**HYDRA-I: A Three-Dimensional
Finite Difference Code for
Calculating the Thermohydraulic
Performance of a Fuel Assembly
Contained Within a Canister**

R. A. McCann

December 1980

**Prepared for the U.S. Department of Energy
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HYDRA-I: A THREE-DIMENSIONAL
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ABSTRACT

A finite difference computer code, named HYDRA-I, has been developed to simulate the three-dimensional performance of a spent fuel assembly contained within a cylindrical canister. The code accounts for the coupled heat transfer modes of conduction, convection, and radiation and permits spatially varying boundary conditions, thermophysical properties, and power generation rates.

This document is intended as a manual for potential users of HYDRA-I. A brief discussion of the governing equations, the solution technique, and a detailed description of how to set up and execute a problem is presented. HYDRA-I is designed for operation on a CDC 7600 computer.

An appendix is included that summarizes approximately two dozen different cases that have been examined. The cases encompass variations in fuel assembly and canister configurations, power generation rates, filler materials, and gases. The results presented show maximum and various local temperatures and heat fluxes illustrating the changing importance of the three heat transfer modes. Finally, the need for comparison with experimental data is emphasized as an aid in code verification although the limited data available indicate excellent agreement.

SUMMARY

A finite difference computer code, named HYDRA-I, has been developed to simulate the three-dimensional thermohydraulic performance of a spent fuel assembly contained within a vertical cylindrical canister. The code accounts for the coupled heat transfer modes of conduction, convection, and radiation and permits spatially varying boundary conditions, thermophysical properties, and power generation rates.

This document is intended as a manual for potential users of HYDRA-I. A brief discussion of the governing equations, the solution technique, and a detailed description of how to set up and execute a problem is presented. This documented version of HYDRA-I is intended primarily for the simulation of steady-state conditions within those fuel assembly/canister configurations considered most likely to be of current interest. The code, in its present form, is restricted to fuel assemblies that have an odd number of rods and models one quadrant of the canister with a 45° line of symmetry. The above restrictions can be removed, but their implementation is not described in this document. HYDRA-I is designed for operation on a CDC 7600 computer.

An appendix is included that summarizes approximately two dozen different cases that have been examined. The cases encompass variations in fuel assembly and canister configurations, power generation rates, filler materials, and gases. The results presented show maximum and various local temperatures and heat fluxes illustrating the changing importance of the three heat transfer modes. Finally, the need for comparison with experimental data is emphasized as an aid in code verification although the limited data available indicate excellent agreement.

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1.0 INTRODUCTION

This document describes the application of the HYDRA-I computer code to the thermohydraulic analysis of a spent fuel assembly contained within a canister. In addition, results obtained by simulations over the last several years are consolidated and presented for a variety of fuel assembly/canister configurations.

HYDRA-I is a specialized version of a very general thermohydraulics code capable of transient three-dimensional analysis of coupled conduction, convection, and radiation problems. This current version is intended primarily for the simulation of steady-state conditions within those fuel assembly/canister configurations considered most likely to be of current interest. A specialized version was deemed appropriate for two reasons: 1) it provides a reasonable level of generality for most potential users without the unwelcome burden of excess complexity and cost, and 2) it permits public availability of the code in a more timely fashion. HYDRA-I is designed for operation on a CDC 7600 computer.

HYDRA-I provides a finite-difference solution in Cartesian coordinates to the equations governing the conservation of mass, momentum, and energy. The equation of momentum or motion is based on a generalization of flow through porous media, which adequately, in this case, accounts for flow in free-field regions. The conservation equations of momentum and mass are solved implicitly with no stability restrictions. The energy equation is also solved implicitly with no stability restrictions. However, the facts that the coupled set of equations is solved serially rather than simultaneously and that the radiation heat transfer is explicit do result in an overall stability criterion. The symptoms are easily recognized and may be controlled by the user through reduction of a pseudo time-step parameter. The code also has in-place logic for treating the outer boundary of the canister as a cylinder even though the coordinate system is Cartesian.

Section 2 of this report presents the governing equations and their translation into finite-difference form. A general overview of the solution

technique is contained in Section 3. A detailed description of how to set up a problem is presented in Section 4. Input description is found in Section 5 followed by a listing of selected output in Section 6. The appendix summarizes most of the results obtained using HYDRA-I for a variety of fuel assembly/canister configurations and offers a comparison with limited experimental data.

2.0 GOVERNING EQUATIONS

The coupled set of equations governing the transport of mass and energy are embodied by the conservation laws:

- conservation of momentum
- conservation of mass
- conservation of energy.

In addition, an equation of state for the fluid (e.g., perfect gas law), temperature-dependent thermophysical properties, and initial and boundary conditions are required for a complete solution to the problem.

The coordinate system is conventional as depicted in Figure 2.1. Gravitational components are considered as positive when directed in the positive coordinate directions. For the special case of vertical canisters, only the Z-direction component is non-zero.

FIGURE 2.1. Cartesian Coordinate System

2.1 CONSERVATION OF MOMENTUM

The momentum equation will be considered first because it is in some respects rather nonstandard for the motion of fluids. The impediment is

that the fuel assembly, the nozzles, and the support structure are most easily treated as anisotropic, discontinuous porous media while there are, in addition, substantial regions inside the canister that are free-field. A detailed derivation of the momentum equation appropriate to such flow regions has been accomplished, but the results were not totally satisfying if for no other reason than the excessive complexity. Instead, a simplified version is proposed similar to that suggested by Brinkman (1947a, 1947b) as an empirical modification to Darcy's law:

$$\frac{\partial}{\partial t} (\rho V) = \rho G - \nabla P - \mu K^{-1} \cdot \bar{V} + \nabla \cdot (\mu \nabla \bar{V}) \quad (2.1)$$

The terms in Equation (2.1) represent on a per unit volume basis reading from left to right: rate of increase of momentum, gravitational force, pressure force, Darcy's law, and viscous forces. The term accounting for the rate of momentum change by convection has been eliminated, as well as some additional terms reflecting viscous forces. Within a porous medium, the viscous force term will be relatively small except near a no-slip boundary; and, in the free-field, the permeability is set to a very large value.

A number of natural recirculating flow free-field systems were simulated using both the proposed formulation and several codes based on the full Navier-Stokes equation. The comparison between the codes and the comparison with limited experimental data is excellent, except in certain corners where mass fluxes of large magnitude changed direction abruptly. This result is just what would be expected since the term accounting for the rate of change of convected momentum per unit volume is not present. This approximation is considered acceptable since little interest in fuel assembly/canister problems is likely to be focused at canister corners.

2.1.1 Discrete Form of the Momentum Equation

The discrete form of the momentum equation is obtained from Equation (2.1) using the standard control volume approach. Equation (2.1) is integrated term by term over the appropriate control volume(s), and the results are

combined to provide a conservative force balance over a momentum cell.
Figure 2.2 shows the computational cell structure.

FIGURE 2.2. Computational Cell Structure for Cell i, j, k

The subscripting convention that is adopted is to denote all quantities related to cell i, j, k by no subscripts. Furthermore, all subscripting is suppressed, except for those indices that are different from i, j, k . The mass fluxes, MX , MY , and MZ are cell-faced quantities, while all others are cell-centered. For example:

$MZ_{i,j,k}$	denoted by MZ	(mass flux at top face of cell i, j, k)
$MZ_{i,j,k+1}$	denoted by MZ_{k+1}	(mass flux at top face of cell $i, j, k+1$)
$\rho_{i+1,j,k+1}$	denoted by $\rho_{i+1,k+1}$	(density centered in cell $i+1, j, k+1$)

This convention provides the same information as other conventions that use three subscripts and fractional subscripts. Less confusion should arise as long as each variable's defined position is kept in mind.

Returning to the discretization of the momentum equation, the determination of the temporal, the gravitational, and the pressure terms in the X-direction will be shown for illustration. The other terms are determined in a similar fashion. Integrating over flow volumes, one has:

$$\int_V \frac{\partial(\rho u)}{\partial t} dV = \int_V (\rho g_x - \frac{\partial P}{\partial x} + \text{other terms}) dV \quad (2.2)$$

Note in Figure 2.3 that the momentum cell spans a portion of two cell-centered computational cells. Since quantities other than the mass fluxes are cell-centered and may change discontinuously across the cell boundary, the integration is done in two parts: the right-hand region of cell i,j,k and the left-hand region of cell $i+1,j,k$.

FIGURE 2.3. Momentum Cell for which MX is Defined

For the right-hand region of cell i,j,k , Equation (2.2) becomes (approximately):

$$\frac{\partial(\rho u)}{\partial t} \frac{\Delta X}{2} A_{X\alpha x} = \rho g_x \frac{\Delta X}{2} A_{X\alpha x} - (P_{\text{boundary}} - P) A_{X\alpha x} \quad (2.3a)$$

+ other terms

and for the left hand region of cell $i+1,j,k$:

$$\left[\frac{\partial(\rho u)}{\partial t} \frac{\Delta X}{2} AX_{\alpha X} \right]_{i+1} = \left[\rho g_X AX_{\alpha X} \right]_{i+1} - \left[(P - P_{\text{boundary}}) AX_{\alpha X} \right]_{i+1} + [\text{other terms}]_{i+1} \quad (2.3b)$$

where AX = actual cross sectional area (usually $\Delta Y \Delta Z$), and
 α_X = fraction of AX available for flow in X -direction

Dividing Equations (2.3a) and (2.3b) by their respective AX_{α_X} products and adding the result gives:

$$\frac{1}{2} \left[\left(\frac{\Delta X}{\alpha_X} \right) + \left(\frac{\Delta X}{\alpha_X} \right)_{i+1} \right] \frac{\partial MX}{\partial t} = \left[(\rho \Delta X) + (\rho \Delta X)_{i+1} \right] \frac{g_X}{2} - (P_{i+1} - P) + \text{other terms} \quad (2.4)$$

Note that in the temporal term, use has been made of the relation

$$\rho \alpha_X u = MX \quad (2.5)$$

The complete discrete form of the momentum equation in the X -direction is as follows:

$$\begin{aligned} & \frac{1}{2} \left[\left(\frac{\Delta X}{\alpha_X} \right) + \left(\frac{\Delta X}{\alpha_X} \right)_{i+1} \right] \frac{\partial MX}{\partial t} = \left[(\rho \Delta X) + (\rho \Delta X)_{i+1} \right] \frac{g_X}{2} - (P_{i+1} - P) \\ & - \frac{1}{2} \left[\left(\frac{\mu \Delta X}{\rho k_X} \right) + \left(\frac{\mu \Delta X}{\rho k_X} \right)_{i+1} \right] MX \\ & + \left(\frac{\mu}{\rho \Delta X} \right)_{i+1} MX_{i+1} - \left[\left(\frac{\mu}{\rho \Delta X} \right)_{i+1} + \left(\frac{\mu}{\rho \Delta X} \right) \right] MX + \left(\frac{\mu}{\rho \Delta X} \right) MX_{i-1} \\ & + \frac{\Delta X}{\Delta Y} \left[\frac{MX_{j+1} - MX}{\left(\frac{\rho \Delta Y}{\mu} \right)_{j+1} + \left(\frac{\rho \Delta Y}{\mu} \right)} + \frac{MX_{j-1} - MX}{\left(\frac{\rho \Delta Y}{\mu} \right)_{j-1} + \left(\frac{\rho \Delta Y}{\mu} \right)} \right] \end{aligned} \quad (2.6)$$

$$\begin{aligned}
& + \frac{\Delta X_{i+1}}{\Delta Y} \left[\frac{MX_{j+1} - MX}{\left(\frac{\rho \Delta Y}{\mu}\right)_{i+1,j+1} + \left(\frac{\rho \Delta Y}{\mu}\right)_{i+1}} + \frac{MX_{j-1} - MX}{\left(\frac{\rho \Delta Y}{\mu}\right)_{i+1,j-1} + \left(\frac{\rho \Delta Y}{\mu}\right)_{i+1}} \right] \\
& + \frac{\Delta X}{\Delta Z} \left[\frac{MX_{k+1} - MX}{\left(\frac{\rho \Delta Z}{\mu}\right)_{k+1} + \left(\frac{\rho \Delta Z}{\mu}\right)} + \frac{MX_{k-1} - MX}{\left(\frac{\rho \Delta Z}{\mu}\right)_{k-1} + \left(\frac{\rho \Delta Z}{\mu}\right)} \right] \\
& + \frac{\Delta X_{i+1}}{\Delta Z} \left[\frac{MX_{k+1} - MX}{\left(\frac{\rho \Delta Z}{\mu}\right)_{i+1,k+1} + \left(\frac{\rho \Delta Z}{\mu}\right)_{i+1}} + \frac{MX_{k-1} - MX}{\left(\frac{\rho \Delta Z}{\mu}\right)_{i+1,k-1} + \left(\frac{\rho \Delta Z}{\mu}\right)_{i+1}} \right]
\end{aligned}$$

The Y- and Z-direction components will not be shown, but are easily obtained by a rotation of axes $(MX,i) \rightarrow (MY,j) \rightarrow (MZ,k)$.

2.2 CONSERVATION OF MASS

The continuity equation has the usual form:

$$\nabla \cdot \mathbf{M} = 0 \quad (2.7)$$

Note that there is no temporal term. The reason for this is that HYDRA-I, in its user-oriented form, is intended to calculate steady-state solutions where the temporal term is zero.

The discrete form may be written directly with reference to Figure 2.2:

$$(MX - MX_{i-1})AX + (MY - MY_{j-1})AY + (MZ - MZ_{k-1})AZ = 0 \quad (2.8)$$

2.3 CONSERVATION OF ENERGY

The energy equation has the form:

$$\rho C_p \frac{DT}{Dt} = \nabla \cdot (\lambda \nabla T) + \dot{q} \quad (2.9)$$

Terms representing the rate of energy change due to viscous dissipation and compression have been eliminated. The source term, $\dot{q}$, in Equation (2.9) reflects the presence of heat-generating fuel rods and heat transfer due to thermal radiation. Heat transfer due to thermal radiation is modeled in the fashion of Klepper (1963)^(a), which includes the essential features: 1) radiosity around the circumference of a rod is not necessarily constant, and 2) rods extending out to at least the next-nearest neighbors from a given rod interact radiatively.

2.3.1 Discrete Form of the Energy Equation

There are a variety of discrete forms that can and have been used for the energy equation. The question of what form to use arises primarily because Equation (2.9) contains both a convective and a diffusive term. The matter should logically be settled on the basis of accuracy, computational ease, and stability, factors that are also somewhat algorithm-dependent. Central differencing is simple, but is associated with a time-step limitation to preserve diagonal dominance, a matter of special concern for iterative solution techniques. Upwind differencing is a common approach to ease the diagonal dominance problem at the expense of some additional computational effort and a potential loss in accuracy.

The discrete form employed in HYDRA-I uses a variable upwind differencing scheme based on the local Peclet number (a measure of the ratio of convection to diffusion). At small Peclet numbers, the form of the equations approaches central differencing, while large Peclet numbers provide upwind differencing. The derivation of this discrete form is straightforward, but somewhat lengthy and will not be given here, but can be found in Spaulding (1972).

The final discrete form of the energy equation is as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{\Delta X} \left[\overline{A} T_{i+1} - (\overline{C} + \overline{A}_{i-1}) T + \overline{C}_{i-1} T_{i-1} \right]$$

^(a) Additional information may be found in Cox (1977).

$$\begin{aligned}
& + \frac{1}{\Delta Y} \left[\overline{AJ} \tau_{j+1} - (\overline{CJ} + \overline{AJ}_{j-1}) \tau + \overline{CJ}_{j-1} \tau_{j-1} \right] \\
& + \frac{1}{\Delta Z} \left[\overline{AK} \tau_{k+1} - (\overline{CK} + \overline{AK}_{k-1}) \tau + \overline{CK}_{k-1} \tau_{k-1} \right] \\
& + Q / \Delta X \Delta Y \Delta Z
\end{aligned} \tag{2.10}$$

The connectors $\overline{AI}$ and $\overline{CI}$ are constructed with the aid of the following definitions; corresponding definitions apply to $\overline{AJ}$, $\overline{CJ}$, $\overline{AK}$, and $\overline{CK}$. Peclet numbers:

$$Pe = \left(\frac{C_{pfluid} \Delta X}{2\lambda} \right) Mx \tag{2.11a}$$

$$Pe'_{i+1} = \left(\frac{C_{pfluid} \Delta X}{2\lambda} \right)_{i+1} Mx \tag{2.11b}$$

Two functions of the local Peclet number, $f(Pe)$ and $g(Pe)$, provide variable upwind weighting according to the expressions:

$$f(Pe) = DIM [0.5 DIM (Pe, -2.0), Pe] \tag{2.12a}$$

$$g(Pe) = Pe + f(Pe) \tag{2.12b}$$

Figure 2.4 illustrates the function $f(Pe)$. The function $g(Pe)$ is a reflection of $f(Pe)$ about the ordinate.

And finally, the connectors $\overline{AI}$ and $\overline{CI}$ are given by:

$$\overline{AI} = 2.0 \frac{f(Pe'_{i+1}) f(Pe)}{f(Pe) \left(\frac{\Delta X}{\lambda} \right)_{i+1} + g(Pe'_{i+1}) \left(\frac{\Delta X}{\lambda} \right)} \tag{2.13a}$$

$$\overline{CI} = 2.0 \frac{g(Pe'_{i+1}) g(Pe)}{f(Pe) \left(\frac{\Delta X}{\lambda} \right)_{i+1} + g(Pe'_{i+1}) \left(\frac{\Delta X}{\lambda} \right)} \tag{2.13b}$$

FIGURE 2.4. Definition of the Function $f(Pe)$ versus the Peclet Number

3.0 SOLUTION TECHNIQUE

The solution of the coupled set of energy and mass transfer equations proceeds in a sequential fashion. The mass transfer equations are advanced by one time-step using previous-time information for temperature. The mass fluxes and pressure field thus determined are now used in the energy equation to obtain new-time temperatures. Heat transfer by radiation (a portion of the source term in the energy equation) is calculated explicitly based on old-time temperatures. Time-steps for the energy and mass transfer equations are not necessarily the same, and more than one energy time step may be used before updating the mass fluxes and pressures. This procedure of advancing through psuedo time-steps is of no particular concern since only the steady-state solution is of interest.

The two algorithms used in the solution of the mass and energy equations have demonstrated stability with respect to time-step size. However, the sequential solution method will occasionally result in a stability problem that manifests itself as a low level of noise preventing monotonic convergence. Furthermore, radiation heat transfer is done explicitly, and in radiation-dominated situations, is a potential source of instability.

HYDRA-I incorporates several automatic means to ensure stability that have proved effective for most situations. A variety of schemes have been tried that were intended to provide complete protection from instability. In the final analysis, our experience has shown that the most effective of all the schemes if convergence problems arise is simply direct time-step limitation by the user. Convergence problems are easily recognizable, are not catastrophic, and code restart with a smaller maximum time-step will suffice to continue the solution process.

3.1 MASS FLUXES AND PRESSURE FIELD

The linear momentum equations are substituted into the mass conservation equation, and the pressure field is determined in a semi-implicit

fashion. The resulting Poisson equation is sufficiently implicit so that numerical instability has not been evident. The technique proceeds in the following way.

