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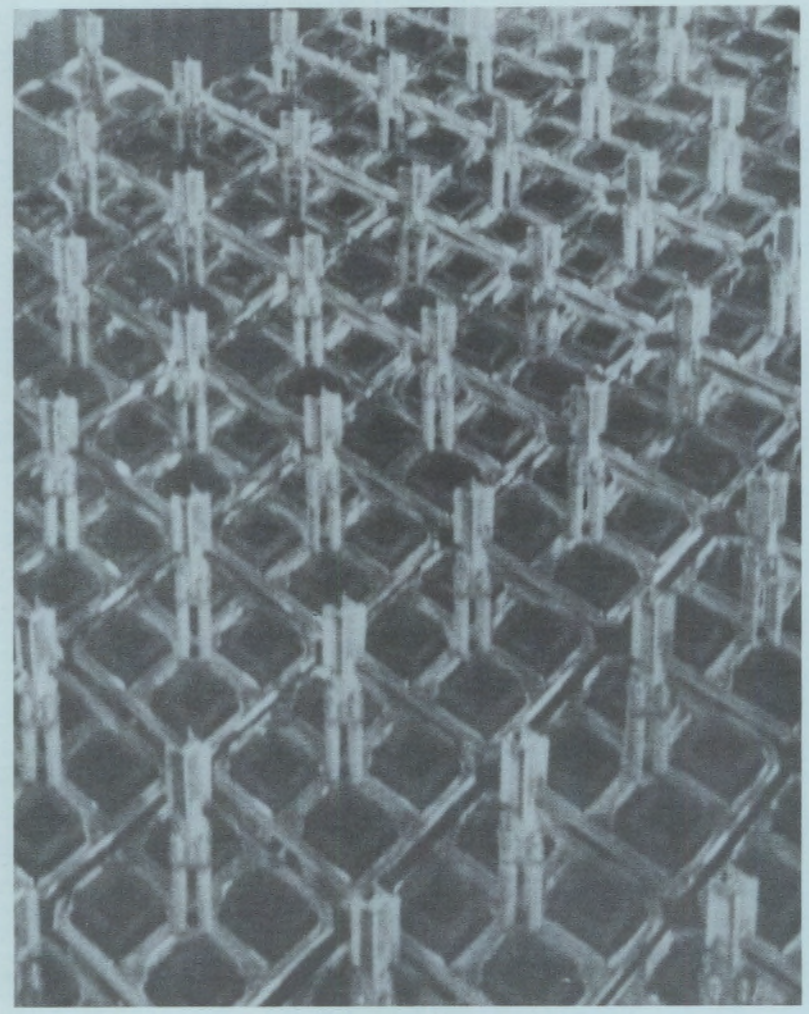
HYDRA-II: A Hydrothermal Analysis Computer Code

Volume II

User's Manual



September 1987

Prepared for the U.S. Department of Energy
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PNL-6206 Vol. II
UC-85

HYDRA-II: A HYDROTHERMAL ANALYSIS COMPUTER CODE

VOLUME II

USER'S MANUAL

R. A. McCann
P. S. Lowery
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September 1987

Prepared for
the U.S. Department of Energy
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Pacific Northwest Laboratory
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SUMMARY

HYDRA-II is a hydrothermal computer code capable of three-dimensional analysis of coupled conduction, convection, and thermal radiation problems. This code is especially appropriate for simulating the steady-state performance of spent fuel storage systems. The code has been evaluated for this application for the U.S. Department of Energy's Commercial Spent Fuel Management Program.

HYDRA-II provides a finite-difference solution in cartesian coordinates to the equations governing the conservation of mass, momentum, and energy. A cylindrical coordinate system may also be used to enclose the cartesian coordinate system. This exterior coordinate system is useful for modeling cylindrical cask bodies.

The difference equations for conservation of momentum incorporate directional porosities and permeabilities that are available to model solid structures whose dimensions may be smaller than the computational mesh. The equation for conservation of energy permits modeling of orthotropic physical properties and film resistances. Several automated methods are available to model radiation transfer within enclosures and from fuel rod to fuel rod.

The documentation of HYDRA-II is presented in three separate volumes. Volume I - Equations and Numerics describes the basic differential equations, illustrates how the difference equations are formulated, and gives the solution procedures employed. This volume, Volume II - User's Manual, contains code flow charts, discusses the code structure, provides detailed instructions for preparing an input file, and illustrates the operation of the code by means of a sample problem. The final volume, Volume III - Verification/Validation Assessments, provides a comparison between the analytical solution and the numerical simulation for problems with a known solution. This volume also documents comparisons between the results of simulations of single- and multi-assembly storage systems and actual experimental data.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

Implementation of spent fuel dry storage systems is required in the late 1980s because several at-reactor storage basins will attain maximum capacity (DOE 1986). The Nuclear Waste Policy Act of 1982 (NWPA) assigns the U.S. Department of Energy (DOE) the responsibility for assisting utilities with their spent fuel storage problems. One of the provisions of the NWPA is that DOE shall provide generic research and development of alternative spent fuel storage systems to assist utilities in their licensing activities.

One of the important requirements for storage systems is that they dissipate heat while maintaining the temperature of the stored materials below established limits. The thermal performance of a storage system can be assessed by a comprehensive testing program. Such testing programs are typically time-consuming and expensive. Analysis tools (e.g., computer codes), while not intended to entirely supplant testing methods, can perform a valuable service. Appropriately qualified computer codes can provide predictions of thermal performance as a function of system design and operating conditions. Moreover, when tests are to be performed, computer codes can help select test conditions, spent fuel decay heat generation rates, and instrumentation placements, as well as aid in interpreting test data.

HYDRA-II, developed by the Pacific Northwest Laboratory (PNL), is a computer code for heat transfer and fluid flow analysis. An enhanced version of HYDRA-I (McCann 1980), it is a member of the HYDRA family of general purpose codes collectively capable of transient three-dimensional analysis of coupled conduction, convection, and radiation problems. This current version is especially appropriate for simulating the steady-state performance of spent fuel storage systems 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 timely fashion.

The documentation of HYDRA-II is presented in three separate volumes. Volume I - Equations and Numerics describes the basic differential equations, illustrates how the difference equations are formulated, and gives the solution

procedures employed. This volume, Volume II - User's Manual, contains code flow charts, discusses the code structure, provides detailed instructions for preparing an input file, and illustrates the operation of the code by means of a model problem. The final volume, Volume III - Verification/Validation Assessments, provides a comparison between the analytical solution and the numerical simulation for problems with a known solution. This volume also documents comparisons between the results of simulations of single- and multi-assembly storage systems and actual experimental data.

A detailed overview of the HYDRA-II code is presented in Chapter 2.0. The code structure and solution sequence are described and illustrated with flow charts. General guidance on conventions to be followed in preparing the input file is also provided. Chapters 3.0 through 28.0 present specific descriptions of the code's individual subroutines. Each of these chapters contains the FORTRAN PARAMETERS and information needed to prepare the input file relevant to a specific subroutine. Chapter 29.0 contains a sample problem illustrating many characteristics of a typical spent fuel cask. The complete input file is included in Appendix A, and selected output is described in Appendix B. Code setup and operation, as well as output interpretation, are explained and illustrated using the sample problem.

2.0 CODE OVERVIEW

HYDRA-II provides a finite-difference solution in cartesian coordinates to the equations governing the conservation of mass, momentum, and energy. A cylindrical coordinate system may also be used to enclose the cartesian coordinate system. This exterior coordinate system is useful for modeling cylindrical cask bodies. When both coordinate systems are invoked, the code will automatically align the two systems and enforce conservation of energy at their interface.

The difference equations for conservation of momentum are enhanced by the incorporation of directional porosities and permeabilities that aid in modeling solid structures whose dimensions may be smaller than the computational mesh. The specification of inflow and outflow boundary conditions has been eliminated as appropriate for sealed storage systems. The equation for conservation of energy permits modeling of orthotropic physical properties and film resistances. Several automated procedures are available to model radiation transfer within enclosures and from fuel rod to fuel rod. An implicit solution algorithm is used for both the momentum and energy equations to ease time-step limitations and stability requirements.

HYDRA-II has been designed to provide a user-oriented input interface, which eliminates the need for internal code changes. Any application for which the code is an appropriate choice can be completely described through the construction of an input file. The user may optionally request a formatted echo of the input file to confirm that the intended parameters are actually those used by the code. A selectable commentary monitoring the progress of the code toward a steady-state solution is available, as is a summary of energy balances. Finally, a tape may be written at the conclusion of a run if the user wishes to restart the solution from its most recent point.

2.1 CODE STRUCTURE AND SOLUTION SEQUENCE

HYDRA-II is intended for steady-state applications. The method used by the code to approach steady state is similar to a transient simulation that ultimately converges to the steady-state condition. Starting from specified

initial conditions, the solution will evolve through time using automatically selected time-steps for both the energy and the momentum equations. Because only a steady-state solution is desired, the time-dependent terms for the energy, momentum, and continuity equations have been modified to accelerate convergence. Therefore, before it reaches steady state, the evolving solution will not correspond exactly to an actual transient solution, and the numerical values of the time-steps do not represent real time.

The overall structure of HYDRA-II is shown in Figure 2.1. If the run is to be restarted based on the results of a previous run, then the code will read a restart file. This file contains the thermal and momentum time-steps, temperatures, mass fluxes, densities, and pressures. If no restart file is present, the code will prescribe initial values for the above variables and proceed to initialize all subroutines in accordance with instructions read from the input file. The initial temperature field(s) may be printed, if desired, at this time.

Next, the outer loop for solution of the energy and momentum equations begins. The flow chart shown in Figure 2.2 illustrates the computational sequence. The appropriate subroutines are called in the correct order to determine a solution for either the energy equation(s) or the momentum equations or both. If a solution to both energy and momentum equations is desired, then the sequence is to solve for new-time temperatures using old-time mass fluxes and then solve the momentum equations using updated (temperature-dependent) density and viscosity. The solution is advanced by incrementing time by a thermal and momentum time-step. The magnitude of the two time-steps need not be the same because only the steady-state solution is desired. After the prescribed number of time-steps is reached, the code will exit this outer loop.

The final phase of the run consists of printing user-selected energy balances and field variables. A restart file is also written if desired.

A more detailed explanation of the energy and momentum solution sequences is now given. Figure 2.3 shows the flow chart for solution of the energy equation(s). If thermal radiation is present on the cartesian coordinate system, then, according to input file instructions, the selected subroutines embodying

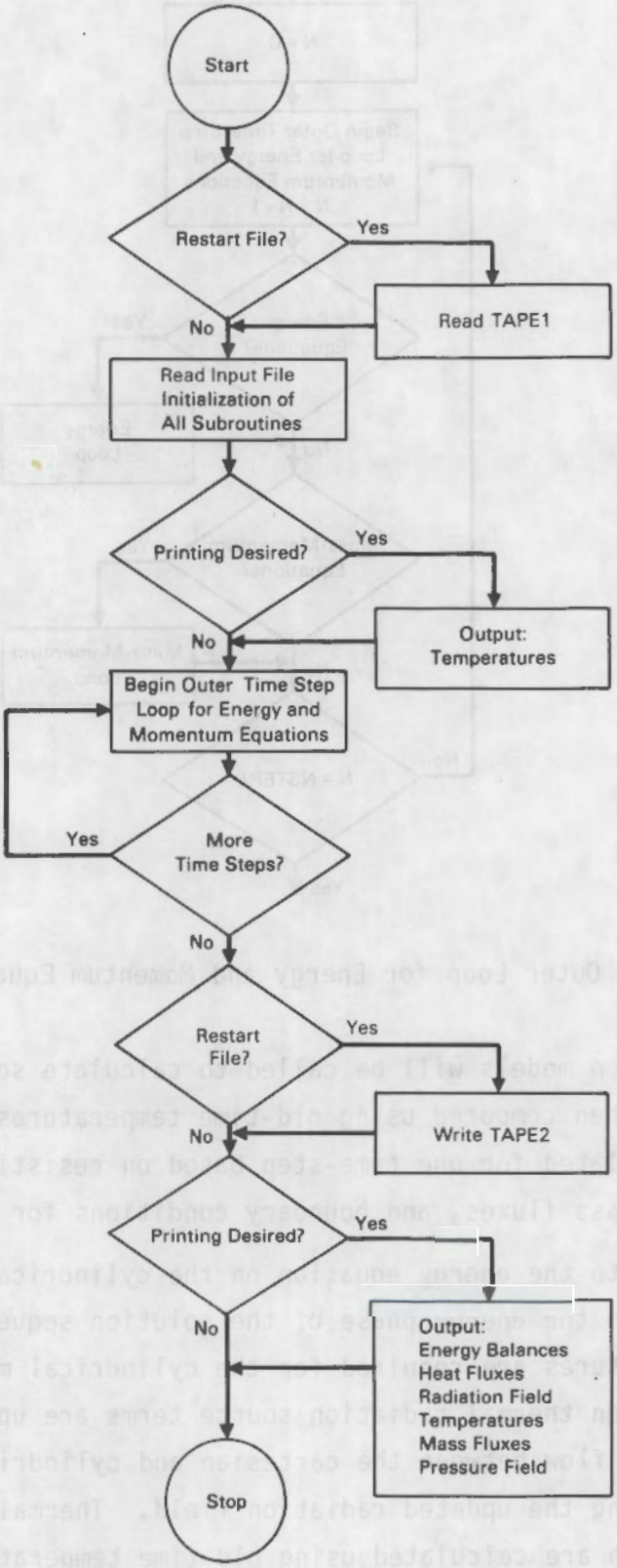


FIGURE 2.1. HYDRA-II Overall Structure

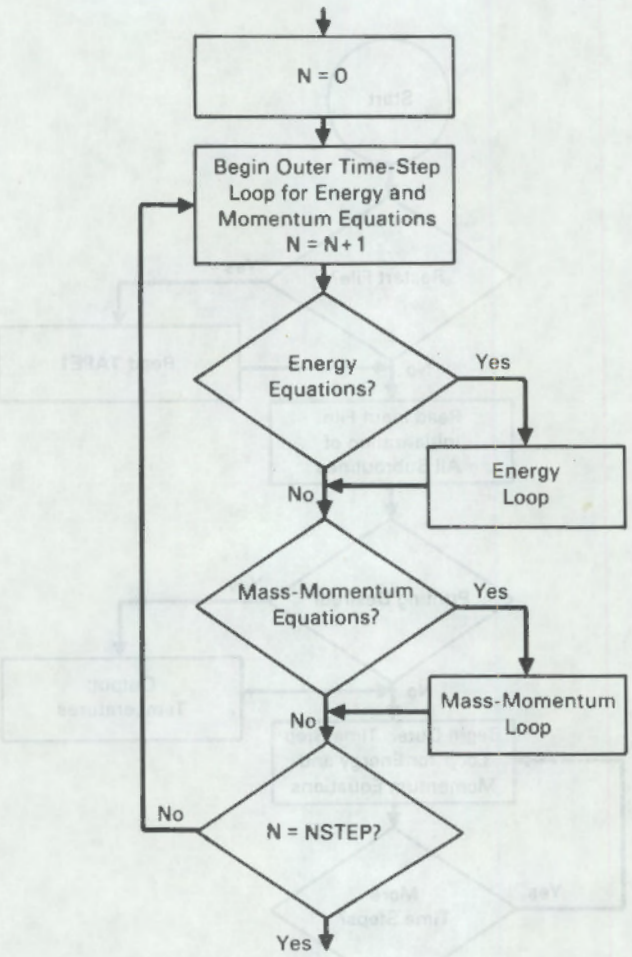


FIGURE 2.2. Outer Loop for Energy and Momentum Equation Solution

appropriate radiation models will be called to calculate source terms. Thermal resistivities are then computed using old-time temperatures. The new-time temperatures are calculated for one time-step based on resistivities, heat sources, old-time mass fluxes, and boundary conditions for the cartesian mesh.

If a solution to the energy equation on the cylindrical coordinate system is not desired, then the energy phase of the solution sequence is complete. However, if temperatures are required for the cylindrical mesh (e.g., a cask body), then cartesian thermal radiation source terms are updated using new-time temperatures. Heat flow between the cartesian and cylindrical coordinate system is computed using the updated radiation field. Thermal resistivities for the cylindrical mesh are calculated using old-time temperatures. New-time temperatures for the cylindrical coordinate system are computed for one thermal

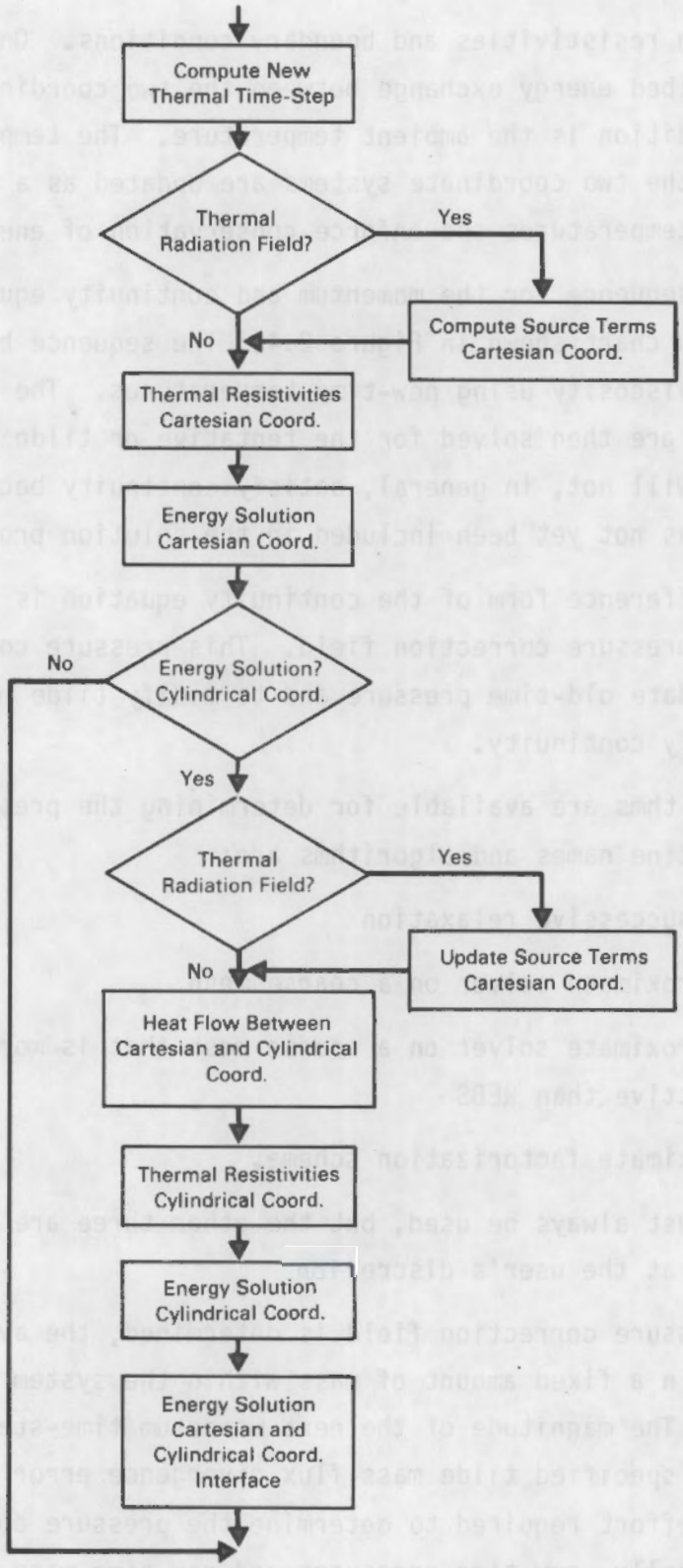


FIGURE 2.3. Energy Equation Solution Loop

time-step, based on resistivities and boundary conditions. One boundary condition is the prescribed energy exchange between the two coordinate systems; the other boundary condition is the ambient temperature. The temperatures on the interface between the two coordinate systems are updated as a final step to ensure continuous temperatures and enforce conservation of energy.

The solution sequence for the momentum and continuity equations is illustrated by the flow chart shown in Figure 2.4. The sequence begins by updating fluid density and viscosity using new-time temperatures. The three linear momentum equations are then solved for the tentative or tilde mass fluxes. The tilde mass fluxes will not, in general, satisfy continuity because the continuity equation has not yet been included in the solution process.

The finite-difference form of the continuity equation is now constructed for solution of a pressure correction field. This pressure correction field will be used to update old-time pressure and to modify tilde mass fluxes so that they do satisfy continuity.

Several algorithms are available for determining the pressure correction field. The subroutine names and algorithms are:

- PILES - line successive relaxation
- REBS - an approximate solver on a coarse mesh
- REBQ - an approximate solver on a coarse mesh that is more elaborate and more effective than REBS
- AF - an approximate factorization scheme.

Subroutine PILES must always be used, but the other three are optional; one or more may be called at the user's discretion.

After the pressure correction field is determined, the average pressure is adjusted to maintain a fixed amount of mass within the system or a specified average pressure. The magnitude of the next momentum time-step is computed such that either a specified tilde mass flux divergence error is maintained or the computational effort required to determine the pressure correction field is held constant. Finally, new-time pressures and new-time mass fluxes are computed using the pressure correction field.

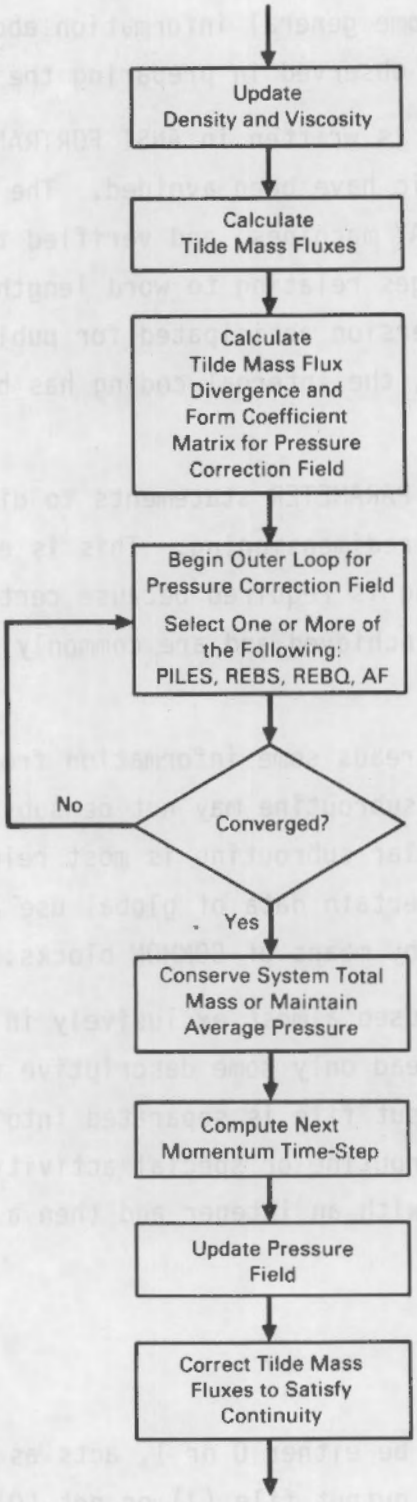


FIGURE 2.4. Momentum and Continuity Equation Solution Loop

2.2 CODE CONVENTIONS

This section contains some general information about the HYDRA-II source, as well as conventions to be observed in preparing the input file.

The source for HYDRA-II is written in ANSI FORTRAN 77. Extensions that might be installation-specific have been avoided. The code has been run on CDC-7600, VAX 11/780, and CRAY machines, and verified to produce essentially the same results (minor changes relating to word length on the VAX were needed). Because the code version anticipated for public release has been run extensively on CRAY machines, the internal coding has been structured to favor vector machines.

The source uses FORTRAN PARAMETER statements to dimension arrays. Each new application will require redimensioning. This is easily accomplished with a line editor. Redimensioning is required because certain economies in computer memory are more easily achieved and are commonly necessary for large-scale simulations.

Almost every subroutine reads some information from the input file during initialization, even if that subroutine may not be subsequently used. The information read by a particular subroutine is most relevant to the function of the respective subroutine. Certain data of global use are read by a few subroutines and then propagated by means of COMMON blocks.

List-directed reads are used almost exclusively in the source. The few formatted reads in HYDRA-II read only some descriptive text for echoing to the output file. The physical input file is separated into logical sections, each dealing with a particular subroutine or special activity within a subroutine. The section boundaries begin with an integer and then a slash followed by identifying text. For example,

```
1/HYDRO/MONITOR/MX
```

The first integer, which will be either 0 or 1, acts as a flag to either echo succeeding input lines to the output file (1) or not (0). The slash terminates reading of the record. The text (in this example) identifies the lines to

follow as being read by subroutine HYDRO and related to monitoring selected mass fluxes in the x-direction. The text is very helpful in searching for a desired section of input with the aid of a line editor.

The code runs internally using a metric system of units. The input file must be prepared using the same units. Table 2.1 lists the system of consistent units that is to be used.

All echoing of the input file to the output file is done without conversion. Computed temperatures, however, are converted to degrees centigrade when printing is requested.

2.3 SUBROUTINE DESCRIPTIONS

Each chapter in the remainder of this volume deals with a single subroutine. The function of the subroutine is discussed, and general guidance is given for preparing an input file. PARAMETER statement information is provided. Next, the general input format is given with a description of the individual variables whose values are to appear on the file. Finally, an input file example of an actual application is shown, to lend concreteness to the description for general input.

TABLE 2.1. Input Data Units

Quantity	Units
Length	centimeter (cm)
Mass	gram (g)
Time	second (s)
Force	dyne (dyn)
Power	watt (W)
Temperature	degree Kelvin (°K)
Density	g/cm^3
Pressure	dyn/cm^2
Mass flux	g/cm^2-s
Viscosity	Poise ($dyn-s/cm^2$)
Specific heat	W-s/g-°K
Thermal conductivity	W/cm-°K

3.0 PROGRAM MAIN

Program MAIN functions primarily as an executive that calls appropriate subroutines as they are needed according to the requirements of the application. Program MAIN also reads and writes restart tapes (if required) and controls many of the printing options.

3.1 PARAMETER STATEMENT INFORMATION

Program MAIN requires the specification of parameters IP, JP, KP, ISP, JSP, KBP, and KTP. These parameters define the overall computational mesh and are described in Chapter 4.0, Subroutine GRID. Two additional parameters are required for specification of printing options:

- NPLA1P - Most three-dimensional arrays may be printed in their entirety (the default condition). It may be desirable, at times, that only selected k-planes be printed, to reduce the amount of output. NPLA1P-1 is the maximum number of k-planes that can be selected for any printing option. If no options are desired (other than the default), then NPLA1P should be set to 1.
- NPLA2P - This parameter designates the maximum number of printing options. The default printing condition does not constitute an option. If no options are desired, then NPLA2P should be set to 1.

3.2 INPUT FORMAT

3.2.1 Descriptive Text for the Application

A user may optionally insert text to be printed on the output file that describes the application.

