance array corresponding to gap conductance index array and axial power factor array.
Z	Total fuel pin length.

ORNL/TM-7100
Distribution Category UC-79b

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