The linear momentum equation for the X-direction as given by Equation (2.6) can be written as:

$$\tilde{M}\dot{X} = -\left(\frac{\Delta Y}{\delta t} + BX\right)(P_{i+1} - P) + \left(\frac{\tilde{\Phi}X}{\delta t} + BX\right) \quad (3.1)$$

where the tilde represents tentative new-time values and the term $\tilde{\Phi}X$ includes the old-time value of $M\dot{X}$, a gravitation force term (if present) and the mass fluxes at all surrounding faces. Equation (3.1) and similar expressions for $M\dot{X}_{i-1}$, $M\dot{Y}$, etc. are introduced directly into the continuity equation (Equation 2.8). This results in a Poisson-type equation for pressure of the form:

$$\begin{aligned} & -AI P_{i+1} + BI P - CI P_{i-1} \\ & -AJ P_{j+1} + BJ P - CJ P_{j-1} \\ & -AK P_{k+1} + BK P - CK P_{k-1} \\ & = SX_{i-1} - SX + SY_{j-1} - SY + SZ_{k-1} - SZ \end{aligned} \quad (3.2)$$

In the code, the pressure appearing in Equation (3.2) is actually the deviatoric pressure (i.e., the local pressure deviation from the average canister pressure). The algorithm used to solve for the deviatoric pressure is line-successive overrelaxation. Sweeps are made alternately in the X-, Y-, and Z-directions. Following a set of triple sweeps, the gas density and average gas pressure are calculated and adjusted to conserve mass globally. The tilde phase mass fluxes are updated, and the cycle is repeated. Convergence is established when changes in mass fluxes and local continuity errors are less than prescribed values.

3.2 TEMPERATURE FIELD

The temperatures are advanced in time toward steady-state using an alternating direction implicit scheme of Douglas and Gunn (1964). This scheme is implemented in the following way:

The energy equation (Equation 2.10) can be written compactly as:

$$\rho C_p \frac{\partial T}{\partial t} = (L_x + L_y + L_z) T + Q/V \quad (3.3)$$

The ADI algorithm solves this difference equation in three successive sweeps per time step:

$$\left(\frac{1}{\tau} - L_z\right) \delta T^* = \frac{1}{\theta} [(L_x + L_y + L_z) T^n + Q/V] \quad (3.4a)$$

$$\left(\frac{1}{\tau} - L_y\right) \delta T^{**} = \frac{1}{\tau} \delta T^* \quad (3.4b)$$

$$\left(\frac{1}{\tau} - L_x\right) \delta T^{***} = \frac{1}{\tau} \delta T^{**} \quad (3.4c)$$

$$T^{n+1} = T^n + \delta T^{***} \quad (3.4d)$$

where

$$\tau = \theta \delta t / \rho C_p \quad (3.5)$$

and

$$0 \leq \theta \leq 1 \quad (3.6)$$

In the code, τ is not calculated based on Equation (3.5) but instead as:

$$\tau = \theta \delta t / [(\overline{CI} + \overline{AI}_{i-1})/\Delta X + (\overline{CJ} + \overline{AJ}_{j-1})/\Delta Y + (\overline{CK} + \overline{AK}_{k-1})/\Delta Z] \quad (3.7)$$

This definition of τ ensures unconditional stability for $\frac{1}{2} \leq \theta \leq 1$ with strong convection and reduces certain local truncation errors. This

definition also means that only the steady-state temperature field will have physical significance. A value for θ of $\frac{1}{2}$ has been found to work well and is the default value.

4.0 CODE SET-UP

This section is intended to guide the HYDRA-I user through the steps required to set up the problem. A case study approach will be adopted, that is, a typical problem will be used as the basis for illustrating what is to be done on a step-by-step basis. The reason for this approach is that some internal modification of the code is required to approximate different fuel assembly configurations and thus, an extra appreciation of a few sections of the code is helpful.

The main program and each subroutine will be dealt with individually in succeeding subsections. For a brief preview, they are as follows:

<u>Program Element</u>	<u>Main Function</u>
HYDRA1	solves the energy equation
HYDRO	solves the mass transport equation
SYM	ensures one-quarter symmetry
LEVEL	ensures global conservation of mass
REBAL	accelerates convergence of pressure iteration
PRINTS	prints arrays held in small core
PRINTL	prints arrays held in large core
RAD	determines radiation heat transfer
CANFLX	computes heat fluxes to canister

The program is designed to operate with a metric system of units: centimeter, second, gram, dyne, watt, and degrees Kelvin. Any other consistent set of units would be possible, but changes in appropriate constants and formats would be required. This version of HYDRA-I is restricted to those fuel assemblies that have an odd number of fuel rods. Code modifications required to simulate an even number of fuel rods are not discussed in this document.

4.1 THE SAMPLE PROBLEM

The fuel assembly selected is typical of pressurized water reactor (PWR) fuel assemblies. Table 4.1 shows some of the more relevant physical parameters of the system.

TABLE 4.1. Fuel Assembly/Canister Parameters

Number of Fuel Rods (including guide thimbles)	225 (15 x 15 array)
Fuel Rod Diameter	1.07 cm
Cladding Thickness	0.0617 cm
Pitch-to-Diameter Ratio	1.334
Active Length (includes swelling)	369.5 cm
Overall Length (including nozzles)	405.7 cm
Emittance of Rods	0.4
Canister Inside Diameter	33.66 cm
Canister Inside Length	410.1 cm
Emittance of Canister	0.45
Canister Internal Atmosphere	Helium
Assembly Power Generation Rate	1.0 kW

A cross-sectional view of the canister and fuel assembly is shown in Figure 4.1.

The position of the computational nodes and cell dimensions may now be specified based on the physical dimensions of the system. The number of cells in the Z-direction is 21 and is denoted in the code as KMAX. All nodes are cell-centered. Cell dimensions in the vertical direction were apportioned as indicated in Table 4.2.

The rods were assumed to have swelled sufficiently to be in contact with the top and bottom nozzles.

FIGURE 4.1. Cross Section of Canister and Fuel Assembly. The positions of the guide thimbles (no power generation) are indicated by open circles.

TABLE 4.2. Cell Dimensions in the Vertical Direction

K	DZ(k), cm	Comments
1	1.27	canister bottom plate
2	4.145	gap
3	2.54	bottom nozzle
4	1.753	rods with no heat generation
5	5.08	rods with heat generation
6	10.16	
7	20.32	
8	30.48	
9	40.64	
10	50.8	
11	54.59	
12	50.8	
13	40.64	
14	30.48	
15	20.32	
16	10.16	
17	5.08	rods with heat generation
18	18.567	rods with no heat generation
19	8.839	top nozzle
20	4.445	gap
21	4.445	canister top plate

The computational cell arrangement in the X- and Y-directions is shown in Figure 4.2. Symmetry is assumed such that $DX(I) = DY(J)$. The number of cells in the X- and Y-directions is 19 and is denoted in the code by IMAX and JMAX, respectively. The values shown in Table 4.3 are calculated based on the dimensions of the fuel assembly and canister.

FIGURE 4.2. Computational Cell Arrangement in the Horizontal Plane

The values shown in Table 4.3 are not precisely what would be obtained from Table 4.1 due to rounding in the conversion from English to metric units shown in the latter table.

TABLE 4.3. Cell Dimensions in the X-Direction

I	DX(I), cm	Comments
1	0.71501	phantom cell, 1/2 pitch
2	0.71501	fuel assembly, 1/2 pitch
3	1.43002	fuel assembly, 1 pitch
4	↑	↑
5	↑	↑
6	↑	↑
7	↓	↓
8	↓	↓
9	1.43002	fuel assembly, 1 pitch
10	1.17369836	outside of fuel assembly
11	1.06788397	
12	1.06058271	↑
13	0.84901074	↑
14	0.67213565	↑
15	0.51747520	↑
16	0.37742281	↑
17	0.24687432	↓
18	0.12207779	outside of fuel assembly
19	0.12207779	canister

4.2 THE MAIN PROGRAM

The primary function of the main program is to solve the energy equation. In addition, cell dimensions, thermophysical properties, power generation rates, thermal boundary conditions, etc., are defined. Each item requiring user definition will be addressed in the following subsections.

4.2.1 Array Dimensions

The partial listing for the sample problem reproduced below is shown for reference.

```
PROGRAM HYDRA1 (INPUT,OUTPUT,TAPE1,TAPE2)
DIMENSION E(20),F(20),DY(19),JMAXI(19),TCEN(21)
DIMENSION CAP(19,19,21),QGEN(9,9,20),QRODPL(20)
COMMON/SCM1/IROD,JROD,IMAX,JMAX,KMAX,IMAXJ(19),DX(19),DZ(21)
COMMON/SCM2/CLADOD,PITCH
LEVEL 2,RESX,RESZ,DT
COMMON/LCM1/RESX(19,19,21),RESZ(19,19,21),DT(19,19,21)
LEVEL 2,PREF,TREF,DENREF,T,TCAN
COMMON/LCM2/PREF,TREF,DENREF,T(19,19,21),TCAN(21)
LEVEL 2,DTIME,MX,MZ
COMMON/LCM3/DTIME,MX(18,18,20),MZ(18,18,20)
LEVEL 2,AIBAR,CIBAR,AJBAR,CJBAR,AKBAR,CKBAR
COMMON/LCM4/AIBAR(18,18,20),CIBAR(18,18,20),
1 AJBAR(18,18,20),CJBAR(18,18,20),AKBAR(18,18,20),CKBAR(18,18,20)
LEVEL 2,QRAD
COMMON/LCM5/QRAD(19,19,21)
EQUIVALENCE (IMAXJ,JMAXI),(DX,DY),(RESX,CAP)
REAL MX,MY,MZ
DATA IROD/9/,JROD/9/,IMAX/19/,JMAX/19/,KMAX/21/
```

Arrays are listed below according to their dimensions:

- Maximum of IMAX-1, JMAX-1, or KMAX-1:
E,F
- IMAX:
DX, JMAXI
- JMAX:
DY, IMAXJ
- KMAX:
DZ, TCEN, TCAN
- KMAX-1:
QRODPL
- IMAX, JMAX, KMAX:
CAP, RESX, RESZ, DT, T, QRAD
- IMAX-1, JMAX-1, KMAX-1:
MX, MZ, AIBAR, CIBAR, AJBAR, CJBAR, AKBAR, CKBAR
- IROD, JROD, KMAX-1
QGEN

4.2.2 Data Statements

A listing of the data statements required is as follows:

```

DATA IROD/9/,JROD/9/,IMAX/19/,JMAX/19/,KMAX/21/
DATA DX/2*0.71501,7*1.43002,1.17368936,1.06788397,1.06058271,
1 0.84901074,0.67213565,0.51747520,0.37742281,0.24687432,
2 2*0.12207779/
DATA DZ/1,27,4,145,2,54,1,753,5,08,10,16,20,32,30,48,40,64,50,8,
1 54,59,50,8,40,64,30,48,20,32,10,16,5,08,18,567,8,839,2*4,445/
DATA QRODPL/4*0.0,13*0.01326468,3*0.0/
DATA RESX/7581*0.0/,RESZ/7581*0.0/
DATA TCAN/340.,342.,347.,349.,352.,360.,373.,385.,393.,396.,
1 394.,388.,382.,377.,374.,372.,371.,369.,367.,366.,366./
DATA TCEN/340.,352.,370.,373.,384.,402.,425.,442.,451.,454.,
1 453.,448.,443.,439.,435.,426.,416.,389.,376.,375.,366./
DATA PREF/1013250./,TREF/323./,DENREF/0.1508E-3/,SPHTF/5.234/      HE
DATA CONUD/0.0209/,CONZI/0.115/
DATA FUELOD/0.9484/,CLADOD/1.0719/,PITCH/1.4300/
DATA PI/3.141592654/
DATA THETA/0.5/,NN/0/
DATA DTDTO/1000./,DTIMUP/1.1/,DTIMDN/0.9/
C CONF(T)=(0.688E-4)+(0.634E-6)*T                                AIR

```

- IROD, JROD. The largest value of the index I in which a fuel rod is present. JROD is constrained to be equal to IROD because of symmetry.
- IMAX, JMAX, KMAX. The maximum values of the respective indices, I, J, and K, including phantom cells.
- DX, DZ. Cell dimensions in the X- and Z-direction, respectively. The first and last cells are phantom cells. Although their values do not influence the computed results, some value must be specified.
- QRODPL. Fuel rod power generation rate per unit length for each cell in the Z-direction.
- TCAN: Canister temperatures for the bottom ($K=1$), side ($2 \leq K \leq KMAX-1$), and top ($K=MAX$).
- TCEN: Estimated fuel assembly centerline temperatures to be used for starting values.
- PREF, TREF, DENREF. A consistent set of average total pressure, temperature, and density for the gas. A perfect gas is assumed. These values are used to compute the total mass of gas present that is to be conserved.
- SPHTF. Specific heat of the fluid

- CONUO, CONZI. Thermal conductivity of the fuel (UO_2 is assumed), and cladding (zircalloy is assumed).
- FUELOD, CLADOD, PITCH. Diameter of fuel, outside diameter of cladding, and pitch, respectively.

4.2.3 Statement Functions

A partial listing of statement functions is shown below:

```

C      DATA DTDT0/1000./,DTIMUP/1.1/,DTIMDN/0.9/
CONF(T)=(0.688E-4)+(0.634E-6)*T
CONF(T)=(6.0E-4)+(3.0E-6)*T
C      CONF(T)=(0.882E-4)+(0.588E-6)*T
CONASX(C1,C2,C3)=X1/(X1*C1+(X2-X1)*C2+(X3-X2)*C3)
1  +(X2-X1)/(X2*C2+(X3-X2)*C3)+(X3-X2)/(X3*C3)
CONASZ(C1,C2,C3)=Z1*C1+Z2*C2+Z3*C3
CON304(T)=0.09215+(1.465E-4)*T
RESY(I,J,K)=RESX(J,I,K)
MY(I,J,K)=MX(J,I,K)
AIR
HF
N2

```

CONF(T) represents the temperature-dependent thermal conductivity of the fluid. The top and bottom nozzles in this sample problem are assumed to be of Type 304 stainless steel and therefore, CON304(T) is used in the code to reflect their presence. The thermal conductivity of additional materials may be incorporated by adding appropriate statement functions, and incorporating these statement functions into the section of the code that defines cell resistivities.

4.2.4 Power Generation in Fuel Rods

Power generation in the fuel rods is represented by an expression of the form:

$$QGEN(I,J,K) = f(I,J) * QRODPL(K) \quad (4.1)$$

The power generation rate will vary over this cross section of the fuel assembly for at least two reasons: 1) differing cell cross sections, and 2) the presence of guide thimbles. The following section of the code indicates how power generation rates are defined.

```

      DO 20 J=2,JROD
      DO 30 I=2,IROD
      QGEN(I,J,1)=1.0
      IF (I.EQ.2) QGEN(I,J,1)=0.5*QGEN(I,J,1)
      IF (J.EQ.2) QGEN(I,J,1)=0.5*QGEN(I,J,1)
30    CONTINUE
20    CONTINUE
C**** SPECIAL RODS IN ASSEMBLY WITH NO POWER GENERATION
      QGEN(2,2,1)=0.0
      QGEN(6,2,1)=0.0
      QGEN(7,4,1)=0.0
      QGEN(5,5,1)=0.0
      QGEN(2,6,1)=0.0
      QGEN(4,7,1)=0.0
      QGEN(7,7,1)=0.0
      DO 40 K=2,KMAXM1
      DO 50 J=2,JROD
      DO 60 I=2,IROD
      QGEN(I,J,K)=QGEN(I,J,1)*QRDPL(K)
60    CONTINUE
50    CONTINUE
40    CONTINUE

```

Loop 20 accounts for those cells that are one-half of the interior cell area and are found along the boundary of the computational region, and the center-line cell, which is one-quarter of the interior cell area (see Figure 4.2). A power generation profile, which is different from uniform, could also be incorporated within this loop, keeping in mind the required symmetry in the quarter-section computational region.

Following loop 20, those rods that have special power generation rates (e.g., zero) are identified. Note again the requirement of symmetry.

Loop 40 then extends the cross-sectional power generation rate along the vertical axis modified by QRDPL(K) as indicated in Equation (4.1).

4.2.5 Cell Thermal Resistivities

Thermal resistivities (the reciprocal of thermal conductivity) are employed in the code. The user must identify the position of such features as nozzles and any support structure, and define their respective resistivities. The following section of the code shows how the thermal resistivities were defined for this sample problem:

```

C**** DEFINE CELL THERMAL RESISTIVITIES
DO 210 K=2,KMAXM1
DO 220 J=1,JMAXM1
INCO=IMAXJ(J)-1
DO 230 I=1,INCO
REC01=T(I,J,K)
REC02=CONF(REC01)
REC03=1.0/REC02
RESX(I,J,K)=REC03
RESZ(I,J,K)=REC03
IF(K.GT.19) GO TO 230
IF((J.GT.JROD).OR.(I.GT.IROD)) GO TO 230
IF(K.LT.3) GO TO 230
IF(K.EQ.3) GO TO 231
IF(K.EQ.19) GO TO 232
GO TO 233
231 REC04=1.0/(0.5587*CON304(REC01))
RESX(I,J,K)=REC04
RESZ(I,J,K)=REC04
GO TO 230
232 REC04=1.0/(0.0931*CON304(REC01)+0.9069*REC02)
RESX(I,J,K)=REC04
RESZ(I,J,K)=REC04
GO TO 230
233 REC04=CONASX(CONUOI,CONZII,REC03)
REC05=CONASX(CONUO,CONZI,REC02)
RESX(I,J,K)=2.0/(REC04+1.0/REC05)
RESZ(I,J,K)=1.0/CONASZ(CONUO,CONZI,REC02)
230 CONTINUE
220 CONTINUE
210 CONTINUE

```

Tables 4.2 and 4.3 identify the cells that contain such components as nozzles, fuel rods, and free-field. The effective thermal conductivity of the bottom nozzle (K=3) was estimated to be 0.5587 of the thermal conductivity of Type 304 stainless steel and to be isotropic. Statement label 231 performs this computation.

Statement label 232 performs the computation for the top nozzle. A weighted average of stainless steel and gas is used for an estimated effective thermal conductivity and for simplicity, isotropy is again assumed.

Statement label 233 applies to the fuel rods. The statement functions CONASX and CONASZ determine the effective thermal conductivities in X- and Z-directions, respectively, and ordinarily will not require the attention of the user. CONASX and CONASZ are based on a method for estimating effective thermal conductivities similar to that by Crane and Vachon (1977).

If any support structure or other features are present, the user may insert the necessary logic in this section of the code; all that is required is that the user specify the effective thermal conductivity of each entire cell and its location.

4.3 SUBROUTINE HYDRO

The combined continuity and linear momentum equations are solved in this subroutine. Local gas pressures and mass fluxes are calculated. The principal items requiring user definition are the volume of each cell occupied by fluid and cell flow resistances.