General Input Format

```
NECHO
LINES
TEXT
 .
 .
 .
TEXT
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- LINES - The number of lines of text that follow and that are to be read from the input file.
- TEXT - Text that the user wishes to have printed on the output file. Each line of text may be up to 48 characters long.

Input File Example

```
 1 1/main
 2 15
 3
 4
 5
 6
 7
 8
 9
10
11 so they chop and change, and each fresh move
12   is inly a fresh mistake.
13                                robert service
14
15 input for castor-v/21 6/6/85
16 source is cv15v, input file is cinv15v6
17 1/2 symmetry, vertical, he, 28.09kw, case 6
```

Echoed Input File Example

```
 1 1
 2
 3
 4
 5
 6
 7
 8
 9
10                                    so they chop and change, and each fresh move
11                                      is inly a fresh mistake.
12                                                          robert service
13
14                                    input for castor-v/21 6/6/85
15                                    source is cv15v, input file is cinv15v6
16                                    1/2 symmetry, vertical, he,28.09kw, case 6
17
```

NECHO is set to 1 on line 1. LINES on line 2 indicates that 15 lines of text are to follow. Note that a line of text may consist entirely of spaces.

3.2.2 Run Control Information

The next section of input is used to provide some of the information needed for general code operation. This information includes the number of time-steps to be allowed, reading or writing restart tapes, and the selection of certain subroutines to be called.

General Input Format

```
NRUN, NSTEP, NSINFO
NREAD, NWRITE, NDUMP
STEADY, NOBODY, NOTEMP, NOVEL
NEWTA
NDTIME, DTIMEN DTIMAX, DTIMIN
RADCON, RADPON, RADRON
REBAON, NREB, NREBN
```

General Input Description

- NRUN - This constant indicates the run number for identification only.
- NSTEP - The number of time-steps for this run.

- NSINFO - This constant controls the printing frequency of diagnostic information and monitored variables. For example, if NSINFO = 20, then information will be printed for time-steps 1, 21, 41, etc. Information is always printed for the first and last time-steps of a run.
- NREAD - If a restart tape is to be read at the start of a run, then NREAD = 1; otherwise, 0.
- NWRITE - If a restart tape is to be written at the end of a run, then NWRITE = 1; otherwise, 0.
- NDUMP - If NWRITE = 1, then a restart tape is written every NDUMP time-steps. This feature is useful for a long run where a crash may occur before the conclusion of the run.
- STEADY - Used to distinguish between a transient and a steady-state simulation. Because HYDRA-II is intended only for steady-state simulation, STEADY should always have the value of 1.0.
- NOBODY - If the simulation does not include a cask body, then NOBODY = 1; otherwise, 0.
- NOTEMP - If NOTEMP = 1, then the temperature field(s) will not be updated during this run; otherwise, 0.
- NOVEL - If NOVEL = 1, then the flow field will not be updated during the run; otherwise, 0.
- NEWTA - If new ambient temperatures are desired, then NEWTA = 1; otherwise, 0. New ambient temperatures are read from subroutines THERM and TSIDE.
- NDTIME - If a new initial time-step is desired for the solution of the energy equation, the NDTIME = 1; otherwise, 0. This new time-step is applied to the first time-step of the run, and must be given if the run is not restarted from a tape.

- DTIMEN - The value of the initial thermal time-step at the start of a run. Subsequent thermal time-steps are computed automatically within the code. The thermal time-steps may be different from the time-steps used in the solution of the momentum equations for a steady-state application.
- DTIMAX - The maximum value of the thermal time-step. A value of 1.0 or less is recommended for the steady-state mode of operation.
- DTIMIN - The minimum value of the thermal time-step.
- RADCON - If the radiation model embodied in subroutine RADC is to be invoked for the application, then RADCON = 1.0; otherwise, 0.0.
- RADPON - If the radiation model embodied in subroutine RADP is to be invoked for the application, then RADPON = 1.0; otherwise, 0.0.
- RADRON - If the radiation model embodied in subroutine RADR is to be invoked for the application, then RADRON = 1.0; otherwise, 0.0.
- REBAON, NREB, NREBN - Subroutine REBA provides a numerical method for accelerating the thermal solution toward a steady state. If this subroutine is to be called, then REBAON = 1.0; otherwise, 0.0. The subroutine will be called at the beginning of a time-step, NS, when the relationship MOD(NS,NREB) .EQ. NREBN is satisfied. Subroutine REBA should be called only if both subroutines THERM and TSIDE are being used.

Input File Example

```
18 10,4,1
19 1,1,100
20 1.0,0,0,0
21 0
22 0,0.1,1.0,0.01
23 1.0,1.0,0.0
24 1.0,100,1
```

Echoed Input File Example

```
18                                                                    run number  10
19
20      main    nrun=10   nstep=   4   nsinfo=   1
21      main    nread=1   nwrite=1   ndump= 100
22      main    steady=1.0   nobody=0   notemp=0   novel=0
23      main    newta=0
24      main    ndtime=0   dtimen=0.100e+00   dtimax=0.100e+01   dtimin=0.100e-01
25      main    radcon=1.0   radpon=1.0   radron=0.0
26      main    rebaon=1.0   nreb=100   nrebn=  1
```

There is a one-to-one correspondence between each line of input and its respective echo. For example, the sequence of integers 10,4,1, on line 18 of the input file corresponds to line 20 of the echoed input file where NRUN = 10, NSTEP = 4, and NSINFO = 1.

3.2.3 Print Plane Options

The amount of information that could be sent to the output file can be almost overwhelming for most large-scale simulations. The print plane options allow the user to print selected k-planes of most three-dimensional arrays. The default option is that the entire array is printed.

General Input Format

```
NECHO
NPLA2
NPLA1, KPLANE, KPLANE, ... KPLANE
                    .
                    .
                    .
NPLA1, KPLANE, KPLANE, ... KPLANE
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.

- NPLA2 - The number of sets of k-planes available (the number of lines to follow).
- NPLA1 - The number of k-planes to be specified for this set of k-planes.
- KPLANE - The k-plane to be printed in a given set. When more than one KPLANE is specified for a given set, the k-planes are printed in the order listed.

Input File Example

```
25 1/main/print plane sets
26 2
27 1,18
28 2,25,2
```

Echoed Input File

```
28      main    print plane sets are  2 maximum allowed is  4 with  5 planes per set
29              option  1: 18
30              option  2: 25  2
```

The input file shows that the echoing switch, NECHO, is on and that two k-plane sets are to be defined. Line 27 indicates that one k-plane, namely k = 18, will be printed for the first set. The second set shown on line 28 indicates that two k-planes are to be printed, namely k = 25 and k = 2, in that order.

The echoed input file shows on line 28 that two print plane sets are available, and that a total of four could have been defined. Also, each set could specify up to five planes.

3.2.4 Specification of Output

Most of the arrays that hold variables of interest (e.g., temperature, pressure, mass fluxes) may be printed at the discretion of the user. The arrays can be quite large and, even if the user wishes to print some variable, not all of the arrays may be needed. This section of the input file allows the user to specify what arrays to print and which print plane options are to be selected.

General Input Format

```
NECHO
PRINT, NOPTION/PTI
PRINT, NOPTION/PTSI
PRINT/PQBND
PRINT, NOPTION/PQI
PRINT, NOPTION/PQRAD
PRINT, NOPTION/PTS1
PRINT, NOPTION/PT
PRINT, NOPTION/PTS
PRINT, NOPTION/PMX
PRINT, NOPTION/PMY
PRINT, NOPTION/PMZ
PRINT, NOPTION/PDPF
PRINT, NOPTION/PPF
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- PRINT - If the array or information is to be printed, then PRINT = 1.0; otherwise, 0.0.
- NOPTION - This integer specifies the number of the print plane option selected (0 indicates the default option of printing the entire array).

The following definitions are used to indicate variables or information to be printed. A slash precedes each character string in the input file; therefore, the character string is not used in the code.

- PTI, PTSI - Temperatures in the inside and side of the cask, respectively. These temperatures are those that exist prior to the first time-step of a run.
- PQBND - Provides a summary of useful heat transfer information. Net heat transfer rates to, from, and within various regions of the cask are displayed. This information is not contained in an array; therefore, no print plane option is needed.
- PQI - Heat fluxes within the cask cavity.

- PQRAD - Radiation heat transfer to each cell within the cask cavity. This is a summary of radiation source strength computed by subroutines RADC, RADP, and/or RADR.
- PTS1 - Heat flow into each cell of the side of the cask from the inside.
- PT, PTS - Temperature in the inside and side of the cask, respectively.
- PMX, PMY, PMZ - Mass fluxes in the x-, y-, and z-directions, respectively.
- PDPF - The change in the pressure field for the last time-step.
- PPF - The pressure field.

Input File Example

```
29 1/main/print arrays or info
30 0.0,0/pti
31 0.0,0/ptsi
32 1.0/pqbnd
33 1.0,1/pqi
34 0.0,0/pqrad
35 0.0,0/pts1
36 1.0,0/pt
37 1.0,0/pts
38 1.0,2/pmx
39 0.0,0/pmy
40 1.0,0/pmz
41 0.0,0/pdpf
42 0.0,0/ppf
```

Echoed Input File Example

```
32      main    print arrays or info
33              pti=0.0   npti= 0
34              ptsi=0.0   nptsi= 0
35              pqbnd=1.0
36              pqi=1.0   npqi= 1
37              pqrad=0.0   npqrad= 0
38              ptsi=0.0   nptsi= 0
39              pt=1.0   npt= 0
40              pts=1.0   npts= 0
41              pmx=1.0   npmx= 2
42              pmy=0.0   npmy= 0
43              pmz=1.0   npmz= 0
44              pdpf=0.0   npdpf= 0
45              ppf=0.0   nppf= 0
```

Line 29 on the input file shows that NECHO has been set to 1; therefore, the echoed input file is printed as shown. Line 30 on the input file shows that PRINT is set to 0.0 for PTI, so initial temperatures inside the cask are not to be printed. Line 32 on the input file shows that PRINT is set to 1.0 for PQBND; hence, a summary of heat transfer information will be printed. Line 38 shows that PRINT is set to 1.0 and that print plane option 2 is desired for PMX (mass fluxes in the x-direction). This specification results in printing of k-planes 25 and 2 in this order.

4.0 SUBROUTINE GRID

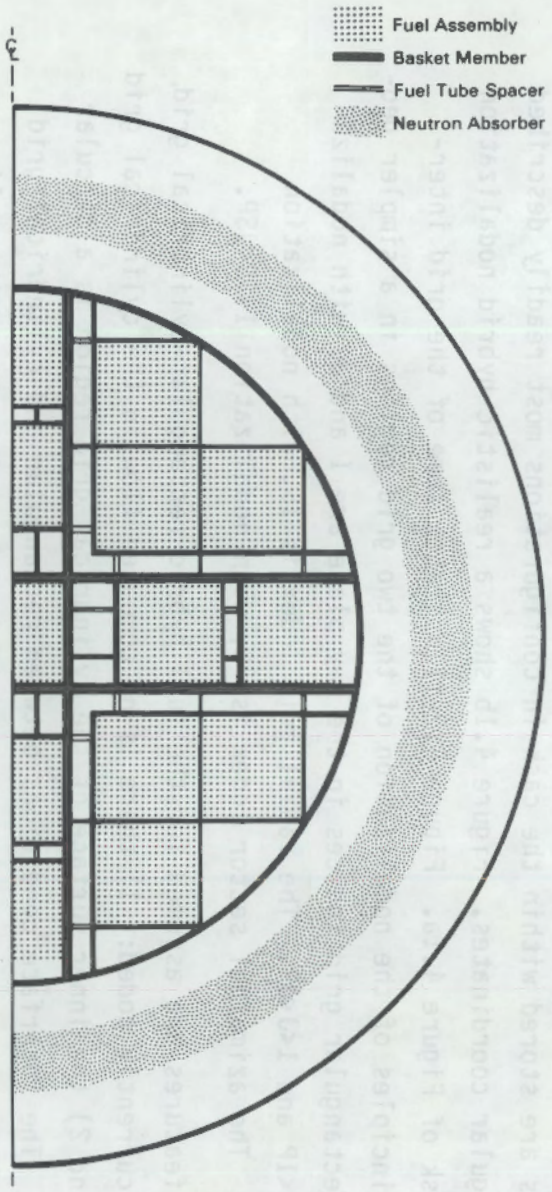
Subroutine GRID allows the user to set up the computational grid for a HYDRA-II application.

4.1 GRID FUNCTIONS

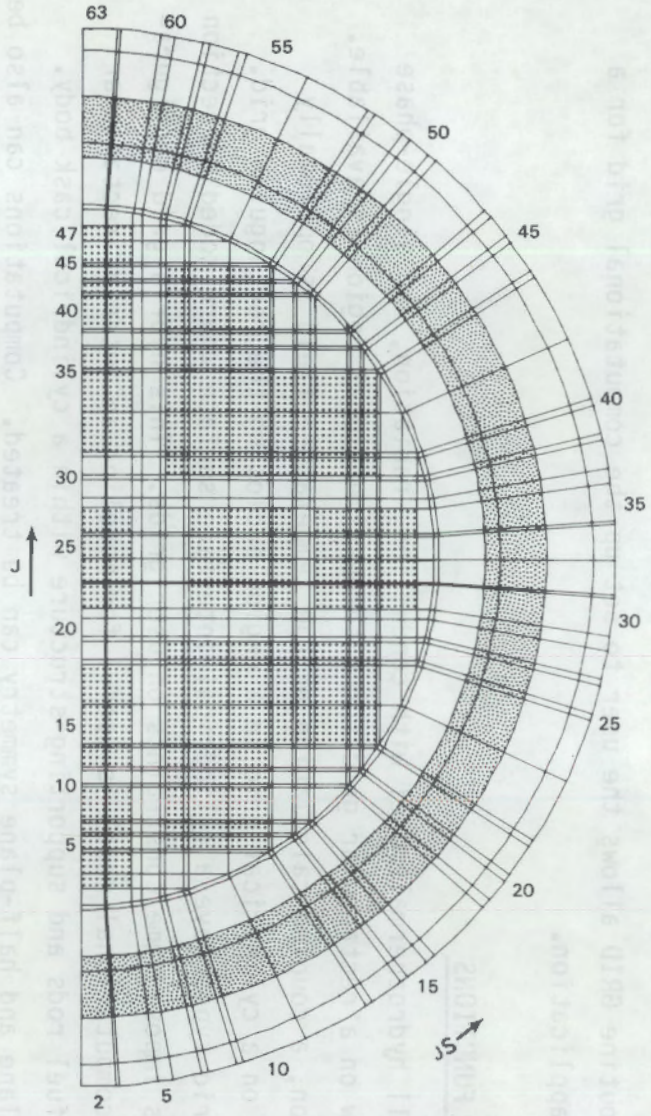
A full hydrothermal model with conduction, radiation, and single-phase fluid flow on a rectangular grid for a three-dimensional region is available. In addition, a coupled calculation of the temperature field is optionally available on a cylindrical grid in a region enclosing the rectangular grid. The two grid types have a cylindrical interface surface where coded connection techniques impose some constraints on user grids. This hybrid grid configuration and computational model is useful for modeling an interior rectangular array of fuel rods and supporting structure within a cylindrical cask body. Quarter-plane and half-plane symmetry can be treated. Computations can also be performed on a rectangular grid alone without a surrounding cylindrical grid.

Figure 4.1a shows a typical cross-section of a spent fuel cask. The fuel assemblies are stored within the cask in configurations most readily described in rectangular coordinates. Figure 4.1b shows a realistic hybrid nodalization of the cask of Figure 4.1a. Figure 4.2 illustrates some of the grid interfacing principles of the nodalization of the two grid regions in a simpler geometry. Rectangular grid indices in the x-y plane are I and J, with nodalizations $1 \le I \le IP$ and $1 \le J \le JP$. The radial grid index is IS, with nodalization $1 \le IS \le ISP$. The azimuthal sector index is JS, with nodalization $1 \le JS \le JSP$.

Two features are assumed for the full hybrid rectangular-cylindrical grid model as currently coded: 1) there is no computed flow in the cylindrical grid region, and 2) the inner surface of the cylindrical grid region is a circular cylinder. The interface conditions between rectangular and cylindrical grid regions assume that heat flow from the rectangular region enters the cylindrical region at the inner radius of the second radial cell in the azimuthal sectors. Consistent coding of this energy flow imposes constraints on both the cylindrical and the rectangular grids. A rectangular grid interface cell (I,J) must have a unique connection to an azimuthal sector, as illustrated in

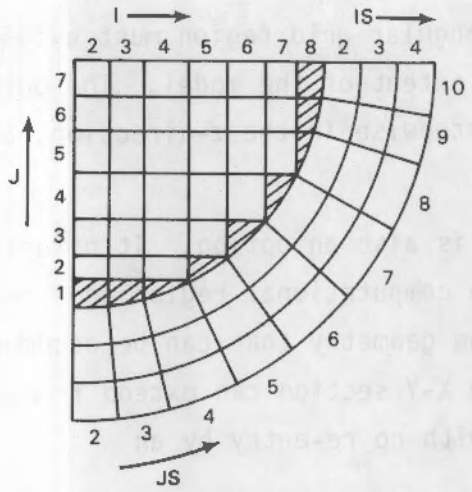


a. Cask Cross Section

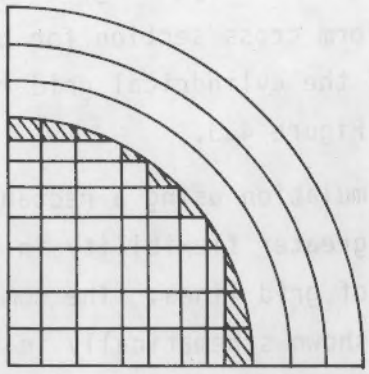


b. HYDRA Computational Mesh

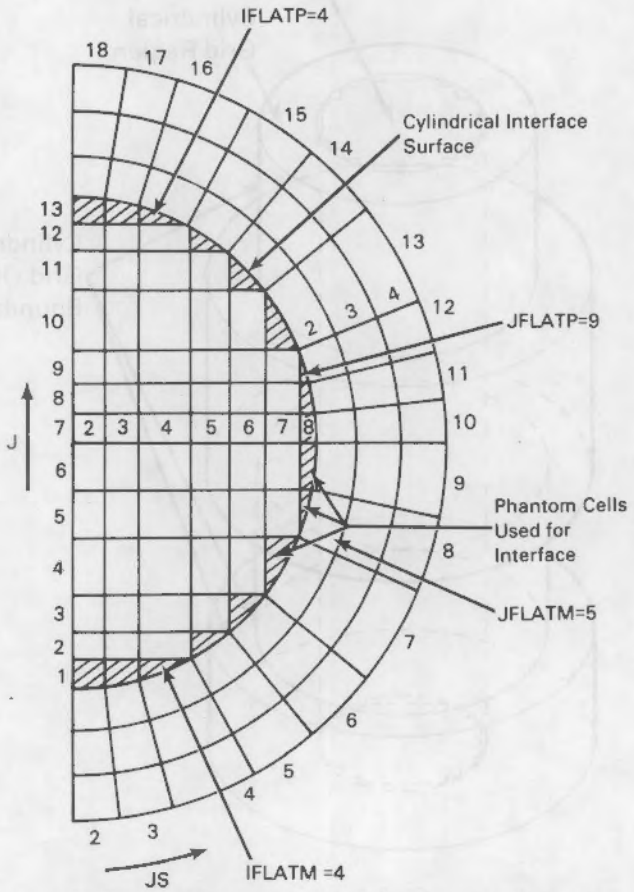
FIGURE 4.1. Alignment of Mesh and Physical Features and Proper Interfacing of Cartesian and Cylindrical Grid Regions



a. Allowed Orientation for Quarter-Plane Symmetry



b. Nonallowed Orientation for Quarter-Plane Symmetry



c. Orientation for Half-Plane Symmetry

FIGURE 4.2. Mesh Orientation and Interfacing Principles

Figure 4.2. If a hybrid grid is used, the rectangular grid region must extend with uniform cross section for the entire axial extent of the model. The outer radius of the cylindrical grid region can vary stepwise in the z-direction, as shown in Figure 4.3.

A simulation using a rectangular grid only is also an option. It offers somewhat greater flexibility in the shape of the computational region and the location of grid lines. The computational region geometry that can be accommodated is shown schematically in Figure 4.4. The X-Y section can extend from the y-axis outward in the positive x-direction with no re-entry by an

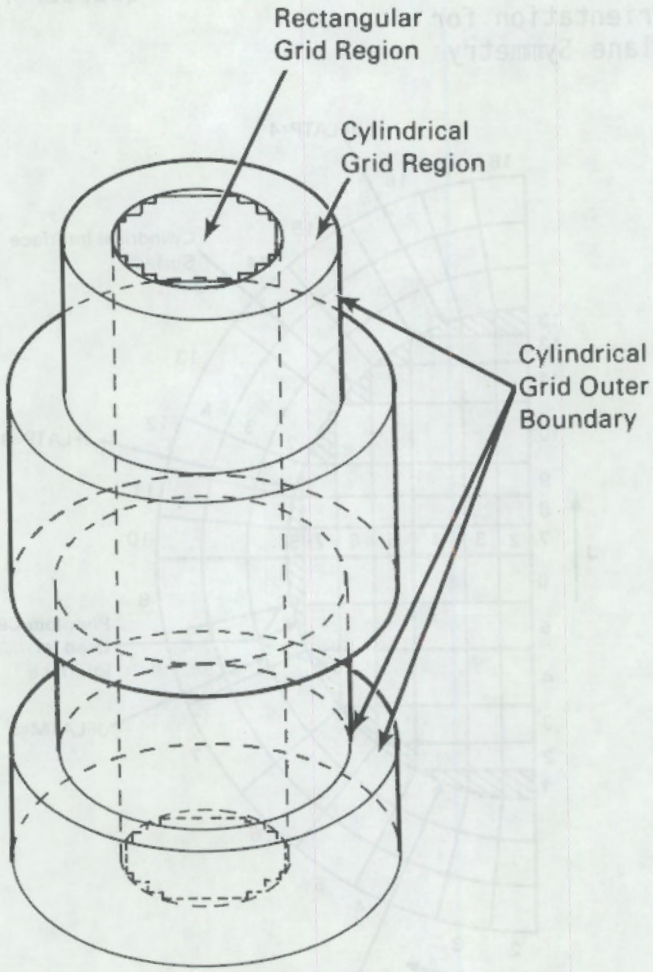


FIGURE 4.3. Rectangular and Cylindrical Grid Regions for Cask Simulation, Showing Possible Stepped Variations in Outer Cask Radius

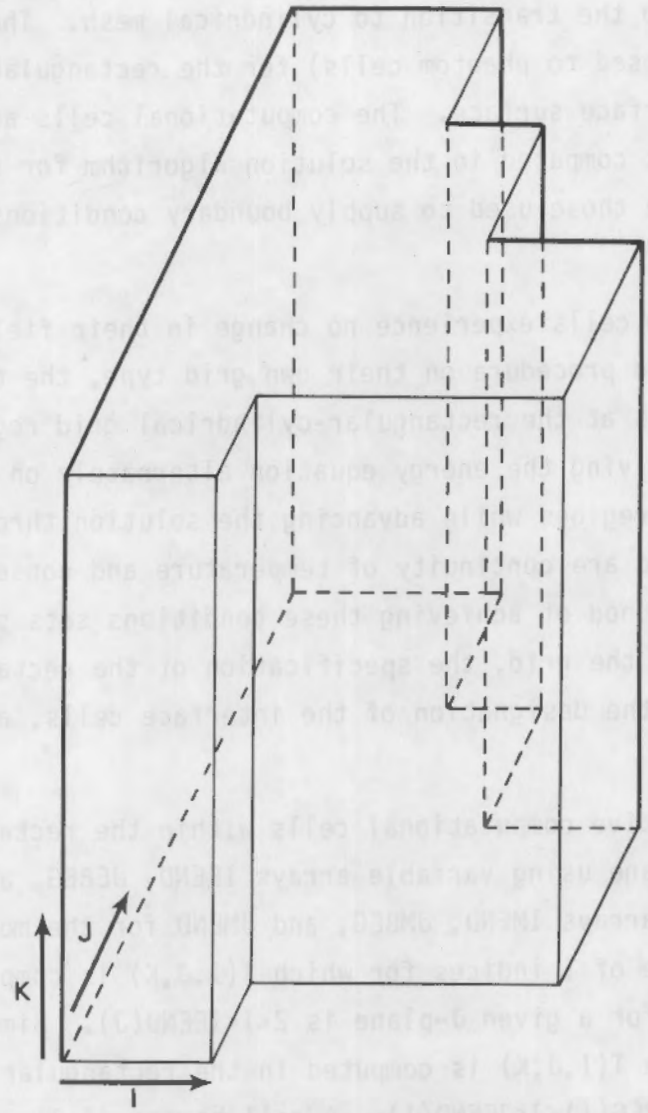


FIGURE 4.4. Potential Modeling Region for Rectangular-Grid-Only Simulation

x-direction grid line, and y-direction grid lines can enter the computation region only once and leave it once. The cross section modeled in an X-Y plane is invariant in the z-direction.

4.1.1 Choosing the Grid

To set up a computational grid, users should obtain cross sections in the x-y plane of the system to be simulated, as shown in Figure 4.1a. They should select a cylindrical surface outside of which there is no modeled flow and

which lends itself to the transition to cylindrical mesh. The active computational cells (as opposed to phantom cells) for the rectangular mesh will all lie inside this interface surface. The computational cells are those on which the field variable is computed in the solution algorithm for that grid type. The phantom cells are those used to supply boundary conditions for the solution on that grid type.

Although phantom cells experience no change in their field variables in executing the solution procedure on their own grid type, the temperature variable for phantom cells at the rectangular-cylindrical grid region interface will be altered in solving the energy equation alternately on the rectangular and cylindrical grid regions while advancing the solution through a time-step. The conditions imposed are continuity of temperature and conservation of energy. The coded method of achieving these conditions sets specific requirements on the setup of the grid, the specification of the rectangular grid computation region, and the designation of the interface cells, as will be explained here.

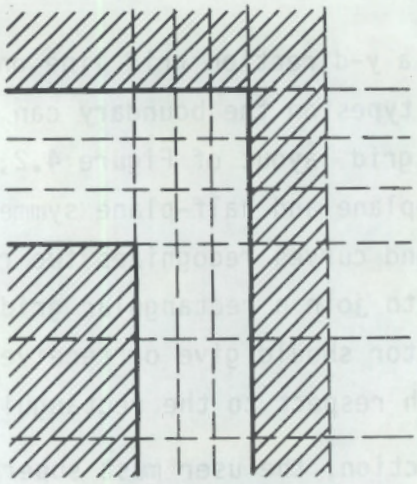
The region of active computational cells within the rectangular grid is defined in the x-y plane using variable arrays IEEND, JEBEG, and JEEND for the energy equation, and arrays IMEND, JMBEG, and JMEND for the momentum equations. For example, the range of I indices for which T(I,J,K) is computed in the rectangular grid region for a given J-plane is $2 \leq I \leq IEEND(J)$. Similarly, the range of J indices for which T(I,J,K) is computed in the rectangular grid region for a given I plane is $JEBEG(I) \leq J \leq JEEND(I)$. A cell having (I,J) = (IEEND(J)+1,J), or (I,J) = (I,JEEND(I)+1), or (I,J) = (I,JEBEG(I)-1) is a phantom cell used in setting boundary conditions in the rectangular grid region and in interfacing with the cylindrical grid region. The interface conditions will be imposed by the code, but the user must specify the interface cells in arrays ICART and JCART, along with the IEEND, JEBEG, and JEEND arrays. Every azimuthal sector (azimuthal index JS) will interface with a rectangular grid cell of indices (I,J) = (ICART(JS), JCART(JS)), and this must be a phantom cell.

There are typically three types of geometric regions in the boundary between a satisfactory rectangular and cylindrical grid: 1) a "flat spot" at constant y, 2) a "flat spot" at constant x, and 3) a curved region in which

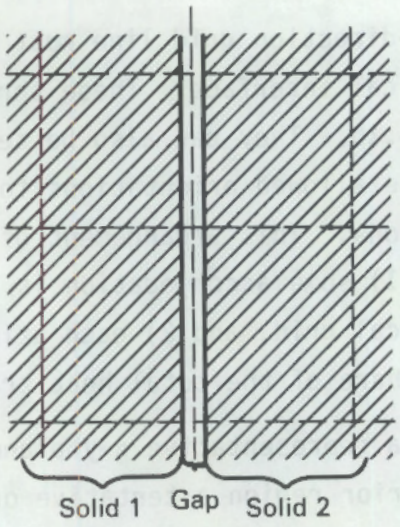
every x-direction grid line must intersect a y-direction grid line on the cylindrical interface. These three region types on the boundary can be seen in Figure 4.1b. They can also be seen in the grid layout of Figure 4.2, which shows the allowed orientations for quarter-plane and half-plane symmetry simulations. This arrangement of "flats" and curves recognizes two requirements: 1) some accommodation is necessary to join a rectangular grid to a cylindrical grid, and 2) each azimuthal sector should give or receive an appropriate share of the total heat transfer with respect to the rectangular grid.

In a representative x-y plane cross section, the user must superimpose on the interior region a tentative orthogonal network or grid. An early step is to select the flat parts of the boundary of the rectangular computational grid, using some discretion about the amount of gap that can be tolerated between the rectangular grid and the cylindrical interface. Grid lines that penetrate perpendicularly through these flat side boundaries can be chosen primarily to optimize resolution of physical detail. By contrast, grid lines (x- or y-direction) that intersect the cylinder interface without intersecting a flat boundary must intersect a perpendicular grid line (y or x) at the interface cylinder, and this imposes some constraints on their location. For example, the right boundary of the grid columns I = 2 or I = 3 in Figure 4.2 can be chosen to optimize resolution in the x-direction in the region $2<I<4$, whereas the grid boundary between I = 5 and I = 6 must meet an x-direction grid line at the interface, like the one between J = 2 and J = 3.

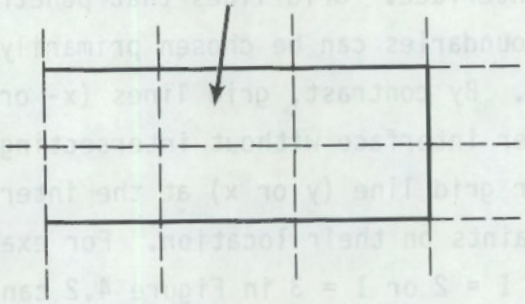
Grid lines should pass along the major material boundaries. In choosing them, the user should keep in mind the models available to describe the heat transfer phenomena: flow in the available open spaces, radiative transfer from cell to cell by rods, radiative exchange among cells facing interior enclosures, conduction from cell to cell through homogeneous materials and laminar composites, and inhibition of conduction from cell to cell by film resistances. Grid lines should be inserted as needed to represent the physical phenomena. Some nodalization principles and models are illustrated in Figure 4.5. Those grid lines that do not intersect a flat side boundary will generate an orthogonal grid line from their point of intersection with the cylinder interface.



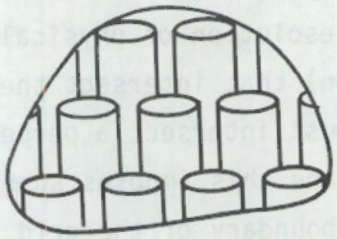
a. Grid Lines Chosen to Follow Material Boundaries



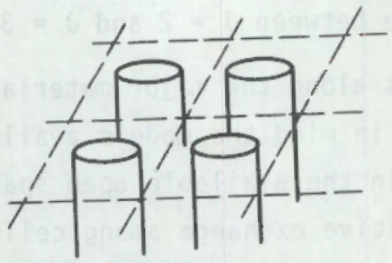
b. Radiation Across Narrow Gap Modeled with Inter-Cell Film Resistance



c. Two-Dimensional Radiation Enclosure (Infinite in Z-Direction)



d. Array of Cylinders Modeled as Orthotropic Continuum



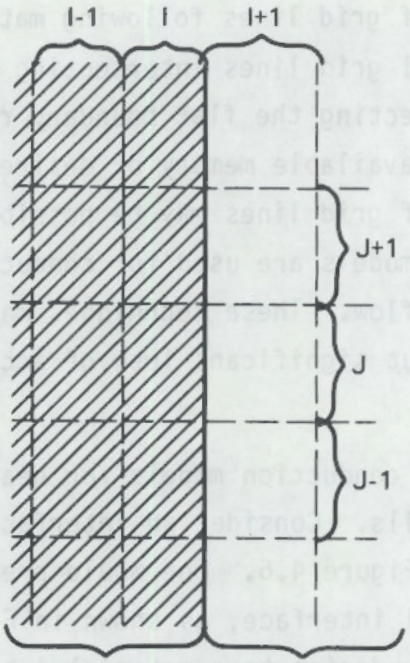
e. Array of Cylinders Modeled as One per Cell Column in Z-Direction

FIGURE 4.5. Some Nodalization Principles and Available Models

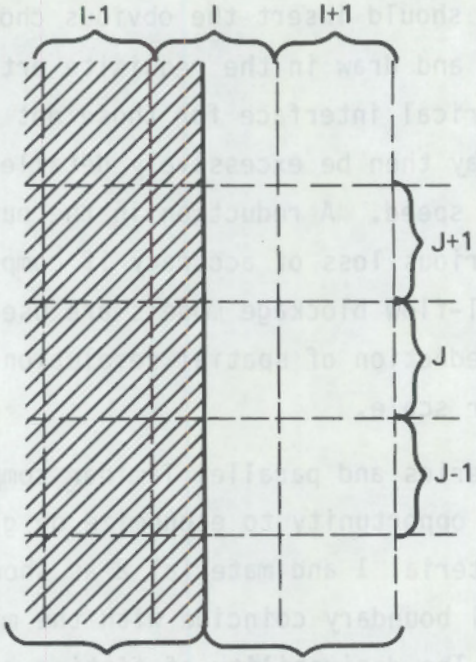
Users should insert the obvious choices of grid lines following material boundaries and draw in the requisite orthogonal grid lines intersecting them on the cylindrical interface for those not intersecting the flat boundary regions. The grid may then be excessively detailed for available memory or desired computational speed. A reduction in the number of grid lines may be possible without serious loss of accuracy if composite models are used for conduction and partial-flow blockage models are used for flow. These techniques may lead to local reduction of spatial resolution without significant loss of accuracy on a larger scale.

The series and parallel laminar composite conduction models for heat flow allow some opportunity to economize on grid cells. Consider an interface between material 1 and material 2 as shown in Figure 4.6. One would prefer to make a cell boundary coincide with the material interface, as shown in Figure 4.6a. The desirability of fitting cell boundaries to a material interface in the y-direction, the requirement that x and y grid lines intersect on the cylindrical interface on the curved part of the rectangular grid boundary, and a need to reduce the number of computational cells may require grid lines as shown in Figure 4.6b. A medium-straddling cell such as the (I,J) cell of Figure 4.6b can be considered as having series conduction through layers in the x-direction and parallel conduction in the y-direction as shown in Figure 4.6c. The approximate laminar composite model is shown schematically in Figure 4.6d. The input for laminar composite conduction is described in Chapter 5.0, but its availability is described here to aid nodalization. If one of two media within a computational cell contains a fluid, some use of directional permeabilities, directional surface porosities, directional velocity-dependent drag coefficients, and altered viscosities may be appropriate to model flow effects.

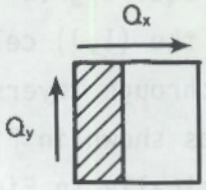
The preceding discussion and Figure 4.2 should indicate both the reasons and the method for assigning IEEND, JEBEG, JEEND, ICART, and JCART values. Specifically, the rules for assigning IEEND(J) values are:



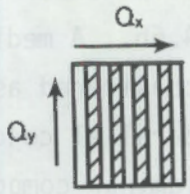
a. Preferred Nodalization at a Material Medium Interface



b. Compromise Nodalization



c. Series Paths for Heat Flow Qx and Parallel Paths for Heat Flow Qy in Medium-Straddling Cell from b



d. Orthotropic Laminar Composite Approximation to the Cell in c

FIGURE 4.6. Series and Parallel Conduction Models

- J = 1 - IEEND(1) = 1
- J = 2 to JFLATM, i.e,, along curved boundary - Set IEEND(J) to one less than the I index of the cell bisected by the interface curve.
- J = JFLATM to JFLATP - Set IEEND(J) to one less than the I value of the cells that extend from the "flat" boundary there to the cylindrical interface curve.
- J = JFLATP+1 to JP-1 - Set IEEND(J) to one less than the I index of the cell bisected by the interface curve.
- J = JP - IEEND(JP) = 1.

JEBEG and JEEND(I) values should be assigned according to:

- I = 1 to IFLATM - JEBEG(I) = 2
- I = 1 to IFLATP - JEEND(I) = the J value of layer below "flat" upper boundary, that is JEEND(I) = JP-1
- I = IFLATM+1 to I = the I index just left of the "flat" right boundary
  - JEBEG(I) = one more than the J value of the cell bisected by the interface curve
  - JEEND(I) = one less than the J value of the cell bisected by the interface curve.

In the most correct nodalization, the I index just left of the flat right boundary will be IP-1.

The ICART(JS) and JCART(JS) values are the I and J indices, respectively, of the phantom cell to which the JS azimuthal sector connects. The lowest active computational sector is JS = 2, and it should be connected to the cell (I,J) = (ICART(2),JCART(2)) = 2,1. The subsequent ICART and JCART values can be read directly from a user diagram analogous to Figure 4.2. Figure 4.7 shows input data appropriate to Figure 4.2.

The limits of the computational region for the momentum equations are set in the arrays IMEND, JMBEG, and JMEND, and they are related to the choices for the energy equation. The momentum equations apply only to the rectangular

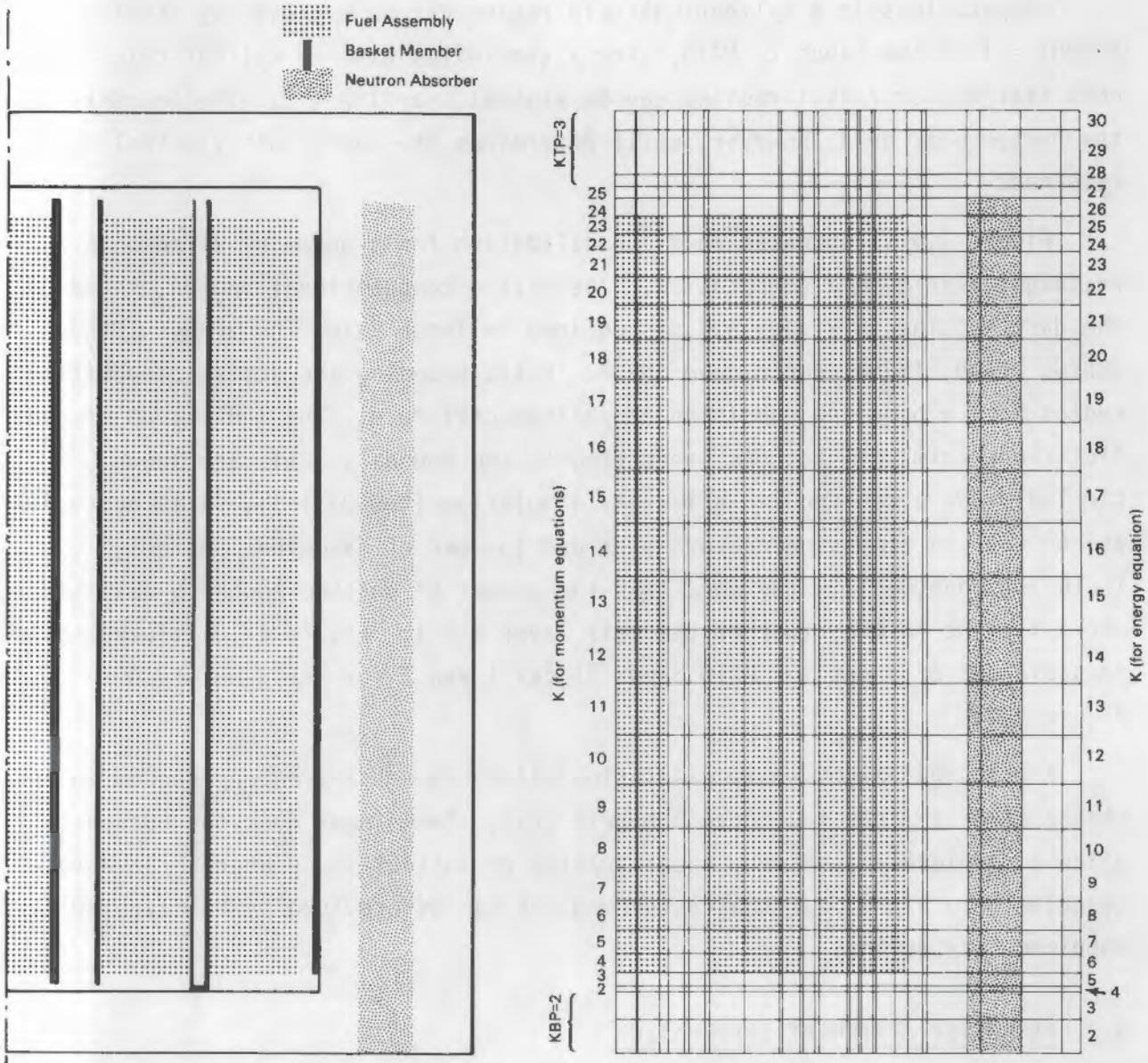
```
2.0,4,4,5,9
1/grid/ieend  ends of energy eq. comp. reg. in x-direction
1,4,5,6,5*7,6,5,4,1
1/grid/jebeg  beginning of energy eq. comp. reg. in y-direction
4*2,3,4,5
1/grid/jeend   ends of energy eq. comp. reg. in y-direction
4*12,11,10,9
1/grid/imend  ends of mom. eq. comp. reg. in x-direction
4,5,6,7,5*8,7,6,5,4
1/grid/jmbeg  beginning of mom. eq. comp. reg. in y-direction
4*2,2,3,4
1/grid/jmend  ends of mom. eq. comp. reg. in y-direction
4*12,12,11,10
1/grid/icart  i indices for hookup to azimuth reg. js=2 thru js=18
2,3,4,5,6,7,5*8,7,6,5,4,3,2
1/grid/jcart  j indices for hookup to azimuth reg. js=2 thru js=18
3*1,2,3,4,5,6,7,8,9,10,11,12,3*13
1/grid/isend  is indices of radial comp. reg. limits (for kp=10)
10*4
```

FIGURE 4.7. Subroutine GRID Input Blocks 1 and 2 for Mesh Shown in Figure 4.2c

grid. One should extend the momentum equation computation to include the curved part of the rectangular grid boundary.

Users must identify the z-direction region for which the momentum equations are solved. This is done with parameters KBP (K bottom parameter) and KTP (K top parameter), which are set by a parameter statement defined in Chapter 6.0. KBP and KTP are the number of active computational cells which are used for the energy equation at the bottom and at the top of the cask nodalization, respectively, which are not used as active computational cells for the momentum equations. The K-indices in arrays used exclusively for the momentum equation solution (and not used for the energy equation) will have a restricted range. A z-direction index K in an array used exclusively in the

momentum equations will apply to the same cell as an index K+KBP in an array used in the energy equation. While no specific input in GRID is for the "offset" or reduced range arrays, the user should keep this in mind in choosing the z-direction nodalization. Figure 4.8 shows this restricted range and



a. Cask Cross Section

b. HYDRA Computational Mesh

FIGURE 4.8. Ranges of Axial Indices in Energy Momentum Equations for Sample Cask Nodalization with KP = 31, KBP = 2, and KTP = 3

K-offset for a real cask nodalization. The K-nodalization and KBP and KTP parameters for the cask shown in Figure 4.8 were chosen to model the conduction at the solid cask ends without a meaningless fluid flow calculation there.

4.1.2 Simulations Using Only a Rectangular Grid

Computations in a cylindrical grid region can be bypassed by setting NOBODY = 1 in the input to MAIN. For a simulation with no cylindrical region, nodalization for radial regions can be minimal, say ISP = 3. The boundary of the rectangular grid, however, still determines the number of azimuthal nodes required.

Figure 4.9 illustrates an X-Y nodalization for a geometry allowed in a rectangular-grid-only computation. The active computational region, shown by the dark outline in Figure 4.4, is defined in input using the arrays IEEND, JEBEG, JEEND, IMEND, JMBEG, and JMEND. Cells bounding the active computation region have a boundary condition or phantom cell role. The indices JS of the fictitious azimuthal sectors connecting to the boundary cells are shown circled. For a rectangular-grid-only simulation (NOBODY = 1), it is appropriate to set the dimensioning parameter JSP (number of azimuthal sectors, including phantoms) to two more than the number of phantom boundary cells in one X-Y plane to the right of the cell layer I = 1. Figure 4.10 illustrates a possible set of input for GRID Input Blocks 1 and 2 for the geometry of Figure 4.9.

A rectangular-grid-only simulation offers somewhat greater freedom in the choice of grid lines than does a hybrid grid. Code input does not currently allow a completely arbitrary specification of initial temperatures for a rectangular grid alone. If that is needed, it can be provided by fairly simple supplementary coding.

4.2 PARAMETER STATEMENT INFORMATION

Subroutine GRID requires the specification of the following parameters:

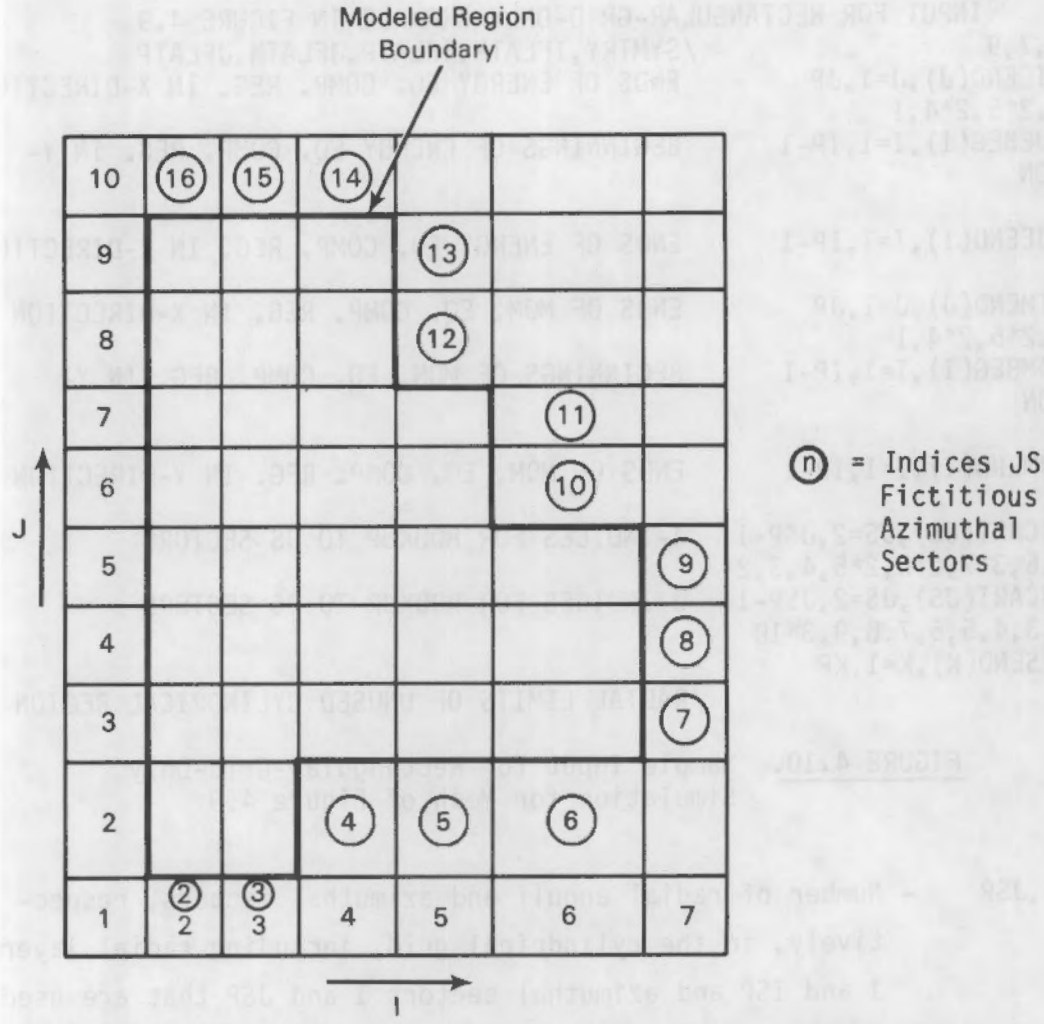


FIGURE 4.9. Nodalization in X-Y Plane of a Region Treatable in Rectangular-Grid-Only Simulation

- IP,JP,KP - Number of mesh planes in the x-, y-, and z-directions of the rectangular mesh, respectively, including those cell layers that are used for imposing boundary conditions or for interfacing: layers 1 and IP in the x-direction, layers 1 and JP in the y-direction, and layers 1 and KP in the z-direction.