4.3.1 Array Dimensions

The partial listing for the sample problem reproduced below is shown for reference:

```
SUBROUTINE HYDRO
DIMENSION E(20),F(20),DY(19),JMAXJ(19),AY(18,20)
DIMENSION AX(18,20),AZ(18,18),AI(18,18,20),AK(18,18,20)
COMMON/SCM1/IROD,JROD,IMAX,JMAX,KMAX,IMAXJ(19),DX(19),DZ(21)
COMMON/SCM4/PL(19,19,21)
COMMON/SCM5/SAI(18),SDI(18),SAJ(18),SDJ(18),SAK(20),SDK(20)
COMMON/SCM7/MXTLDE(19,19,21),MZTLDE(19,19,21)
COMMON/SCM8/CLADOD,PITCH
LEVEL 2,RESX,RESZ,VIS
COMMON/LCM1/RESX(19,19,21),RESZ(19,19,21),VIS(19,19,21)
LEVEL 2,PREF,TREF,DENREF,T,TCAN
COMMON/LCM2/PREF,TREF,DENREF,T(19,19,21),TCAN(21)
LEVEL 2,DTIME,MX,MZ
COMMON/LCM3/DTIME,MX(18,18,20),MZ(18,18,20)
LEVEL 2,PAVG,PS,VFTOT,VF
COMMON/LCM4/PAVG,PS(20),VFTOT,VF(18,18,20)
LEVEL 2,SX,SZ
COMMON/LCM5/SX(18,18,20),SZ(18,18,20)
LEVEL 2,AIX,AJX,AKX,AIZ,AJZ,AKZ
COMMON/LCM6/AIX(18,18,20),AJX(18,18,20),AKX(18,18,20),
1 AIZ(18,18,20),AJZ(18,18,20),AKZ(18,18,20)
EQUIVALENCE (DX,DY),(AX,AY),(IMAXJ,JMAXI)
```

Arrays are listed below according to their dimensions:

- Maximum of IMAX-1, JMAX-1, KMAX-1:
E,F
- IMAX:
DX, JMAXI
- JMAX:
DY, IMAXJ

- KMAX:
DZ, TCAN
- IMAX-1:
SAI, SDI
- JMAX-1:
SAJ, SDJ
- KMAX-1:
SAK, SDK, PS
- IMAX-1, KMAX-1:
AY
- JMAX-1, KMAX-1:
AX
- IMAX-1, JMAX-1:
AZ
- IMAX, JMAX, KMAX:
PL, MXTLDE, MZTLDE, RESX, RESZ, VIS, T
- IMAX-1, JMAX-1, KMAX-1:
AI, AK, MX, MZ, VF, SX, SZ, AIX, AJX, AKX, AIZ, AJZ, AKZ

4.3.2 Statement Functions

The only statement functions requiring user specification are those that specify the temperature-dependent viscosity of the gas. A partial listing is shown below for reference:

```

      DEN(I,J,K)=(PAVG*PS(K)+PL(I,J,K))/(RREF*T(I,J,K))
C      FVIS(I,J,K)=(0.608E-4)+(0.4E-6)*T(I,J,K)          AIR
      FVIS(I,J,K)=(4.04E-6)*(T(I,J,K)**0.676)           HE
C      FVIS(I,J,K)=(0.726E-4)+(0.368E-6)*T(I,J,K)       N2

```

4.3.3 Definition of Cell Fluid Volume

The volume available in each cell that is occupied by the fluid must be specified. In the free-field region, the fluid volume is the same as the computational cell volume. However, where solid objects are present inside the canister, all or a portion of the cell may be unavailable to the fluid. The section of code shown on the following page illustrates how cell fluid volumes are defined for this sample problem.

```

C**** DEFINE FLUID VOLUME IN EACH CELL
REC01=1.0-0.25*PI*((CLADOD/PITCH)**2)
VFTOT=0.0
DO 40 K=2,KMAXM1
DO 50 J=2,JMAXM1
INCO=IMAXJ(J)-1
DO 60 I=2,INCO
VF(I,J,K)=AZ(I,J)*DZ(K)
IF(K.GT.19) GO TO 69
IF((J.GT.JROD).OR.(I.GT.IROD)) GO TO 69
IF(K.LT.3) GO TO 69
IF(K.EQ.19) GO TO 61
GO TO 62
61 VF(I,J,K)=0.9069*VF(I,J,K)
GO TO 69
62 VF(I,J,K)=REC01*VF(I,J,K)
69 VFTOT=VFTOT+VF(I,J,K)
60 CONTINUE
50 CONTINUE
40 CONTINUE

```

Tables 4.2 and 4.3 indicate which cells contain solid materials. The fluid-volume fraction for the bottom nozzle (K=3) is assumed to be the same as in the region occupied by the rods; this volume fraction is denoted by REC01. The fluid volume fraction of the top nozzle (K=19) is estimated as 0.9069.

4.3.4 Cell Flow Resistances

Cell resistivities (the reciprocal of permeability as it appears in Darcy's law) must be defined for those cells where partial or complete obstruction of the flow by solid objects is present. In the free-field, these resistivities are zero. The relevant section of the code is reproduced below:

```

C**** DEFINE CELL FLOW RESISTANCES
DO 100 K=2,KMAXM1
DO 110 J=2,JMAXM1
INCO=IMAXJ(J)-1
DO 120 I=2,INCO
VIS(I,J,K)=FVIS(I,J,K)/DEN(I,J,K)
IF((J.GT.2).AND.(I.EQ.INCO)) VIS(I,J,K)=2.0*VIS(I,J,K)
RESX(I,J,K)=0.0
RESZ(I,J,K)=0.0
IF(K.GT.19) GO TO 120
IF((J.GT.JROD).OR.(I.GT.IROD)) GO TO 120
IF(K.LT.3) GO TO 120
IF(K.EQ.3) GO TO 121
IF(K.EQ.19) GO TO 122
GO TO 123
121 RESX(I,J,K)=1.0E+20
RESZ(I,J,K)=RESASZ
GO TO 120
122 IF((J.LT.JROD).AND.(I.LT.IROD)) GO TO 120
RESX(I,J,K)=1.0E+20
RESZ(I,J,K)=1.0E+20
GO TO 120
123 RESX(I,J,K)=RESASX
RESZ(I,J,K)=RESASZ
120 CONTINUE
110 CONTINUE
100 CONTINUE

```

Resistivities in the X- and Z-directions (RESX and RESZ, respectively) are set first to zero as for the free-field, and then, exceptions are specified. The exceptions for this sample problem comprise the top and bottom nozzles and fuel rods. Resistivities in the X- and Z-directions for the fuel rods were previously automatically calculated in the code for rods on a square pitch and are denoted as RESASX and RESASZ, respectively. The values for RESASX and RESASZ are based on the procedures recommended by Knudsen and Katz (1958) and Butterworth (1978).

Statement label 121 applies to the bottom nozzle. No flow is possible in the horizontal plane, and the effective flow resistance in the Z-direction is estimated to be the same as that in the fuel rod region.

Statement label 122 applies to the top nozzle. The majority of the top nozzle is approximated as a free-field region, except for sides that are impermeable.

Statement label 123 applies to the fuel rods proper. This computation will not ordinarily require user attention.

Other fuel assemblies with different nozzle configurations or with the presence of support structures or other features within the canister will require appropriate estimates of effective flow resistances. As long as the user recalls that these cell-centered resistivities are to be defined consistent with Darcy's law, no particular difficulty should arise in inserting additional logic in this section of the code. It is acknowledged, however, that a good value of the effective permeability of certain configurations is sometimes hard to estimate.

4.4 SUBROUTINE SYM

This version of HYDRA-I is restricted to symmetric thermohydraulic problems. That is, the quadrant used as the computational region has a line of symmetry at 45° between the X- and Y-axes. This subroutine, while not essential to code operation, was added to smooth small perturbations arising from truncation errors in the energy equation and small continuity errors in the mass transport equations.

4.4.1 Array Dimensions

The only attention in subroutine SYM required by the user is to specify array dimensions. The relevant portion of this subroutine is listed below:

```
SUBROUTINE SYM
COMMON/SCM1/IROD,JROD,IMAX,JMAX,KMAX,IMAXJ(19),DX(19),DZ(21)
COMMON/SCM4/PL(19,19,21)
COMMON/SCM7/MXTLDE(19,19,21),MZTLDE(19,19,21)
LEVEL 2,PREF,TREF,DENREF,T,TCAN
COMMON/LCM2/PREF,TREF,DENREF,T(19,19,21),TCAN(21)
REAL MXTLDE,MZTLDE
```

- IMAX:
DX
- JMAX:
IMAXJ
- KMAX:
DZ, TCAN
- IMAX, JMAX, KMAX:
PL, MXTLDE, MZTLDE, T

4.5 SUBROUTINE LEVEL

This subroutine computes the average gas pressure within the canister and adjusts, when necessary, the deviatory pressures in such a way that the total mass of gas is conserved. An adjustment of pressure reconciles the accumulation of small, but finite, continuity errors arising during the solution of the mass transport equation with the requirement of global continuity.

4.5.1 Array Dimensions

The user will need to specify array dimensions; no other user attention in subroutine LEVEL is required:

```
SUBROUTINE LEVEL
COMMON/SCM1/IROD,JROD,IMAX,JMAX,KMAX,IMAXJ(19),DX(19),DZ(21)
COMMON/SCM4/PL(19,19,21)
LEVEL 2,PREF,TREF,DENREF,T,TCAN
COMMON/LCM2/PREF,TREF,DENREF,T(19,19,21),TCAN(21)
LEVEL 2,PAVG,PS,VFTOT,VF
COMMON/LCM4/PAVG,PS(20),VFTOT,VF(18,18,20)
```

- IMAX:
DX
- JMAX:
IMAXJ
- KMAX:
DZ, TCAN
- KMAX-1:
PS
- IMAX, JMAX, KMAX:
PL, T
- IMAX-1, JMAX-1, KMAX-1:
VF

4.6 SUBROUTINE REBAL

The purpose of this subroutine is to accelerate the convergence of the pressure solution.

4.6.1 Array Dimensions

Only array dimensions require user specification.

```
SUBROUTINE REBAL
  DIMENSION ALPHA(18),BETA(18),GAMMA(20)
  COMMON/SCM1/IROD,JROD,IMAX,JMAX,KMAX,IMAXJ(19),DX(19),DZ(21)
  COMMON/SCM4/PL(19,19,21)
  COMMON/SCM5/SAI(18),SDI(18),SAJ(18),SDJ(18),SAK(20),SDK(20)
```

- IMAX:
DX
- JMAX:
IMAXJ
- KMAX:
DZ
- IMAX-1:
ALPHA, SAI, SDI
- JMAX-1:
BETA, SAJ, SDJ

- KMAX-1:
GAMMA, SAK, SDK
- IMAX, JMAX, KMAX:
PL

4.7 SUBROUTINE PRINTS

This subroutine, when called, prints arrays held in small core. The only attention required by the user, in addition to array dimensions, is the potential adjustment of some format statements. Certain format statements depend upon array dimensions. The adjustments required for a tidy and pleasing output will be obvious to the user upon inspection.

4.7.1 Array Dimensions

```
SUBROUTINE PRINTS(N,A,II,JJ,KK)
  DIMENSION JMAXI(19),B(10)
  DIMENSION A(II,JJ,KK)
  COMMON/SCM1/IROD,JROD,IMAX,JMAX,KMAX,IMAXJ(19),DX(19),DZ(21)
  EQUIVALENCE (IMAXJ,JMAXI)
```

- IMAX:
DX, JMAXI
- JMAX:
IMAXJ
- KMAX:
DZ
- IROD + 1:
B

4.8 SUBROUTINE PRINTL

This subroutine, when called, prints arrays held in large core. The only attention required by the user, in addition to array dimensions, is the potential adjustment of some format statements. Certain format statements depend upon array dimensions. The adjustments required for a tidy and pleasing output will be obvious to the user upon inspection.

4.8.1 Array Dimensions

```
SUBROUTINE PRINTL(N,A,II,JJ,KK)
  DIMENSION JMAXI(19)
  COMMON/SCM1/IROD,JROD,IMAX,JMAX,KMAX,IMAXJ(19),DX(19),DZ(21)
  LEVEL 2,A
  DIMENSION A(II,JJ,KK)
  EQUIVALENCE (IMAXJ,JMAXI)
```

- IMAX:
DX, JMAXI
- JMAX:
IMAXJ
- KMAX:
DZ

4.9 SUBROUTINE RAD

This subroutine computes the radiation heat transfer within the fuel assembly and between the fuel assembly and the canister. This subroutine will also accommodate radiation heat transfer when there is intervening support structure.

4.9.1 Array Dimensions

The listing for this sample problem reproduced below is shown for reference:

```
SUBROUTINE RAD
  DIMENSION DY(19),JMAXI(19)
  DIMENSION H(10,12,12),T4(12,12)
  COMMON/SCM1/IROD,JROD,IMAX,JMAX,KMAX,IMAXJ(19),DX(19),DZ(21)
  LEVEL 2,PREF,TREF,DENREF,T,TCAN
  COMMON/LCM2/PREF,TREF,DENREF,T(19,19,21),TCAN(21)
  LEVEL 2,QRAD
  COMMON/LCM7/QRAD(19,19,21)
  EQUIVALENCE (DX,DY),(IMAXJ,JMAXI)
```

Arrays are listed below according to their dimensions:

- IMAX:
DX, JMAXI
- JMAX:
DY, IMAXJ

- KMAX:
DZ, TCAN
- IMAX, JMAX, KMAX:
T, QRAD
- IROD+1, JROD+3, 12:
H
- IROD+3, JROD+3:
T4

4.9.2 Data Statements

The data required for this subroutine consist of various radiation connectors between fuel rods and emittances of nozzles and canister. Radiation connectors for support structure, when present, would also be needed. A listing of the data statements required for the sample problem is as follows:

```
EQUIVALENCE (DX,DY),(IMAXJ,JMAXI)
DATA SIGMA/5.67E-12/
DATA QRAD/7581*0.0/
DATA H1/0.0831/,H2/0.0020/,H3/0.0170/,H4/0.1414/,H4BI/0.3526/,
1 H5/0.0148/,H5BJ/0.0148/,H5BI/0.0621/,H6/0.0170/,H7/0.0831/,
2 H8/0.0020/,H9/0.0170/,H10/0.1414/,H10BJ/0.3526/,H11/0.0148/,
3 H11BI/0.0148/,H11BJ/0.0621/,H12/0.0170/
DATA ECAN/0.45/,ENOZZL/0.8/
FT4(I,J)=T4(I,J)-TCEN
```

The Hs (H1, H2, etc.), when multiplied by SIGMA (Stephan-Boltzmann constant), become the radiation connectors (H(I,J,N)) for lateral radiation heat transfer within the canister. Figure 4.3 shows the Hs that couple interior rods.

The calculational procedure used in the code using H1 as an example will be followed through:

$$\text{Step 1 } H(I,J,1) = \begin{cases} \text{SIGMA} * H1 & \text{for interior rods} \\ 0 & \text{otherwise} \end{cases}$$

$$\text{Step 2 } Q_{I+1,J-1,K \rightarrow I,J,K} = H(I,J,1) * (T(I+1,J-1,K)^4 - T(I,J,K)^4)$$

$$\text{Step 3 } QRAD(I,J,K) = \sum_{I'} \sum_{J'} Q_{I',J',K \rightarrow I,J,K}$$

FIGURE 4.3. Radiation Connectors within the Interior of the Fuel Assembly

In step 3, the sum over I' and J' will include all rods or surfaces that participate with rod I, J , and can be as many as 24 in number. The user need not be concerned about implementing the above steps, since they are accomplished automatically in the code.

The user must, however, define H_1, H_2 , etc. These parameters depend on the emittance of the rods, their pitch, and their diameter. The user is referred to Klepper (1963) and Cox (1977) for an exposition of their derivation and tables of tabulated values. Certain principal restrictions on the use of these tabulated values of H should be mentioned. They are:

1. the tabulated H s are not valid near the outer surface of the fuel assembly, and
2. all rods have the same emittance and diameter, and the pitch is a constant.

The user must determine the H_s that connect rods on the assembly surface to other surface rods and to the canister. A rather exact determination can be made in principle, but is somewhat laborious. As an alternative, the H_s may be estimated by several approximate methods. We have computed the connectors using both exact and approximate methods. For the fuel assembly/canister configurations examined to date, appropriate approximate methods seem quite adequate for engineering calculations; this may not always be valid, and the user is advised to use caution. Figure 4.4 illustrates the boundary connectors. While not explicitly shown in Figure 4.4, each boundary fuel rod is intended to be connected to the immediately adjacent canister surface. For example, an average value of H_{4BI} will be used for each rod (four as shown in Figure 4.4).

FIGURE 4.4. Radiation Connectors on the Boundary of the Fuel Assembly

This subroutine computes $H(I,J,N)$ on the basis that no support structure is present. If support structure is present to intercept lateral thermal

radiation, the user has only to redefine those connectors that are affected by support structure and to implement steps 1, 2, and 3 for the nodes representing the structure.

As an aid to the user in verifying that the $H(I,J,N)$ are actually specified as intended, an option to print them is provided. This feature will be explained in Section 5.

Radiation heat transfer in the vertical direction, such as between the top of a nozzle and the canister top, requires the definition of the effective emittances of the nozzles. In this sample problem, both nozzles have the same emittance, and both exchange radiation directly with the canister. If the nozzles have different emittance or if there is some intervening structure, some slight code change is required similar to that for lateral radiation exchange. The changes required should be obvious to the user upon inspection of this subroutine.

4.10 SUBROUTINE CANFLX

This subroutine computes the thermal power absorbed at each vertical section (as denoted by the index K) of the canister. This subroutine also sums the absorbed thermal power at each section; this sum should equal the total power generated by the fuel assembly at steady-state. The subroutine is an optional feature in HYDRA-I and may or may not be used at the user's discretion. The only attention required in this subroutine is to specify array dimensions, and possibly, modify a print statement to accommodate the maximum number of vertical sections (KMAX).

4.10.1 Array Dimensions

The partial listing for this sample problem reproduced below is shown for reference:

```
SUBROUTINE CANFLX
  DIMENSION DY(19),QCAN(21)
  COMMON/SCM1/IROD,JROD,IMAX,JMAX,KMAX,IMAXJ(19),DX(19),DZ(21)
  LEVEL 2,PREF,TREF,DENREF,T,TCAN
  COMMON/LCM2/PREF,TREF,DENREF,T(19,19,21),TCAN(21)
  LEVEL 2,AIBAR,CIBAR,AJBAR,CJBAR,AKBAR,CKBAR
  COMMON/LCM6/AIBAR(18,18,20),CIBAR(18,18,20),
1 AJBAR(18,18,20),CJBAR(18,18,20),AKBAR(18,18,20),CKBAR(18,18,20)
  LEVEL 2,QRAD
  COMMON/LCM7/QRAD(19,19,21)
  EQUIVALENCE (DX,DY)
```

Arrays are listed below according to their dimensions:

- IMAX:
DX
- JMAX:
DY, IMAXJ
- KMAX:
DZ, TCAN, QCAN
- IMAX, JMAX, KMAX:
T, QRAD
- IMAX-1, JMAX-1, KMAX-1:
AIBAR, CIBAR, AJBAR, CJBAR, AKBAR, CKBAR

5.0 INPUT DESCRIPTION

This section describes the input required for this version of HYDRA-I; four cards are used.

The first card is read from the main program:

```
      READ 2010,NEWT,NRUN,NMAX,UPDATE,DTIMAX,DTIMIN
2010    FORMAT(3I10,3E10.1)
```

- NEWT. The integer NEWT controls the initialization of the temperature field. The number 1 will set the temperatures on the canister to their correct values and provide an estimate of internal temperatures. Specifying 0 for NEWT will permit the code to use old values of temperature, as in a restart.
- NRUN. An integer value used to identify the particular problem or run number within a particular problem (e.g., This is run number 1).
- NMAX. The number of pseudo time-steps the user wishes executed. After NMAX time steps, the temperature and the mass flux fields will be printed for user inspection to determine if steady-state is satisfactorily approached or if an adjustment of some parameter may be required.
- UPDATE. HYDRA-I accumulates the maximum temperature change. When this maximum value reaches the value specified by UPDATE (degrees Kelvin), new mass fluxes and temperature-dependent thermophysical properties will be calculated. In problems that are convection-dominated, it is helpful to reduce UPDATE (say, one degree Kelvin) as the convergence is approached.
- DTIMAX. The largest value of the pseudo time-step that is permitted. A value of the order of unity is a reasonable starting point for most problems.
- DTIMIN. The smallest pseudo time-step that is allowed. A value of the order of one-tenth is a good starting value. DTIMIN may have to be reduced (along with UPDATE) to approach convergence smoothly in convection-dominated problems.

The second card is read from subroutine HYDRO:

```
      READ 2010,NMAXC,NMAX,EPSP,EPSPM  
2010  FORMAT(2I10,2E10,1)
```

- NMAXC. An integer specifying the desired number of iterations needed to achieve convergence of the momentum equations. A discrepancy between NMAXC and the actual number of iterations will automatically result in an adjustment of the pseudo time-step in the momentum equations.
- NMAX. The maximum number of iterations allowed in the solution of the momentum equations. The code will proceed even if the convergence criteria are not met in NMAX iterations.
- EPSP. Local continuity errors must be less than EPSP to meet the convergence criteria.
- EPSPM. After a number of pressure iterations are completed, the tilde phase mass fluxes are updated. Updated mass fluxes must change less than EPSPM to meet this convergence criterion.

- The third card is also read from subroutine HYDRO:

```
      READ 2020,NREAD,N1,REC01,N2,REC02,NWRITE  
2020  FORMAT(2I10,E10,1,I10,E10,1,I10)
```

- NREAD. If HYDRA-I is to be started from a file containing previously generated information, NREAD equals 1. If this is the first run with no previous information, NREAD equals 0.
- N1. If the code is started from a file, and the user desires to alter the thermal pseudo time-step, N1 equals 1. If the initial time step on the restart file is satisfactory, N1 equals 0.
- REC01. The thermal pseudo time-step whose value will have effect only when NREAD equals 0 or if NREAD equals 1 and N1 equals 1. A value must always be supplied, however.
- N2. N2 performs the same function for the momentum pseudo time-step as N1 does for the thermal pseudo time-step.

- RECO2. The momentum pseudo time-step whose value must be supplied. Comments analogous to those made for RECO1 apply.
- NWRITE. If the results of the run are to be written to a file and used as a restart capability, NWRITE equals 1. If not, NWRITE equals 0.

The last card is read from subroutine RAD:

```
      READ 2010,NH
2010  FORMAT(I10)
```

- NH. If the user wishes to print the values stored in the array H(I,J,N), NH equals 1; if the values are not to be printed, NH equals 0. What is actually printed is H(I,J,N)/SIGMA (H1, H2, etc.), for ease in direct comparison with the input data. We have found that this portion of the code presents the most potential for some confusion, and that it is worthwhile to the user to check that the values of H(I,J,N) are those that are actually intended.

The four input cards used to start this sample problem are as follows:

1	1	4	1.0	1.0	0.1
20	40	0.1E-6	0.4E-6		
0	0	0.5	0	0.005	1
1					

6.0 SELECTED OUTPUT

This section illustrates the type of output that the user can expect. Explanatory comments accompany each portion of the output. In addition, the user can verify the proper functioning of the code for the sample problem.

When a new problem is run for the first time, it is advisable to print the radiation connectors. It is relatively easy for the user to determine if the connectors have the values intended through a comparison between the output and the data input in subroutine RAD. The output for the radiation connectors is as follows:

FUEL ASSEMBLY RADIATION CONNECTORS

[illegible]

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This sample problem was started with an estimate of the temperature distribution rather than from temperatures based on a restart. The initialized temperature field is automatically printed. A portion of the initialized temperature field is as follows:

```

***INITIALIZATION***
***TEMPERATURE: C***

```

[illegible][illegible]

K=19												
7	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.103E+03	.103E+03	.103E+03	.103E+03	.102E+03	.102E+03	.102E+03	.101E+03	.100E+03	.999E+02	.999E+02	.982E+02
2	.072E+02	.962E+02	.952E+02	.940E+02	.940E+02	.940E+02						

[illegible][illegible][illegible]

As an aid to the user in following the progress toward a converged solution, it is helpful to monitor the changes in temperature, mass fluxes, and thermal and momentum pseudo time-steps. This is especially helpful in the latter stages as convergence is approached. If the temperatures do not appear to be settling down, it may be necessary to reduce the maximum permissible thermal pseudo time-step and/or reduce the convergence criteria for continuity and/or mass flux changes. The first run for this sample problem was limited to four thermal pseudo time-steps and the diagnostics are as follows:

MOMENTUM TIME STEP= .450E+02 SEC. AVERAGE GAS PRESSURE (PAVG-PREF)/PREF= .2794161E+00
 CONTINUITY ITER. MAX. ERROR I-DIR. MASS FLUX ITER. MAX. CHANGE K-DIR. MASS FLUX ITER. MAX. CHANGE

1	.581E-04	0	0.	0	0.
2	.393E-04	0	0.	0	0.
3	.292E-04	0	0.	0	0.
4	.200E-04	0	0.	0	0.
5	.139E-04	0	0.	0	0.
6	.961E-05	0	0.	0	0.
7	.843E-05	0	0.	0	0.
8	.733E-05	0	0.	0	0.
9	.628E-05	0	0.	0	0.
10	.535E-05	0	0.	0	0.
11	.453E-05	0	0.	0	0.
12	.386E-05	0	0.	0	0.
13	.327E-05	0	0.	0	0.
14	.277E-05	0	0.	0	0.
15	.234E-05	0	0.	0	0.
16	.197E-05	0	0.	0	0.
17	.167E-05	0	0.	0	0.
18	.141E-05	0	0.	0	0.
19	.119E-05	0	0.	0	0.
20	.101E-05	0	0.	0	0.
21	.843E-06	0	0.	0	0.
22	.715E-06	2	.967E-05	3	.675E-04
23	.197E-05	0	0.	0	0.
24	.146E-05	0	0.	0	0.
25	.860E-06	0	0.	0	0.
26	.516E-06	1	.190E-06	2	.250E-05
27	.418E-06	1	.155E-07	1	.176E-06
28	.351E-06	1	.111E-07	1	.214E-07
29	.294E-06	1	.909E-08	1	.732E-08
30	.247E-06	1	.757E-08	1	.619E-08
31	.207E-06	1	.633E-08	1	.523E-08
32	.174E-06	1	.531E-08	1	.440E-08
33	.146E-06	1	.446E-08	1	.371E-08
34	.123E-06	1	.375E-08	1	.312E-08
35	.103E-06	1	.315E-08	1	.262E-08
36	.867E-07	1	.265E-08	1	.220E-08

THERMAL# 1 TIME STEP= .500E+00 SEC. MAX. RATE= .974E+01 C/SEC. MAX. CHANGE= .487E+01 C AT I,J,K 10 10 14

MOMENTUM TIME STEP= .405E+02 SEC. AVERAGE GAS PRESSURE (PAVG-PREF)/PREF= .2782966E+00
 CONTINUITY ITER. MAX. ERROR I-DIR. MASS FLUX ITER. MAX. CHANGE K-DIR. MASS FLUX ITER. MAX. CHANGE

1	.669E-05	0	0.	0	0.
2	.421E-05	0	0.	0	0.
3	.259E-05	0	0.	0	0.
4	.166E-05	0	0.	0	0.
5	.109E-05	0	0.	0	0.
6	.805E-06	0	0.	0	0.
7	.638E-06	2	.840E-05	3	.548E-04
8	.132E-05	0	0.	0	0.
9	.107E-05	0	0.	0	0.
10	.811E-06	1	.131E-06	2	.181E-05
11	.303E-06	1	.124E-07	1	.117E-06
12	.173E-06	1	.729E-08	1	.120E-07
13	.118E-06	1	.464E-08	1	.315E-08
14	.995E-07	1	.294E-08	1	.257E-08

THERMAL# 2 TIME STEP= .550E+00 SEC. MAX. RATE= .606E+01 C/SEC. MAX. CHANGE= .333E+01 C AT I,J,K 10 10 14

MOMENTUM TIME STEP= .446E+02 SEC. AVERAGE GAS PRESSURE (PAVG-PREF)/PREF= .2772513E+00
 CONTINUITY ITER. MAX. ERROR I-DIR. MASS FLUX ITER. MAX. CHANGE K-DIR. MASS FLUX ITER. MAX. CHANGE

1	.693E-05	0	0.	0	0.
---	----------	---	----	---	----

2	.446E-05	0	0.	0	0.
3	.279E-05	0	0.	0	0.
4	.184E-05	0	0.	0	0.
5	.147E-05	0	0.	0	0.
6	.114E-05	0	0.	0	0.
7	.933E-06	0	0.	0	0.
8	.772E-06	2	.874E-05	3	.551E-04
9	.128E-05	0	0.	0	0.
10	.101E-05	0	0.	0	0.
11	.612E-06	1	.140E-06	2	.177E-05
12	.297E-06	1	.122E-07	1	.126E-06
13	.210E-06	1	.678E-08	1	.133E-07
14	.178E-06	1	.524E-08	1	.874E-09
15	.150E-06	1	.451E-08	1	.390E-08
16	.126E-06	1	.383E-08	1	.325E-08
17	.106E-06	1	.323E-08	1	.271E-08
18	.888E-07	1	.272E-08	1	.227E-08

THERMAL# 3 TIME STEP= .605E+00 SEC. MAX. RATE= .384E+01 C/SEC. MAX. CHANGE= .232E+01 C AT I,J,K 10 10 14
 MOMENTUM TIME STEP= .490E+02 SEC. AVERAGE GAS PRESSURE (PAVG-PRFF)/PRFF= .2762610E+00
 CONTINUITY ITER. MAX. ERROR I-DIR. MASS FLUX ITER. MAX. CHANGE K-DIR. MASS FLUX ITER. MAX. CHANGE

1	.738E-05	0	0.	0	0.
2	.486E-05	0	0.	0	0.
3	.310E-05	0	0.	0	0.
4	.207E-05	0	0.	0	0.
5	.155E-05	0	0.	0	0.
6	.124E-05	0	0.	0	0.
7	.102E-05	0	0.	0	0.
8	.853E-06	0	0.	0	0.
9	.715E-06	2	.892E-05	3	.553E-04
10	.131E-05	0	0.	0	0.
11	.105E-05	0	0.	0	0.
12	.434E-06	1	.152E-06	2	.172E-05
13	.305E-06	1	.125E-07	1	.135E-06
14	.195E-06	1	.675E-08	1	.151E-07
15	.166E-06	1	.496E-08	1	.455E-08
16	.140E-06	1	.429E-08	1	.375E-08
17	.118E-06	1	.366E-08	1	.311E-08
18	.694E-07	1	.309E-08	1	.260E-08

THERMAL# 4 TIME STEP= .666E+00 SEC. MAX. RATE= .249E+01 C/SEC. MAX. CHANGE= .166E+01 C AT I,J,K 10 10 14

At the conclusion of the maximum number of thermal pseudo time-steps, the thermal power absorbed by the canister, the temperature field, and the mass fluxes in the I- and K-directions are printed. Note that the total thermal power being absorbed by the canister is substantially above the 1000 watts being generated by the fuel assembly. This clearly indicates that steady-state has not been reached. A partial listing of the output is as follows:

THERMAL POWER (WATTS) ABSORBED BY CANTISTED AT LEVEL K LISTED IN ORDER K=1 TO K=KMAX

.109E+02	.195E+01	.264E+01	.284E+01	.109E+02	.245E+02	.765E+02	.331E+02	.183E+02	.231E+02	.251E+02	.233E+02
.186E+03	.139E+03	.902E+02	.394E+02	.162E+02	.253E+02	.375E+01	.140E+01	.543E+01			

TOTAL THERMAL POWER= .1672E+04, WATTS

TEMPERATURE, C

	J=2	3	4	5	6	7	8	9	10	11	12	13
7	J=2											
2	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
2	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
3	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
3	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
4	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
4	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
5	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
5	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
6	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
6	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
7	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
7	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
8	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
8	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
9	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
10	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
11	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
12	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
13	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
14	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
15	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
16	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
17	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
18	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02
19	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02	.930E+02

	J=2	3	4	5	6	7	8	9	10	11	12	13
7	J=2											
2	.102E+03	.101E+03	.101E+03	.101E+03	.101E+03	.101E+03	.100E+03	.996E+02	.990E+02	.988E+02	.977E+02	.968E+02
2	.959E+02	.949E+02	.940E+02	.934E+02	.931E+02	.930E+02		.999E+02	.998E+02	.988E+02	.975E+02	.967E+02
3	.101E+03	.101E+03	.101E+03	.101E+03	.101E+03	.100E+03	.999E+02	.998E+02	.988E+02	.982E+02	.975E+02	.967E+02
3	.958E+02	.949E+02	.940E+02	.933E+02	.930E+02			.999E+02	.998E+02	.988E+02	.975E+02	.967E+02
4	.101E+03	.101E+03	.101E+03	.101E+03	.100E+03	.100E+03	.997E+02	.992E+02	.987E+02	.981E+02	.974E+02	.966E+02
4	.957E+02	.947E+02	.938E+02	.930E+02				.992E+02	.987E+02	.981E+02	.974E+02	.966E+02
5	.101E+03	.101E+03	.101E+03	.100E+03	.100E+03	.999E+02	.995E+02	.990E+02	.985E+02	.979E+02	.972E+02	.963E+02
5	.953E+02	.941E+02	.930E+02					.990E+02	.985E+02	.979E+02	.972E+02	.963E+02
6	.101E+03	.101E+03	.100E+03	.100E+03	.100E+03	.997E+02	.993E+02	.988E+02	.982E+02	.976E+02	.968E+02	.957E+02
6	.944E+02	.930E+02						.988E+02	.982E+02	.976E+02	.968E+02	.957E+02
7	.101E+03	.100E+03	.100E+03	.999E+02	.997E+02	.993E+02	.989E+02	.984E+02	.979E+02	.972E+02	.961E+02	.947E+02
7	.930E+02							.984E+02	.979E+02	.972E+02	.961E+02	.947E+02
8	.100E+03	.999E+02	.997E+02	.995E+02	.993E+02	.989E+02	.985E+02	.980E+02	.973E+02	.964E+02	.949E+02	.930E+02
8	.996E+02	.994E+02	.992E+02	.990E+02	.988E+02	.984E+02	.980E+02	.974E+02	.964E+02	.950E+02	.930E+02	
9	.990E+02	.988E+02	.987E+02	.985E+02	.982E+02	.979E+02	.973E+02	.964E+02	.949E+02	.930E+02		
10	.984E+02	.982E+02	.981E+02	.979E+02	.976E+02	.972E+02	.964E+02	.950E+02	.930E+02			
11	.977E+02	.975E+02	.974E+02	.972E+02	.968E+02	.961E+02	.949E+02	.930E+02				
12	.968E+02	.967E+02	.966E+02	.963E+02	.957E+02	.947E+02	.930E+02					
13	.959E+02	.958E+02	.957E+02	.953E+02	.944E+02	.930E+02						
14	.949E+02	.949E+02	.947E+02	.941E+02	.930E+02							
15	.940E+02	.940E+02	.930E+02									
16	.934E+02	.933E+02	.930E+02									
17	.931E+02	.930E+02										
18	.930E+02											

K=19

MASS FLUX IN TWO DIRECTION, G/50, CM SEC

K=20												
J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.165E-05	.164E-04	.162E-05	.155E-05	.146E-05	.130E-04	.117E-05	.949E-04	.823E-04	.671E-04	.495E-06	.300E-04
2	.112E-06	.607E-07	.204E-06	.250E-06	.871E-07							
3	.890E-05	.488E-05	.476E-05	.457E-05	.429E-05	.592E-04	.145E-05	.287E-05	.241E-05	.193E-05	.139E-05	.817E-04
3	.279E-06	.200E-06	.559E-06	.478E-06	0.							
4	.217E-05	.812E-05	.793E-05	.760E-05	.712E-05	.648E-05	.568E-05	.471E-05	.391E-05	.311E-05	.221E-05	.128E-05
4	.016E-06	.339E-06	.710E-06	0.								
5	.115E-04	.114E-04	.112E-04	.107E-04	.999E-05	.907E-05	.788E-05	.645E-05	.528E-05	.412E-05	.287E-05	.157E-05
5	.362E-06	.607E-06	0.									
6	.150E-04	.149E-04	.145E-04	.139E-04	.130E-04	.117E-04	.101E-04	.806E-05	.642E-05	.486E-05	.321E-05	.147E-05
6	.190E-06	0.										
7	.188E-04	.188E-04	.182E-04	.174E-04	.162E-04	.145E-04	.123E-04	.944E-05	.718E-05	.513E-05	.295E-05	.482E-06
7	0.											
8	.229E-04	.227E-04	.222E-04	.212E-04	.198E-04	.178E-04	.149E-04	.104E-04	.729E-05	.452E-05	.142E-05	0.
8	.210E-04	.208E-04	.203E-04	.195E-04	.182E-04	.164E-04	.139E-04	.104E-04	.617E-05	.214E-05	0.	
10	.192E-04	.190E-04	.184E-04	.174E-04	.159E-04	.139E-04	.113E-04	.780E-05	.308E-05	0.		
11	.172E-04	.170E-04	.163E-04	.151E-04	.134E-04	.112E-04	.824E-05	.398E-05	0.			
12	.145E-04	.143E-04	.134E-04	.120E-04	.101E-04	.744E-05	.360E-05	0.				
13	.116E-04	.113E-04	.103E-04	.868E-05	.640E-05	.300E-05	0.					
14	.845E-05	.814E-05	.698E-05	.513E-05	.228E-05	0.						
15	.528E-05	.492E-05	.364E-05	.146E-05	0.							
16	.239E-05	.200E-05	.698E-06	0.								
17	.551E-06	.154E-06	0.									
18	0.	0.										

K=19												
J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.370E-06	.363E-06	.353E-06	.341E-06	.327E-06	.316E-06	.305E-06	.138E-24	.287E-04	.256E-06	.224E-06	.165E-06
2	.102E-06	.420E-07	.999E-08	.356E-07	.115E-07							
3	.109E-05	.109E-05	.106E-05	.103E-05	.989E-06	.950E-04	.915E-06	.419E-24	.862E-04	.794E-06	.659E-06	.480E-06
3	.299E-06	.132E-06	.244E-08	.402E-07	0.							
4	.168E-05	.167E-05	.164E-05	.159E-05	.152E-05	.146E-05	.140E-05	.674E-24	.139E-04	.128E-05	.106E-05	.781E-06
4	.500E-06	.234E-06	.395E-07	0.								
5	.201E-05	.200E-05	.196E-05	.189E-05	.181E-05	.173E-05	.165E-05	.915E-24	.183E-05	.168E-05	.140E-05	.103E-05
5	.646E-06	.257E-06	0.									
6	.195E-05	.194E-05	.190E-05	.183E-05	.175E-05	.166E-05	.158E-05	.129E-24	.212E-05	.195E-05	.161E-05	.114E-05
6	.669E-06	0.										
7	.134E-05	.134E-05	.131E-05	.126E-05	.120E-05	.113E-05	.107E-05	.283E-24	.219E-05	.201E-05	.161E-05	.901E-04
7	0.											
8	.333E-22	.334E-22	.337E-22	.343E-22	.351E-22	.368E-22	.419E-22	.114E-22	.194E-05	.173E-05	.114E-05	0.
8	.373E-22	.373E-22	.373E-22	.374E-22	.374E-22	.370E-22	.356E-22	.120E-22	.114E-05	.886E-06	0.	
10	.216E-05	.213E-05	.204E-05	.188E-05	.168E-05	.144E-05	.118E-05	.914E-06	.639E-06	0.		
11	.229E-05	.325E-05	.307E-05	.278E-05	.240E-05	.195E-05	.141E-05	.626E-06	0.			
12	.265E-05	.358E-05	.331E-05	.289E-05	.234E-05	.164E-05	.627E-06	0.				
13	.333E-05	.325E-05	.291E-05	.238E-05	.166E-05	.622E-06	0.					
14	.262E-05	.251E-05	.211E-05	.148E-05	.547E-06	0.						
15	.171E-05	.158E-05	.113E-05	.396E-06	0.							
16	.793E-06	.656E-06	.203E-06	0.								
17	.148E-06	.480E-07	0.									
18	0.	0.										