```
1/GRID     INPUT FOR RECTANGULAR-GRID-ONLY EXAMPLE IN FIGURE 4.9
4.0,3,4,7,9                    /SYMTRY,IFLATM,IFLATP,JFLATM,JFLATP
1/GRID/IEEND(J),J=1,JP          ENDS OF ENERGY EQ. COMP. REG. IN X-DIRECTION
1,3,3*6,2*5,2*4,1
1/GRID/JEBEG(I),I=1,IP-1        BEGINNINGS OF ENERGY EQ. COMP. REG. IN Y-
DIRECTION
3*2,3*3
1/GRID/JEEND(I),I=1,IP-1        ENDS OF ENERGY EQ. COMP. REG. IN Y-DIRECTION
3*9,5,6
1/GRID/IMEND(J),J=1,JP          ENDS OF MOM. EQ. COMP. REG. IN X-DIRECTION
1,3,3*6,2*5,2*4,1
1/GRID/JMBEG(I),I=1,IP-1        BEGINNINGS OF MOM. EQ. COMP. REG. IN Y-
DIRECTION
3*2,3*3
1/GRID/JMEND(I),I=1,IP-1        ENDS OF MOM. EQ. COMP. REG. IN Y-DIRECTION
3*9,5,6
1/GRID/ICART(JS),JS=2,JSP-1     I-INDICES FOR HOOKUP TO JS SECTORS
2,3,4,5,6,3*7,2*6,2*5,4,3,2
1/GRID/JCART(JS),JS=2,JSP-1     J-INDICES FOR HOOKUP TO JS SECTORS
2*1,3*2,3,4,5,6,7,8,9,3*10
1/GRID/ISEND(K),K=1,KP
12*2                           /RADIAL LIMITS OF UNUSED CYLINDRICAL REGION
```

FIGURE 4.10. Sample Input for Rectangular-Grid-Only Simulation for Mesh of Figure 4.9

- ISP,JSP - Number of radial annuli and azimuthal sectors, respectively, in the cylindrical grid, including radial layers 1 and ISP and azimuthal sectors 1 and JSP that are used in imposing boundary conditions.
- NEFAP - Dimension of a scratch array used for both grids and which should satisfy NEFAP = MAX(IP-1,JP-1,KP-1, ISP-1,JSP-1).

4.3 INPUT FORMAT

4.3.1 Overview

The input to subroutine GRID consists of 1) general specifications on the symmetry of the simulation and the region types in the rectangular-cylindrical grid interface; 2) integer arrays defining the computational mesh of the rectangular region for the energy and the momentum equation, and arrays specifying

the rectangular grid cells that interface with cylindrical grid sectors; and 3) arrays of mesh spacings for the rectangular and cylindrical meshes.

4.3.2 Symmetry and Interface Regions. Input Block 1

General Input Format

```
NECHO
SYMTRY,IFLATM,IFLATP,JFLATM,JFLATP
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise 0.
- SYMTRY - Number of quadrants in modeled region: 1.0 for quarter-plane symmetry, and 2.0 for half-plane symmetry.
- IFLATM - The value of the highest I index in the rectangular grid for the flat part of the rectangular computational grid boundary at the lower constant y-value. See Figure 4.2.
- IFLATP - The value of the highest I index in the rectangular grid for the flat part of the rectangular computational grid boundary at the higher constant y-value. See Figure 4.2.
- JFLATM - The value of the lowest J index in the rectangular grid for the flat part of the rectangular computational grid boundary at constant x-value. See Figure 4.2.
- JFLATP - The value of the highest J index in the rectangular grid for the flat part of the rectangular computational grid boundary at constant x-value. See Figure 4.2.

Note: The grid shown in Figure 4.1 has IP = 25, JP = 48, ISP = 8, and JSP = 64, with the x-direction layer at I = 1 and the radial layer IS = 8 not shown. The phantom azimuthal sectors JS = 1 and JS = JSP = 64 are also not shown. This example also has IFLATM = 9, IFLATP = 9, JFLATM = 17, and JFLATP = 32. Because of the amount of detail and the fineness of the mesh in places, it is useful to also examine the grid shown in

Figure 4.2c, which has IP = 8, JP = 13, ISP = 5 (with radial section IS = ISP = 5 not shown), JSP = 19, IFLATM = 4, IFLATP = 4, JFLATM = 5, and JFLATP = 9.

Input File Example

```
43      1/grid
44      2.0,9,9,17,32
```

Echoed Input File Example

```
46
47   grid   symtry=2.0    iflatm=9    iflatp=9    jflatm=17    jflatp=32
```

SYMTRY is set to 2.0 for the half-plane symmetry model shown in Figure 4.1. This simulation has IP = 25, JP = 48, KP = 31, ISP = 8, JSP = 64. IFLATM is set to 9, because I = 9 is the highest included I plane in the flat cartesian grid boundary between J = 1 and J = 2. IFLATP is similarly set to 9 for the flat part of the cartesian grid boundary between J = 47 and J =48 = JP. JFLATM and JFLATP are set to 17 and 32, respectively, for the upper and lower J indices of the flat part of the rectangular grid boundary between I = 24 and I = 25 = IP.

4.3.3 Rectangular Grid Computational Region Definition Grid. Input Block 2

General Input Format

```
NECHO
IEEND(J),J=1,JP
INCO
JEBEG(I),I=1,IP-1
INCO
JEEND(I),I=1,IP-1
INCO
IMEND(J),J=1,JP
INCO
JMBEG(I),I=1,IP-1
INCO
JMEND(I),I=1,IP-1
INCO
ICART(JS),JS=2,JSP-1
INCO
JCART(JS),JS=2,JSP-1
INCO
ISEND(K),K=1,KP
```

General Input Definition

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- IEEND(J) - The highest I index of a computational cell as a function of J for which the energy equation is solved on the rectangular grid. Phantom cells are not included.
- INCO - Integer variable used to update NECHO according to NECHO = MAX(NECHO,INCO), and which also serves as a line-holder for user comments in the input file.
- JEBEG(I) - The lowest J index of a computational cell (as opposed to phantom cells) for layer I in the rectangular grid for the energy equation.
- JEEND(I) - The highest J index of a computational cell in the I layer in the rectangular grid for the energy equation.
- IMEND(J) - The highest I index of a computational cell in layer J in the solution of the momentum equations on the rectangular grid.
- JMBEG(I) - The lowest J index of a computational cell for layer I in the solution of the momentum equations on the rectangular grid.
- JEND(I) - The highest J index of a computational cell for layer I in the solution of the momentum equations on the rectangular grid.
- ICART(JS) - The I index of the rectangular grid phantom cell that has an interface with azimuthal sector JS at the inner radius of the cylindrical annulus IS = 2. See Figures 4.1 and 4.2.
- JCART(JS) - The J index of the rectangular grid phantom cell that has an interface with azimuthal sector JS at the inner radius of the cylindrical annulus IS = 2.

- ISEND(K) - The highest IS index (cylindrical region radial index) of computational cells in the energy equation in the cylindrical grid at plane K. See Figure 4.3 for an example of a variable radial region. The outer cylindrical surface of a cell with IS = ISEND(K) at a given K-plane can be a radiating surface. If the outer surface is a single cylinder, then ISEND(K) = ISP-1 for all K.

The computational cells in the rectangular grid extend for the energy equation from I = 2 to I = IEEND(J) for a given J, and from J = JEBEG(I) to J = JEEND(I) for a given I. This is true for all K values. Phantom cells adjacent to computational cells are used in imposing interface conditions between rectangular and cylindrical grid regions. The arrays ICART and JCART specify the linkup of the two grids, but the grids and their interface must be set up as shown in Figures 4.1 and 4.2, with the previously discussed constraints imposed.

Input File Example

```
45 1/grid/ieend
46 1,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,16*24,
47 23,22,21,20,19,18,17,16,15,14,13,12,11,10,9,1
48 1/grid/jebeg
49 9*2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17
50 1/grid/jeend
51 9*47,46,45,44,43,42,41,40,39,38,37,36,35,34,33,32
52 1/grid/imend
53 9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,18*24,
54 23,22,21,20,19,18,17,16,15,14,13,12,11,10,9
55 1/grid/jmbeg
56 10*2,3,4,5,6,7,8,9,10,11,12,13,14,15,16
57 1/grid/jmend
58 10*47,46,45,44,43,42,41,40,39,38,37,36,35,34,33
59 1/grid/icart
60 2,3,4,5,6,7,8,9,
61 10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,16*25,
62 24,23,22,21,20,19,18,17,16,15,14,13,12,11,10,
63 9,8,7,6,5,4,3,2   64 1/grid/jcart
65 8*1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,
66 21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,
67 37,38,39,40,41,42,43,44,45,46,47,8*48
68 1/grid/isend
69 31*7
```

Note: This input applies to Figure 4.1.

Output File Example

49	grid	ieend(j)	jebeg(i)	jeend(i)	imend(j)	jmbeg(i)	jmend(i)	icart(js)	jcart(js)	isend(k)
50	1	1	2	47	9	2	47	**	**	7
51	2	9	2	47	10	2	47	2	1	7
52	3	10	2	47	11	2	47	3	1	7
53	4	11	2	47	12	2	47	4	1	7
54	5	12	2	47	13	2	47	5	1	7
55	6	13	2	47	14	2	47	6	1	7
56	7	14	2	47	15	2	47	7	1	7
57	8	15	2	47	16	2	47	8	1	7
58	9	16	2	47	17	2	47	9	1	7
59	10	17	3	46	18	2	47	10	2	7
60	11	18	4	45	19	3	46	11	3	7
61	12	19	5	44	20	4	45	12	4	7
62	13	20	6	43	21	5	44	13	5	7
63	14	21	7	42	22	6	43	14	6	7
64	15	22	8	41	23	7	42	15	7	7
65	16	23	9	40	24	8	41	16	8	7
66	17	24	10	39	24	9	40	17	9	7
67	18	24	11	38	24	10	39	18	10	7
68	19	24	12	37	24	11	38	19	11	7
69	20	24	13	36	24	12	37	20	12	7
70	21	24	14	35	24	13	36	21	13	7
71	22	24	15	34	24	14	35	22	14	7
72	23	24	16	33	24	15	34	23	15	7
73	24	24	17	32	24	16	33	24	16	7
74	25	24	**	**	24	**	**	25	17	7
75	26	24	**	**	24	**	**	25	18	7
76	27	24	**	**	24	**	**	25	19	7
77	28	24	**	**	24	**	**	25	20	7
78	29	24	**	**	24	**	**	25	21	7
79	30	24	**	**	24	**	**	25	22	7
80	31	24	**	**	24	**	**	25	23	7
81	32	24	**	**	24	**	**	25	24	**
82	33	23	**	**	24	**	**	25	25	**
83	34	22	**	**	23	**	**	25	26	**
84	35	21	**	**	22	**	**	25	27	**
85	36	20	**	**	21	**	**	25	28	**
86	37	19	**	**	20	**	**	25	29	**
87	38	18	**	**	19	**	**	25	30	**
88	39	17	**	**	18	**	**	25	31	**
89	40	16	**	**	17	**	**	25	32	**
90	41	15	**	**	16	**	**	24	33	**
91	42	14	**	**	15	**	**	23	34	**
92	43	13	**	**	14	**	**	22	35	**
93	44	12	**	**	13	**	**	21	36	**
94	45	11	**	**	12	**	**	20	37	**
95	46	10	**	**	11	**	**	19	38	**
96	47	9	**	**	10	**	**	18	39	**
97	48	1	**	**	9	**	**	17	40	**
98	49	**	**	**	**	**	**	16	41	**
99	50	**	**	**	**	**	**	15	42	**
100	51	**	**	**	**	**	**	14	43	**
101	52	**	**	**	**	**	**	13	44	**
102	53	**	**	**	**	**	**	12	45	**
103	54	**	**	**	**	**	**	11	46	**
104	55	**	**	**	**	**	**	10	47	**
105	56	**	**	**	**	**	**	9	48	**
106	57	**	**	**	**	**	**	8	48	**
107	58	**	**	**	**	**	**	7	48	**
108	59	**	**	**	**	**	**	6	48	**
109	60	**	**	**	**	**	**	5	48	**
110	61	**	**	**	**	**	**	4	48	**
111	62	**	**	**	**	**	**	3	48	**
112	63	**	**	**	**	**	**	2	48	**

The input shown corresponds to Figure 4.1, for which IP = 25, JP = 48, KP = 31, ISP = 8, JSP = 64. The 48 (=JP) entries for IEEND mark the limits of the computational region in the x-direction. The IEEND(1) and IEEND(JP) values are not significant, as they lie within J planes that are intrinsically phantom cells. In counting I-direction layers of cells in Figure 4.1, note that I = 3

corresponds to an extremely thin layer. Note IEEND(2) is set to 9, making the cell (I,J) = (10,2) a phantom cell. This is appropriate because the cell (I,J) = (10,2) is bisected by the cylinder and is appropriate for interfacing with the azimuthal sector JS = 10. The energy computations in the rectangular grid for J = 2 through J = 16 stop one short of a bisected interface cell in the I-direction. Energy computations for J = 17 through J = 32 stop at I = 24, leaving the cells at I = 25 in the region between this flat part of the rectangular grid boundary and the cylinder interface as phantom cells connecting to the azimuthal sectors JS = 25 through JS = 40.

The JEBEG and JEEND arrays give upper and lower J indices for the rectangular grid computational region, leaving the interface cell at either end (upper and lower) for interfaces. The IP-1 entries in either of these two arrays (for I = 1 to IP-1) specify these limits, whose correspondence to Figure 4.1 should be noted.

The computational limits for the momentum equation are similarly defined in IMEND, JMBEG, and JMEND. Note that the choices make the momentum equation computational region somewhat larger. The cells on the curved part of the interface boundary can be treated as having a partial flow area, with a zero flow condition on the next outward computational cell.

The ISEND(K) are set to 7 (=ISP-1) for all K indices, indicating that all radial regions in the cylindrical grid out to the phantom layer at IS = ISP = 8 are to be included, and that the cask exterior is a cylinder.

The echoed output of these arrays uses a running multipurpose integer index in a column on the left, i.e., the integer is I, J, JS, or K as needed, followed by columns to report IEEND(J), JEBEG(I), JEEND(I), IMEND(J), JMBEG(I), JMEND(I), ICART(JS), JCART(JS), or ISEND(K).

For convenience to users in seeing the region definitions and interface hookup input, a possible set of input for GRID Input Blocks 1 and 2 for the mesh shown in Figure 4.2c is presented in Figure 4.7.

4.3.4 Cartesian and Radial Mesh Spacings. Input Block 3

General Input Format

```
NECHO
DX(I),I=1,IP
INCO
DY(J),J=1,JP
INCO
DZ(K),K=1,JP
INCO
DR(IS),IS=1,ISP
```

General Input Definition

- NECHO - Echoing switch for this section of input. If input is be echoed, then NECHO = 1; otherwise, 0.
- DX(I) - The width of the Ith layer of cells in the x-direction.
- INCO - Integer variable used to update NECHO according to NECHO = MAX(NECHO,INCO), and which also serves as a line-holder for user comments in the input file.
- DY(J) - The width of the Jth layer of cells in the y-direction.
- DZ(K) - The width of the Kth layer of cells in the z-direction.
- DR(IS) - The mesh spacing for the ISth radial cell. DR(1) should be set to the radius of the cylindrical interface with the cartesian grid.

Input File Example

```
70 1/grid/dx
71 1.0,5.0,0.5,5.5,2.0,4.02422514,1.0,3.97577486,1.0,
72 2*8.51211257,1.0,3.97577486,1.0,2.59636862,1.0,
73 6.93008731,0.8619833,2.10139183,0.75998222,2.77441184,
74 0.63974744,4.61506347,3.31733259,1.0
75 1/grid/dy
76 1.0,3.31733259,4.61506347,0.63974744,2.77441184,
77 0.75998222,2.10139183,0.8619833,6.93008731,1.0,
78 2.59636862,1.0,3.97577486,1.0,2*8.51211257,1.0,
79 3.97577486,1.0,4.02422514,2.0,5.5,0.5,2*5.0,0.5,
80 5.5,2.D,4.02422514,1.0,3.97577486,1.0,2*8.51211257,
81 1.0,3.97577486,1.0,2.59636862,1.0,6.93008731,
82 0.8619833,2.10139183,0.75998222,2.77441184,
83 0.63974744,4.61506347,3.31733259,1.0
```

```
84 1/grid/dz
85 1.0,18.0,14.0,3.0,7.0,10.0,12.5,15.0,17.5,20.0,
86 22.5,25.0,27.0,27.3,27.4,27.3,27.0,25.0,22.5,20.0,
87 17.5,15.0,12.5,9.5,9.0,9.0,6.5,5.5,23.5,9.3,1.0
88 1/grid/dr
89 75.2,1.0,10.0,3.2,2*10.0,4.8,1.0
```

Output File Example

```
113
114  grid          dx(i)            dy(j)            dz(k)            dr(is)           dtheta(js)
115             1 0.100000000e+01  0.100000000e+01  0.100000000e+01  0.752000000e+02  0.381237231e+01
116             2 0.500000000e+01  0.331733259e+01  0.180000000e+02  0.100000000e+01  0.381237231e+01
117             3 0.500000000e+00  0.461506347e+01  0.140000000e+02  0.100000000e+02  0.381888490e+00
118             4 0.550000000e+01  0.639747440e+00  0.300000000e+01  0.320000000e+01  0.421695021e+01
119             5 0.200000000e+01  0.277441184e+01  0.700000000e+01  0.100000000e+02  0.154365417e+01
120             6 0.402422514e+01  0.759982220e+00  0.100000000e+02  0.100000000e+02  0.312952654e+01
121             7 0.100000000e+01  0.210139183e+01  0.125000000e+02  0.480000000e+01  0.783489668e+00
122             8 0.397577486e+01  0.861983300e+00  0.150000000e+02  0.100000000e+01  0.314299247e+01
123             9 0.100000000e+01  0.693008731e+01  0.175000000e+02  **************** 0.798499400e+00
124            10 0.851211257e+01  0.100000000e+01  0.200000000e+02  **************** 0.696487582e+01
125            11 0.851211257e+01  0.259636862e+01  0.225000000e+02  **************** 0.738247825e+01
126            12 0.100000000e+01  0.100000000e+01  0.250000000e+02  **************** 0.904497665e+00
127            13 0.397577486e+01  0.397577486e+01  0.270000000e+02  **************** 0.369447113e+01
128            14 0.100000000e+01  0.100000000e+01  0.273000000e+02  **************** 0.956983767e+00
129            15 0.259636862e+01  0.851211257e+01  0.274000000e+02  **************** 0.254515233e+01
130            16 0.100000000e+01  0.851211257e+01  0.273000000e+02  **************** 0.100591424e+01
131            17 0.693008731e+01  0.100000000e+01  0.270000000e+02  **************** 0.747250705e+01
132            18 0.861983300e+00  0.397577486e+01  0.250000000e+02  **************** 0.100591424e+01
133            19 0.210139183e+01  0.100000000e+01  0.225000000e+02  **************** 0.254515234e+01
134            20 0.759982220e+00  0.402422514e+01  0.200000000e+02  **************** 0.956983760e+00
135            21 0.277441184e+01  0.200000000e+01  0.175000000e+02  **************** 0.369447113e+01
136            22 0.639747440e+00  0.550000000e+01  0.150000000e+02  **************** 0.904497667e+00
137            23 0.461506347e+01  0.500000000e+00  0.125000000e+02  **************** 0.738247826e+01
138            24 0.331733259e+01  0.500000000e+01  0.950000000e+01  **************** 0.696487582e+01
139            25 0.100000000e+01  0.500000000e+01  0.900000000e+01  **************** 0.798499400e+00
140            26 ****************  0.500000000e+00  0.900000000e+01  **************** 0.314299247e+01
141            27 ****************  0.550000000e+01  0.650000000e+01  **************** 0.783489668e+00
142            28 ****************  0.200000000e+01  0.550000000e+01  **************** 0.312952654e+01
143            29 ****************  0.402422514e+01  0.235000000e+02  **************** 0.154365417e+01
144            30 ****************  0.100000000e+01  0.930000000e+01  **************** 0.421695021e+01
145            31 ****************  0.397577486e+01  0.100000000e+01  **************** 0.381888490e+00
146            32 ****************  0.100000000e+01  **************** **************** 0.381237231e+01
147            33 ****************  0.851211257e+01  **************** **************** 0.381237231e+01
148            34 ****************  0.851211257e+01  **************** **************** 0.381888490e+00
149            35 ****************  0.100000000e+01  **************** **************** 0.421695021e+01
150            36 ****************  0.397577486e+01  **************** **************** 0.154365417e+01
151            37 ****************  0.100000000e+01  **************** **************** 0.312952654e+01
152            38 ****************  0.259636862e+01  **************** **************** 0.783489668e+00
153            39 ****************  0.100000000e+01  **************** **************** 0.314299247e+01
154            40 ****************  0.693008731e+01  **************** **************** 0.798499400e+00
155            41 ****************  0.861983300e+00  **************** **************** 0.696487582e+01
156            42 ****************  0.210139183e+01  **************** **************** 0.738247826e+01
157            43 ****************  0.759982220e+00  **************** **************** 0.904497667e+00
158            44 ****************  0.277441184e+01  **************** **************** 0.369447113e+01
159            45 ****************  0.639747440e+00  **************** **************** 0.956983759e+00
160            46 ****************  0.461506347e+01  **************** **************** 0.254515234e+01
161            47 ****************  0.331733259e+01  **************** **************** 0.100591424e+01
162            48 ****************  0.100000000e+01  **************** **************** 0.747250705e+01
163            49 ****************  **************** **************** **************** 0.100591424e+01
164            50 ****************  **************** **************** **************** 0.254515233e+01
165            51 ****************  **************** **************** **************** 0.956983767e+00
166            52 ****************  **************** **************** **************** 0.369447113e+01
167            53 ****************  **************** **************** **************** 0.904497665e+00
168            54 ****************  **************** **************** **************** 0.738247825e+01
169            55 ****************  **************** **************** **************** 0.696487581e+01
170            56 ****************  **************** **************** **************** 0.798499400e+00
171            57 ****************  **************** **************** **************** 0.314299247e+01
172            58 ****************  **************** **************** **************** 0.783489668e+00
173            59 ****************  **************** **************** **************** 0.312952654e+01
174            60 ****************  **************** **************** **************** 0.154365417e+01
175            61 ****************  **************** **************** **************** 0.421695021e+01
176            62 ****************  **************** **************** **************** 0.381888490e+00
177            63 ****************  **************** **************** **************** 0.381237231e+01
178            64 ****************  **************** **************** **************** 0.381237231e+01
179                                                                                   0.180000000e+03
```

The rectangular and cylindrical mesh spacings are both specified by this set of input. The azimuthal mesh is determined by the rectangular mesh and by the linkup prescribed by the ICART and JCART arrays and the mesh parameters IFLATM, IFLATP, JFLATM, and JFLATP, as can be seen in Figures 4.1 and 4.2. Although the thicknesses of the phantom cell layers set by DX(1), DZ(1), DZ(KP), DR(ISP), etc., are not critical for the boundary conditions usually imposed, they are not completely arbitrary, either. For example, if insulated boundary conditions are desired to impose symmetry about the constant x-plane between the I = 1 and I = 2 layers, then the product of the x-direction resistivity and the half-thickness of the I = 1 layer should be orders of magnitude greater than that for real conduction paths.

The echoed output of these arrays of mesh spacing information uses a running multipurpose integer index in a column on the left; i.e., the integer is I, J, K, IS, or JS as needed, followed by columns with DX(I), DY(J), DZ(K) DR(IS), and DTHETA(JS). The angular mesh spacing array, DTHETA(JS), is reported in degrees.

5.0 SUBROUTINE PROP

Subroutine PROP sets resistances to heat transfer in the rectangular grid region.

5.1 PROP FUNCTIONS

PROP treats heat transfer that is mathematically equivalent to conduction on a finite mesh. Emission and reabsorption of radiation over short distances within and between cells, as well as temperature dependence of true conduction, can be incorporated into thermal resistances by PROP using effective thermal conductivity polynomials. Explicit radiation models, like that among several surfaces facing an enclosure or among fuel pins treated discretely, are treated elsewhere in radiation routines RADC, RADP, and RAOR.

At each time-step, PROP updates the resistances to heat transfer using current temperatures and previously stored sets of numbers referred to here as thermal parameter sets. These thermal parameter sets contain numbers that specify some features of the heat transfer model. For most models, these features include the temperature-dependence of the thermal conductivity of a comprising material or composite.

Heat transfer models available in PROP include:

- conduction in isotropic or orthotropic substances
- conduction through layered composites offering parallel conduction paths
- conduction through layered composites offering series conduction paths
- conduction and radiation among arrays of cylinders having axes in the z-direction (treated as a continuum)
- normal conduction through single or series films between cells, including gaps with combined radiation and conduction
- parallel heat transfer by radiation and by forced or natural convection from cask ends.

Input to PROP sets thermal properties of the system. On initiation or restart of a simulation, PROP reads:

- substance thermal conductivity information
- information specifying the heat transfer models
- information to assign thermal resistance parameters on the computational grid.

The substance thermal conductivity information comprises sets of coefficients for the thermal conductivity λ of material MAT expressed as a polynomial in absolute temperature:

$$\lambda(MAT) = CCONO(MAT) + CCON1(MAT)*T + CCON3(MAT)*T^3$$

The sets of (CCONO(MAT), CCON1(MAT), CCON3(MAT)) are read in PROP Input Block 3. The index MAT indicates a set for a particular material, and the name MAT is used in labeling this information in the echoed input.

The specification of the heat transfer models is done partly in PROP Input Blocks 4, 5, and 6, which direct the construction of thermal parameter sets (of set index MT). The specification of the heat transfer models is completed in PROP Input Block 7, in which I,J,K index ranges for thermal resistance assignment are followed by sets of (ID,MT) pairs. The composite identifier ID indicates the composite thermal model type (orthotropic and parallel conduction, series conduction, continuum fuel assembly conduction and radiation, cask-end convection) and the resistance component affected. The index MT specifies the thermal parameter set to use.

This sequence of operations in setting the thermal resistances from input is summarized in Table 5.1.

The effects of these models are included during the numerical solution only through the resistivity arrays RESX, RESY, and RESZ, and the film resistance arrays RESFX, RESFY, and RESFZ. In conduction, RESX(I,J,K) is the reciprocal of the effective thermal conductivity for heat flow in the x-direction within the (I,J,K) cell. In conduction, RESFX(I,J,K) is the film

TABLE 5.1. Summary of PROP Input Blocks, Operations, and Indices

PROP Input Block	Information Category	Arrays or Variable Sets Sets Read or Constructed	Identifying Name of Set Index
1	Thermal resistance specifications		
2	Rectangular grid cask-end convection specifications	Convection parameter sets (TOPH, TOPL, TOPV, TOPC, TOPN) and (BOTH, BOTL, BOTV, BOTC, BOTN) for the cask-end 51 group (ID = 51 or 52)	
3	Materials conductivity polynomial coefficient sets	(CCON0(MAT), CCON1(MAT), CCON3(MAT)), MAT = 1, MATS	MAT
4	Parallel, isotropic, and orthotropic conduction models	Thermal parameter sets for the isotropic 01 group (ID = 01, 02, 03, or 04) or the parallel conduction 11 group (ID = 11, 12, 13, 14, 15, or 16)	MT
5	Series conduction models	Thermal parameter sets for the cell-centered series conduction 21 group (ID = 21, 22, or 23) or the intercell film 41 group (ID = 41, 42, or 43)	MT
6	Fuel assembly conduction-radiation models	Thermal parameter sets for the fuel assembly conduction-radiation group 31 (ID = 31)	MT
7	Assignment of thermal resistance to cell locations	Mesh ranges and (ID,MT) pairs for assigning thermal resistances	

thickness divided by its conductivity for heat flow at the interface between cell (I,J,K) and cell (I+1,J,K). Similar definitions apply for y- and z-direction heat flow.

The user will get insight for the use of the models and the RES and RESF arrays by considering how they are used in the finite-difference equations.

HYDRA-II assumes a total heat transfer rate $Q_{K\to K+1}$ from cell (I,J,K) to cell (I,J,K+1) to have the form

$$Q_{K\to K+1} = (CK)_K\, T_K - (AK)_K\, T_{K+1} + (SK)_K \qquad (5.1)$$

where CK_K, AK_K, and SK_K are functions of conductivity, flow velocity, properties of flowing material, cell size, and heat source. Indices I and J are suppressed in Equation (5.1). Specializing to no flow and no volumetric heat source simplifies the expressions of Equation (5.1) to

$$Q_{K\to K+1} = \frac{\Delta x \Delta y}{\left(\frac{\Delta z}{2\lambda}\right)_K + \frac{1}{h_K} + \left(\frac{\Delta z}{2\lambda}\right)_{K+1}} \left(T_K - T_{K+1}\right) \qquad (5.2)$$

$$= \frac{\Delta x \Delta y}{\frac{1}{2}\,\Delta z_K * RESZ_K + RESFZ_K + \frac{1}{2}\,\Delta z_{K+1} * RESZ_{K+1}} \left(T_K - T_{K+1}\right) \qquad (5.3)$$

Here, λ is the thermal conductivity and 1/h is the film resistance. Equation (5.3) shows the additive nature of resistances to heat flow from the parts of the series path from the midplane of cell K to the film, through the film, and to the midplane of cell K+1.

A few observations follow from inspection of Equation (5.3):

1. If either the film resistance or the volumetric resistivity for heat conduction into a cell in a given direction is infinite, then no conductive heat flow will occur. This provides two ways of imposing an insulated boundary condition or zero heat flow condition required for symmetry, namely setting either the normal resistivity or the normal film resistance effectively infinite. If high phantom cell resistivity is used to impose insulated boundary conditions, the phantom cell thickness in the normal direction must not be infinitesimal but must have a resistivity times thickness that is relatively large.

2. If the effective resistivity within a cell for conduction in a particular direction is zero, the effect is equivalent to moving the cell center temperature to the cell boundary in that direction. This should be used in setting a temperature boundary condition at the edge of the computation region; i.e., set the resistivity in the phantom cell to zero and the phantom cell temperature to the value desired at the edge of the adjacent computational cell.

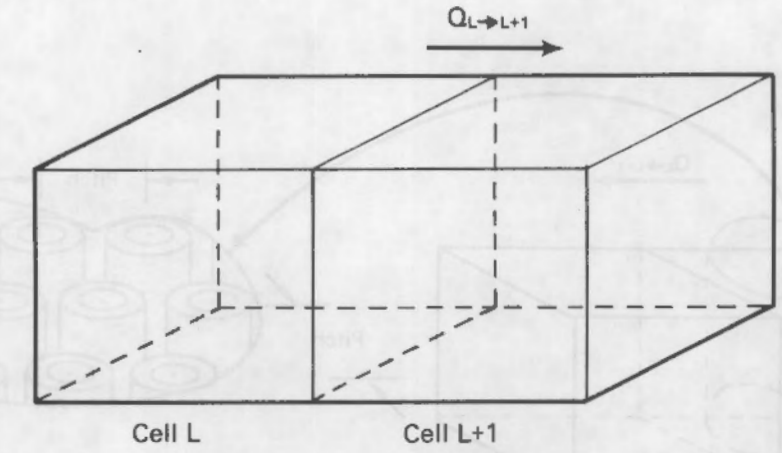
3. Resistances to heat transfer by processes other than conduction can be modeled by appropriate temperature-dependent choices of resistivity and/or film resistance parameters, as we will show for specific cases.

The process of setting the RESX, RESY, RESZ, RESFX, RESFY, and RESFZ variables in subroutine PROP occurs in phases for these models. Descriptive input for these models is read in PROP in a series of input blocks. PROP Input Block 2 specifies some parameters needed for the cask end convection models. Input Block 3 specifies a number of sets of polynomial coefficients for conductivity of substances, the sets CCON0(MAT), CCON1(MAT), and CCON3(MAT) for MAT = 1 to MATS. Subsequent input blocks 4, 5, and 6 specify the construction of thermal parameter sets for use in the heat transfer models. These thermal parameters include the arrays C0(MT), C1(MT), C3(MT), and selected others for the specific models. Most commonly, the set C0(MT), C1(MT), and C3(MT) is a set of polynomial coefficients for a conduction-related variable. A final block of input to PROP gives final specifications for the construction of the resistance-related arrays according to these models, including the mesh locations at which they apply. The actual setting of resistance arrays is done at each time-step, using the latest temperatures, the constructed thermal parameter sets, and the resistance assignment directive sets.

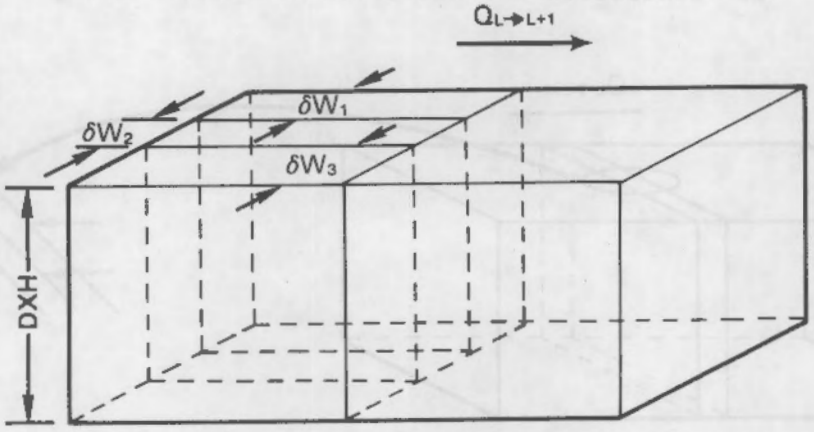
Table 5.2 provides summary information for construction of the thermal parameter sets needed in the thermal models. It should be referred to in the following discussions of models and of input data. Figure 5.1 shows schematic

TABLE 5.2. Thermal Parameter Set Construction for Heat Transfer Models

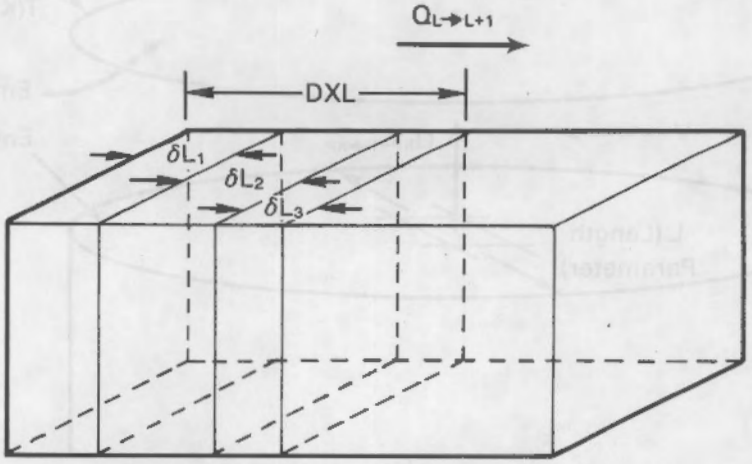
Model	Nature of C0, C1, and C3 Arrays	Input Block Where Specified	Other Thermal Parameters of Model
Single isotropic or orthotopic conduction	Polynomial for effective conductivity in the L coordinate direction in the form $\lambda_L(MT) = CO(MT)+C1(MT)*T+C3(MT)*T^3$	PROP Input Block 4	None
Conduction through layers offering parallel paths to heat flow in a coordinate direction	Polynomial for $\Sigma_i\lambda_i\delta W_i$ for the composite in the form $\Sigma_i\lambda_i\delta W_i = CO(MT)+C1(MT)*T+C3(MT)*T^3$ $= (\Sigma_{MAT}CCONO(MAT)*\delta W_{MAT})$ $+ (\Sigma_{MAT}CCON1(MAT)*\delta W_{MAT})*T$ $+ (\Sigma_{MAT}CCON3(MAT)*\delta W_{MAT})*T^3$	PROP Input Block 4	None
Conduction through layers offering series paths to heat flow in a coordinate direction	Polynomial for $\lambda/\delta L$ for one material in the series: $(\lambda/\delta L)_{MT} = CO(MT)+C1(MT)*T+C3(MT)*T^3$ C3(MT) is optionally set from a gap radiation model as $C3(MT) = 4.*\sigma/(1/\varepsilon_1 + 1/\varepsilon_2 - 1)$	PROP Input Block 5	None
Array of cylinders or fuel assembly conduction-radiation model	C1(MT) and C2(MT) are polynomial coefficients for conductivity of intervening gas. C3(MT) can be coefficient of T^3 in radiation contribution to transverse conduction. All are used with other parameters (pitch, diameters, and conductivities) in model	PROP Input Block 6	CFUEL(MT), CCLAD(MT)
Conduction through cell interface	Polynomial for $\lambda/\delta L$ for one film layer type: $(\lambda/\delta L)_{MT} = CO(MT)+C1(MT)*T+C3(MT)*T^3$ C3(MT) is optionally set from a gap radiation model as $C3(MT) = 4.*\sigma/(1/\varepsilon_1 + 1/\varepsilon_2 - 1)$	PROP Input Block 5	TWF(MT)
Cask end radiation and convection	No set constructed for this model. C3(MT) from a set constructed for conduction through a film or a series layer should be referenced in INDEX in PROP Input Block 7	PROP Input Block 2	TOPV, BOTV, TOPC, BOTC, TOPL, BOTL, TOPN, BOTN, TWF(MT)