K=18												
J	2	3	4	5	6	7	8	9	10	11	12	13
2	.300E-06	.298E-06	.287E-06	.268E-06	.240E-06	.208E-06	.168E-06	.123E-06	.761E-06	.298E-06	.230E-06	.164E-06
2	.105E-06	.540E-07	.128E-07	.939E-08	.241E-08							
3	.903E-06	.895E-06	.861E-06	.805E-06	.724E-06	.624E-06	.499E-06	.358E-06	.106E-05	.869E-06	.666E-06	.469E-06
3	.299E-06	.156E-06	.468E-07	.138E-08	0.							
4	.150E-05	.149E-05	.143E-05	.134E-05	.120E-05	.102E-05	.817E-06	.581E-06	.169E-05	.138E-05	.105E-05	.733E-06
4	.464E-06	.238E-06	.694E-07	0.								
5	.210E-05	.208E-05	.200E-05	.186E-05	.167E-05	.143E-05	.113E-05	.787E-06	.222E-05	.178E-05	.134E-05	.915E-06
5	.848E-06	.221E-06	0.									

6	.268E-05	.264E-05	.255E-05	.238E-05	.213E-05	.182E-05	.142E-05	.944E-06	.257E-05	.202E-05	.148E-05	.946E-06
6	.438E-06	0.										
7	.224E-05	.321E-05	.304E-05	.288E-05	.258E-05	.214E-05	.169E-05	.110E-05	.265E-05	.201E-05	.138E-05	.652E-06
7	0.											
8	.178E-05	.378E-05	.360E-05	.337E-05	.302E-05	.257E-05	.197E-05	.115E-05	.231E-05	.164E-05	.990E-06	0.
9	.506E-05	.500E-05	.476E-05	.437E-05	.342E-05	.304E-05	.216E-05	.103E-05	.123E-05	.709E-06	0.	
10	.486E-05	.480E-05	.455E-05	.413E-05	.356E-05	.284E-05	.200E-05	.111E-05	.517E-06	0.		
11	.446E-05	.439E-05	.412E-05	.367E-05	.308E-05	.234E-05	.149E-05	.508E-06	0.			
12	.278E-05	.371E-05	.341E-05	.294E-05	.231E-05	.151E-05	.499E-06	0.				
13	.300E-05	.292E-05	.267E-05	.209E-05	.140E-05	.474E-06	0.					
14	.216E-05	.207E-05	.173E-05	.118E-05	.402E-06	0.						
15	.133E-05	.123E-05	.869E-06	.284E-06	0.							
16	.592E-06	.488E-06	.144E-06	0.								
17	.109E-06	.343E-07	0.									
18	0.	0.										

K=17

J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.677E-06	.682E-06	.667E-06	.633E-06	.568E-06	.531E-06	.443E-06	.335E-06	.126E-05	.112E-05	.913E-06	.651E-06
2	.371E-06	.909E-07	.155E-06	.262E-06	.891E-07							
3	.209E-05	.208E-05	.203E-05	.194E-05	.179E-05	.162E-05	.133E-05	.995E-06	.772E-05	.324E-05	.262E-05	.183E-05
3	.103E-05	.257E-06	.373E-06	.432E-06	0.							
4	.356E-05	.353E-05	.345E-05	.330E-05	.300E-05	.263E-05	.221E-05	.164E-05	.406E-05	.530E-05	.426E-05	.302E-05
4	.177E-05	.570E-06	.276E-06	0.								
5	.512E-05	.507E-05	.492E-05	.464E-05	.429E-05	.380E-05	.313E-05	.229E-05	.820E-05	.713E-05	.573E-05	.407E-05
5	.232E-05	.557E-06	0.									
6	.678E-05	.675E-05	.659E-05	.621E-05	.572E-05	.506E-05	.411E-05	.291E-05	.495E-05	.857E-05	.681E-05	.459E-05
6	.190E-05	0.										
7	.871E-05	.865E-05	.837E-05	.795E-05	.730E-05	.638E-05	.513E-05	.350E-05	.110E-04	.926E-05	.899E-05	.347E-05
7	0.											
8	.110E-04	.109E-04	.106E-04	.100E-04	.918E-05	.798E-05	.634E-05	.405E-05	.106E-04	.848E-05	.494E-05	0.
8	.138E-04	.137E-04	.133E-04	.125E-04	.115E-04	.999E-05	.789E-05	.478E-05	.712E-05	.445E-05	0.	
10	.174E-04	.172E-04	.166E-04	.156E-04	.141E-04	.123E-04	.997E-05	.715E-05	.407E-05	0.		
11	.190E-04	.188E-04	.179E-04	.165E-04	.146E-04	.122E-04	.921E-05	.453E-05	0.			
12	.187E-04	.184E-04	.172E-04	.153E-04	.128E-04	.952E-05	.434E-05	0.				
13	.165E-04	.162E-04	.146E-04	.123E-04	.901E-05	.394E-05	0.					
14	.130E-04	.124E-04	.107E-04	.776E-05	.323E-05	0.						
15	.861E-05	.800E-05	.582E-05	.222E-05	0.							
16	.402E-05	.335E-05	.110E-05	0.								
17	.760E-06	.251E-06	0.									
18	0.	0.										

K=16

J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.414E-06	.409E-06	.392E-06	.364E-06	.326E-06	.275E-06	.212E-06	.137E-06	.447E-06	.376E-06	.294E-06	.211E-06
2	.136E-06	.704E-07	.165E-07	.122E-07	.276E-08							
3	.124E-05	.123E-05	.118E-05	.110E-05	.979E-06	.824E-06	.633E-06	.407E-06	.132E-05	.110E-05	.854E-06	.608E-06
3	.390E-06	.205E-06	.628E-07	.435E-08	0.							
4	.207E-05	.205E-05	.196E-05	.182E-05	.163E-05	.137E-05	.105E-05	.666E-06	.211E-05	.175E-05	.135E-05	.959E-06
4	.616E-06	.324E-06	.104E-06	0.								
5	.289E-05	.286E-05	.274E-05	.254E-05	.226E-05	.190E-05	.144E-05	.900E-06	.276E-05	.227E-05	.173E-05	.121E-05
5	.744E-06	.318E-06	0.									
6	.368E-05	.364E-05	.349E-05	.323E-05	.287E-05	.239E-05	.180E-05	.110E-05	.319E-05	.257E-05	.193E-05	.127E-05
6	.616E-06	0.										
7	.443E-05	.438E-05	.420E-05	.386E-05	.343E-05	.284E-05	.210E-05	.123E-05	.328E-05	.257E-05	.182E-05	.937E-06
7	0.											
8	.508E-05	.503E-05	.486E-05	.442E-05	.389E-05	.319E-05	.232E-05	.128E-05	.286E-05	.211E-05	.119E-05	0.
8	.556E-05	.550E-05	.524E-05	.480E-05	.419E-05	.339E-05	.240E-05	.120E-05	.156E-05	.934E-06	0.	
10	.565E-05	.558E-05	.528E-05	.480E-05	.414E-05	.332E-05	.237E-05	.138E-05	.472E-06	0.		
11	.538E-05	.530E-05	.497E-05	.444E-05	.373E-05	.285E-05	.184E-05	.649E-06	0.			
12	.471E-05	.462E-05	.425E-05	.366E-05	.288E-05	.189E-05	.625E-06	0.				
13	.381E-05	.371E-05	.330E-05	.265E-05	.178E-05	.597E-06	0.					
14	.279E-05	.267E-05	.222E-05	.152E-05	.512E-06	0.						
15	.173E-05	.160E-05	.113E-05	.365E-06	0.							
16	.773E-06	.636E-06	.186E-06	0.								
17	.142E-06	.444E-07	0.									
18	0.	0.										

K=15

MASS FLUX IN K-DIRECTION, G/SD. CM SEC

K=20													
J=2	3	4	5	6	7	8	9	10	11	12	13		
1 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
2 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
3 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
4 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
5 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
6 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
7 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
8 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
9 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
10 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
11 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
12 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
13 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
14 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
15 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
16 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
17 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
18 0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		

K=19													
J=2	3	4	5	6	7	8	9	10	11	12	13		
1 .205E-04	.203E-04	.202E-04	.200E-04	.199E-04	.200E-04	.202E-04	.719E-23	.157E-05	.427E-05	.812E-05	.134E-04		
2 .199E-04	.276E-04	.353E-04	.364E-04	.170E-04	.170E-04	.170E-04	.701E-23	.185E-05	.466E-05	.457E-05	.139E-04		
3 .203E-04	.200E-04	.199E-04	.197E-04	.196E-04	.196E-04	.198E-04	.701E-23	.185E-05	.466E-05	.457E-05	.139E-04		
4 .205E-04	.281E-04	.355E-04	.340E-04	.197E-04	.197E-04	.197E-04	.701E-23	.185E-05	.466E-05	.457E-05	.139E-04		
5 .202E-04	.199E-04	.196E-04	.195E-04	.193E-04	.192E-04	.194E-04	.665E-23	.149E-05	.541E-05	.943E-05	.148E-04		
6 .215E-04	.291E-04	.351E-04	.222E-04	.192E-04	.189E-04	.188E-04	.609E-23	.150E-05	.659E-05	.108E-04	.165E-04		
7 .200E-04	.197E-04	.195E-04	.192E-04	.189E-04	.188E-04	.188E-04	.609E-23	.150E-05	.659E-05	.108E-04	.165E-04		
8 .237E-04	.322E-04	.303E-04	.189E-04	.185E-04	.182E-04	.179E-04	.530E-23	.494E-05	.830E-05	.129E-04	.195E-04		
9 .199E-04	.196E-04	.193E-04	.189E-04	.185E-04	.182E-04	.179E-04	.530E-23	.494E-05	.830E-05	.129E-04	.195E-04		
10 .290E-04	.353E-04	.192E-04	.188E-04	.182E-04	.176E-04	.170E-04	.421E-23	.185E-05	.107E-04	.164E-04	.263E-04		
11 .285E-04	.198E-04	.194E-04	.188E-04	.179E-04	.170E-04	.160E-04	.247E-23	.941E-05	.147E-04	.242E-04	.407E-04		
12 .719E-23	.701E-23	.665E-23	.609E-23	.530E-23	.421E-23	.247E-23	.247E-23	.135E-04	.233E-04	.422E-04			
13 .157E-05	.185E-05	.249E-05	.350E-05	.494E-05	.685E-05	.941E-05	.135E-04	.233E-04	.419E-04				
14 .427E-05	.466E-05	.541E-05	.659E-05	.830E-05	.107E-04	.147E-04	.233E-04	.419E-04					
15 .812E-05	.857E-05	.943E-05	.108E-04	.129E-04	.164E-04	.242E-04	.422E-04						
16 .134E-04	.139E-04	.148E-04	.165E-04	.195E-04	.263E-04	.407E-04							
17 .199E-04	.205E-04	.215E-04	.237E-04	.290E-04	.385E-04								
18 .276E-04	.281E-04	.291E-04	.322E-04	.353E-04									
19 .353E-04	.355E-04	.351E-04	.303E-04										
20 .364E-04	.340E-04	.222E-04											
21 .170E-04	.107E-04												

K=18													
J=2	3	4	5	6	7	8	9	10	11	12	13		
1 .296E-04	.293E-04	.281E-04	.262E-04	.236E-04	.201E-04	.157E-04	.337E-22	.183E-04	.848E-05	.238E-05	.146E-04		
2 .280E-04	.426E-04	.569E-04	.597E-04	.279E-04	.279E-04	.279E-04	.198E-04	.153E-04	.329E-22	.178E-04	.786E-05	.312E-05	.154E-04
3 .293E-04	.290E-04	.276E-04	.260E-04	.233E-04	.201E-04	.153E-04	.329E-22	.178E-04	.786E-05	.312E-05	.154E-04		
4 .288E-04	.434E-04	.572E-04	.557E-04	.276E-04	.222E-04	.187E-04	.143E-04	.306E-22	.161E-04	.614E-05	.488E-05	.172E-04	
5 .281E-04	.276E-04	.267E-04	.248E-04	.222E-04	.187E-04	.143E-04	.306E-22	.161E-04	.614E-05	.488E-05	.172E-04		
6 .307E-04	.452E-04	.566E-04	.363E-04										
7 .262E-04	.260E-04	.248E-04	.230E-04	.204E-04	.169E-04	.125E-04	.269E-22	.134E-04	.333E-05	.774E-05	.203E-04		
8 .345E-04	.506E-04	.494E-04											

6	.236E-04	.233E-04	.222E-04	.204E-04	.178E-04	.144E-04	.101E-04	.216E-22	.049E-05	.648E-06	.120E-04	.259E-04
7	.041E-04	.572E-04	.187E-04	.109E-04	.144E-04	.110E-04	.683E-05	.149E-22	.444E-05	.610E-05	.190E-04	.384E-04
8	.619E-04	.153E-04	.143E-04	.125E-04	.101E-04	.683E-05	.277E-05	.648E-27	.208E-05	.144E-04	.336E-04	.649E-04
9	.237E-22	.329E-22	.306E-22	.269E-22	.216E-22	.149E-22	.668E-23	.552E-24	.115E-04	.310E-04	.668E-04	
10	.183E-04	.178E-04	.161E-04	.134E-04	.949E-05	.440E-05	.208E-05	.115E-04	.208E-04	.658E-04		
11	.048E-05	.786E-05	.614E-05	.333E-05	.648E-06	.610E-05	.144E-04	.310E-04	.658E-04			
12	.238E-05	.312E-05	.488E-05	.774E-05	.120E-04	.190E-04	.336E-04	.668E-04				
13	.146E-04	.154E-04	.172E-04	.203E-04	.259E-04	.344E-04	.649E-04					
14	.280E-04	.288E-04	.307E-04	.345E-04	.441E-04	.619E-04						
15	.426E-04	.434E-04	.452E-04	.506E-04	.572E-04							
16	.569E-04	.572E-04	.566E-04	.494E-04								
17	.597E-04	.557E-04	.363E-04									
18	.279E-04	.176E-04										

K=17

J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.051E-04	.448E-04	.434E-04	.409E-04	.373E-04	.326E-04	.270E-04	.198E-04	.245E-04	.911E-05	.114E-05	.275E-04
3	.084E-04	.710E-04	.929E-04	.963E-04	.846E-04							
4	.048E-04	.445E-04	.430E-04	.406E-04	.371E-04	.325E-04	.266E-04	.193E-04	.237E-04	.809E-05	.932E-05	.288E-04
5	.097E-04	.722E-04	.932E-04	.898E-04	.240E-04							
6	.034E-04	.430E-04	.416E-04	.391E-04	.356E-04	.308E-04	.251E-04	.180E-04	.209E-04	.525E-05	.122E-04	.317E-04
7	.526E-04	.749E-04	.919E-04	.580E-04								
8	.009E-04	.406E-04	.391E-04	.365E-04	.332E-04	.267E-04	.228E-04	.157E-04	.164E-04	.640E-06	.168E-04	.365E-04
9	.585E-04	.831E-04	.792E-04									
10	.373E-04	.371E-04	.356E-04	.332E-04	.298E-04	.253E-04	.196E-04	.124E-04	.993E-05	.589E-05	.237E-04	.452E-04
11	.731E-04	.918E-04										
12	.328E-04	.325E-04	.308E-04	.287E-04	.253E-04	.207E-04	.153E-04	.848E-05	.159E-05	.148E-04	.348E-04	.645E-04
13	.095E-04											
14	.270E-04	.266E-04	.251E-04	.228E-04	.196E-04	.153E-04	.985E-05	.327E-05	.908E-05	.280E-04	.873E-04	.104E-03
15	.198E-04	.193E-04	.180E-04	.157E-04	.126E-04	.848E-05	.327E-05	.322E-05	.242E-04	.536E-04	.108E-03	
16	.245E-04	.237E-04	.209E-04	.164E-04	.993E-05	.159E-05	.908E-05	.242E-04	.535E-04	.106E-03		
17	.911E-05	.809E-05	.525E-05	.640E-06	.589E-05	.148E-04	.280E-04	.536E-04	.106E-03			
18	.814E-05	.932E-05	.122E-04	.168E-04	.237E-04	.348E-04	.573E-04	.108E-03				
19	.275E-04	.288E-04	.317E-04	.365E-04	.452E-04	.645E-04	.104E-03					
20	.084E-04	.497E-04	.526E-04	.585E-04	.731E-04	.995E-04						
21	.710E-04	.722E-04	.749E-04	.831E-04	.918E-04							
22	.929E-04	.932E-04	.919E-04	.792E-04								
23	.063E-04	.898E-04	.580E-04									
24	.046E-04	.280E-04										

K=16

J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.548E-04	.547E-04	.533E-04	.510E-04	.472E-04	.435E-04	.383E-04	.322E-04	.491E-04	.246E-04	.317E-05	.355E-04
3	.722E-04	.114E-03	.156E-03	.165E-03	.769E-04							
4	.547E-04	.540E-04	.530E-04	.507E-04	.473E-04	.431E-04	.378E-04	.315E-04	.478E-04	.229E-04	.519E-05	.378E-04
5	.747E-04	.116E-03	.157E-03	.154E-03	.482E-04							
6	.533E-04	.530E-04	.516E-04	.492E-04	.458E-04	.408E-04	.361E-04	.299E-04	.438E-04	.186E-04	.977E-05	.427E-04
7	.799E-04	.121E-03	.155E-03	.100E-03								
8	.510E-04	.507E-04	.492E-04	.460E-04	.434E-04	.390E-04	.335E-04	.270E-04	.371E-04	.116E-04	.172E-04	.510E-04
9	.907E-04	.138E-03	.137E-03									
10	.072E-04	.473E-04	.458E-04	.434E-04	.400E-04	.354E-04	.297E-04	.230E-04	.276E-04	.152E-05	.284E-04	.663E-04
11	.118E-03	.159E-03										
12	.435E-04	.431E-04	.408E-04	.390E-04	.354E-04	.299E-04	.247E-04	.177E-04	.151E-04	.124E-04	.472E-04	.102E-03
13	.173E-03											
14	.383E-04	.378E-04	.361E-04	.335E-04	.297E-04	.247E-04	.184E-04	.108E-04	.138E-05	.344E-04	.879E-04	.181E-03
15	.322E-04	.315E-04	.298E-04	.270E-04	.230E-04	.177E-04	.108E-04	.194E-05	.264E-04	.804E-04	.186E-03	
16	.091E-04	.478E-04	.438E-04	.371E-04	.276E-04	.151E-04	.138E-05	.264E-04	.798E-04	.164E-03		
17	.246E-04	.229E-04	.186E-04	.116E-04	.152E-05	.124E-04	.344E-04	.804E-04	.184E-03			
18	.317E-05	.519E-05	.977E-05	.172E-04	.284E-04	.472E-04	.879E-04	.186E-03				
19	.355E-04	.378E-04	.427E-04	.510E-04	.663E-04	.102E-03						
20	.722E-04	.747E-04	.799E-04	.907E-04	.118E-03	.173E-03						
21	.114E-03	.116E-03	.121E-03	.138E-03	.159E-03							
22	.156E-03	.157E-03	.155E-03	.137E-03								
23	.165E-03	.154E-03	.100E-03									
24	.769E-04	.482E-04										

K=15

A portion of the final results for the converged (approximately) steady-state solution is as follows:

MOMENTUM TIME STEP=.652E-01 SEC. AVERAGE GAS PRESSURE (PAVG-PREF)/PRFF=.2596779E+00
 CONTINUITY ITER. MAX. ERROR I=DIR. MASS FLUX ITER. MAX. CHANGE K=DIR. MASS FLUX ITER. MAX. CHANGE