a. Simple Conduction

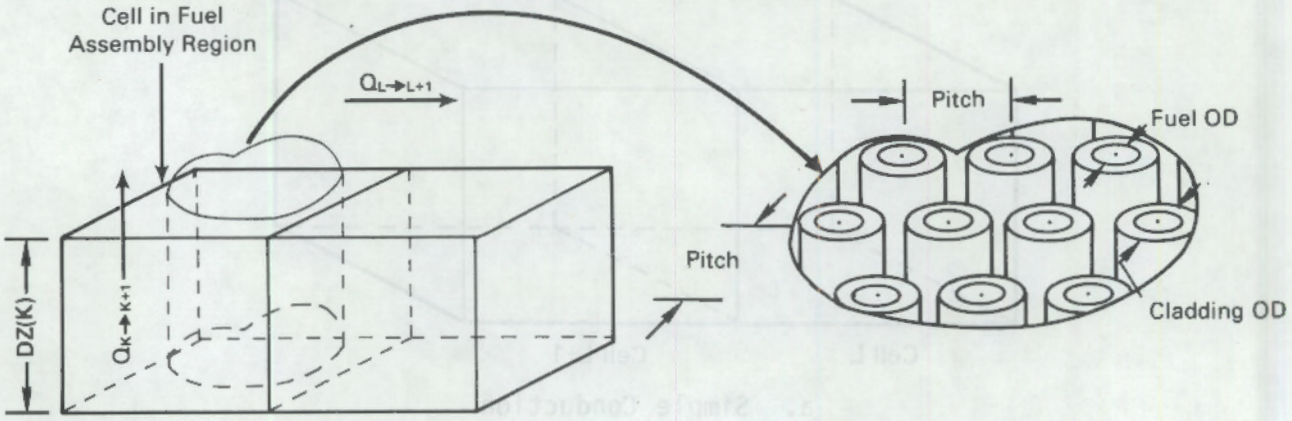


b. Conduction Through Parallel Layers

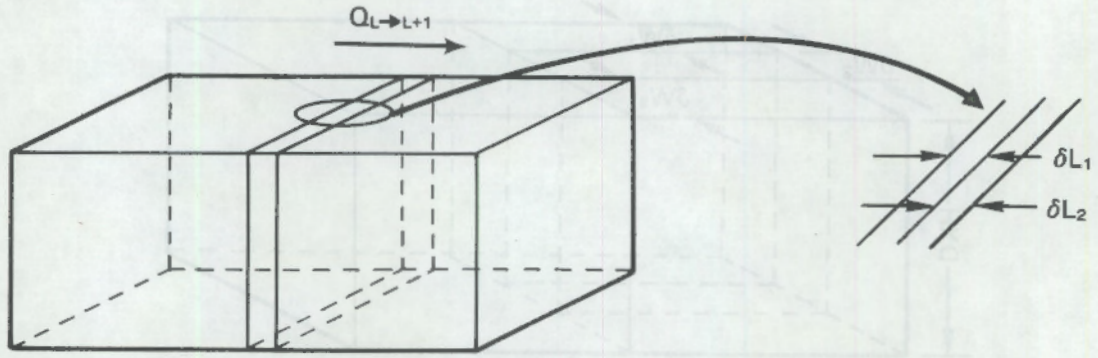


c. Conduction Through Series Layers

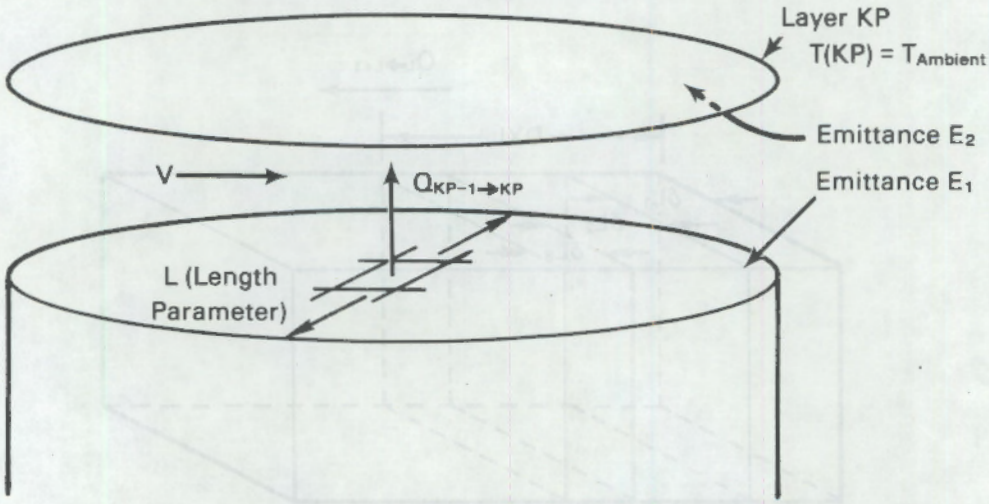
FIGURE 5.1. Heat Transfer Model Schematics



d. Conduction and Radiation in Fuel Assembly



e. Conduction Through Cell Interface Films



f. Cask Top Radiation and Convection

FIGURE 5.1. (contd)

geometry for the heat transfer models. The amount of model detail specified in intermediate blocks varies somewhat according to each model. For example, the parallel conduction model has a set of coefficients for the quantity $\Sigma_i \lambda_i \delta W_i$ formed at the intermediate stage and stored in (CO(MT), C1(MT), C3(MT)), and has the specified RESX, RESY, or RESZ value replaced by a new one in the final stage of applying the parallel conduction model to the prescribed range. By contrast, the series and film conduction models have coefficients for only single $\lambda/\delta L$ variables constructed at the intermediate stage and stored in (CO(MT), C1(MT), C3(MT)), and have the specified RESX, RESY, RESZ, RESFX, RESFY, or RESFZ altered by adding to the RESL new values of $(\lambda/\delta L)^{-1}$/DXL or to existing values of RESFL new values of $(\lambda/\delta L)^{-1}$ in turn at the final stage of applying the series conduction model to the prescribed range. The action requested as a final step assigning resistances according to various models on prescribed ranges is determined by the variable ID and the specified intermediate parameter set MT in PROP Input Block 7. Table 5.3 summarizes the ID values and the action they request on resistance arrays.

The parallel and series conduction models could be used for exotic laminated materials, but they have an important function for modeling more routinely encountered materials. These models can be applied to cells that contain more than one material type, as required to maintain an acceptable number of rectangular mesh cells while also suitably interfacing with the cylindrical grid. Figure 5.2a shows an example in which the analyst has accepted a grid boundary between the I-1 and I layers of grid cells that does not coincide with a material boundary. The heat flow through the (I,J) cell in the x-direction resembles heat flow through two layers in series, as shown in Figure 5.2b; heat flow in the y-direction resembles heat flow through two layers in parallel. The series conduction model allows calculation of the resistivity RESX for heat flow in the x-direction as if the (I,J) cell were filled as in Figure 5.2c. Similarly, the parallel conduction model allows calculation of the resistivity RESY as if the (I,J) cell were filled as in Figure 5.2c. Judicious use of these models can give reasonable global heat flow results with reduction of resolution on the scale of a single cell. The anisotropy of the material resistivity from such models may be a consequence of

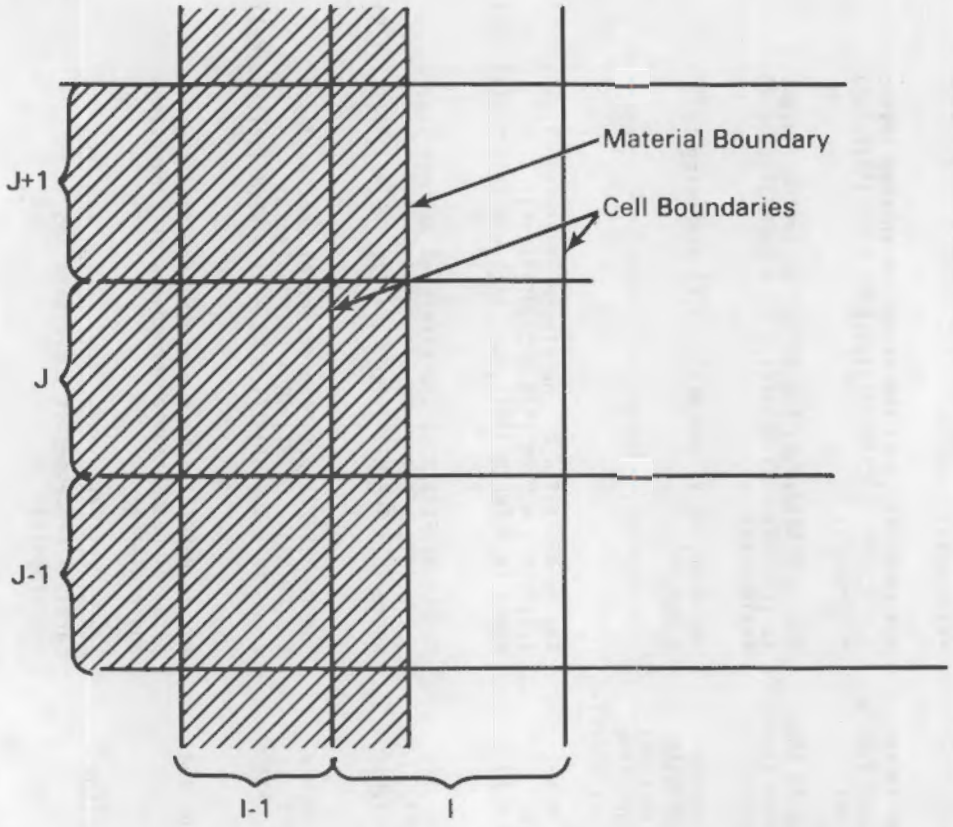
TABLE 5.3. Values, Components Affected, and Actions Requested for the Parameter ID

ID Value	Component(s) Affected	Model	Action Requested
1	RESX - resistivity in the x coordinate direction	Conduction, x-direction	Reset RESX(I,J,K) to (CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K)**3)**(-1)
2	RESY - resistivity in the y coordinate direction	Conduction, y-direction	Reset RESY(I,J,K) to (CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K)**3)**(-1)
3	RESZ - resistivity in the z coordinate direction	Conduction, z-direction	Reset RESZ(I,J,K) to (CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K)**3)**(-1)
4	RESX,RESY, and RESZ - resistivities in all 3 coordinate directions	Isotropic conduction, x-, y-, and z-directions	Reset RESX(I,J,K), RESY(I,J,K), and RESZ(I,J,K) to (CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K) **3)**(-1)
11	RESX - resistivity in the x coordinate direction	Parallel conduction in the x-direction in layers lying in x-y planes	Reset RESX(I,J,K) to DZ(K)/(CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K)**3)
12	RESX - resistivity in the x coordinate direction	Parallel conduction in the x-direction in layers lying in x-z planes	Reset RESX(I,J,K) to DY(J)/(CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K)**3)
13	RESY - resistivity in the y coordinate direction	Parallel conduction in the y-direction in layers lying in x-y planes	Reset RESY(I,J,K) to DZ(K)/(CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K)**3)
14	RESY - resistivity in the y coordinate direction	Parallel conduction in the y-direction in layers lying in y-z planes	Reset RESY(I,J,K) to DX(I)/(CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K)**3)
15	RESZ - resistivity in the z coordinate direction	Parallel conduction in the z-direction in layers lying in x-z planes	Reset RESZ(I,J,K) to DY(J)/(CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K)**3)
16	RESZ - resistivity in the z coordinate direction	Parallel conduction in the z-direction in layers lying in y-z planes	Reset RESZ(I,J,K) to DX(I)/(CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K)**3)

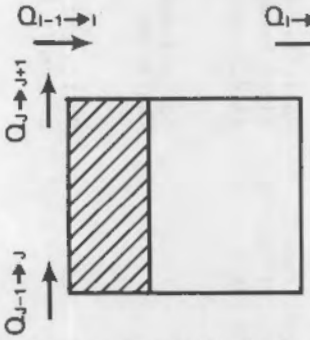
TABLE 5.3. (contd)

ID Value	Component(s) Affected	Model	Action Requested
21	RESX - resistivity in the x coordinate direction	Series conduction in the x-direction through layers lying in y-z planes	Add to RESX(I,J,K) the effect of another layer: 1./((CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K) **3)*DX(I))
22	RESY - resistivity in the y coordinate direction	Series conduction in the y-direction through layers lying in x-z planes	Add to RESY(I,J,K) the effect of another layer: 1./((CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K) **3)*DY(J))
23	RESZ - resistivity in the z coordinate direction	Series conduction in the z-direction through layers lying in x-y planes	Add to RESZ(I,J,K) the effect of another layer: 1./((CO(MT) + C1(MT)*T(I,J,K) + C3(MT)*T(I,J,K) **3)*DZ(K))
31	RESX, RESY and RESZ - resistivities in all three coordinate directions	Conduction in a square array of cylinders with axes in the z-direction. Radiative and conductive transfer between cylinders.	Set RESX, RESY, and RESZ(I,J,K) according to model.
41	RESFX - film resistance (thickness times resistivity) to conduction in the x direction	Resistive layer in y-z plane between cell (I,J,K) and (I+1,J,K)	Add to RESFX(I,J,K) the effect of another layer: 1./(CO(MT) + C1(MT)*TB + C3(MT)*TB**3) where TB = TWF(MT)*T(I,J,K) + (1.-TWF(MT))*T(I+1,J,K)
42	RESFY - film resistance (thickness times resistivity) to conduction in the y direction	Resistive layer in x-z plane between cell (I,J,K) and (I,J+1,K)	Add to RESFY(I,J,K) the effect of another layer: 1./(CO(MT) + C1(MT)*TB + C3(MT)*TB**3) where TB = TWF(MT)*T(I,J,K) + (1.-TWF(MT))*T(I,J+1,K)
43	RESFZ - film resistance (thickness times resistivity) to conduction in the z direction	Resistive layer in x-y plane between cell (I,J,K) and (I,J,K+1)	Add to RESFZ(I,J,K) the effect of another layer: 1./(CO(MT) + C1(MT)*TB + C3(MT)*TB**3) where TB = TWF(MT)*T(I,J,K) + (1.-TWF(MT))*T(I,J,K+1)
51	RESFZ(I,J,KP-1)	Top end convection and radiation	Add to RESFZ(I,J,K) a contribution from the parallel heat transfer processes of convection and radiation
52	RESFZ(I,J,1)	Bottom end convection and radiation	Add to RESFZ(I,J,K) a contribution from the parallel processes of convection and radiation(a)

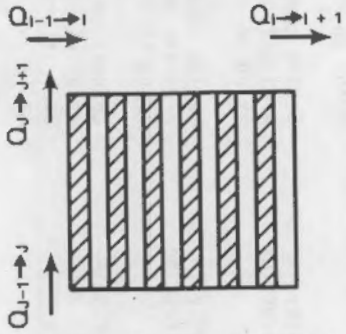
(a) The user should ensure that the K range (KBEG, KEND) is (KP-1, KP-1) for cask top, and (1,1) for cask bottom in the range specifications.



a. Material Boundary Not Coincident with Cell Boundary



b. Series/Parallel Heat Transfer



c. Series/Parallel Heat Transfer Using RESX and RESY

FIGURE 5.2. Parallel and Series Heat Transfer Examples

the noncoincidence of material and cell interfaces, not of intrinsic material structure, but it is useful for optimizing resolution when the number of cells is limited.

5.1.1 Simple Isotropic or Orthotropic Conduction Model

Subroutine PROP reads sets of polynomial coefficients CCON0, CCON1, and CCON3 for calculating conductivity λ of substance MAT at temperature T from

$$\lambda(MAT) = CCON0(MAT)+CCON1(MAT)*T+CCON3(MAT)*T^3 \qquad (5.4)$$

These CCON type substance conductivity coefficient sets are read in PROP Input Block 3. These substance conductivity coefficients can subsequently be used to set arrays of coefficients C0(MT), C1(MT), and C3(MT) for polynomials that give either conduction-related parameters with a similar three-term polynomial or some other set of information used in setting RES or RESF type arrays. For simple isotropic or orthotropic conduction in material MT, the values (C0(MT), C1(MT), C3(MT)) will be set directly to (CCON0(MAT), CCON1(MAT), CCON3(MAT)), where MAT is a designated index for the thermal parameter set MT.

5.1.2 Parallel Conduction Model

For a set of layers that offer parallel paths for conduction in the L direction, the effective resistivity R_L is

$$R_L = W/(\Sigma_i \lambda_i \delta W_i) \qquad (5.5)$$

where λ_i is the conductivity of the ith material in the composite and δW_i is its width. W is the width of the cell in the direction normal to the parallel planes of the composite. It is usually the case that

$$W = \Sigma_i \delta W_i \qquad (5.6)$$

The polynomial coefficient sets for the λ_i are input in PROP Input Block 3 in the CCON0, CCON1, and CCON3 arrays and subsequently used in setting the polynomial coefficients C0, C1, and C3 for $\Sigma\lambda_i\delta W_i$. The variables δW_i are input as WIDTH in PROP Input Block 4, along with the list of material property sets determining the λ_i to use in the $\Sigma\lambda_i\delta W_i$ sum. PROP Input Block 4 directs the construction of polynomial coefficients for $\Sigma\lambda_i\delta W_i$.

5.1.3 Series Conduction Model

For a set of layers offering series conduction paths in the L-direction through a computational cell, the effective resistivity in the L-direction is

$$R_L = \left(\Sigma_i \frac{1}{(\lambda_i / \delta L_i)} \right) \text{DXL} \qquad (5.7)$$

where DXL is the computational cell length in the L-direction, λ_i is the conductivity of the ith material in the composite, and δL_i is the path length per computational cell supplied by the ith material. The variables δL_i for series layers are read as WIDTH in PROP Input Block 5, along with the index of the set of coefficients for the λ_i previously read in PROP Input Block 3. PROP Input Block 5 directs construction of polynomial coefficients for the quantities $\lambda_i/\delta L_i$. The direction of conduction and the orientation of the slabs is specified later by the variable ID read in the array INDEX in PROP Input Block 7. The coefficient sets for quantities of the form $\lambda_i/\delta L_i$ can also be used in the construction of film resistances for interfaces between cells. An option is available for construction of the cubic term in the series for $\lambda_i/\delta L_i$ according to a radiation model (see discussion of conduction through films).

5.1.4 Array of Cylinders or Fuel Assembly Model

The fuel assembly model constructs effective resistivities RESX, RESY, and RESZ for an array of cylinders having axes in the z-direction stored in a square pattern in the x-y plane. The cylinders are assumed to be composed of a circular cylinder core and annular clad, each region having its own characteristic conductivity. Resistivity RESZ is computed on the assumption of parallel conduction paths in the cylinder core, cladding, and intervening gas. Transverse resistivities RESX and RESY are computed on the basis of a two-dimensional model that includes conduction in the cylinder core, cladding, and gas, as well as radiative heat transfer among the cylinders.

It should be noted that the radiative heat transfer among an array of fuel cylinders may, under special conditions, be treated by a more precise model (subroutine RADR) elsewhere in the code. For most practical purposes, RADR will require a region of the Cartesian mesh with one cylinder per cell column

in the z-direction. The user who can and wishes to use the RADR model can specify ignoring the radiative part of the transverse heat transfer in the fuel assembly model by setting either rod emissivity EROD or gap emissivity EGAP to zero in PROP Input Block 6.

5.1.5 Conduction Through Films

Films or gaps whose thicknesses are small compared with computational cells can have a significant effect on heat transfer. The effect as modeled in HYDRA-II can be seen for the case of no flow in Equation (5.3). HYDRA-II allows input of sets of polynomial coefficients for a number of materials in PROP Input Block 3. Subsequent input in PROP Input Block 5 allows construction of polynomial coefficients for series layer type quantities $\lambda/\delta L$, as described for the series conduction model. Coefficients of the $\lambda/\delta L$ type can also be used to construct film resistances singly or in series for the interfaces between grid cells.

A special feature allows construction of a film resistance for a narrow gap across which radiation occurs. RESFX, RESFY, and RESFZ are essentially reciprocals of heat transfer coefficients for the interface film between cell (I,J,K) and cell (I+1,J,K), (I,J+1,K), or (I,J,K+1), respectively. Radiation and conduction across a gas-filled gap are essentially parallel processes. Hence, the total heat transfer rate across a gap of width δL and area A will be

$$Q = \frac{\lambda'}{\delta L} A \left(T_1 - T_2\right) + A\sigma \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \left(T_1^4 - T_2^4\right) \tag{5.8}$$

where σ is the Stefan-Boltzman constant, ε_1 and ε_2 are emittances of the two surfaces facing the narrow gap, λ' is the thermal conductivity, and T_1 and T_2 are absolute temperatures on the two sides. If the absolute temperature difference in Equation (5.8) is not excessive, one can approximate Equation (5.8) by

$$Q = \frac{\lambda'}{\delta L} A \left(T_1 - T_2\right) + 4A\sigma \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} T_B^3 \left(T_1 - T_2\right) \tag{5.9}$$

where T_B is some temperature between T_1 and T_2. Noting that Q/A should be $(T_1 - T_2)*(\lambda/\delta L)$ for an equivalent $\lambda/\delta L$, we can express Equation (5.9) in terms of an effective $\lambda/\delta L$:

$$\frac{\lambda}{\delta L} = \frac{\lambda'}{\delta L} + \frac{4\sigma}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} T_B^3 \qquad (5.10)$$

In constructing polynomial coefficients for the $\lambda/\delta L$ type quantities, HYDRA-II permits the coefficient of the cubic term, C3(MT), to be constructed either directly from a gap radiation model as $4\sigma/(1/\epsilon_1 + 1/\epsilon_2 - 1)$ with ϵ_1 and ϵ_2 as input emittances, or from the specified substance input variable set MAT as C3(MT) = CCON3(MAT)/δL. The constructed polynomial coefficient set can thus optionally model conduction and radiation as parallel processes across the gap in the effective $\lambda/\delta L$, and the implied film or layer resistance can be placed in series with other layer resistances either within or between cells. Film resistance sets can be used in setting boundary conditions for cask ends.

The resistance to heat flow of the phantom cell between the flat parts of the rectangular grid boundary and the cylindrical grid interface can be accurately represented using the film resistance model. The volumetric resistivity for heat flow into these cells from the adjacent rectangular grid computational cell should be set to a low value. The film resistance, however, should be set to a value equal to the resistivity of the material there multiplied by the distance from the outside edge of the adjacent grid computational cell to the cylindrical grid interface. One can set up the $\lambda/\delta L$ polynomial coefficient values in PRDP Input Block 5 for which $(\lambda/\delta L)^{-1}$ will give the desired resistivity multiplied by heat flow distance.

5.1.6 Cask End Convection and Radiation

Cask end boundary conditions are imposed using the resistance RESZ entries for K = 1 and K = KP, the film resistance RESFZ entries for K = 1 and K = KP-1, and the phantom cell temperature entries for K = 1 and K = KP. The physical phenomena modeled for cask ends are radiation and convection, and equivalent film resistance for these processes in parallel being added to whatever other

film resistance the user specifies to be present. Convection and radiation from the ends are modeled as parallel processes with additive heat transfer coefficients. The reciprocal of the sum of the heat transfer coefficients for these processes is added to the film resistance RESFZ(I,J,1) or RESFZ(I,J,KP-1) as directed by entries in PROP Input Block 7. Options for the end conditions are set in PROP Input Block 2. Some entries needed for the radiation model can be set in PROP Input Block 5 as $\lambda/\delta L$ type film information.

The heat transfer coefficient for radiation is calculated as $C3(MT)*T_B^3$, where T_B is a boundary temperature and C3(MT) is a polynomial coefficient stored for the intermediate material properties set MT. In the specified set MT of intermediate material properties, the value of C3(MT) should have been appropriately set either as some CCON3(MAT)/δL, or from a gap radiation model in which $C3(MT) = 4\sigma/(1/E1 + 1/E2 - 1)$. This radiation model option for setting C3(MT) is available in setting the $\lambda/\delta L$ type polynomial coefficients in PROP Input Block 5. The boundary temperature T_B for radiation is a weighted average of the temperature in the edge computational cell and the phantom cell:

$$T_B = TWF(MT)*T(I,J,KBEG)+(1.-TWF(MT))*T(I,J,KBEG+1) \qquad (5.11)$$

Here, KBEG is an entry in PROP Input Block 7 and should be set to 1 for setting bottom boundary conditions and KP-1 for top. TWF(MT) should have been set with the other series layer information in PROP Input Block 5.

The heat transfer coefficient for convection from cask ends can be set according to either natural or forced convection models. The models available are based on parameterized dimensionless correlations, but are specialized to air at atmospheric pressure as the medium and use linear approximations for the temperature dependence of its thermal conductivity and viscosity. The models are summarized below.

Forced Convection

Dimensionless Correlation

$$\frac{hL}{k} = C\left(\frac{\rho VL}{\mu}\right)^n \tag{5.12}$$

Coded Expression

$$h = \left(0.688\text{x}10^{-4} + 0.635\text{x}10^{-6}\ T_B\right)\frac{C}{L}\left(\frac{0.35296\ VL}{T_B\ \ 0.608\text{x}10^{-4} + 0.4\text{x}10^{-6}\ T_B}\right)^n \tag{5.13}$$

User-Selected Parameters

C,n,L,V

Assumptions

$\rho = (\rho_o T_o)/T$

Linear approximations shown for μ and k.

Natural Convection

Dimensionless Correlation

$$\frac{hL}{k} = C\left[\frac{L^3\rho^2 g\beta\Delta T}{\mu^2}\left(\frac{C_p\mu}{k}\right)\right]^n \tag{5.14}$$

Coded Expression

$$h = \left(0.688\text{x}10^{-4} + 0.634\text{x}10^{-6}\ T_B\right)\frac{C}{L} * \left[\frac{87.9638\ (L/T_B)^3\ \Delta T}{\left(0.608\text{x}10^{-4} + 0.4\text{x}10^{-6}\ T_B\right)^2}\right]^n \qquad (5.15)$$

User-Selected Parameters

C,n,L

Assumptions

$$\beta = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_\rho = \frac{1}{T_B}$$

$$\rho = (\rho_0 T_0)/T$$

$$(\rho_0 T_0)^2\ g\ \frac{C_p \mu}{k} = 87.9638 \left(\frac{gm°K}{cm^3}\right)^2 cm/sec^2$$

Linear approximation shown for μ and k.

Definitions in the above forced and natural convection expressions are

h = convective heat transfer coefficient
k = thermal conductivity of gas medium in the boundary layer
ρ = gas medium density
V = forced convection flow velocity
μ = viscosity of the gas medium
T_B = boundary layer Kelvin temperature
$\Delta T = |T_{ambient} - T_{material}|$

L = length parameter representative of convecting surface

g = acceleration of gravity.

The boundary layer temperature T_B is calculated in the code as the average of the end layer (K = 2 for bottom, K = KP-1 for top) temperature in the Cartesian grid region and the respective ambient temperatures.

5.2 PARAMETER STATEMENT INFORMATION

The following array-dimensioning parameters have the same significance and should have the same value as in subroutine GRID (Chapter 4.0):

IP,JP,KP,ISP,JSP

Additional parameters appearing in subroutine PROP are:

- NMATP - An array-dimensioning parameter greater than or equal to the number of substance conductivity polynomial coefficient sets read in PROP Input Block 3.
- MTP - An array-dimensioning parameter greater than or equal to the largest value of MT for the intermediate variable sets (in arrays C0, C1, C3, TWF, CFUEL, CCLAD, etc.) for heat transfer models constructed from directives in PROP Input Blocks 4, 5, and 6.
- NSPECP - Dimension of the array SPECS used in PROP Input Blocks 4, 5, and 6 to read in end-to-end all the intermediate heat transfer model specifications in each of the blocks. The SPECS array is overwritten by each of those input blocks in turn, but it must be long enough to accommodate the longest of the three blocks.
- NREGP,NPAIRP - Two parameters used in setting length of the INDEX array (to INDEXP = 7*NREGP+2*NPAIRP) containing directives for assigning resistivity and film resistance values to cell locations (in PROP Input Block 7). NREGP is the maximum allowed number of region (range)

specifications for resistance assignment. NPAIRP is the sum over all the region specifications of the number of (ID,MT) pairs, where ID is an identifier of the resistance parameter affected and the model used, and MT is an identifier of the intermediate heat transfer variable set to use for that model. Each region directive set may request implementation of one or several changes in the resistance arrays for that region by including one or several (ID,MT) pairs.

5.3 INPUT FORMAT

5.3.1 Overview

The input to Subroutine PROP can be broken into seven blocks:

1. thermal resistance print specifications
2. rectangular grid cask end convection specifications
3. materials conductivity polynomial coefficient sets
4. parallel, isotropic, and orthotropic conduction models
5. series conduction models
6. fuel assembly conduction-radiation models
7. assignment of resistance to cell locations.

Detailed input will be described for these blocks.

5.3.2 Thermal Resistance Print Specifications. PROP Input Block 1

General Input Format

```
NECHO
NSX,NSFX,NSY,NSFY,NSZ,NSFZ,INFO
```

General Input Definition

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- NSX,NSFX,NSY,NSFY,NSZ,NSFZ - The number of the time-step at which to print the RESX, RESFX, RESY, RESFY, RESZ, and RESFZ

arrays, respectively. A negative entry suppresses printing of that array.

- INFO - Integer flag variable that, if equal to 1, requests printing of each resistivity or film resistivity array at its designated (by NSX, NSFX, etc.) time-step. No printing occurs if INFO = 0.