1	.727E-05	0	0.	0	0.
2	.195E-05	0	0.	0	0.
3	.460E-06	0	0.	0	0.
4	.639E-06	3	.272E-04	4	.114E-03
5	.228E-05	0	0.	0	0.
6	.167E-05	0	0.	0	0.
7	.783E-06	2	.153E-05	3	.707E-05
8	.560E-06	1	.134E-06	2	.785E-06
9	.439E-06	1	.544E-07	1	.132E-06
10	.362E-06	1	.389E-07	1	.613E-07
11	.304E-06	1	.298E-07	1	.321E-07
12	.256E-06	1	.244E-07	1	.200E-07
13	.215E-06	1	.202E-07	1	.169E-07
14	.181E-06	1	.169E-07	1	.143E-07
15	.153E-06	1	.142E-07	1	.120E-07
16	.129E-06	1	.120E-07	1	.101E-07
17	.108E-06	1	.101E-07	1	.856E-08
18	.914E-07	1	.851E-08	1	.722E-08

THERMAL# 1 TIME STEP=.990E+00 SEC. MAX. RATE=.136E+00 C/SEC. MAX. CHANGE=.134E+00 C AT I,J,K 3 6 20
 THERMAL# 2 TIME STEP=.100E+01 SEC. MAX. RATE=.116E+00 C/SEC. MAX. CHANGE=.116E+00 C AT I,J,K 2 6 20
 THERMAL# 3 TIME STEP=.100E+01 SEC. MAX. RATE=.107E+00 C/SEC. MAX. CHANGE=.107E+00 C AT I,J,K 2 6 20
 THERMAL# 4 TIME STEP=.100E+01 SEC. MAX. RATE=.983E-01 C/SEC. MAX. CHANGE=.983E-01 C AT I,J,K 2 6 20
 THERMAL# 5 TIME STEP=.100E+01 SEC. MAX. RATE=.897E-01 C/SEC. MAX. CHANGE=.897E-01 C AT I,J,K 2 6 20
 THERMAL# 6 TIME STEP=.100E+01 SEC. MAX. RATE=.819E-01 C/SEC. MAX. CHANGE=.819E-01 C AT I,J,K 2 6 20

MOMENTUM TIME STEP=.717E-01 SEC. AVERAGE GAS PRESSURE (PAVG-PREF)/PRFF=.2596755E+00
 CONTINUITY ITER. MAX. ERROR I=DIR. MASS FLUX ITER. MAX. CHANGE K=DIR. MASS FLUX ITER. MAX. CHANGE

1	.233E-05	0	0.	0	0.
2	.148E-05	0	0.	0	0.
3	.541E-06	3	.276E-04	4	.119E-03
4	.229E-05	0	0.	0	0.
5	.167E-05	0	0.	0	0.
6	.816E-06	0	0.	0	0.
7	.619E-06	2	.167E-05	3	.796E-05
8	.434E-06	1	.170E-06	2	.953E-06
9	.371E-06	1	.665E-07	1	.159E-06
10	.329E-06	1	.409E-07	1	.739E-07
11	.282E-06	1	.305E-07	1	.381E-07
12	.238E-06	1	.244E-07	1	.210E-07
13	.200E-06	1	.201E-07	1	.167E-07
14	.168E-06	1	.168E-07	1	.140E-07
15	.141E-06	1	.141E-07	1	.118E-07
16	.119E-06	1	.112E-07	1	.994E-08
17	.999E-07	1	.993E-08	1	.837E-08

THERMAL# 7 TIME STEP=.100E+01 SEC. MAX. RATE=.123E+00 C/SEC. MAX. CHANGE=.123E+00 C AT I,J,K 3 6 20
 THERMAL# 8 TIME STEP=.990E+00 SEC. MAX. RATE=.105E+00 C/SEC. MAX. CHANGE=.949E-01 C AT I,J,K 2 6 20
 THERMAL# 9 TIME STEP=.990E+00 SEC. MAX. RATE=.977E-01 C/SEC. MAX. CHANGE=.968E-01 C AT I,J,K 2 6 20
 THERMAL# 10 TIME STEP=.100E+01 SEC. MAX. RATE=.895E-01 C/SEC. MAX. CHANGE=.895E-01 C AT I,J,K 2 6 20
 THERMAL# 11 TIME STEP=.100E+01 SEC. MAX. RATE=.816E-01 C/SEC. MAX. CHANGE=.816E-01 C AT I,J,K 2 6 20
 THERMAL# 12 TIME STEP=.100E+01 SEC. MAX. RATE=.744E-01 C/SEC. MAX. CHANGE=.744E-01 C AT I,J,K 2 6 20

MOMENTUM TIME STEP=.789E-01 SEC. AVERAGE GAS PRESSURE (PAVG-PREF)/PRFF=.2596728E+00
 CONTINUITY ITER. MAX. ERROR I=DIR. MASS FLUX ITER. MAX. CHANGE K=DIR. MASS FLUX ITER. MAX. CHANGE

1	.228E-05	0	0.	0	0.
2	.440E-06	0	0.	0	0.
3	.339E-06	3	.279E-04	4	.123E-03
4	.243E-05	0	0.	0	0.

12	.864E-06	0	0.	0	0.
13	.635E-06	2	.845E-06	2	.105E-05
14	.226E-06	1	.237E-06	1	.343E-06
15	.423E-06	1	.790E-07	1	.257E-06
16	.343E-06	1	.522E-07	1	.187E-06
17	.275E-06	1	.661E-07	1	.139E-06
18	.200E-06	1	.772E-07	1	.102E-06
19	.133E-06	1	.794E-07	1	.774E-07
20	.783E-07	1	.725E-07	1	.452E-07
THERMAL#193	TIME STEP= .100E+01 SEC.	MAX. RATE= .106E-01 C/SEC.	MAX. CHANGE= .106E-01 C AT I,J,K	5	2 19
THERMAL#194	TIME STEP= .100E+01 SEC.	MAX. RATE= .105E-01 C/SEC.	MAX. CHANGE= .105E-01 C AT I,J,K	5	2 19
THERMAL#195	TIME STEP= .100E+01 SEC.	MAX. RATE= .104E-01 C/SEC.	MAX. CHANGE= .104E-01 C AT I,J,K	5	2 19
THERMAL#196	TIME STEP= .100E+01 SEC.	MAX. RATE= .103E-01 C/SEC.	MAX. CHANGE= .103E-01 C AT I,J,K	2	5 19
THERMAL#197	TIME STEP= .100E+01 SEC.	MAX. RATE= .102E-01 C/SEC.	MAX. CHANGE= .102E-01 C AT I,J,K	2	5 19
THERMAL#198	TIME STEP= .100E+01 SEC.	MAX. RATE= .100E-01 C/SEC.	MAX. CHANGE= .100E-01 C AT I,J,K	2	5 19
MOMENTUM TIME STEP= .100E+01 SEC. AVERAGE GAS PRESSURE (PAVG-PREF)/PRPF= .2995431E+00					
CONTINUITY	ITER. MAX. ERROR	I=0 IN. MASS FLUX ITER. MAX. CHANGE	K=0 IN. MASS FLUX ITER. MAX. CHANGE		
1	.128E-05	0	0.	0	0.
2	.985E-06	0	0.	0	0.
3	.581E-06	3	.263E-05	4	.487E-05
4	.157E-05	0	0.	0	0.
5	.141E-05	0	0.	0	0.
6	.118E-05	0	0.	0	0.
7	.987E-06	0	0.	0	0.
8	.822E-06	0	0.	0	0.
9	.814E-06	0	0.	0	0.
10	.744E-06	2	.847E-06	2	.183E-05
11	.843E-06	0	0.	0	0.
12	.540E-06	2	.759E-06	2	.993E-06
13	.169E-06	1	.231E-06	1	.332E-06
14	.261E-06	1	.987E-07	1	.234E-06
15	.248E-06	1	.428E-07	1	.170E-06
16	.209E-06	1	.332E-07	1	.126E-06
17	.160E-06	1	.481E-07	1	.927E-07
18	.114E-06	1	.554E-07	1	.678E-07
19	.722E-07	1	.535E-07	1	.496E-07
THERMAL#199	TIME STEP= .100E+01 SEC.	MAX. RATE= .996E-02 C/SEC.	MAX. CHANGE= .996E-02 C AT I,J,K	5	2 19
THERMAL#200	TIME STEP= .100E+01 SEC.	MAX. RATE= .985E-02 C/SEC.	MAX. CHANGE= .985E-02 C AT I,J,K	5	2 19

063E+01 0210E+01 0250E+01 0337E+01 0110E+02 0237E+02 0448E+02 0896E+02 0041E+02 0120E+03 0129E+03 0123E+03

TEMPERATURE.C

[illegible][illegible]

K 19

J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.116E+03	.116E+03	.117E+03	.117E+03	.118E+03	.118E+03	.120E+03	.121E+03	.122E+03	.123E+03	.125E+03	.119E+03
3	.113E+03	.107E+03	.101E+03	.971E+02	.948E+02	.940E+02						
4	.116E+03	.116E+03	.117E+03	.117E+03	.118E+03	.119E+03	.120E+03	.121E+03	.122E+03	.123E+03	.125E+03	.119E+03
5	.113E+03	.106E+03	.100E+03	.964E+02	.940E+02							
6	.117E+03	.117E+03	.117E+03	.117E+03	.118E+03	.118E+03	.119E+03	.120E+03	.122E+03	.127E+03	.123E+03	.117E+03
7	.111E+03	.104E+03	.981E+02	.940E+02								
8	.117E+03	.117E+03	.117E+03	.118E+03	.118E+03	.118E+03	.119E+03	.119E+03	.123E+03	.124E+03	.120E+03	.115E+03
9	.107E+03	.998E+02	.940E+02									
10	.118E+03	.118E+03	.118E+03	.118E+03	.118E+03	.118E+03	.118E+03	.118E+03	.120E+03	.121E+03	.117E+03	.110E+03
11	.102E+03	.940E+02										
12	.119E+03	.119E+03	.115E+03	.116E+03	.118E+03	.118E+03	.118E+03	.118E+03	.118E+03	.118E+03	.113E+03	.104E+03
13	.940E+02											
14	.120E+03	.120E+03	.119E+03	.119E+03	.118E+03	.118E+03	.117E+03	.117E+03	.116E+03	.113E+03	.105E+03	.940E+02
15	.121E+03	.121E+03	.120E+03	.119E+03	.118E+03	.118E+03	.117E+03	.116E+03	.112E+03	.109E+03	.940E+02	
16	.124E+03	.124E+03	.126E+03	.123E+03	.120E+03	.118E+03	.116E+03	.112E+03	.104E+03	.940E+02		
17	.130E+03	.129E+03	.127E+03	.124E+03	.121E+03	.118E+03	.113E+03	.105E+03	.940E+02			
18	.125E+03	.125E+03	.123E+03	.120E+03	.117E+03	.113E+03	.105E+03	.940E+02				
19	.119E+03	.119E+03	.117E+03	.115E+03	.110E+03	.104E+03	.940E+02					
20	.113E+03	.113E+03	.111E+03	.107E+03	.102E+03	.940E+02						
21	.107E+03	.104E+03	.104E+03	.998E+02	.940E+02							
22	.101E+03	.100E+03	.981E+02	.940E+02								
23	.071E+02	.964E+02	.940E+02									
24	.048E+02	.940E+02										
25	.040E+02											

J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.130E+03	.130E+03	.130E+03	.129E+03	.128E+03	.128E+03	.127E+03	.127E+03	.133E+03	.131E+03	.125E+03	.117E+03
3	.111E+03	.105E+03	.101E+03	.982E+02	.965E+02	.960E+02						
4	.130E+03	.130E+03	.129E+03	.129E+03	.128E+03	.127E+03	.127E+03	.127E+03	.133E+03	.131E+03	.124E+03	.117E+03
5	.110E+03	.105E+03	.100E+03	.977E+02	.960E+02							
6	.130E+03	.129E+03	.129E+03	.128E+03	.128E+03	.127E+03	.126E+03	.125E+03	.130E+03	.128E+03	.122E+03	.114E+03
7	.108E+03	.103E+03	.987E+02	.960E+02								
8	.129E+03	.129E+03	.128E+03	.128E+03	.127E+03	.125E+03	.124E+03	.123E+03	.126E+03	.123E+03	.118E+03	.111E+03
9	.105E+03	.998E+02	.960E+02									
10	.124E+03	.124E+03	.124E+03	.127E+03	.125E+03	.124E+03	.122E+03	.121E+03	.121E+03	.118E+03	.113E+03	.107E+03
11	.101E+03	.960E+02										
12	.128E+03	.127E+03	.127E+03	.125E+03	.124E+03	.122E+03	.120E+03	.118E+03	.117E+03	.114E+03	.109E+03	.102E+03
13	.060E+02											
14	.127E+03	.127E+03	.126E+03	.124E+03	.122E+03	.120E+03	.118E+03	.118E+03	.113E+03	.109E+03	.103E+03	.960E+02
15	.127E+03	.127E+03	.125E+03	.123E+03	.121E+03	.118E+03	.115E+03	.112E+03	.109E+03	.103E+03	.960E+02	
16	.133E+03	.133E+03	.130E+03	.126E+03	.121E+03	.117E+03	.113E+03	.109E+03	.102E+03	.960E+02		
17	.131E+03	.131E+03	.124E+03	.123E+03	.118E+03	.114E+03	.109E+03	.103E+03	.960E+02			
18	.125E+03	.124E+03	.122E+03	.118E+03	.113E+03	.109E+03	.103E+03	.960E+02				
19	.117E+03	.117E+03	.114E+03	.111E+03	.107E+03	.102E+03	.960E+02					
20	.111E+03	.110E+03	.108E+03	.105E+03	.101E+03	.960E+02						
21	.105E+03	.104E+03	.103E+03	.998E+02	.960E+02							
22	.101E+03	.100E+03	.987E+02	.960E+02								
23	.082E+02	.977E+02	.960E+02									
24	.065E+02	.960E+02										
25	.060E+02											

J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.154E+03	.154E+03	.153E+03	.152E+03	.149E+03	.147E+03	.144E+03	.141E+03	.141E+03	.135E+03	.127E+03	.120E+03
3	.133E+03	.107E+03	.103E+03	.100E+03	.985E+02	.980E+02						
4	.154E+03	.154E+03	.153E+03	.151E+03	.149E+03	.147E+03	.144E+03	.141E+03	.141E+03	.130E+03	.127E+03	.119E+03
5	.112E+03	.104E+03	.102E+03	.995E+02	.980E+02							
6	.153E+03	.153E+03	.152E+03	.150E+03	.148E+03	.145E+03	.142E+03	.139E+03	.138E+03	.132E+03	.125E+03	.117E+03
7	.110E+03	.104E+03	.100E+03	.980E+02								
8	.152E+03	.151E+03	.150E+03	.148E+03	.146E+03	.143E+03	.140E+03	.137E+03	.135E+03	.128E+03	.121E+03	.113E+03
9	.106E+03	.101E+03	.980E+02									
10	.149E+03	.149E+03	.148E+03	.146E+03	.144E+03	.141E+03	.137E+03	.133E+03	.130E+03	.123E+03	.115E+03	.108E+03
11	.102E+03	.980E+02										
12	.147E+03	.147E+03	.145E+03	.143E+03	.141E+03	.137E+03	.134E+03	.129E+03	.122E+03	.116E+03	.109E+03	.103E+03
13	.080E+02											
14	.144E+03	.144E+03	.142E+03	.140E+03	.137E+03	.134E+03	.129E+03	.124E+03	.116E+03	.110E+03	.103E+03	.980E+02

MASS FLUX IN I-DIRECTION, G/SP. CM SEC

K=20												
J=2	3	4	5	6	7	8	9	10	11	12	13	
1	.166E-03	.153E-03	.104E-03	.795E-04	.277E-04	.697E-04	.144E-03	.199E-03	.275E-03	.707E-03	.292E-03	.237E-03
2	.171E-03	.104E-03	.566E-04	.215E-04	.399E-05							
3	.075E-03	.433E-03	.304E-03	.119E-03	.765E-04	.258E-03	.417E-03	.573E-03	.787E-03	.870E-03	.665E-03	
4	.071E-03	.288E-03	.133E-03	.335E-04	0.							
5	.198E-03	.650E-03	.465E-03	.197E-03	.102E-03	.382E-03	.626E-03	.855E-03	.116E-02	.126E-02	.117E-02	.907E-03
6	.596E-03	.301E-03	.824E-04	0.								
7	.794E-03	.744E-03	.548E-03	.248E-03	.105E-03	.451E-03	.748E-03	.101E-02	.133E-02	.147E-02	.126E-02	.899E-03
8	.086E-03	.139E-03	0.									
9	.754E-03	.707E-03	.522E-03	.236E-03	.115E-03	.474E-03	.787E-03	.104E-02	.132E-02	.134E-02	.110E-02	.638E-03
10	.188E-03	0.										
11	.625E-03	.581E-03	.413E-03	.155E-03	.140E-03	.488E-03	.773E-03	.982E-03	.114E-02	.105E-02	.704E-03	.212E-03
12	0.											
13	.560E-03	.514E-03	.340E-03	.803E-04	.224E-03	.524E-03	.767E-03	.890E-03	.855E-03	.599E-03	.192E-03	0.
14	.058E-03	.888E-03	.627E-03	.237E-03	.192E-03	.586E-03	.859E-03	.890E-03	.911E-03	.118E-03	0.	
15	.376E-03	.330E-03	.157E-03	.869E-04	.348E-03	.560E-03	.640E-03	.485E-03	.939E-04	0.		
16	.125E-03	.336E-03	.377E-03	.288E-03	.467E-03	.453E-03	.336E-03	.772E-04	0.			
17	.737E-03	.716E-03	.642E-03	.531E-03	.387E-03	.212E-03	.134E-04	0.				
18	.703E-03	.667E-03	.540E-03	.360E-03	.163E-03	.460E-03	0.					
19	.466E-03	.428E-03	.295E-03	.131E-03	.323E-03	0.						
20	.220E-03	.186E-03	.909E-04	.167E-05	0.							
21	.654E-04	.452E-04	.342E-05	0.								
22	.802E-05	.170E-05	0.									
23	0.	0.										

K=19												
J=2	3	4	5	6	7	8	9	10	11	12	13	
1	.860E-04	.804E-04	.608E-04	.365E-04	.145E-04	.412E-04	.546E-05	.849E-04	.895E-04	.124E-03	.126E-03	.105E-03
2	.762E-04	.488E-04	.265E-04	.105E-04	.199E-05							
3	.244E-03	.229E-03	.176E-03	.107E-03	.437E-04	.537E-03	.152E-04	.255E-03	.256E-03	.352E-03	.755E-03	.292E-03
4	.208E-03	.128E-03	.609E-04	.156E-04	0.							
5	.349E-03	.331E-03	.262E-03	.166E-03	.725E-04	.516E-03	.197E-04	.378E-03	.771E-03	.505E-03	.497E-03	.391E-03
6	.259E-03	.134E-03	.380E-04	0.								
7	.374E-03	.357E-03	.292E-03	.196E-03	.939E-04	.149E-04	.176E-04	.429E-03	.408E-03	.542E-03	.511E-03	.371E-03
8	.205E-03	.624E-04	0.									
9	.305E-03	.293E-03	.246E-03	.174E-03	.923E-04	.227E-04	.104E-04	.408E-03	.757E-03	.457E-03	.400E-03	.242E-03
10	.782E-04	0.										
11	.159E-03	.153E-03	.131E-03	.959E-04	.550E-04	.175E-04	.302E-05	.436E-03	.251E-03	.299E-03	.220E-03	.766E-04
12	0.											
13	.863E-03	.931E-03	.119E-02	.159E-02	.205E-02	.251E-02	.313E-02	.100E-02	.132E-03	.130E-03	.552E-04	0.
14	.241E-02	.240E-02	.239E-02	.237E-02	.235E-02	.226E-02	.191E-02	.233E-02	.286E-04	.165E-04	0.	
15	.125E-03	.120E-03	.102E-03	.732E-04	.381E-04	.472E-05	.200E-04	.303E-04	.112E-04	0.		
16	.210E-03	.190E-03	.159E-03	.969E-04	.272E-04	.283E-04	.531E-04	.349E-04	0.			
17	.206E-03	.190E-03	.133E-03	.521E-04	.239E-04	.614E-04	.398E-04	0.				
18	.135E-03	.119E-03	.632E-04	.373E-05	.458E-04	.332E-04	0.					
19	.634E-04	.507E-04	.112E-04	.226E-04	.210E-04	0.						
20	.208E-04	.128E-04	.574E-05	.962E-05	0.							
21	.409E-05	.814E-06	.268E-05	0.								
22	.289E-06	.188E-06	0.									
23	0.	0.										