Input File Example

```
90      1/prop
91      -1,-1,-1,-1,-1,-1,0
```

Echoed Input File Example

```
180    prop    nsx= -1    nsfx= -1    nsfy= -1    nsz= -1    nsfz= -1    info= 0
```

The echoing of input is requested by setting NECHO = 1; the remainder of the input line serves for comment. The printout of the RESL and RESFL (with L = x, y, or z) has been doubly suppressed, with INFO = 0 and NSX, NSFX, NSY, etc., set to -1. The user is advised to obtain these resistance array printouts (INFO = 1, NSX = 1, etc.) at least once in an early execution, to verify correctness of thermal model geometry and input.

5.3.3 Cartesian Cask End Convection Specifications

General Input Format

```
TOPH,TOPL,TOPV,TOPC,TOPN
BOTH,BOTL,BOTV,BOTC,BOTN
```

General Input Definition

- TOPH - Floating point flag variable that, if equal to 1.0, indicates a top end convective model is forthcoming. (Note: The line should contain five entries, even if TOPH = 0.0.)
- TOPL - Length L to use in the forced convection [Equation (5.12)] or the natural convection [Equation (5.14)] heat transfer correlations for the cask top.

- TOPV - Velocity to use in forced convection heat transfer correlation for top cask end. Setting TOPV = 0.0 with TOPH = 1.0 invokes the natural rather than forced convection model.
- TOPC - Constant C to use for the top cask end heat transfer correlation in either forced convection [Equation (5.12), TOPV > 0.0] or natural convection [Equation (5.14), TOPV = 0.0].
- TOPN - Exponent n to use for the top cask end heat transfer correlation in either forced convection [Equation (5.12), TOPV > 0.0] or natural convection [Equation (5.14), TOPV = 0.0].
- BOTH,BOTL,BOTV,BOTC,BOTN - Values of convection flag, L, V, C, and n, respectively, for the cask bottom, analogous to TOPH, TOPL, TOPV, TOPC, and TOPN, respectively, for the cask top.

The complete specification of cask end thermal conditions will require entries elsewhere in PROP, such as radiation parameters or surface film resistances in Input Block 5 and resistance assignments in Input Block 7.

Input File Example

```
92      1.0,220.0,0.0,0.14,0.333
93      1.0,220.0,0.0,0.27,0.25
```

Echoed Input File Example

```
182
183     prop    toph=1.0    topl=0.220e+03    topv=0.000e+00    topc=0.140e+00    topn=0.333e+00
184     prop    both=1.0    botl=0.220e+03    botv=0.000e+00    botc=0.270e+00    botn=0.250e+00
```

This input specifies that convection models are to be used on both the top and the bottom surfaces, because both TOPH and BOTH are set to 1.0. The length parameter in the convection correlation is set to 220 cm, on the order of the cask diameter. Setting velocity parameters TOPV and BOTV to zero specifies that the convection is natural, not forced. The coefficient C and the power n in the natural convection correlation, Equation (5.15), are specified as

(TOPC = 0.14, TOPN = 0.333) for the top and (BOTC = 0.27, BOTN = 0.25) for the bottom. Values for C and n should be taken from the heat transfer literature.

5.3.4 Material Conductivity Polynomial Coefficient Sets. PROP Input Block 3

General Input Format

```
NECHO
NMAT
TEXT
CCONO(1),CCON1(1)CCON3(1)
TEXT
CCONO(2),CCON1(2),CCON3(2)
     . . .
     . . .
     . . .
TEXT
CCONO(NMAT),CCON1(NMAT),CCON3(NMAT)
```

General Input Definition

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- NMAT - Number of sets of substance effective conductivity polynomial coefficients forthcoming.
- TEXT - Up to 40 characters of labeling information (5A8) for the next polynomial coefficient set.
- CCONO(MAT),CCON1(MAT),CCON3(MAT) - The MATth set of polynomial coefficients for representing an effective substance thermal conductivity λ(MAT) as $\lambda(MAT) = CCONO(MAT)+CCON1(MAT)*T+CCON3(MAT)*T^3$.

These substance property sets are stored temporarily and are available to construct intermediate property sets (C0(MT), C1(MT), C3(MT)) for repeated use in setting resistance variables on the mesh according to the heat transfer models. The C0(MT), C1(MT), C3(MT) sets are saved and used for updating resistance variables as temperature changes.

Input File Example

```
94 1/prop/ccon0,ccon1,ccon3
95 9
```

```
 96 low conductivity
 97 0.1e-20,0.0,0.0
 98 high conductivity
 99 0.1e+20,0.0,0.0
100 helium (backfill gas)
101 0.52e-3,0.32e-5,0.0
102 sst
103 0.09215,0.1465e-3,0.0
104 boron steel (radionox)
105 0.079,0.21e-3,0.0
106 nodular cast iron
107 0.5162,-0.3205e-3,0.0
108 epoxy (not used)
109 0.15e-2,0.0,0.0
110 nitrogen (not used)
111 0.075e-3,0.6167e-6,0.0
112 air (not used)
113 0.6880e-4,0.6340e-6,0.0
```

Echoed Input File Example

```
186    prop    nmat= 9   maximum current dimension for nmat is  20
187    prop    ccon0,ccon1,ccon3                material thermal conductivity, W/cm-K
188                          k(mat)=  ccon0(mat)+  ccon1(mat)*t+ ccon3(mat)*t*t*t
189                             1  (0.1000e-20)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   low conductivity
190                             2  (0.1000e+20)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   high conductivity
191                             3  (0.5200e-03)+(0.3200e-05)*t+(0.0000e+00)*t*t*t   helium (backfill gas)
192                             4  (0.9215e-01)+(0.1465e-03)*t+(0.0000e+00)*t*t*t   sst
193                             5  (0.7900e-01)+(0.2100e-03)*t+(0.0000e+00)*t*t*t   boron steel (radionox)
194                             6  (0.5162e+00)+(-.3205e-03)*t+(0.0000e+00)*t*t*t   nodular cast iron
195                             7  (0.1500e-02)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   epoxy (not used)
196                             8  (0.7500e-04)+(0.6167e-06)*t+(0.0000e+00)*t*t*t   nitrogen (not used)
197                             9  (0.6880e-04)+(0.6340e-06)*t+(0.0000e+00)*t*t*t   air (not used)
```

The input requests echoing of the nine material conductivity polynomial coefficient sets forthcoming. First descriptive text, then the list of three coefficients, appears for each of the nine sets. Note that some input sets may not be subsequently referenced.

The echoed input specifies the number of such sets NMAT, and also gives the current number, NMATP, of such sets that can be accommodated. The coefficient sets are printed out in a form that suggests their use, followed by the labeling text for that set.

5.3.5 Parallel, Isotropic, and Orthotropic Conduction Models. PROP Input Block 4

General Input Format

```
NECHO
NTMAX
SPECS(I),I=1,NSPECP
```

The entire dimensioned SPECS array is read. The user should construct it with MTMAX sets of entries, the sets being read end-to-end. It is recommended that each set of entries occupy one or more lines of input as needed, but that no lines contain entries for more than one of the sets. The form for a set for simple isotropic or orthotropic conduction or parallel conduction is

$$\left.\begin{array}{l}\text{MT, MATS, MAT}_1\text{, WIDTH}_1\text{, MAT}_2\text{, WIDTH}_2\text{, ... MAT}_{\text{MATS}}\text{, WIDTH}_{\text{MATS}}\text{,}\end{array}\right\} \text{ MTMAX such sets}$$

Unused locations of the NSPECP locations in SPECS should be set to zero. The entries in SPECS are in floating point form, but MT, MATS, MAT_1, ... MAT_{MATS} are integer-type information after conversion.

General Input Definition

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- MTMAX - The number of specification sets forthcoming for the construction of thermal parameter property sets (CO(MT),C1(MT),C3(MT)) of the simple or parallel conduction types.
- MT - Index of a thermal parameter set for setting resistivity or film resistivity arrays.
- MATS - The number of pairs of substance property index MAT and thickness WIDTH for use in setting the MTth intermediate parameters set.
- MAT_1,$WIDTH_1$,MAT_2,$WIDTH_2$ - The substance property set indices MAT and the corresponding laminar layer thickness per cell δW = WIDTH for slabs offering parallel conduction

paths. See Equation (5.5). For simple substance conduction (as opposed to parallel laminar composite conduction), MATS will be 1 and $WIDTH_1$ should be set to 1.0.

The reading of the data in PROP Input Block 4 will direct construction of MTMAX thermal parameter set coefficients (CO(MT),C1(MT),C3(MT), with those for which MATS was 1 and WIDTH was 1.0 being polynomial coefficients for simple material conduction, and the others being for $\Sigma_i \lambda_i \delta W_i$ for parallel laminar composites. The simple substance sets with MATS = 1 and WIDTH = 1.0 are intended for use with ID = 1,2,3, or 4 in PROP Input Block 7. Those with MATS > 1 or WIDTH ≠ 1.0 are intended for use with ID = 11,12,13,14,15 or 16 in PROP Input Block 7.

Input File Example

```
114 1/prop/specs def. 01 isotropic and 11 parallel
115 27
116 1.0,1.0,1.0,1.0,
117 2.0,1.0,2.0,1.0,
118 3.0,1.0,3.0,1.0,
119 4.0,1.0,4.0,1.0,
120 5.0,1.0,5.0,1.0,
121 6.0,2.0,3.0,1.0,
122         5.0,1.0,
123 7.0,1.0,5.0,0.7816,
124 8.0,2.0,3.0,0.5,
125         5.0,0.5,
126 9.0,1.0,3.0,2.0,
127 10.0,1.0,3.0,0.5,
128 11.0,1.0,5.0,2.0,
129 12.0,1.0,5.0,0.5,
130 13.0,2.0,3.0,0.6444,
131         4.0,0.3556,
132 14.0,1.0,3.0,1.552,
133 15.0,2.0,3.0,1.289,
134          4.0,0.7112,
135 16.0,2.0,3.0,0.3222,
136          4.0,0.1778,
137 17.0,1.0,3.0,3.104,
138 18.0,1.0,3.0,3.190,
139 19.0,1.0,3.0,1.431,
140 20.0,2.0,3.0,0.7221,
141          4.0,0.2779,
142 21.0,2.0,3.0,0.8222,
143          4.0,1.778,
```

```
144 22.0,1.0,3.0,1.355,
145 23.0,1.0,3.0,1.276,
146 24.0,2.0,3.0,4.669,
147           4.0,1.143,
148 25.0,2.0,3.0,7.366,
149           4.0,0.7366,
150 26.0,1.0,6.0,1.0,
151 27.0,1.0,4.0,8.0,
152 24*0.0
```

Echoed Input File Example

```
198
199                                   maximum number of material types is currently  45
200                                   maximum array dimension of specs is currently 150
201
202                                 ***composite definition 01 isotropic and 11 parallel***
203      prop     mtmax= 27
204      prop     specs                          mt   mats   mat    width
205                                              1     1     1   0.1000e+01
206                                              2     1     2   0.1000e+01
207                                              3     1     3   0.1000e+01
208                                              4     1     4   0.1000e+01
209                                              5     1     5   0.1000e+01
210                                              6     2     3   0.1000e+01
211                                                          5   0.1000e+01
212                                              7     1     5   0.7816e+00
213                                              8     2     3   0.5000e+00
214                                                          5   0.5000e+00
215                                              9     1     3   0.2000e+01
216                                             10     1     3   0.5000e+00
217                                             11     1     5   0.2000e+01
218                                             12     1     5   0.5000e+00
219                                             13     2     3   0.6444e+00
220                                                          4   0.3556e+00
221                                             14     1     3   0.1552e+01
222                                             15     2     3   0.1289e+01
223                                                          4   0.7112e+00
224                                             16     2     3   0.3222e+00
225                                                          4   0.1778e+00
226                                             17     1     3   0.3104e+01
227                                             18     1     3   0.3190e+01
228                                             19     1     3   0.1431e+01
229                                             20     2     3   0.7221e+00
230                                                          4   0.2779e+00
231                                             21     2     3   0.8222e+00
232                                                          4   0.1778e+01
233                                             22     1     3   0.1355e+01
234                                             23     1     3   0.1276e+01
235                                             24     2     3   0.4669e+01
236                                                          4   0.1143e+01
237                                             25     2     3   0.7366e+01
238                                                          4   0.7366e+00
239                                             26     1     6   0.1000e+01
240                                             27     1     4   0.8000e+01
241
242                                     computed coefficients from specs array
```

```
243
244
245
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256
257
258
259
260
261
262
263
264
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266
267
268
269
270
271
```

mt	c0	c1	c3
1	0.1000e-20	0.0000e+00	0.0000e+00
2	0.1000e+20	0.0000e+00	0.0000e+00
3	0.5200e-03	0.3200e-05	0.0000e+00
4	0.9215e-01	0.1465e-03	0.0000e+00
5	0.7900e-01	0.2100e-03	0.0000e+00
6	0.7952e-01	0.2132e-03	0.0000e+00
7	0.6175e-01	0.1641e-03	0.0000e+00
8	0.3976e-01	0.1066e-03	0.0000e+00
9	0.1040e-02	0.6400e-05	0.0000e+00
10	0.2600e-03	0.1600e-05	0.0000e+00
11	0.1580e+00	0.4200e-03	0.0000e+00
12	0.3950e-01	0.1050e-03	0.0000e+00
13	0.3310e-01	0.5416e-04	0.0000e+00
14	0.8070e-03	0.4966e-05	0.0000e+00
15	0.6621e-01	0.1083e-03	0.0000e+00
16	0.1655e-01	0.2708e-04	0.0000e+00
17	0.1614e-02	0.9933e-05	0.0000e+00
18	0.1659e-02	0.1021e-04	0.0000e+00
19	0.7441e-03	0.4579e-05	0.0000e+00
20	0.2598e-01	0.4302e-04	0.0000e+00
21	0.1643e+00	0.2631e-03	0.0000e+00
22	0.7046e-03	0.4336e-05	0.0000e+00
23	0.6635e-03	0.4083e-05	0.0000e+00
24	0.1078e+00	0.1824e-03	0.0000e+00
25	0.7171e-01	0.1315e-03	0.0000e+00
26	0.5162e+00	-0.3205e-03	0.0000e+00
27	0.7372e+00	0.1172e-02	0.0000e+00

The initial line of the input data for this block asks for echoing of input (NECHO = 1) and contains a user comment as a reminder that the thermal parameter sets constructed here will be used either with the isotropic or orthotropic simple conduction 01 group (ID = 01,02,03, or 04), in which the constructed polynomial coefficients are for an effective conductivity $\lambda(MT)$, or with the parallel laminar conduction 11 group (ID = 11,12,13,14,15, or 16), in which the polynomial coefficients are for a sum $\Sigma_i \lambda_i \delta W_i$. Explanations of the ID values used in PROP Input Block 7 will be discussed later and are summarized in Table 5.2.

The data specifies MTMAX = 27 sets of parallel and isotropic conduction model specifications. The SPECS entries are all floating point, with conversion to integers occurring in deconvoluting the end-to-end thermal parameter specification sets. The sets MT = 1 through MT = 5 in the example shown are simple substance sets with WIDTH = 1.0. By contrast, sets MT = 6 and MT = 8 are both parallel composites with two materials present. The set MT = 6 (lines 121 and 122) could be applied to cells having one slab of thickness 1 cm of

material MAT = 3, and a second slab of thickness 1 cm of material MAT = 5. The set MT = 8 has the same two materials (MAT = 3 and MAT = 5), but would be applied to cells with 0.5-cm-thick slabs of each material offering parallel paths. The set MT = 7 (line 123) is of the parallel type, as indicated by WIDTH = 0.7816 rather than 1.0, but it has only one material present. The user is neglecting the contribution to total effective conductivity from other members (lower conductivity) of the set of parallel slabs. Referring to the data for PROP Input Block 3, we see that MT = 6 describes a composite of helium (MAT = 3) and boron steel (MAT = 5). Such composites are very useful when grid lines cannot be conveniently assigned for all material interfaces.

Note that the input data for this block ends with 24 zero values to fill out the SPECS array, which was dimensioned for this simulation to NSPECP = 150.

The echoed output is preceded by a reminder that the largest number, MT, of a thermal parameter set allowed by dimensioning is MTP and the length of the SPECS array used in PROP Input Blocks 4, 5, and 6.

The echoed input presents the MTMAX thermal parameter specification sets of this type, using MATS lines per set. The multiple-material sets thus stand out. The constructed thermal properties polynomial coefficients C0(MT), C1(MT), C3(MT) are presented. For MT sets for which MATS = 1 and WIDTH = 1.0, these sets will be the same as for the specified set MAT of substance conductivity polynomial coefficients read in PROP Input Block 3. These thermal parameter sets will be retained, however, after the substance coefficients are overwritten. Additional thermal parameter specification sets for other heat transfer models will be added in PROP Input Blocks 5 and 6.

5.3.6 Series Conduction Models. PROP Input Block 5

General Input Format

```
NECHO
MTMAX
SPECS(I),I=1,NSPECP
```

The entire dimensioned SPECS array is read. The user should construct it with MTMAX sets of entries, the sets being read end-to-end. It is recommended that

each set occupy one or more lines of input as needed, but that no lines contain entries for more than one of the sets. The input form for a laminar series conduction set is

MT,MAT,WIDTH,E1,E2,TWF(MT)

General Input Definitions

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, D.
- MTMAX - The number of specification sets forthcoming for the construction of thermal parameter sets (CO(MT), C1(MT),C3(MT),TWF(MT)) of the laminar series conduction type.
- MT - Index of a thermal parameter set for setting resistivity or film resistivity arrays. Note: specifying an index already used for other thermal parameter sets of the same or other heat model type will cause overwriting.
- MAT,WIDTH - The substance property set index MAT and the corresponding series path thickness δL = WIDTH per cell or film, for the construction of the thermal parameter set polynomial coefficients for the quantity $(\lambda/\delta L)_{MT} = \lambda(MAT)/WIDTH$.
- E1,E2 - Emittances of the two surfaces facing each other across a planar gap, if a radiation model is to be used in setting C3(MT) to $4\sigma/(1/E1 + 1/E2-1)$. If either E1 or E2 is zero, C3(MT) is instead set as C3(MT) = CCON3(MAT)/WIDTH.
- TWF(MT) - If thermal parameter set MT is used for a film resistance, TWF(MT) is the relative weighting of the

lower-index cell temperature in computing an interface film temperature for the polynomial for $\lambda/\delta L$. For example, for RESFX(I,J,K):

$$T_B = TWF(MT)*T(I,J,K) + [1.-TWF(MT)]*T(I+1,J,K)$$
$$RESFX(I,J,K) = 1./(C0(MT) + C1(MT)*T_B + C3(MT)*T_B^3)$$

The reading of the data in PROP Input Block 5 will direct the construction of MTMAX more thermal parameter sets, each set comprising C0(MT), C1(MT), C3(MT), and TWF(MT). TWF(MT) is used for films between computational cells but not for series lamina within cells. The polynomial coefficients for the series model are for $\lambda/\delta L$ for single substance films.

Input File Example

```
153 1/prop/specs def. 21 series
154 11
155 32.0,3.0,1.0,0.0,0.0,0.5,
156 33.0,3.0,0.5,0.0,0.0,0.5,
157 34.0,4.0,4.572,0.0,0.0,0.0,
158 35.0,3.0,4.669,0.0,0.0,0.0,
159 36.0,4.0,2.946,0.0,0.0,0.0,
160 37.0,3.0,7.366,0.0,0.0,0.0,
161 38.0,3.0,0.3,0.2,0.2,0.5,
162 39.0,1.0,1.0,0.2,1.0,0.5,
163 40.0,3.0,0.35,0.83,0.45,0.0,
164 41.0,3.0,0.35,0.83,0.45,1.0,
165 42.0,1.0,1.0,0.8,1.0,0.5,
166 84*0.0
```

Echoed Input File

```
272                                  ***composite definition 21 series***
273     prop    mtmax= 11
274     prop    specs                mt    mat    width        e1          e2          twf
275                                  32     3   0.1000e+01  0.0000e+00  0.0000e+00  0.5000e+00
276                                  33     3   0.5000e+00  0.0000e+00  0.0000e+00  0.5000e+00
277                                  34     4   0.4572e+01  0.0000e+00  0.0000e+00  0.0000e+00
278                                  35     3   0.4669e+01  0.0000e+00  0.0000e+00  0.0000e+00
279                                  36     4   0.2946e+01  0.0000e+00  0.0000e+00  0.0000e+00
280                                  37     3   0.7366e+01  0.0000e+00  0.0000e+00  0.0000e+00
281                                  38     3   0.3000e+00  0.2000e+00  0.2000e+00  0.5000e+00
282                                  39     1   0.1000e+01  0.2000e+00  0.1000e+01  0.5000e+00
283                                  40     3   0.3500e+00  0.8300e+00  0.4500e+00  0.0000e+00
284                                  41     3   0.3500e+00  0.8300e+00  0.4500e+00  0.1000e+01
285                                  42     1   0.1000e+01  0.8000e+00  0.1000e+01  0.5000e+00
286
287                                  computed coefficients fromspecs array
```

```
288                                   mt      c0          c1          c3
289                                   32  0.5200e-03  0.3200e-05  0.0000e+00
290                                   33  0.1040e-02  0.6400e-05  0.0000e+00
291                                   34  0.2016e-01  0.3204e-04  0.0000e+00
292                                   35  0.1114e-03  0.6854e-06  0.0000e+00
293                                   36  0.3128e-01  0.4973e-04  0.0000e+00
294                                   37  0.7059e-04  0.4344e-06  0.0000e+00
295                                   38  0.1733e-02  0.1067e-04  0.2520e-11
296                                   39  0.1000e-20  0.0000e+00  0.4536e-11
297                                   40  0.1486e-02  0.9143e-05  0.9345e-11
298                                   41  0.1486e-02  0.9143e-05  0.9345e-11
299                                   42  0.1000e-20  0.0000e+00  0.1814e-10
```

After the entry NECHO = 1 requesting echoing of input, the first line of this input has a user comment as a reminder that the thermal parameter sets constructed here will be used in the series conduction group 21 (ID = 21,22, or 23) or other groups having the series conduction character, like the film resistance group 41 (ID = 41,42, or 43) or the cask end group 51 (ID = 51 or 52). See PROP Input Block 7 and Table 5.2 for explanations of ID.

The data in this example specifies construction of MTMAX = 11 intermediate property sets of the series conduction type, with indices MT = 32 through 42. Note that the last index MT used for the isotropic and parallel conduction thermal parameter sets was at MT = 27, so a few blank locations are being left for future expansion. Line 156 has for MT = 33 the specifications MAT = 3 (for helium, as seen in PROP Input Block 3), WIDTH = 0.5 (for a 0.5-cm path in the conduction direction), E1 = E2 = 0.0 (for bypassing a gap radiation model), and TWF(33) = 0.5 (for equal weighting of temperatures on either side in calculating the film temperature for the $\lambda/\delta L$ polynomial). Line 162 has for MT = 39 a specification MAT = 1 (for a fictitious extremely low-conductivity material, as seen from PROP Input Block 3), WIDTH = 1.0 (for a 1.0-cm path in the conduction direction), emittances of 0.2 and 1.0 for the surfaces facing the gap, and TWF(39) = 0.5 (for equal forward and backward temperature weighting). One might expect MT = 39 to be a satisfactory set for a cask end radiation treatment for use with a convection model.

The 11 specification sets require 66 entries, leaving 84 of the 150 locations in SPECS to be filled with zeros in the last line of this input block.

The input variables of these specification sets and the resulting computed polynomial coefficients are echoed in the output in the form shown.

5.3.7 Fuel Assembly Conduction-Radiation Models. PROP Input Block 6

General Input Format

```
NECHO
MTMAX
SPECS(I),I=1,NSPECP
```

The entire dimensioned array SPECS is read. SPECS comprises MTMAX sets of entries making up the fuel assembly thermal parameter sets construction directives and having the form (after conversion from floating point to integer form as needed):

MT,MTA,FUELOD,CLADOD,PITCH,CFUEL,CCLAD,EROD,EGAP

General Input Definition

- NECHO - Integer flag variable that, if positive, directs echoing of forthcoming input in the output.
- MTMAX - Number of specification sets forthcoming for construction of thermal parameter sets (CO(MT),C1(MT),C3(MT), X1(MT),X2(MT), Z1(MT),Z2(MT),Z3(MT)) of the fuel assembly type.
- MT - Index of the thermal property set being constructed.
- MTA - Index of a previously set thermal parameter set of the simple conduction type for calculating conductivity of the gas between the square array of cylinders. [CO(MT) gets set to CO(MTA), C1(MT) to C1(MTA)].
- FUELOD - Outside diameter of the fuel pellets.
- CLADOD - Outside diameter of the fuel cladding.
- PITCH - Distance between corresponding points on adjacent fuel rods in the array.
- CFUEL - Thermal conductivity of the fuel.
- CCLAD - Thermal conductivity of the cladding.

- EROD - Emittance of the fuel rods.
- EGAP - Emittance of the gap between fuel rods when treating a single rectangular array of pins as a radiation enclosure (set to a value near 0.95).

Input File Example

```
167 1/prop/specs def. 31 fuel assembly
168 1
169 45.0,3.0,0.9484,1.072,1.430,0.0209,0.1150,0.8,0.95,
170 141*0.0
```

Echoed Input File Example

```
300
301                                  ***composite definition 31 fuel assembly***
302     prop    mtmax=  1
303     prop    specs   mt    mta   fuelod      cladod      pitch      cfuel      cclad      erod       egap
304                     45     3  0.9484e+00  0.1072e+01  0.1430e+01 0.2090e-01 0.1150e+00 0.8000e+00 0.9500e+00
305
306                                          computed coefficients from specs array
307                     mt     c0          c1          c3          x1          x2          z1          z2          z3
308                     45  0.5200e-03  0.3200e-05  0.8052e-11  0.1130e+01 0.1701e+01  0.3455e+00  0.9591e-01  0.5586e+00
309
```

Following the request (NECHO = 1) for echoing of input, a user comment indicates that the resulting parameter set will go with ID = 31 in the assignment of resistance parameters to cells in PROP Input Block 7. The input example directs construction of a single thermal parameter set for a rectangular array fuel assembly heat transfer model. Index MT = 45 again allows a few spaces from the last previously used MT value, MT = 42. Thermal parameter sets for similar heat transfer models are grouped only for convenience. The data on line 169 directs use of the thermal parameter index MTA = 3 (assigned in Input Block 4 from the helium data in Input Block 3) for conductivity of the gas. Fuel core and cladding outside diameters are set at 0.9484 and 1.072 cm, respectively. The pitch of the square array is 1.430 cm. Thermal conductivity of the fuel and clad are set to 0.0209 and 0.1150 watts/cm°K), respectively. The emittances of rod and gap are set to 0.8 and 0.95, respectively.

5.3.8 Assignment of Resistance to Cell Locations. PROP Input Block 7

General Input Format

```
NECHO
NREG,NPAIR
INDEX(I),I=1,INDEXP
```

The entire array INDEX is read. The NREG sets of region resistance assignment directives stored end-to-end in INDEX have the form:

IBEG,IEND,JBEG,JEND,KBEG,KEND,NPAIR,ID_1,MT_1,ID_2,MT_2,...ID_{NPAIR},MT_{NPAIR}

General Input Definitions

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- NREG,NPAIR - Number of region resistance assignment directive sets forthcoming in INDEX and the total number NPAIR of (ID,MT) pairs included in all of them.
- IBEG,IEND,JBEG,JEND,KBEG,KEND - The beginning and ending mesh indices in the I, J, and K directions in turn for the current region resistance specification set.
- NPAIR - (Redefined for the current resistance assignment directive set). Number of (ID,MT) pairs of resistance assignment directives in the current region resistance assignment directive set. Actions requested by (ID,MT) pairs are implemented in turn.
- ID,MT - A pair of directives for modifying the thermal resistance arrays in the current region. ID specifies the heat transfer model type, structure orientation, and the action to be taken on one of RESX, RESY, RESZ, RESFX, RESFY, or RESFZ. MT is the index of the intermediate parameter set to use in this resistance parameter change. The changes specified by ID can be either replacement or addition to the resistance array variable for each I,J,K in the range set by IBEG $\leq$ I $\leq$ IEND, JBEG $\leq$ J $\leq$ JEND, KBEG $\leq$ K $\leq$ KEND. ID values are defined in Table 5.3.

Input File Example

```
171 1/prop/index
172 158,332
```

```
173 1,1,2,47,2,30,1,1,1,
174 2,24,2,47,1,1,1,52,42,
175 2,24,2,47,30,30,3,51,39,1,1,2,1,
176 2,24,2,47,4,27,1,4,3,
177 5,5,2,47,5,26,1,4,5,
178 2,24,21,21,5,26,1,4,5,
179 2,24,28,28,5,26,1,4,5,
180 2,4,21,21,5,26,2,12,6,15,6,
181 2,4,28,28,5,26,2,12,6,15,6,
182 5,5,22,27,5,26,2,14,6,16,6,
183 2,2,20,20,5,26,1,42,32,
184 4,4,20,20,5,26,1,42,32,
185 2,2,28,28,5,26,1,42,32,
186 4,4,28,28,5,26,1,42,32,
187 5,5,22,22,5,26,1,41,32,
            .   .   .

            .   .   .

            .   .   .

325 13,21,30,30,5,26,1,42,41,
326 13,21,34,34,5,26,1,42,40,
327 12,12,15,18,5,26,1,41,41,
328 12,12,31,34,5,26,1,41,41,
329 21,21,15,18,5,26,1,41,40,
330 21,21,31,34,5,26,1,41,40,
331 65*0
```

Echoed Input File Example

```
310                                    ***available composite definitions***
311                                      group                  id
312                                   01 isotropic               1 resx
313                                                              2 resy
314                                                              3 resz
315                                                              4 resx,resy,resz
316                                   11 parallel                11 resx,x-y plane
317                                                             12 resx,x-z plane
318                                                             13 resy,x-y plane
319                                                             14 resy,y-z plane
320                                                             15 resz,x-z plane
321                                                             16 resz,y-z plane
322                                   21 series                 21 resx
323                                                             22 resy
324                                                             23 resz
325                                   31 fuel assembly          31 resx,resy,resz for rod array
326                                   41 film resistance        41 resfx
327                                                             42 resfy
328                                                             43 resfz
329                                   51 exterior convection    51 resfz for top of cask
330                                      and radiation          52 resfz for bottom of cask
331
332     prop    nreg= 158   npair= 332   maximum current dimensions for nreg and npair are   165   340
333     prop    index          cell location
334                   ibeg iend  jbeg jend  kbeg kend   npair     id   mt    id   mt     id   mt     id   mt     id   mt
335                     1    1     2   47     2   30       1      1    1
336                     2   24     2   47     1    1       1     52   42
337                     2   24     2   47    30   30       3     51   39     1    1     2    1
338                     2   24     2   47     4   27       1      4    3
```

```
339                5   5    2   47    5   26      1      4   5
340                2  24   21   21    5   26      1      4   5
341                2  24   28   28    5   26      1      4   5
342                2   4   21   21    5   26      2     12   6    15   6
343                2   4   28   28    5   26      2     12   6    15   6
344                5   5   22   27    5   26      2     14   6    16   6
345                2   2   20   20    5   26      1     42  32
346                4   4   20   20    5   26      1     42  32
347                2   2   28   28    5   26      1     42  32
348                4   4   28   28    5   26      1     42  32
349                5   5   22   22    5   26      1     41  32

       .   .   .
       .   .   .
       .   .   .

487               13  21   30   30    5   26      1     42  41
488               13  21   34   34    5   26      1     42  40
489               12  12   15   18    5   26      1     41  41
490               12  12   31   34    5   26      1     41  41
491               21  21   15   18    5   26      1     41  40
492               21  21   31   34    5   26      1     41  40
493
```

After requesting echoing of input with NECHO = 1 on line 171 of the input file, the input states on line 172 that 158 region resistance assignment sets are forthcoming (NREG = 158) and that for these 158 regions there are 332 (ID,MT) pairs directing action on specific resistance arrays and telling which intermediate parameter set MT to use. The default values of RESX, RESY, RESZ, RESFX, RESFY, and RESFZ is 0.0. Action is required only if nonzero values are required. The first such set (line 173) specifies that, on a region defined by ($1 \leq I \leq 1$, $2 \leq J \leq 47$, $2 \leq K \leq 30$), one set (ID,MT) is to be imposed, namely (ID = 1, MT = 1). The value ID = 1 specifies that the array to be changed is the RESX array. See Table 5.3 and the summary at the start of the echoed input for ID value significances. The intermediate parameter set used, MT = 1, was constructed as directed by PROP Input Block 4 (line 116 of the input data example there), which, in turn, referenced the input material conductivity parameter set MAT = 1, which was input in PROP Input Block 3 (lines 96 and 97 of the input file example). From the fact that the thermal parameter set used was for low-conductivity material, we conclude that the user is setting the layer I = 1 to be effectively infinitely resistive, thus giving an insulated boundary condition or plane of symmetry there.

Line 174 of the input file example requests implementation of a cask bottom model with ID = 52, requesting that thermal parameter set of MT = 42 be used. Thermal parameter set MT = 42 was constructed from directives in PROP Input Block 5, line 165 of the input example.

Line 175 of the input file example requests implementation of two (ID,MT) resistance assignment pairs on its range ($2 \leq I \leq 24$, $2 \leq J \leq 47$, $30 \leq K \leq 30$), namely (ID,MT) = (1,1) and (ID,MT) = (2,1). Thus, both RESX and RESY are set to large values on this range.

The echoed input summarizes this information.

6.0 SUBROUTINE THERM

Subroutine THERM solves the energy equation on the rectangular grid.

6.1 THERM FUNCTIONS

THERM reads input specifying initial temperatures, heat sources, and numerical procedure options during initiation or restart of a simulation. If solution of the energy equation on the rectangular grid is requested, THERM is called at each time-step to advance the temperature solution.

The actions performed by THERM in the solution sequence include the following:

1. THERM sets the connector arrays for the energy equation. These are the coefficients that relate temperature to heat flow rates, mass fluxes, and heat sources.
2. THERM executes an algorithm that advances the temperatures on the rectangular computational grid through a time-step.
3. If requested, THERM prints monitoring information, including the location and amount of the largest temperature change in each time-step and the temperature in cells designated for temperature printout.
4. THERM makes tentative adjustments in the time-step by comparing the maximum temperature change and a user-specified maximum target temperature change.

The algorithm used in THERM for advancing the temperature through a time-step is discussed in Volume I - Equations and Numerics (McCann 1987). To carry on this and its other functions in solving the energy equation on the rectangular grid, THERM is called at initialization or restart to read input to guide the solution and to set or reset temperatures.

Actions performed by THERM in the initialization or restart operation include:

1. THERM reads certain options for numerical procedures and printouts.

2. THERM reads specifications for heat sources.

3. THERM reads specifications for initial temperatures on the rectangular grid region and the rectangular-cylindrical grid interface, including ambient temperatures at cask top and bottom.

4. THERM modifies or resets the temperature distribution according to user input, as may be desired in a restart.

6.1.1 Numerical Procedures

If a solution for both temperatures and flows is requested, calls from MAIN to the flow-solving routines are interspersed with the calls to the energy equation-solving routines (such as THERM and REBT for the rectangular grid, TSIDE for the cylindrical grid, and TBND or REBA for their connection). The algorithm in REBT solves the energy equation on slab partitions of the rectangular grid region, and its calling sequence is specified in input to THERM. The use of REBA, a solver of the energy equations on both grids, is specified in MAIN. The periodic use of REBT and REBA in the solution of the energy equations accelerates convergence, particularly as steady state is approached. See the guidance for the use of REBT in Chapter 7.0 and for REBA in Chapter 14.0.

6.1.2 Heat Sources

The technique for specifying heat sources has been designed especially for heat generating spent fuel assemblies. As a result, the input specifications are relatively simple. Three items of information are required: the toal heat generation rate of a fuel assembly; the locations of reduced heat generation within a fuel assembly, such as instrumentation tubes; and the relative axial activity of the fuel assembly. The longitudinal axis of each fuel assembly is in the z-direction.

The total heat being generated in a single column of cells, assumed to extend in the z-direction from K = 2 to K = KP-1, can be expressed as

$$Q^C(I,J) = Q^g \frac{W(I,J)DX(I)DY(J)}{\Sigma_g W(I,J)DX(I)DY(J)} \qquad (6.1)$$

where $Q^C(I,J)$ is the total heat generation in a column I,J

Q^g is the total heat generation in the fuel assembly (group power)

W(I,J) is a relative weighting factor for heat generation within the fuel assembly (group).

Different group powers and weighting factors may be specified for each fuel assembly. The weighting factor is automatically halved for phantom cells on the curved boundary.

The axial distribution of heat generation is determined from the relative activity curve for a spent fuel assembly. The heat generation sources used in the code are computed as

$$QGEN(I,J,K) = Q^C(I,J) \frac{RA(K)DZ(K)}{\Sigma_k RA(K)DZ(K)} \tag{6.2}$$

where QGEN(I,J,K) is the total heat generation in cell I,J,K

RA(K) is the relative activity as a function of K.

The code assigns the same relative activity curve to all fuel assemblies. The relative activity data specified on the input file need not be normalized; the code does this automatically.

It can be seen from the preceding discussion that a completely arbitrary distribution of heat sources cannot be specified in this version of the code. The basic restriction is that heat generation sources be expressed in the form

$$Q(I,J,K) = FXY(I,J)*FZ(K) \tag{6.3}$$

6.1.3 Setting or Resetting Temperatures

Subroutine THERM can set the initial temperature on the rectangular grid and its interface with the cylindrical grid in a new simulation, or it can alter or reset them in a restart.

To set or reset the temperature distribution with input, the user supplies temperatures TS1(JS,K) on the cylindrical interface between rectangular and cylindrical grid regions, where JS is the azimuthal sector index and K is the

axial plane index. An array of temperatures, TCEN(K), on a user-specified axial "center line" in the rectangular grid is also read. An array, TCAN(K), of azimuthal average interface temperatures is calculated as

$$TCAN(K) = \sum_{JS} TS1(JS,K)*DTHETA(JS)/\sum_{JS} DTHETA(JS) \qquad (6.4)$$

These arrays can be used to reset temperatures in three regions as indicated in Figure 6.1 according to options as follows:

1. NEWT = 1. Set an initial temperature distribution in the rectangular grid computational region (but not the phantom cells) according to

   $$T(I,J,K) = TCEN(K) + (TCAN(K) - TCEN(K))*(FAC/FACMX)$$

   where $FAC = (REAL(I) - 1.5)^2 + (REAL(J) - CENJ)^2$

   and FACMX is the largest value of FAC in the rectangular grid computational region.

2. NEWTC = 1. Reset temperatures in the rectangular grid phantom cells at the cylindrical grid interface as

   $$T(ICART(JS),JCART(JS),K) = TS1(JS,K)$$

   for azimuthal indices JS in the range $2 \leq JS \leq JSP-1$ and axial indices K in the range $2 \leq K \leq KP-1$.

3. NEWTA = 1. Reset cask end ambient temperatures in the rectangular grid region as

   $$T(I,J,1) = TCAN(1)$$
   $$T(I,J,KP) = TCAN(KP)$$

   The azimuthal average value TCAN(1) of TS1(JS,1) becomes the cask bottom ambient temperature, and the average value TCAN(KP) of TS1(JS,KP) becomes the cask top ambient temperature.

These temperatures will be altered in the subsequent calculations with two exceptions:

1. The cask end ambient temperatures T(I,J,1) and T(I,J,KP) will be held constant.

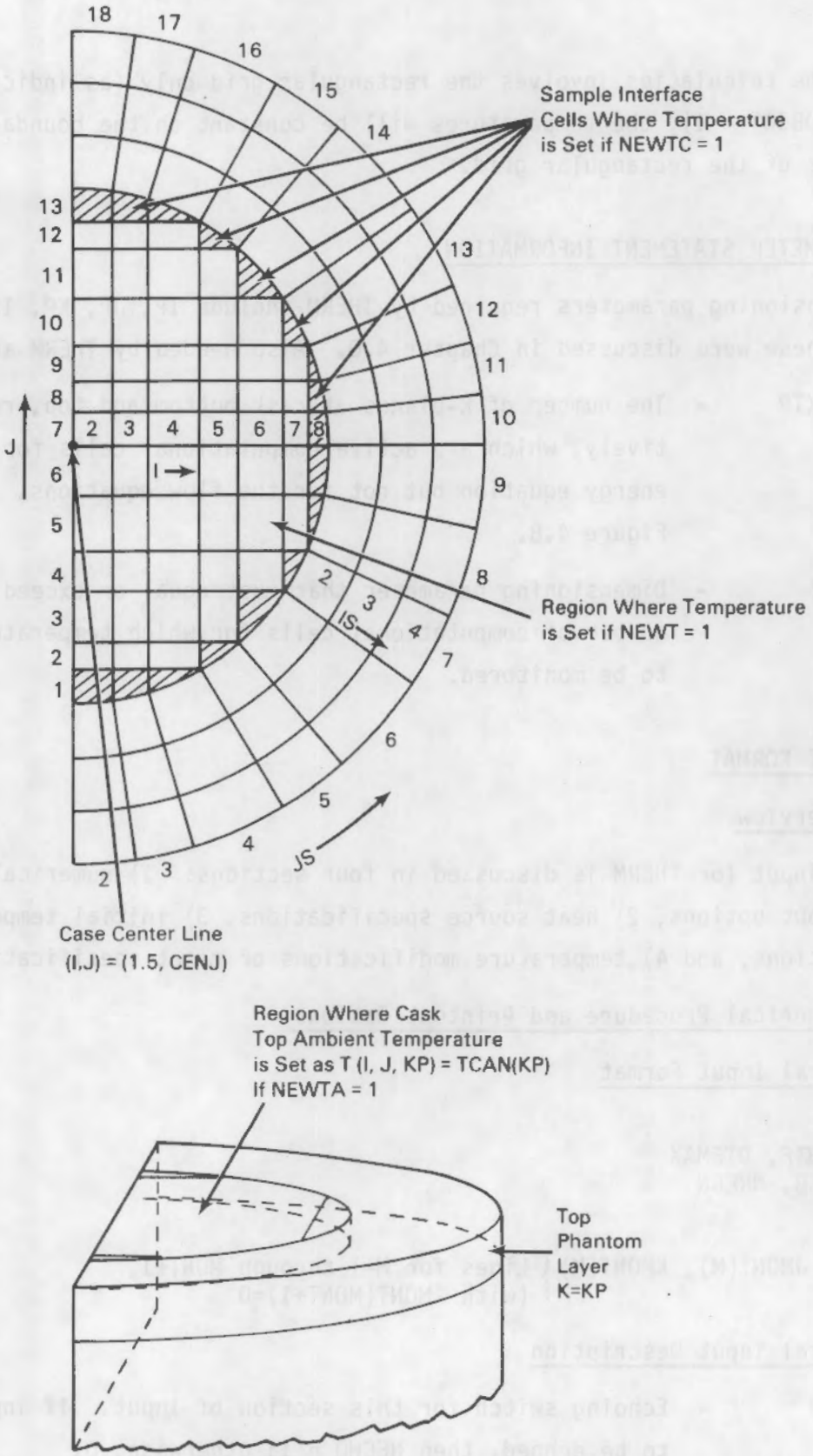


FIGURE 6.1. Regions Where Temperature is Set or Reset by Input to THERM

2. If the calculation involves the rectangular grid only (as indicated by NOBODY = 1), the temperatures will be constant on the boundary cells of the rectangular grid.

6.2 PARAMETER STATEMENT INFORMATION

Dimensioning parameters required by THERM include IP, JP, KP, ISP, JSP, NEFAP. These were discussed in Chapter 4.D. Also needed by THERM are:

- KBP,KTP - The number of K-planes at cask bottom and top, respectively, which are active computational cells for the energy equation but not for the flow equations. See Figure 4.8.
- MONTP - Dimensioning parameter that must equal or exceed the number of computational cells for which temperature is to be monitored.

6.3 INPUT FORMAT

6.3.1 Overview

The input for THERM is discussed in four sections: 1) numerical procedure and printout options, 2) heat source specifications, 3) initial temperature specifications, and 4) temperature modifications or reset specifications.

6.3.2 Numerical Procedure and Printout Options

General Input Format

```
NECHO
THETA, SPHTF, DTEMAX
REBON, NREB, NREBN
NECHO
MONT
IMONT(M), JMONT(M), KMONT(M)  } Lines for M=1 through MONT+1,
                              } (with IMONT(MONT+1)=0
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.

- THETA - Temporal weighting for the energy equation. THETA should be chosen in the range 0.5 ≤ THETA ≤ 1.0. A value 0.5 has been proven satisfactory for steady-state applications.

- SPHTF - The specified heat of fluid in joules/(gm°C).

- DTEMAX - Target value of the maximum magnitude temperature change per time-step on the rectangular grid. A new tentative time-step DTIMEI is set as

```
DTIMEI = 1.1*DTIME    if ABS(DTMAX)<DTEMAX
```

or

```
DTIMEI = DTEMAX*DTIME/ABS(DTMAX) if
         ABS(DTMAX)>DTEMAX
```

where DTIME is the current time-step and DTMAX is the largest temperature increase on the grid in the current time-step.

- REBON, NREB, NREBN - Criteria for the use of slab rebalance in Subroutine REBT during time-stepping. If STEADY = 1.0 and REBON = 1.0, then REBT is called for time-step NS when MOD(NS,NREB) = NREBN, where MOD is the FORTRAN modulo or remaindering function. Preferred values of NREB and NREBN are simulation-dependent. See Chapter 7.0, Subroutine REBT, for an expanded discussion.

- MONT - Number of computational cells for which temperature monitoring is requested.

- IMONT(M), JMONT(M), KMONT(M) - The (I,J,K) indices of the Mth cell for which temperature monitoring is requested.

Input File Example

```
332 1/therm
333 0.5,5.234,0.5
334 1.0,100,50
335 1/therm/monitor/t
336 12
337 2,24,7
338 2,24,11
```

```
339 2,24,15
340 2,24,16
341 2,24,18
342 2,24,22
343 2,41,7
344 2,41,11
345 2,41,15
346 2,41,16
347 2,41,18
348 2,41,22
349 0,0,0
```

Echoed Input File Example

```
494     therm   theta=0.5   sphtf=0.5234e+01   dtemax=0.500e+00
495     therm   rebon=1.0   nreb=100   nrebn= 50
496
497     therm   monitor cells=12   maximum number currently allowed is 12
498                                                  m   i  j  k
499                                                  1   2 24  7
500                                                  2   2 24 11
501                                                  3   2 24 15
502                                                  4   2 24 16
503                                                  5   2 24 18
504                                                  6   2 24 22
505                                                  7   2 41  7
506                                                  8   2 41 11
507                                                  9   2 41 15
508                                                 10   2 41 16
509                                                 11   2 41 18
510                                                 12   2 41 22
511
```

Echoed input is requested with NECHO = 1 on line 332 of the input. THETA, SPHTF, and DTEMAX are set to 0.5, 5.234, and 0.5, respectively. One of the requirements for use of a coarse mesh rebalance of the energy equation, REBON = 1.0, is met. The input specifies rebalancing at time-steps NS = 50, 150, 250, etc. Monitoring of the temperature in the list of 12 cells is requested. Line 349 has a zero first entry, indicating the end of the list of cells for monitoring.

The echoed output confirms these numbers, and also compares the numbers MONT of cells requested for temperature printouts with the number currently allowed by dimensions.

6.3.3 Heat Source Specifications

General Input Format

```
NECHO
QWTFAC,IBEG,IEND,JBEG,JEND - Repeated until IBEG = 0 is encountered
NECHO
GRPPOW,IBEG,IEND,JBEG,JEND - Repeated until IBEG = 0 is encountered
NECHO
RELACT(K),K=2,KP-1
NECHO
PQGEN
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.

- QWTFAC - The relative weighting factor per unit area for each heat source in the range

  $JBEG \leq J \leq JEND$

  $IBEG \leq I \leq MIN(IEND,IMEND(J))$

  The range is thus restricted to the computational and phantom cells for the energy equation. QWTFAC is automatically reduced by one half if the cell is a phantom cell on the curved part of the Cartesian boundary. The default value of QWTFAC is zero.

IBEG,IEND,JBEG,JEND - Range specifications of the form

$JBEG \leq J \leq JEND$

$IBEG \leq I \leq MIN(IEND,IMEND(J))$

- GRPPOW - Total power in watts for the heat source in the region defined by the range specification on the same line and in the K direction by $2 \leq K \leq KP-1$. The default value of GRPPOW is zero.

- RELACT(K) - The relative activity at each K-plane. Normalization is arbitrary.

- PQGEN - Floating point flag variable that, if equal to 1.0, requests printout of the heat source array QGEN(I,J,K). No printing occurs if PQGEN = 0.0.

Input File Example

```
350 1/therm/q weighting factor
351 1.0,2,4,2,9
352 1.0,2,4,13,16
353 1.0,2,4,22,27
354 1.0,2,4,33,36
355 1.0,2,4,40,47
356 1.0,8,11,5,13
357 1.0,8,11,15,18
358 1.0,8,11,31,34
359 1.0,8,11,36,44
360 1.0,10,13,22,27
361 1.0,17,24,22,27
362 1.0,13,21,15,18
363 1.0,13,21,31,34
364 0.0,4*0
365 1/therm/group power
366 552.5,2,4,2,9
367 552.5,2,4,13,16
368 505.0,2,4,22,27
369 552.5,2,4,33,36
370 552.5,2,4,40,47
371 1783.0,8,11,5,13
372 993.0,8,11,15,18
373 993.0,8,11,31,34
374 1783.0,8,11,36,44
375 1105.0,10,13,22,27
376 1105.0,17,24,22,27
377 1783.0,13,21,15,18
378 1783.0,13,21,31,34
379 0.0,4*0
380 1/therm/relact
381 4*0.0,0.5,0.72,0.94,1.12,1.19,1.23,5*1.24,
382 1.23,1.21,1.16,1.03,0.83,0.61,0.44,0.26,6*0.0
383 1/therm/pqgen
384 0.0
```

Echoed Input File Example

512	therm	q weighting	cell location			
513		factor	ibeg	iend	jbeg	jend
514		0.1000e+01	2	4	2	9
515		0.1000e+01	2	4	13	16
516		0.1000e+01	2	4	22	27
517		0.1000e+01	2	4	33	36
518		0.1000e+01	2	4	40	47
519		0.1000e+01	8	11	5	13
520		0.1000e+01	8	11	15	18
521		0.1000e+01	8	11	31	34
522		0.1000e+01	8	11	36	44
523		0.1000e+01	10	13	22	27

```
                                  0.1000e+01          17   24   22   27
                                  0.1000e+01          13   21   15   18
                                  0.1000e+01          13   21   31   34

therm                               group                  cell location
                                    power             ibeg iend jbeg jend
                                  0.5525e+03           2    4    2    9
                                  0.5525e+03           2    4   13   16
                                  0.5050e+03           2    4   22   27
                                  0.5525e+03           2    4   33   36
                                  0.5525e+03           2    4   40   47
                                  0.1783e+04           8   11    5   13
                                  0.9930e+03           8   11   15   18
                                  0.9930e+03           8   11   31   34
                                  0.1783e+04           8   11   36   44
                                  0.1105e+04          10   13   22   27
                                  0.1105e+04          17   24   22   27
                                  0.1783e+04          13   21   15   18
                                  0.1783e+04          13   21   31   34

therm                           k    relact(k)
                                2   0.0000e+00
                                3   0.0000e+00
                                4   0.0000e+00
                                5   0.0000e+00
                                6   0.5000e+00
                                7   0.7200e+00
                                8   0.9400e+00
                                9   0.1120e+01
                               10   0.1190e+01
                               11   0.1230e+01
                               12   0.1240e+01
                               13   0.1240e+01
                               14   0.1240e+01
                               15   0.1240e+01
                               16   0.1240e+01
                               17   0.1230e+01
                               18   0.1210e+01
                               19   0.1160e+01
                               20   0.1030e+01
                               21   0.8300e+00
                               22   0.6100e+00
                               23   0.4400e+00
                               24   0.2600e+00
                               25   0.0000e+00
                               26   0.0000e+00
                               27   0.0000e+00
                               28   0.0000e+00
                               29   0.0000e+00
                               30   0.0000e+00

                                    total generated power = 0.280860e+05, watts


therm   pqgen=0.0
```

The Q weighting factor is equal to 1.0 for 13 regions in the rectangular grid. These regions correspond to the fuel assembly regions in Figure 4.1. In this example, group powers for the entire axial extent of the 13 fuel assemblies of Figure 4.1 are set to values varying from 505 watts to 1783 watts. The relative activities at axial positions from K = 2 to K = KP-1 = 30 are set in the RELACT(K) array. Normalization of the input for RELACT(K) is arbitrary. In this example, non-negligible heat sources are from the axial positions K = 6 to K = 24.

The echoed input shows the Q weighting factors by region, the group powers by region, and the relative activity by position in the Z-direction. The total power shown is calculated for the entire cask (i.e., four quadrants), and not just the modeled region. Because PQGEN was set to zero, the final QGEN (I,J,K) heat source per cell was not printed.