K=18												
J=2	3	4	5	6	7	8	9	10	11	12	13	
1	.648E-06	.641E-06	.604E-06	.545E-06	.468E-06	.395E-06	.324E-06	.318E-06	.134E-06	.188E-06	.193E-06	.161E-06
2	.117E-06	.750E-05	.404E-05	.159E-05	.300E-06							
3	.195E-05	.192E-05	.181E-05	.164E-05	.142E-05	.119E-05	.964E-06	.933E-06	.792E-06	.545E-06	.558E-06	.457E-06
4	.326E-04	.190E-04	.939E-05	.239E-05	0.							
5	.321E-05	.317E-05	.300E-05	.272E-05	.236E-05	.196E-05	.157E-05	.146E-05	.809E-06	.830E-06	.821E-06	.647E-06
6	.426E-06	.218E-06	.612E-05	0.								
7	.441E-05	.435E-05	.414E-05	.378E-05	.332E-05	.275E-05	.216E-05	.185E-05	.741E-06	.977E-06	.917E-06	.659E-06
8	.360E-06	.108E-06	0.									

6	.550E-05	.545E-05	.523E-05	.484E-05	.429E-05	.358E-05	.273E-05	.205E-05	.129E-04	.778E-04	.461E-04
7	.147E-04	0.	.634E-05	.619E-05	.584E-05	.527E-05	.444E-05	.332E-05	.208E-05	.548E-04	.630E-04
8	.644E-05	.634E-05	.619E-05	.584E-05	.527E-05	.444E-05	.332E-05	.208E-05	.548E-04	.630E-04	.450E-04
9	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
10	.714E-05	.712E-05	.700E-05	.676E-05	.629E-05	.544E-05	.407E-05	.194E-05	.297E-04	.285E-04	.120E-04
11	.155E-04	.152E-04	.138E-04	.116E-04	.878E-05	.557E-05	.203E-05	.130E-05	.584E-05	.383E-05	0.
12	.065E-04	.454E-04	.404E-04	.333E-04	.226E-04	.958E-05	.185E-05	.730E-05	.246E-05	0.	0.
13	.570E-04	.550E-04	.474E-04	.348E-04	.181E-04	.525E-04	.977E-05	.743E-05	0.	0.	0.
14	.056E-04	.430E-04	.334E-04	.186E-04	.165E-05	.990E-05	.785E-05	0.	0.	0.	0.
15	.271E-04	.246E-04	.195E-04	.326E-05	.644E-05	.607E-05	0.	0.	0.	0.	0.
16	.123E-04	.102E-04	.373E-05	.269E-05	.352E-05	0.	0.	0.	0.	0.	0.
17	.006E-05	.276E-05	.408E-05	.148E-05	0.	0.	0.	0.	0.	0.	0.
18	.049E-06	.296E-06	.382E-06	0.	0.	0.	0.	0.	0.	0.	0.
19	.094E-07	.213E-07	0.	0.	0.	0.	0.	0.	0.	0.	0.

K=17											
J	J=2	3	4	5	6	7	8	9	10	11	12
2	.130E-05	.131E-05	.126E-05	.113E-05	.918E-06	.744E-06	.451E-06	.168E-07	.248E-04	.332E-04	.340E-04
3	.234E-04	.162E-04	.934E-05	.388E-05	.746E-06	.231E-05	.139E-05	.976E-07	.653E-04	.919E-04	.942E-04
4	.008E-05	.400E-05	.385E-05	.349E-05	.295E-05	.231E-05	.139E-05	.976E-07	.653E-04	.919E-04	.942E-04
5	.638E-04	.421E-04	.211E-04	.555E-05	0.	.391E-05	.248E-05	.411E-06	.864E-04	.117E-03	.121E-03
6	.712E-05	.702E-05	.667E-05	.608E-05	.512E-05	.391E-05	.248E-05	.411E-06	.864E-04	.117E-03	.121E-03
7	.773E-04	.435E-04	.129E-04	0.	0.	.609E-05	.401E-05	.117E-05	.268E-04	.961E-04	.105E-03
8	.105E-04	.104E-04	.983E-05	.889E-05	.769E-05	.609E-05	.401E-05	.117E-05	.268E-04	.961E-04	.105E-03
9	.594E-04	.196E-04	0.	0.	0.	.887E-05	.603E-05	.238E-05	.224E-04	.497E-04	.697E-04
10	.144E-04	.142E-04	.137E-04	.125E-04	.109E-04	.887E-05	.603E-05	.238E-05	.224E-04	.497E-04	.697E-04
11	.227E-04	0.	0.	0.	0.	.122E-04	.857E-05	.358E-05	.270E-05	.309E-04	.494E-04
12	.193E-04	.191E-04	.183E-04	.169E-04	.149E-04	.122E-04	.857E-05	.358E-05	.270E-05	.309E-04	.494E-04
13	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
14	.256E-04	.254E-04	.244E-04	.228E-04	.204E-04	.170E-04	.122E-04	.857E-05	.358E-05	.270E-05	.309E-04
15	.351E-04	.344E-04	.341E-04	.325E-04	.298E-04	.254E-04	.186E-04	.847E-05	.194E-05	.815E-05	0.
16	.204E-03	.206E-03	.211E-03	.214E-03	.202E-03	.164E-03	.103E-03	.407E-04	.578E-05	0.	0.
17	.253E-03	.255E-03	.260E-03	.257E-03	.231E-03	.165E-03	.815E-04	.177E-04	0.	0.	0.
18	.190E-03	.191E-03	.190E-03	.180E-03	.142E-03	.759E-04	.173E-04	0.	0.	0.	0.
19	.107E-03	.107E-03	.104E-03	.944E-04	.547E-04	.136E-04	0.	0.	0.	0.	0.
20	.082E-04	.477E-04	.448E-04	.307E-04	.914E-05	0.	0.	0.	0.	0.	0.
21	.164E-04	.164E-04	.131E-04	.461E-05	0.	0.	0.	0.	0.	0.	0.
22	.011E-05	.367E-05	.152E-05	0.	0.	0.	0.	0.	0.	0.	0.
23	.066E-06	.212E-06	0.	0.	0.	0.	0.	0.	0.	0.	0.

K=16											
J	J=2	3	4	5	6	7	8	9	10	11	12
2	.020E-06	.904E-06	.847E-06	.752E-06	.623E-06	.454E-06	.250E-06	.672E-07	.720E-04	.457E-04	.480E-04
3	.314E-04	.207E-04	.114E-04	.458E-05	.867E-06	.137E-05	.763E-06	.185E-06	.932E-04	.132E-03	.138E-03
4	.277E-05	.274E-05	.256E-05	.228E-05	.188E-05	.137E-05	.763E-06	.185E-06	.932E-04	.132E-03	.138E-03
5	.075E-04	.550E-04	.264E-04	.675E-05	0.	0.	0.	0.	0.	0.	0.
6	.064E-05	.462E-05	.434E-05	.387E-05	.321E-05	.237E-05	.134E-05	.234E-06	.143E-04	.201E-03	.206E-03
7	.117E-03	.615E-04	.174E-04	0.	0.	0.	0.	0.	0.	0.	0.
8	.672E-05	.663E-05	.624E-05	.559E-05	.467E-05	.347E-05	.201E-05	.169E-06	.174E-03	.240E-03	.238E-03
9	.103E-03	.315E-04	0.	0.	0.	0.	0.	0.	0.	0.	0.
10	.086E-05	.874E-05	.826E-05	.743E-05	.626E-05	.472E-05	.282E-05	.910E-07	.176E-03	.234E-03	.216E-03
11	.050E-04	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
12	.110E-04	.104E-04	.103E-04	.937E-05	.797E-05	.612E-05	.381E-05	.652E-06	.141E-03	.174E-03	.142E-03
13	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
14	.131E-04	.130E-04	.123E-04	.113E-04	.972E-05	.761E-05	.493E-05	.140E-05	.847E-04	.947E-04	.453E-04
15	.146E-04	.144E-04	.140E-04	.131E-04	.118E-04	.978E-05	.697E-05	.304E-05	.224E-04	.166E-04	0.
16	.010E-04	.422E-04	.468E-04	.529E-04	.580E-04	.596E-04	.512E-04	.315E-04	.715E-05	0.	0.
17	.095E-04	.518E-04	.601E-04	.706E-04	.785E-04	.784E-04	.601E-04	.257E-04	0.	0.	0.
18	.353E-04	.370E-04	.472E-04	.577E-04	.643E-04	.563E-04	.265E-04	0.	0.	0.	0.
19	.160E-04	.187E-04	.275E-04	.363E-04	.368E-04	.194E-04	0.	0.	0.	0.	0.
20	.072E-05	.718E-05	.141E-04	.180E-04	.109E-04	0.	0.	0.	0.	0.	0.
21	.048E-06	.262E-05	.606E-05	.462E-05	0.	0.	0.	0.	0.	0.	0.
22	.131E-06	.899E-06	.127E-05	0.	0.	0.	0.	0.	0.	0.	0.
23	.050E-07	.115E-06	0.	0.	0.	0.	0.	0.	0.	0.	0.

K=15

MASS FLUX IN K-DIRECTION, G/50. CM SEC

J	J=2	3	4	5	6	7	K=20	8	9	10	11	12	13
2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
9	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
11	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
12	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
15	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
16	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
17	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
18	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

J	J=2	3	4	5	6	7	K=19	8	9	10	11	12	13
2	-.206E-02	-.191E-02	-.134E-02	-.545E-03	-.297E-03	-.961E-04	-.110E-02	-.545E-22	-.791E-02	-.482E-02	-.354E-02	-.130E-02	
3	-.509E-03	-.144E-02	-.146E-02	-.900E-03	-.267E-03								
4	-.191E-02	-.178E-02	-.124E-02	-.541E-03	-.267E-03	-.913E-04	-.105E-02	-.557E-22	-.371E-02	-.453E-02	-.326E-02	-.107E-02	
5	-.666E-03	-.151E-02	-.142E-02	-.745E-03	-.149E-03								
6	-.134E-02	-.128E-02	-.100E-02	-.498E-03	-.157E-03	-.727E-04	-.876E-03	-.447E-22	-.291E-02	-.344E-02	-.218E-02	-.218E-03	
7	-.123E-02	-.170E-02	-.119E-02	-.331E-03									
8	-.545E-03	-.541E-03	-.498E-03	-.319E-03	-.501E-04	-.465E-04	-.613E-03	-.249E-22	-.177E-02	-.190E-02	-.712E-03	-.918E-03	
9	-.186E-02	-.161E-02	-.551E-03										
10	-.297E-03	-.267E-03	-.157E-03	-.501E-04	-.598E-04	-.213E-03	-.317E-03	-.113E-22	-.542E-03	-.245E-03	-.450E-03	-.198E-02	
11	-.203E-02	-.809E-03											
12	-.961E-03	-.913E-03	-.727E-04	-.465E-03	-.213E-03	-.843E-04	-.726E-04	-.578E-23	-.636E-03	-.133E-02	-.223E-02	-.246E-02	
13	-.111E-02												
14	-.110E-02	-.105E-02	-.876E-03	-.613E-03	-.317E-03	-.726E-04	-.414E-04	-.210E-22	-.177E-02	-.267E-02	-.295E-02	-.146E-02	
15	-.545E-22	-.557E-22	-.447E-22	-.289E-22	-.113E-22	-.578E-23	-.210E-22	-.547E-22	-.260E-02	-.319E-02	-.184E-02		
16	-.791E-02	-.371E-02	-.291E-02	-.177E-02	-.542E-03	-.636E-03	-.172E-02	-.260E-02	-.316E-02	-.168E-02			
17	-.442E-02	-.453E-02	-.344E-02	-.190E-02	-.245E-03	-.133E-02	-.267E-02	-.319E-02	-.168E-02				
18	-.754E-02	-.326E-02	-.218E-02	-.712E-03	-.850E-03	-.223E-02	-.295E-02	-.184E-02					
19	-.130E-02	-.107E-02	-.218E-03	-.918E-03	-.198E-02	-.246E-02	-.146E-02						
20	-.509E-03	-.666E-03	-.123E-02	-.186E-02	-.203E-02	-.111E-02							
21	-.144E-02	-.151E-02	-.170E-02	-.161E-02	-.809E-03								
22	-.146E-02	-.142E-02	-.119E-02	-.551E-03									
23	-.200E-03	-.745E-03	-.331E-03										
24	-.267E-03	-.149E-03											

J	J=2	3	4	5	6	7	K=18	8	9	10	11	12	13
2	-.17E-04	-.615E-04	-.604E-04	-.583E-04	-.553E-04	-.517E-04	-.479E-04	-.165E-21	-.596E-02	-.706E-02	-.506E-02	-.186E-02	
3	-.510E-03	-.157E-02	-.153E-02	-.906E-03	-.263E-03								
4	-.615E-04	-.613E-04	-.600E-04	-.577E-04	-.545E-04	-.507E-04	-.466E-04	-.157E-21	-.464E-02	-.660E-02	-.460E-02	-.149E-02	
5	-.751E-03	-.167E-02	-.149E-02	-.750E-03	-.146E-03								
6	-.604E-04	-.600E-04	-.582E-04	-.553E-04	-.513E-04	-.466E-04	-.413E-04	-.126E-21	-.439E-02	-.485E-02	-.285E-02	-.111E-03	
7	-.160E-02	-.194E-02	-.126E-02	-.332E-03									
8	-.583E-04	-.577E-04	-.553E-04	-.514E-04	-.462E-04	-.400E-04	-.329E-04	-.805E-22	-.255E-02	-.232E-02	-.424E-03	-.163E-02	
9	-.244E-02	-.183E-02	-.570E-03										

6	.553E+04	.545E+04	.514E+04	.462E+04	.395E+04	.314E+04	.221E+04	.145E+04	.112E+04	.736E+03	.194E+02	.301E+02
6	-.249E+02	-.862E+03										
7	.517E+04	.507E+04	.466E+04	.400E+04	.314E+04	.211E+04	.145E+04	.112E+04	.736E+03	.194E+02	.301E+02	
7	-.120E+02											
8	.479E+04	.464E+04	.413E+04	.329E+04	.221E+04	.145E+04	.112E+04	.736E+03	.194E+02	.301E+02		
8	.165E+21	.157E+21	.126E+21	.105E+22	.285E+22	.194E+22	.112E+22	.736E+21	.194E+21	.301E+21	.194E+02	
10	.596E+02	.564E+02	.439E+02	.255E+02	.512E+01	.126E+02	.261E+02	.346E+02	.376E+02	.174E+02		
11	.706E+02	.660E+02	.485E+02	.232E+02	.369E+03	.259E+02	.399E+02	.393E+02	.174E+02			
12	.506E+02	.460E+02	.285E+02	.124E+03	.196E+02	.362E+02	.385E+02	.194E+02				
13	.186E+02	.149E+02	.111E+02	.163E+02	.301E+02	.319E+02	.157E+02					
14	.510E+03	.751E+03	.160E+02	.244E+02	.249E+02	.120E+02						
15	.157E+02	.167E+02	.195E+02	.183E+02	.862E+03							
16	.153E+02	.144E+02	.126E+02	.570E+03								
17	.006E+04	.750E+03	.332E+03									
18	.263E+03	.144E+03										

K=17

J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.054E+04	.950E+04	.925E+04	.881E+04	.816E+04	.742E+04	.655E+04	.117E+03	.480E+02	.773E+02	.536E+02	.187E+02
2	-.614E+03	-.167E+02	-.156E+02	-.924E+03	-.266E+03							
3	.050E+04	.944E+04	.918E+04	.873E+04	.811E+04	.732E+04	.643E+04	.111E+03	.645E+02	.723E+02	.486E+02	.147E+02
3	-.876E+03	-.177E+02	-.154E+02	-.764E+03	-.148E+03							
4	.025E+04	.914E+04	.890E+04	.843E+04	.777E+04	.691E+04	.598E+04	.950E+04	.510E+02	.533E+02	.295E+02	.347E+04
4	-.179E+02	-.200E+02	-.130E+02	-.337E+03								
5	.081E+04	.873E+04	.843E+04	.789E+04	.723E+04	.633E+04	.525E+04	.677E+04	.406E+02	.254E+02	.266E+03	.195E+02
5	-.269E+02	-.193E+02	-.583E+03									
6	.016E+04	.811E+04	.777E+04	.723E+04	.647E+04	.548E+04	.426E+04	.349E+04	.715E+03	.536E+03	.243E+02	.344E+02
6	-.268E+02	-.890E+03										
7	.742E+04	.732E+04	.691E+04	.633E+04	.548E+04	.435E+04	.303E+04	.205E+04	.143E+02	.311E+02	.423E+02	.350E+02
7	-.125E+02											
8	.655E+04	.643E+04	.598E+04	.525E+04	.426E+04	.303E+04	.155E+04	.277E+04	.300E+02	.457E+02	.425E+02	.163E+02
8	.117E+03	.113E+03	.950E+04	.677E+04	.349E+04	.205E+04	.277E+04	.864E+04	.387E+02	.428E+02	.199E+02	
10	.680E+02	.644E+02	.510E+02	.306E+02	.715E+03	.143E+02	.300E+02	.387E+02	.402E+02	.174E+02		
11	.773E+02	.723E+02	.533E+02	.254E+02	.536E+03	.311E+02	.457E+02	.426E+02	.174E+02			
12	.936E+02	.486E+02	.295E+02	.266E+03	.243E+02	.423E+02	.425E+02	.199E+02				
13	.187E+02	.147E+02	.347E+04	.195E+02	.344E+02	.350E+02	.163E+02					
14	.014E+03	.876E+03	.179E+02	.269E+02	.268E+02	.125E+02						
15	.167E+02	.177E+02	.208E+02	.193E+02	.890E+03							
16	.158E+02	.154E+02	.130E+02	.583E+03								
17	.024E+03	.764E+03	.337E+03									
18	.260E+03	.144E+03										

K=16

J	J=2	3	4	5	6	7	8	9	10	11	12	13
2	.114E+03	.114E+03	.112E+03	.108E+03	.102E+03	.969E+04	.911E+04	.151E+03	.736E+02	.773E+02	.482E+02	.116E+02
2	-.122E+02	-.209E+02	-.182E+02	-.103E+02	-.291E+03							
3	.114E+03	.114E+03	.112E+03	.108E+03	.102E+03	.960E+04	.900E+04	.147E+03	.704E+02	.726E+02	.433E+02	.778E+03
3	-.147E+02	-.217E+02	-.175E+02	-.841E+03	-.160E+03							
4	.112E+03	.112E+03	.109E+03	.105E+03	.991E+04	.912E+04	.855E+04	.130E+03	.580E+02	.547E+02	.252E+02	.631E+03
4	-.229E+02	-.239E+02	-.143E+02	-.360E+03								
5	.108E+03	.108E+03	.105E+03	.989E+04	.942E+04	.868E+04	.788E+04	.105E+03	.492E+02	.283E+02	.465E+04	.244E+02
5	-.307E+02	-.211E+02	-.616E+03									
6	.102E+03	.102E+03	.991E+04	.942E+04	.877E+04	.790E+04	.691E+04	.725E+04	.162E+02	.235E+03	.273E+02	.385E+02
6	-.290E+02	-.930E+03										
7	.969E+04	.960E+04	.912E+04	.868E+04	.790E+04	.673E+04	.564E+04	.359E+04	.758E+03	.303E+02	.448E+02	.375E+02
7	-.124E+02											
8	.911E+04	.900E+04	.855E+04	.788E+04	.691E+04	.564E+04	.412E+04	.558E+04	.263E+02	.466E+02	.446E+02	.167E+02
8	.151E+03	.147E+03	.130E+03	.105E+03	.725E+04	.359E+04	.627E+04	.556E+04	.471E+02	.430E+02	.200E+02	
10	.736E+02	.704E+02	.580E+02	.392E+02	.162E+02	.758E+03	.263E+02	.371E+02	.499E+02	.174E+02		
11	.773E+02	.726E+02	.547E+02	.283E+02	.235E+03	.303E+02	.466E+02	.430E+02	.174E+02			
12	.482E+02	.433E+02	.252E+02	.465E+04	.273E+02	.458E+02	.446E+02	.200E+02				
13	.166E+02	.778E+03	.631E+03	.244E+02	.385E+02	.375E+02	.167E+02					
14	.122E+02	.147E+02	.224E+02	.307E+02	.290E+02	.129E+02						
15	.209E+02	.217E+02	.239E+02	.211E+02	.930E+03							
16	.182E+02	.175E+02	.143E+02	.616E+03								
17	.103E+02	.841E+03	.360E+03									
18	.291E+03	.160E+03										

K=15

REFERENCES

- Brinkman, H. C. 1947. "A Calculation of the Viscous Force Exerted by a Flowing Fluid on a Dense Swarm of Particles." Appl. Sci. Res. Vol. A1, pp. 27-34. (a)
- Brinkman, H. C. 1947. "On the Permeability of Media Consisting of Closely Packed Porous Particles." Appl. Sci. Res. Vol. A1, pp. 81-86. (b)
- Butterworth, D. 1978. "The Development of a Model for Three-Dimensional Flow in Tube Bundles." Int. J. Heat and Mass Transfer. Vol. 21, pp. 253-256.
- Cox, R. L. 1977. Radiative Heat Transfer in Arrays of Parallel Cylinders, ORNL-5239, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Crane, R. A., and R. I. Vachon. 1977. "A Prediction of the Bounds on the Effective Thermal Conductivity of Granular Materials." Int. J. of Heat and Mass Transfer. Vol. 20, pp. 711-723.
- Douglas, J., and J. Gunn. 1964. "A General Formulation of Alternating Direction Methods," I. Numer. Math. Vol. 6, pp. 428-453.
- Klepper, O. H. 1963. Radiant Interchange Factors for Heat Transfer in Parallel Rod Arrays. ORNL-TM-583, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Knudsen, J. G., and D. L. Katz. 1958. Fluid Dynamics and Heat Transfer. McGraw-Hill, New York, New York.
- Spaulding, D. B. 1972. "A Novel Finite Difference Formulation for Differential Expressions Involving Both First and Second Derivatives." Int. J. for Numer. Method. in Engr. Vol. 4, pp. 551-559.

APPENDIX

The Predicted Thermohydraulic Performance of Several
Fuel Assembly/Canister Configurations

APPENDIX

THE PREDICTED THERMOHYDRAULIC PERFORMANCE OF SEVERAL FUEL ASSEMBLY/CANISTER CONFIGURATIONS

INTRODUCTION

This appendix summarizes some recent information on the predicted thermohydraulic performance of an intact PWR spent fuel assembly contained within a canister. The effects of various parameters, including fuel age, filler material, and canister temperature, are presented. All of the results are based on simulations using the computer code, HYDRA-I, which accounts for the coupled heat transfer modes of conduction, convection, and radiation. Analytical predictions are compared with limited experimental data that are currently available.

RESULTS AND DISCUSSION

Two different fuel assembly/canister configurations have been simulated. The two fuel assemblies reflect typical PWR assemblies, but differ in the number of rods, assumed emittance, and certain dimensions. The canisters also differed somewhat in emittance and dimensions and the presence (or lack of) assembly support structure; however, both are vertical pipes with top and bottom ends closed.

Computational cells were distributed vertically, as well as horizontally, to model the essential features of top and bottom nozzles, fuel rods, and any support structure. A separate computational cell was allocated to each fuel rod and guide thimble in the horizontal plane. Power generation rate per unit length was taken to be constant over the active length of the assembly. It is recognized that a constant power generation rate along the active length is unlikely for a real spent fuel assembly, and a consequence of this simplification will be apparent when some of the results are compared to experimental

data. All thermophysical properties used were based on the recommended values found in Touloukian and Ho (1970).

Table A.1 shows some of the more relevant physical parameters for the first set of results.

TABLE A.1. Fuel Assembly/Canister Parameters

Number of Fuel Rods (including guide thimbles)	289 (17x17)
Fuel Rod Diameter	0.94 cm
Cladding Thickness	0.0572 cm
Pitch-to-Diameter Ratio	1.3
Active Length	366 cm
Overall Length (including nozzles)	406 cm
Emittance of Rods	0.4
Canister Inside Diameter	33 cm
Canister Inside Length	457 cm
Emittance of Canister	0.3

No fuel assembly support structure is present. The power levels used are considered maximum for their respective ages (time after reactor discharge) and are as follows:

<u>Spent Fuel Age, Yr</u>	<u>PWR Fuel Assembly Thermal Power, kW</u>
3	1.786
5	0.964
10	0.554

The power generation rate is constant over the cross-section of a fuel assembly.

Figure A.1 presents a pictorial representation of the first set of cases that have been examined. It will be noted that the various cases (e.g., IA, IIA, etc.) generally fall into two categories: 1) a single stabilizer medium fills all void space within the canister, and 2) the stabilizer

medium contained within the fuel assembly region is different from that found exterior to the fuel assembly. Each case is discussed in following paragraphs.

- IA. GAS (He, Ar, N₂) THROUGHOUT SYSTEM
- IB. HELIUM WITH FINE PARTICLES OF Al₂O₃ THROUGHOUT SYSTEM
- IC. HELIUM WITH FINE PARTICLES OF MULLITE THROUGHOUT SYSTEM
- ID. SOLID STABILIZER THROUGHOUT SYSTEM

- IIA. HELIUM WITH COARSE PARTICLES OF Al₂O₃ OUTSIDE FUEL ASSEMBLY

- IIIA. HELIUM IN ASSEMBLY; MULLITE BLOCKS WITH COARSE PARTICLES OF Al₂O₃ OUTSIDE ASSEMBLY
- IIIB. HELIUM WITH FINE PARTICLES OF Al₂O₃ IN ASSEMBLY; MULLITE BLOCKS WITH COARSE PARTICLES OF Al₂O₃ OUTSIDE ASSEMBLY

FIGURE A.1. Pictorial Representation of Stabilizer Arrangements

Figure A.2 shows the temperature difference between the cladding of the hottest (central) fuel rod and the canister temperature as a function of stabilizer conductivity (case ID of Figure A.1). This curve, for five-year-old fuel, applies strictly to only those situations where the effects of radiation and convection can be shown to be negligible (i.e., the case of opaque solid stabilizers). The consequences of solid stabilizers, such as metallic lead or an aluminum-12.5 wt% silicon alloy, may be predicted with confidence. Even the effect of some granular materials with helium, but not necessarily other gases, can be indicated with some degree of confidence, but caution is advised.

FIGURE A.2. Cladding Temperature of Hottest Rod Above Canister Temperatures Versus Thermal Conductivity of Stabilizer for a Thermal Power of 0.964 kW

Steady-state results for a helium stabilizer (case IA) are shown in Figure A.3. Maximum cladding temperature is indicated as a function of canister temperature with thermal power level as a parameter. The effects at other power levels may be obtained by interpolation. Natural convection, while present, does not have an especially significant impact on the maximum cladding temperature. The shape of the curves generally reflect the increasing heat transfer rate due to radiation and conduction as the temperature increases.

FIGURE A.3. Maximum Fuel Cladding Temperature Versus Canister Temperature for Helium Stabilizer

Results for argon and nitrogen gas stabilizers, in addition to helium, are shown for five-year-old fuel in Figure A.4. The temperature penalty associated with argon and nitrogen relative to helium is much smaller than might be predicted based solely on their thermal conductivities. The primary reason for this is that convection is now playing a much more important role in determining maximum cladding temperature and illustrates just one of many situations where, in addition to thermal conductivity, other thermophysical properties are important, in this case, density, viscosity, and specific heat.

FIGURE A.4. Maximum Fuel Cladding Temperature Versus Canister Temperature for He, N₂, and Ar Stabilizers (five-year-old fuel)

A comparison of results for the other cases illustrated in Figure A.1 are presented in Figure A.5. The maximum temperature difference between the

FIGURE A.5. Maximum Temperature Difference Between Cladding and Canister Versus Canister Temperature of Five-year-old Fuel. Refer to Figure A.1 for curve identification.

cladding and canister versus canister temperature is predicted for five-year-old fuel. The results will be discussed in order of increasing heat transfer effectiveness (i.e., efficacy in minimizing cladding temperature). The top curve in the figure, for reference, shows the previously discussed situation of helium gas alone, Case IA.

Next in effectiveness are cases IIA and IIIA. The coarse alumina particles surrounding the fuel assembly are sufficiently large (~ 0.3 -cm diameter) so as not to infiltrate into the fuel assembly. The thermal conductivities of both alumina and mullite reflect 20-30% microporosity. The void fraction selected in the region of the alumina particles accounts for the near presence of boundaries, and thus is somewhat greater than what would be predicted by theoretical maximum packing. In any event, the potential uncertainty in the analytically predicted thermal conductivity of granular materials can be relatively large, and therefore, the slight difference indicated between cases IIA and IIIA is probably not significant.

Case IC represents fine (approximately 100 micron) mullite particles and helium gas filling the entire canister. The effects of convection and radiation are largely suppressed. Since this is a conduction-dominated situation, at least for helium, this curve is in agreement with that which could be obtained from Figure A.2.

The most effective cases are IB and IIIB. Fine (approximately 100 micron) alumina particles are in the fuel assembly region and either alumina particles or mullite blocks fill the space between the fuel assembly and canister. For reasons mentioned previously, little significance should be attached to the slight difference between these two cases.

The solid stabilizers used as examples for potential package designs are, of course, just two of many candidates. Alumina particles were selected primarily because of superior leach resistance and thermal conductivity. Mullite is a trade-off when fabrication of large blocks is involved.

Figure A.6 indicates the maximum cladding temperature as a function of power generation rate for several different stabilizers. The fuel assembly/

FIGURE A.6. Maximum Temperature Difference Between Cladding and Canister Versus Fuel Assembly Power Generation Rate

canister configuration is identical to that shown in Table A.1, except that the emittances of both fuel rods and canister are now 0.5.

Figure A.7 shows the transient response of a fuel assembly to a step change in canister temperature. The fuel assembly/canister configuration and initial conditions correspond to curve A in Figure A.6 for 10-year-old fuel (0.554 kW and nitrogen gas). The canister temperature was suddenly decreased by 10°C to 90°C. The shapes of the three curves are influenced by the relatively cooler gas flowing down the canister wall, entering the bottom

portion of the fuel assembly, and flowing primarily up between the rods. If heat transfer by convection were not so significant, such disparity in centerline temperatures would not be exhibited.

FIGURE A.7. Cladding Temperature of Central Fuel Rod Versus Time due to a Step Decrease in Canister Temperature. Nitrogen gas stabilizer, 10-year-old fuel (0.554 kW).

The second set of results simulate the expected performance of a fuel assembly/canister configuration for which experimental data is being developed. The experimental aspects are described in Driesen et al. (1980). Table A.2 summarizes the most relevant physical parameters of this system.

TABLE A.2. Fuel Assembly/Canister Parameters

Number of Fuel Rods (including guide thimbles)	225 (15x15 array)
Fuel Rod Diameter	1.07 cm
Cladding Thickness	0.0617 cm
Pitch-to-Diameter Ratio	1.334
Active Length (includes swelling)	369.5 cm
Overall Length (including nozzles)	405.7 cm
Emittance of Rods	0.4
Canister Inside Diameter	33.66 cm
Canister Inside Length	410.1 cm
Emittance of Canister and Support Cage	0.45

A cross-sectional view of the fuel assembly is shown in Figure A.8 along with the internal support cage and canister. Thermocouple locations are indicated by the solid circles. These locations correspond to most of the guide thimbles.

FIGURE A.8. Cross Section of Fuel Assembly and Canister

Computational cells were distributed vertically, as well as horizontally, to model the essential features of the support cage, the top and bottom nozzles, and the fuel rods. A separate computational cell was allocated to each fuel rod and guide thimble in the horizontal plane. Power generation rate per unit length was taken to be a constant over the active length of the assembly with no power generation in the guide thimbles.

TABLE A.3. Case Specifications

<u>Case</u>	<u>Power Level (kW)</u>	<u>Canister Internal Atmosphere</u>	<u>Canister Temperature Profile</u>
1	0.85	Helium	Drywell
2	1.0	Helium	Drywell
3	0.85	Air	Soil Temperature Test
4	2.0	Air	Soil Temperature Test

The canister temperature profiles designated in Table A.3 represent experimentally defined temperatures along the vertical axis of the canister. These temperature profiles were used as boundary conditions in the code. The initial conditions for the gas (i.e., average temperature and pressure) were uncertain, but were estimated at 50°C and one atmosphere to establish the total mass of gas present.

Figures A.9 and A.10 depict the results for Case 1. This is the only case for which there are at present experimental data for fuel rod temperatures. In Figure A.9, the temperatures measured at the central fuel rod position are seen to closely reflect the adjacent canister temperature, and is an indication of the relatively dominant role of conduction through helium at these temperatures. The experimentally determined centerline temperatures are a few degrees above the predicted temperatures in the central region of the active length, but near the top of the active length, the measured temperature is significantly lower. A probable, but

FIGURE A.9. Centerline Temperature and Canister Heat Flux.
Case 1: 0.85 kW, helium atmosphere

FIGURE A.10. Comparison Between Experimentally Measured and Analytically Predicted Temperatures at Axial Position of Maximum Center-line Temperature. Case 1: 0.85 kW, helium atmosphere

not the only, explanation is that the actual power generation peaks near the center of the active length and falls off near the ends. The code employed a flat profile as an approximation to the uncertain power peaking profile.

Also shown in Figure A.9 is the heat flux to the inside surface of the canister. The shape of the curve, which is somewhat different than the temperature profile, reflects the additional role that convection plays. Heat fluxes to the top and bottom of the canister are an average over the total surface area. The average gas pressure inside the canister is 1.245 atm.

Figure A.10 shows the temperatures at guide thimble locations at the axial level of peak temperature. At all locations, the predicted temperatures are two degrees lower than the experimental data. A quadrant is

shown since the code used quarter symmetry for economy in this case. The experimental data shown are, however, based on the average over the entire cross section.

Figure A.11 presents the results for Case 2. This case differs from the previous one only by an increase in power generation rate to 1.0 kW from 0.85 kW (18%). The temperature difference between the maximum centerline temperature and adjacent canister temperature also increased 18% over the previous case. In general, increases in power will not be as closely correlated with increases in temperature due to the varying dominances of conduction, convection, or radiation. The average gas pressure inside the canister is 1.255 atm.

Figures A.12 and A.13 indicate the results for Cases 3 and 4, respectively, in which air is used as the atmosphere, and will be discussed together because of their similar features. It will be noted that the close parallel between canister temperature and maximum centerline temperature observed for the helium cases is no longer apparent. Furthermore, raising the power generation rate from 0.85 kW to 2.0 kW (135% increase) resulted in only an increase of 36% in the maximum centerline-canister temperature difference. Radiation and, especially, convection are relatively much more important with air as opposed to a lighter more conductive gas such as helium. The average gas pressures for the two cases are 1.319 atm and 1.711 atm, respectively.

The heat flux to the inside surface of the canister illustrates another interesting phenomenon. Notice the wave-like character of the heat flux curve. The short wave length oscillations are particularly evident for 2 kW (Figure A.13). There is no steady solution to these two natural convection cases; it is not a matter of numerical instability or lack of convergence, in fact, for both cases the total power absorbed by the canister was within 0.5% of that being generated internally for the results shown. It is, however, known that for certain ranges of the Rayleigh number steady solutions are not physically realizable.

FIGURE A.11. Centerline Temperature and Canister Heat Flux.
Case 2: 1.0 kW, helium atmosphere

FIGURE A.12. Centerline Temperature and Canister Heat Flux.
Case 3: 0.85 kW, air atmosphere

FIGURE A.13. Centerline Temperature and Canister Heat Flux.
Case 4: 2.0 kW, air atmosphere

The numerical simulation was continued in time in an effort to establish an average or at least bounds to the temperatures and heat fluxes. It shortly became apparent that this would result in substantial computational cost, and the attempt was abandoned. Nevertheless, some information was gained. The maximum centerline temperature was essentially constant, while temperatures in the gas near the top of the canister would rise and fall around the total being generated. The flow patterns in the vicinity of the top nozzle were quite complex. There were a changing number of recirculation cells and rapid changes in velocity (speed and direction). This behavior is, of course, just what would be predicted for an unsteady flow regime. It should be recalled at this point, however, that certain terms were omitted from the linear momentum equation and that these terms are believed to have their largest influence near the top nozzle and the upper corner of the canister. For this reason, the results may be quantitatively less accurate in this upper region than in the remainder of the canister.

SUMMARY AND CONCLUSIONS

Heat transfer with helium as the internal atmosphere is primarily conduction-dominated with radiation increasing in importance as the temperature rises. No unsteady flow has been observed even with centerline temperatures as high as 450°C. In contrast to helium, the higher density and less conductive gases, such as air, nitrogen or argon, show strong convective dependence. As an illustration, the maximum vertical velocities for helium (Figure A.10) and air (Figure A.12) at 0.85 kW are approximately 1 cm/sec and 17 cm/sec, respectively. Steady flow may or may not be present for the higher density gases depending on such factors as the power generation rate, the design of the canister and internal support structure, and the canister temperature profile.

When the flow is unsteady, the centerline temperatures show very little temperature fluctuation. The same cannot, however, be said for fuel rods near the top exterior of the assembly. The precise magnitudes and average

periods of these spatially and temporally varying temperature excursions have not yet been established. They may be sufficiently large to cause measurable cyclic loading of individual fuel rods. Continuing experimental investigation should establish if this is a potential failure mechanism.

Other fuel assembly/stabilizer/canister combinations could give results quite different from those presented. It is understandably tempting to infer the characteristics of alternate package designs from other apparently similar designs, but this should be done cautiously, especially when natural convection is present, and it should be emphasized that the use of experimental rather than analytically derived values of granular material effective conductivity is advisable.

The heat transfer results displayed are not necessarily intended as an endorsement of any particular gas or package design since other factors must also be considered. Nuclear activation products, chemical reactivity with the fuel assembly, ease of leak detection, structural need for solid stabilizers, leach rate under geothermal conditions, costs, etc., will all be influential elements of any package design.

As far as code verification is concerned, it should be emphasized that these calculations were performed without prior knowledge or use of experimental results to improve agreement. The data in Figures A.9 and A.10 suggest that the modeling of conduction heat transfer was adequate for engineering purposes. Convection modeling can be more adequately assessed when data for air become available; it will be of interest in the future to examine a well-defined vacuum case to verify the modeling of thermal radiation.

REFERENCES

- Touloukian, Y. S., and C. Y. Ho. 1970. Thermophysical Properties of Matter. Thermophysical Properties Research Center (TPRC), Purdue University, LaFayette, Indiana.
- Driesen, G. E., D. F. Moran, P. S. Sherba and R. J. Steffen. 1980. "Heat Transfer Associated with Dry Storage of Spent LWR Fuel." Paper presented at the American Society of Mechanical Engineers (ASME) Winter Annual Meeting, November 16, 1980, Chicago, Illinois.

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