6.3.4 Initial Temperatures on the Rectangular Grid

General Input Format

```
NECHO
NEWT, CENJ
TCEN(K), K=2, KP-1
NECHO
NEWTC, INFO
[TS1(JS,K),JS=2,JSP-1],K=1,KP
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- NEWT - An integer variable that, if equal to 1, requests setting of temperatures on the rectangular grid based on input temperatures TS1(JS,K) on the cylindrical interface and TCEN(K) on the cask centerline. If NEWT = 0, then temperatures are not reset.
- CENJ - A floating point number for the J index along which "cask center line" temperatures TCEN(K) are specified. The floating point number for the I index is at I = 1.5.

- TCEN(K) - The initial temperature (°K) for each K-plane along the cask center line. No value for ambient (K = 1 or K = KP) is included.
- NEWTC - An integer variable that, if equal to 1, requests setting a temperatures on the rectangular grid phantom cells at the cylindrical grid interface from the TS1 data. If NEWTC = 0, temperatures of the rectangular grid interface phantom cells are not reset.
- INFO - An integer flag variable that, if equal to 1, requests printing of the interface temperatures. If INFO equals 0, then no printing occurs.
- TS1(JS,K) - An input temperature array for the JS azimuthal sector at the Kth plane of the rectangular-cylindrical grid interface. Its uses are defined by flag variables:
  NEWT = 1 - Set T(I,J,K) for computational cells of the rectangular grid.
  NEWTC = 1 - Set T(ICART(JS),JCART(JS),K) for K = 2 to KP-1, i.e., temperatures at rectangular grid phantom cells at the grid interface.
  NEWTA = 1 - Set cask end ambient temperatures T(I,J,1) and T(I,J,KP) from TCAN(1) and TCAN(KP), which are averages over JS of TS1(JS,1) and TS1(JS,KP), respectively. NEWTA is set in the input to MAIN.

If a run is started without using a restart tape, then all temperatures must be defined. If a restart tape is used, then only those temperatures that need to be changed are to be reset.

Input File Example

```
385 1/therm/tcen
386 0,24.5
387 380.0,385.0,395.0,410.0,430.0,470.0,505.0,545.0,575.0,
388 610.0,640.0,660.0,5*673.0,655.0,635.0,600.0,570.0,
389 535.0,510.0,475.0,445.0,415.0,395.0,385.0,380.0
390 1/therm/ts1
```

```
391 0,0
392 62*297.0,1798*373.0,62*297.0
```

Echoed Input File Example

```
580      therm   newt=0   cenj=24.5      k     tcen(k)
581                                        2   0.380e+03
582                                        3   0.385e+03
583                                        4   0.395e+03
584                                        5   0.410e+03
585                                        6   0.430e+03
586                                        7   0.470e+03
587                                        8   0.505e+03
588                                        9   0.545e+03
589                                       10   0.575e+03
590                                       11   0.610e+03
591                                       12   0.640e+03
592                                       13   0.660e+03
593                                       14   0.673e+03
594                                       15   0.673e+03
595                                       16   0.673e+03
596                                       17   0.673e+03
597                                       18   0.673e+03
598                                       19   0.655e+03
599                                       20   0.635e+03
600                                       21   0.600e+03
601                                       22   0.570e+03
602                                       23   0.535e+03
603                                       24   0.510e+03
604                                       25   0.475e+03
605                                       26   0.445e+03
606                                       27   0.415e+03
607                                       28   0.395e+03
608                                       29   0.385e+03
609                                       30   0.380e+03
610
611      therm   newtc=0   info=0                  * * * initial interface temperatures, °K * * *
```

NECHO is set to 1 in input line 385. NEWT is set to zero on line 386, indicating that the temperatures on the rectangular grid are not to be reset. No reset will usually be the desired option on a restart. CENJ is set to 24.5 as the J value for the "cask center line". The pseudo-mesh location (I,J) = (1.5, 24.5) can be seen in Figure 4.1 to be the appropriate cask center line. The model for setting initial cask temperatures is approximate. The NEWTC and INFO entries (line 391) are both zero, indicating that new temperatures are not be set on the rectangular-cylindrical grid interface and that the grid interface temperatures are not to be printed. Nevertheless, 1922 entries (62+1798+62) are read for the TS1(JS,K) array for $2 \leq JS \leq JSP-1$ and $1 \leq K \leq KP$. For this simulation, JSP is 64 and KP is 31.

6.3.5 Temperature Modification Specifications

General Input Format

```
NECHO
NDELTA
IBEG,IEND,JBEG,JEND
DELTA(K), K=2, KP-1
```

General Input Description

- NECHO - Integer flag variable that, if positive, requests echoing of forthcoming input in the output.

- NDELTA - A flag whose values indicate the following actions:

  NDELTA = 0 - Oo not add user-prescribed temperature increments in the rectangular grid or grid interface region.

  NDELTA = 1 - Add temperature increment DELTA(K) to temperature T(I,J,K) in the rectangular grid. The range is
  JBEG ≤ J ≤ JEND
  IBEG≤I≤MIN(IEND,IEEND(J))
  2 ≤ K ≤ KP-1

  NDELTA = 2 - Add temperature increment OELTA(K) to rectangular-cylindrical grid interface cells according to
  T(ICART(JS),JCART(JS),K) = T(ICART(JS), JCART(JS),K) + DELTA(K) for 2 ≤ K ≤ KP-1 and 2 ≤ JS ≤ JSP-1.

  NDELTA = 3 - Perform the actions described for both NDELTA = 1 and NOELTA = 2.

- IBEG,IEND,JBEG,JEND - A set of mesh indices that describe an (I,J) range according to
  JBEG(3)≤J≤JEND
  IBEG≤I≤MIN(IEEND(J),IEND

- DELTA(K) - Increment to be added to all temperatures at the Kth plane for the (I,J) range.

Input File Example

```
393 1/therm/delta
394 0
395 2,18,2,34
396 29*0.0
```

Echoed Input File Example

```
613      therm   ndelta=0
614      therm   ibeg= 2   iend=18   jbeg= 2   jend=34
615                                      k    delta(k)
616                                      2   0.000e+00
617                                      3   0.000e+00
618                                      4   0.000e+00
619                                      5   0.000e+00
620                                      6   0.000e+00
621                                      7   0.000e+00
622                                      8   0.000e+00
623                                      9   0.000e+00
624                                     10   0.000e+00
625                                     11   0.000e+00
626                                     12   0.000e+00
627                                     13   0.000e+00
628                                     14   0.000e+00
629                                     15   0.000e+00
630                                     16   0.000e+00
631                                     17   0.000e+00
632                                     18   0.000e+00
633                                     19   0.000e+00
634                                     20   0.000e+00
635                                     21   0.000e+00
636                                     22   0.000e+00
637                                     23   0.000e+00
638                                     24   0.000e+00
639                                     25   0.000e+00
640                                     26   0.000e+00
641                                     27   0.000e+00
642                                     28   0.000e+00
643                                     29   0.000e+00
644                                     30   0.000e+00
```

This input requests echoing (NECHO = 1) on line 393. Line 394 requests no adjustments of temperatures in the rectangular grid region (NDELTA = 0). The IBEG, IENO, JBEG, JEND, and DELTA(K) are read, nevertheless. The echoed input reflects these entries.

7.0 SUBROUTINE REBT

Subroutine REBT provides an optional numerical procedure intended to accelerate convergence of the solution of the energy equation toward steady state on the rectangular grid.

7.1 REBT FUNCTIONS

REBT solves the energy equation on a coarser mesh, specifically, on three slab partitions of the rectangular grid region. REBT is made available because the algorithm used in THERM reduces small long-range errors slowly as steady state is approached. Long-range errors are departures from the exact solution over distances much larger than the mesh spacing.

The prescription for calling REBT is provided by the user in the input to subroutine THERM. Additional minimal but rather important input for this convergence acceleration scheme is read by subroutine REBT during an initiation or restart. To use REBT judiciously, it is helpful to review some of the features of the solution for the physical system and of the energy equation in subroutine THERM.

HYDRA-II is set up to find steady-state conditions, using time-stepping to generate the approach to steady state. The finite-difference formulation in HYDRA-II discussed in Volume I (McCann 1987) presents the energy equation in a form relating temperature change $\delta T(I,J,K)$ in the (I,J,K) cell during time-step δt to the net energy flow into the (I,J,K) cell and energy sources there. Subroutine REBT, by contrast, solves a comparable energy equation on a coarser mesh for some time increment, δt = XDTIME, adding the temperature change δT found for a coarse region to the T(I,J,K) for all the (I,J,K) points within the region. REBT actually uses three coarse meshes, each a set of slabs. In the first coarse mesh, there is a slab for each I value. Each temperature increment $\delta T(I)$ found in this coarse mesh solution is added to all the T(I,J,K) for that I value. A similar procedure is followed in a coarse mesh with a slab for each J value and in a coarse mesh with a slab for each K value.

Because the user is seeking only a steady-state solution for the coupled system of heat and mass flow, the time-step in REBT need not be the same as

that being used in THERM. Nor does it matter that the energy and flow equations are not advanced in near-synchronous fashion, so long as the steady-state solution is economically obtained. Although the algorithm in REBT allows arbitrarily large time-steps in the linearized energy equation, nonlinearities will limit the preferred time-step size. Nonlinearities arise because the radiation rates, the material properties, and the flow rates are dependent on the temperature. The choice of input to REBT (and the pattern of calling REBT set in THERM) should be based primarily on these considerations. The procedure within REBT is applicable only if a steady state is desired, as the user should indicate by setting STEADY = 1.0 in the input to Program MAIN.

The use of the coarser mesh solution in REBT will usually introduce short-range error (departures from the true solution over distances of a few cell lengths) while reducing the long-wavelength error. The user should expect this in evaluating the effectiveness of REBT.

It is recommended that the user follow this procedure to use REBT effectively:

1. Perform one or more HYDRA-II runs in which the solution for the composite system is allowed to proceed through enough time-steps that the temperature change per time-step becomes small before applying REBT. The velocities and material properties should have attained some measure of realism, but convergence will probably not have been reached, as indicated by heat balance information printed by QINFO. Create a restart file at this point.

2. Set the time-step δt = XDTIME in REBT to some value in the approximate range 100 to 10^8. Select a trial number NMAX of times to execute the three directions of slab solutions in REBT at each call, say NMAX~15. Run a restart case through a time-step in which REBT is called. The pattern of calls to REBT is set in THERM by input variables NREB and NREBN. INFO should be set to 1 or 2 in REBT for this restart, to get printout of the maximum divergence error total for a slab (labeled DIMAX, DJMAX, or DKMAX) following the I-, J-, or K-slab coarse solutions. Plot one or more of DIMAX, DJMAX, or DKMAX as a function of iteration number in REBT. Choose a value of NMAX for

subsequent use at a point of diminishing effectiveness in reducing this divergence error. A schematic plot of DKMAX versus iteration number in REBT is shown in Figure 7.1, showing diminishing effectiveness.

3. With number NMAX of iterations in REBT fixed, run a number of restarts (from the same restart file) in which REBT is called with various values of time-step δt = XDTIME, say 100, 10^4, and 10^6 or some comparable set. Follow the REBT call for these restarts by some number (on the order of 50 to 100) of time-steps with the energy equation solved on the rectangular grid by the algorithm in THERM. For economy, turn the momentum solution off with NOVEL = 1 in MAIN. Set NSINFO to 1 in the input to MAIN to obtain printouts of δT from THERM at every time-step for this test.

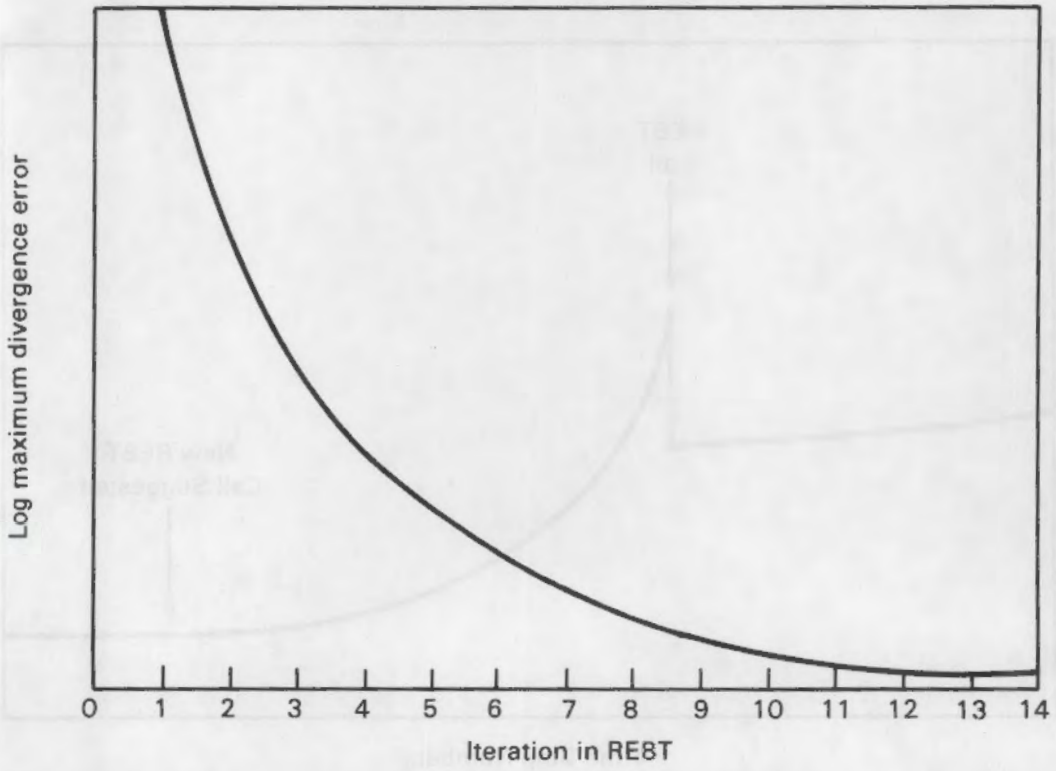


FIGURE 7.1. Qualitative Plot of Maximum Divergence Error in a K-Layer Versus Number of Iterations in REBT

4. Tentatively identify the preferred value of XDTIME as the one from Step 3 that offers the best improvement in energy balance as printed by QINFO. The energy balance information is printed at the end of a run, so the values from Step 3 to compare will be those after the prescribed number of time-steps (using the algorithm in THERM to solve the energy equation on the rectangular grid) after use of REBT.

5. Choose the number of time-steps in THERM for subsequent use between calls to REBT as follows. Plot $|\delta T|_{max}$ values versus time-step number printed by THERM in the run from Step 3 with the best XDTIME value. Include some of the final δT values from step 1 on the plot. The plot should resemble the qualitative one in Figure 7.2. Pick the number of time-steps between calls to REBT as the number of time-steps after the REBT call at which the $|\delta T|_{max}$ values have leveled out.

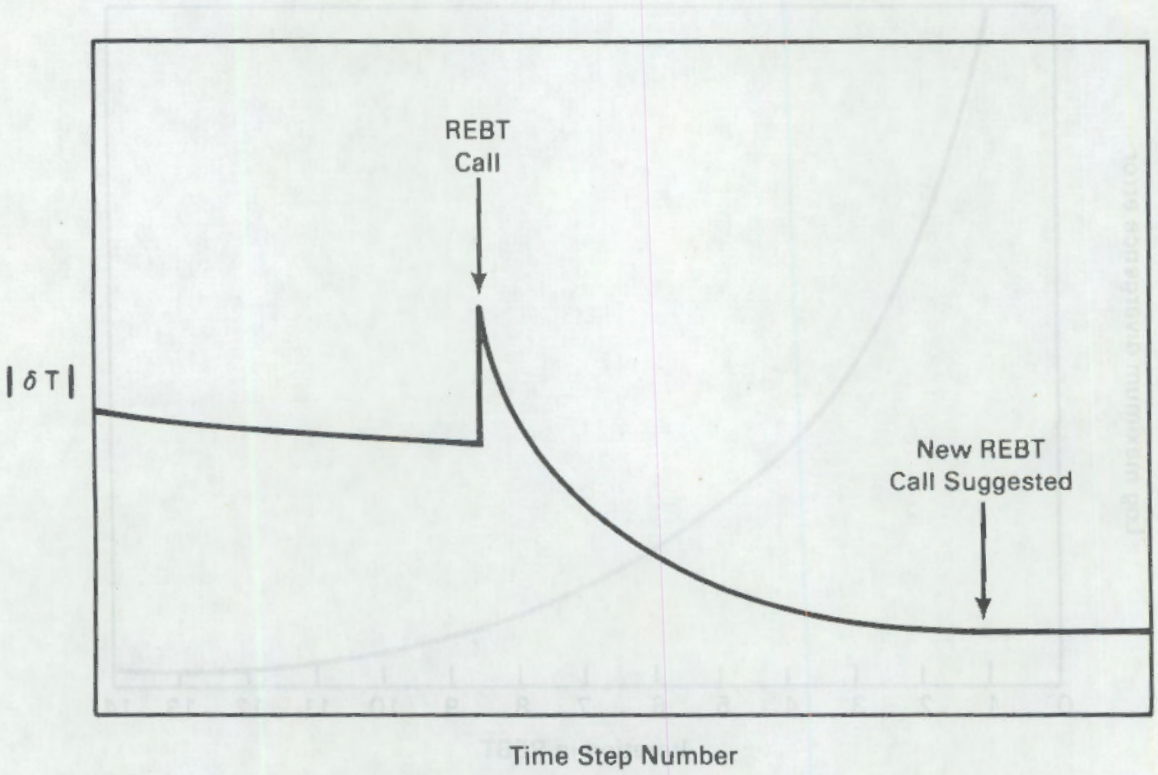


FIGURE 7.2. Schematic Behavior of Maximum Temperature Change $|\delta T|$ Per Time-Step Before and After REBT Call

6. If desired, confirm the choice of XDTIME in step 4 by constructing plots of $|\delta T|_{max}$ versus time-step number for other XDTIME values. The qualitative features to expect are shown in Figure 7.3.

The NMAX and XDTIME values and the frequency of calls to REBT selected by the foregoing procedure should tentatively be chosen for further converging the simulation toward steady state, and the diagnostic printouts can be switched off. For difficult cases, the user may need to re-examine choices later.

The user should remember that the effect of REBT is only on the rate of convergence, not on the final solution given by the model. On simulations characterized by rapid convergence, there may be no need to use REBT at all.

7.2 PARAMETER STATEMENT INFORMATION

Subroutine REBT requires specification of the following parameters to the same values and with the same significance as described in Chapter 4.0 for Subroutine GRID:

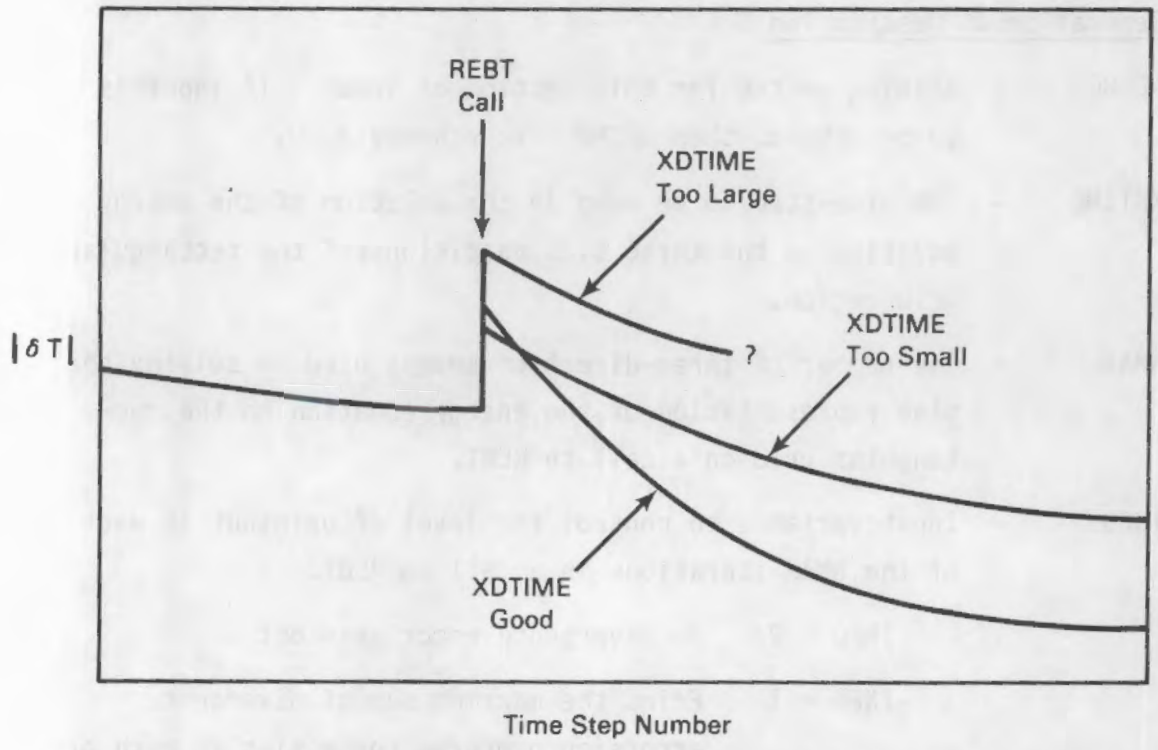


FIGURE 7.3. Schematic Behavior of Maximum Temperature Change $|\delta T|$ Per Time-Step for Varying XDTIME Values in a REBT Call

- IP,JP,KP,NEFAP

The following parameters required by REBT were discussed in Chapter 4.0, Subroutine GRID, and defined in Chapter 6.0, Subroutine THERM:

- KBP,KTP

7.3 INPUT FORMAT

7.3.1 Overview

The input to REBT is minimal, but good choices for the key variables XDTIME and NMAX should be based on previous experience or on systematic studies described in Section 7.1. If REBT is to be used, set STEADY = 1.0 in MAIN and REBON = 1.0 in THERM. The pattern of calls to the REBT procedure is set by variables NREB and NREBN in THERM.

7.3.2 REBT Options Input Block

General Input Format

```
NECHO
XDTIME,NMAX,INFO
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- XDTIME - The time-step to be used in the solution of the energy equation on the three slab partitions of the rectangular grid region.
- NMAX - The number of three-direction sweeps used in solving the slab representation of the energy equation on the rectangular grid on a call to REBT.
- INFO - Input variable to control the level of printout at each of the NMAX iterations in a call to REBT.

  INFO = 0 No divergence error printout

  INFO = 1 Print the maximum sum of divergence errors encountered for a slab in each of

the slab orientations and the index of the slab. Print after all three slab solutions are done. Labels will be (DIMAX,ID), (DJMAX,JD) and (DKMAX,KD) for the three slab orientations.

INFO = 2 Print the maximum sum of divergence errors for any slab after the temperature adjustment based on the slab solution has been made, and the slab location at which it occurred. Print immediately after each slab solution is done.

Input File Example

```
397 1/rebt
398 1.0e+5,12,1
```

Echoed Input File Example

```
645
646      rebt    xdtime=0.100e+06   nmax=12   info=1
```

In this example, echo of input is requested on line 397 of the input file with NECHO = 1. A time-step XDTIME = 1.0E+5 is set on input line 398, and NMAX = 12 slab iterations is requested. Printout at one time of maximum divergence error encountered and its location during the three slab solutions is requested with INFO = 1. The output echoes these values.

8.0 SUBROUTINE PROPS

Subroutine PROPS sets heat transfer properties for the simulation in the cylindrical grid region, much as Subroutine PROP does for the rectangular grid.

8.1 PROPS FUNCTIONS

The effects of heat transfer models used by PROPS are imposed exclusively through the three thermal resistivity arrays RESX, RESY, and RESZ, and the three film resistance arrays RESFX, RESFY, and RESFZ. These X-, Y-, and Z-labeled arrays now apply to the r, θ, and z directions and have meanings for the cylindrical grid as follows:

- RESX - R-direction resistivity
- RESY - θ-direction resistivity
- RESZ - Z-direction resistivity
- RESFX - R-direction film resistance
- RESFY - θ-direction film resistance
- RESFZ - Z-direction film resistance.

Subroutine PROPS reads input and sets up intermediate parameter sets related to heat transfer models for the cylindrical grid. It reads mesh location information assigning resistance array values on the cylindrical grid according to these models. The actual assignment of values to resistance arrays is done during each time-step using the latest temperatures for temperature-dependent properties.

The heat transfer models available in PROPS include 1) simple isotropic or orthotropic conduction in substances, 2) conduction through layered composites offering parallel paths, 3) conduction through layered composites offering series paths, 4) normal conduction through single or series films between cells, and 5) parallel heat transfer by radiation and by forced or natural convection from cask ends and sides. The model for conduction through a film at a cell interface can include a contribution equivalent to radiation across a gap. For an understanding of the models, see Chapter 5.0. The changes in the definitions and relationships from those of Chapter 5.0 for the conversion to cylindrical coordinates need not generally concern the user in supplying input.

Consistent interfacing of the cylindrical and rectangular grid regions requires that the radial resistivity in the first radial phantom cell, RESX(IS = 1,JS,K), be set to a large number.

The user should also know that any resistivity or film resistance component not defined for a mesh location will have the default value of zero.

8.2 PARAMETER STATEMENT INFORMATION

The following dimension-setting parameters have the same significance and should have the same value as in Subroutine GRID (Chapter 4.0):

IP,JP,KP,ISP,JSP

The following dimension-setting parameters play an analogous role to parameters of the same name used in PROP for the rectangular grid, but their numerical values should be set in PROPS according to the need there:

- NMATP - An array-dimensioning parameter greater than or equal to the number of substance conductivity polynomial coefficient sets read in PROPS Input Block 3.
- MTP - An array-dimensioning parameter greater than or equal to the largest value of MT for the intermediate variable sets (in arrays C0, C1, C3, TWF, CFUEL, CCLAD, etc.) for heat transfer models constructed from directives in PROPS Input Blocks 4 and 5.
- NSPECP - Dimension of the array SPECS used in PROPS Input Blocks 4 and 5 to read end-to-end all the intermediate heat transfer model specifications in each of the blocks. The SPECS array is overwritten by each of those input blocks in turn, so it must be long enough to accommodate the longer of them.
- NREGP,NPAIRP - Two parameters used in setting length of the INDEX array (to INDEXP = 7*NREGP+2*NPAIRP) containing directives for assigning resistivity and film resistance

values to cell locations in the cylindrical grid. NREGP is the maximum allowed number of region (range) specifications. NPAIRP is the sum over all regions of the number of (ID,MT) pairs, where ID is an identifier of the resistance parameter affected and the model used, and MT is an identifier of the intermediate heat transfer variable to use for that model. Each region directive set may request implementation of one or several changes in the resistance arrays by including one or several (ID,MT) pairs.

8.3 INPUT FORMAT

8.3.1 Overview

The input to Subroutine PROPS separates into six blocks:

1. thermal resistance print specifications for the cylindrical grid
2. convection specifications for cask side and for cylindrical grid parts of top and bottom
3. materials conductivity polynomial coefficient sets
4. parallel, isotropic, and orthotropic conduction models
5. series conduction models
6. assignment of resistance to cell locations.

The material conductivity polynomial coefficients read in Input Block 3 are overwritten after their use in setting up intermediate parameter sets in Input Blocks 4 and 5. The intermediate parameter sets constructed in response to Input Blocks 4 and 5 are retained as local variables for use in assigning resistances to cell locations at each time-step with most recent temperatures, as directed in PROPS Input Block 6.

8.3.2 Thermal Resistance Print Specifications. PROPS Input Block 1

General Input Format

```
NECHO
NSX,NSFX,NSY,NSFY,NSZ,NSFZ,INFO
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- NSX,NSFX,NSY,NSFY,NSZ,NSFZ - The number of the time-step at which to print respectively the RESX, RESFX, RESY, RESFY,RESZ, and RESFZ arrays.
- INFO - Integer flag variable that, if equal to 1, requests printing of each resistivity or film resistance array at its designated (by NSX, NSFX, etc.) time-step. No printing occurs if INFO = 0.

Input File Example

```
399 1/props
400 -1,-1,-1,-1,-1,-1,0
```

Echoed Input File Example

```
647
648      props   nsx= -1   nsfx= -1   nsy= -1   nsfy= -1   nsz= -1   nsfz=-1   Info=0
```

Echoing of input is requested with NECHO = 1, but printout of the six resistance arrays on the cylindrical grid is doubly suppressed, with INFO = 0 and with NSX = -1, NSFX = -1, etc. The user should set INFO = 1 and the resistance array printout flags to a non-negative time-step number in some early execution to obtain a printout of the resistance arrays to verify the correctness of the input.

8.3.3 Convection Specifications for Cask Side and Cylindrical Grid End Regions. PROPS Input Block 2

General Input Format

```
TOPH,TOPL,TOPV,TOPC,TOPN
BOTH,BOTL,BOTV,BOTC,BOTN
SIDEH,SIDEL,SIDEV,SIDEC,SIDEN
```

General Input Description

- TOPH,BOTH,SIDEH - Floating point flag variables that, if equal to 1.0, indicate a convection model is forthcoming for cask top, bottom, or side, respectively. The five entries on a line must be supplied, even if the flag variable is 0.
- TOPL,TOPV,TOPC,TOPN - Length L, velocity V, multiplier C, and exponent n in the forced or natural convection models for the cylindrical grid region of the cask top. The convection models were described in Chapter 5.0 for the rectangular grid. TOPV > 0.0 requests a forced convection model, while TOPV = 0.0 requests a natural convection model.
- BOTL,BOTV,BOTC,BOTN - Length L, velocity V, multiplier C, and exponent n for the cask bottom convection model, analogous to TOPL, TOPV, TOPC, and TOPN.
- SIOEL,SIDEV,SIDEC,SIDEN - Length L, velocity V, multiplier C, and exponent n for the cask side convection model.

Input File Example

```
401 1.0,220.0,0.0,0.14,0.333
402 1.0,220.0,0.0,0.27,0.25
403 1.0,3.5,0.0,0.45,0.25
```

Echoed Input File Example

```
649
650     props   toph=1.0   topl=0.220e+03   topv=0.000e+00   topc=0.140e+00  topn=0.333e+00
651     props   both=1.0   botl=0.220e+03   botv=0.000e+00   botc=0.270e+00  botn=0.250e+00
652     props   sideh=1.0   sidel=0.350e+01   sidev=0.000e+00  sidec=0.450e+00   siden=0.250e+00
```

Flags that convection models are forthcoming are set by the first entries on three lines of input: TOPH = 1.0 on line 401, BOTH = 1.0 on line 402, and SIDEH = 1.0 on line 403. Natural convection models are requested in this input with TOPV = 0.0, BOTV = 0.0, SIDEV = 0.0. The multiplier C and the power n for the natural convection are set for each of the three models to values from the convection heat transfer literature. The values for the side correlation are appropriate to a fin model.

8.3.4 Materials Conductivity Polynomial Coefficient Sets. PROPS Input Block 3

General Input Format

```
NECHO
NMAT
TEXT
CCONO(1),CCON1(1),CCON3(1)
TEXT
          .   .   .
          .   .   .
          .   .   .
TEXT
CCONO(NMAT),CCON1(NMAT),CCON3(NMAT)
```

General Input Description

These quantities are exactly as defined in Input Block 3 of PROP (Chapter 5.0) for use on the rectangular grid, but they form a separate and independent set of information for use by PROPS on the cylindrical grid.

Input File Example

```
404 1/props/ccon0,ccon1,ccon3
405 8
406 low conductivity
407 0.1e-20,0.0,0.0
408 high conductivity
409 0.1e+20,0.0,0.0
410 helium
411 0.52e-3,0.32e-5,0.0
412 sst
413 0.09215,0.1465e-3,0.0
414 nodular cast iron
415 0.5162,-0.3205e-3,0.0
416 air
417 0.688e-4,0.634e-6,0.0
```

```
418 epoxy (not used)
419 0.15e-2,0.0,0.0
420 nitrogen (not used)
421 0.075e-3,0.6167e-6,0.0
```

Echoed Input File Example

```
654    props   nmat= 8   maximum current dimension for nmat is  20
655    props   ccon0,ccon1,ccon3                material thermal conductivity, W/cm-k
656                           k(mat)=  ccon0(mat)+  ccon1(mat)*t+ ccon3(mat)*t*t*t
657                              1  (0.1000e-20)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   low conductivity
658                              2  (0.1000e+20)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   high conductivity
659                              3  (0.5200e-03)+(0.3200e-05)*t+(0.0000e+00)*t*t*t   helium
660                              4  (0.9215e-01)+(0.1465e-03)*t+(0.0000e+00)*t*t*t   sst
661                              5  (0.5162e+00)+(-.3205e-03)*t+(0.0000e+00)*t*t*t   nodular cast iron
662                              6  (0.6880e-04)+(0.6340e-06)*t+(0.0000e+00)*t*t*t   air
663                              7  (0.1500e-02)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   epoxy (not used)
664                              8  (0.7500e-04)+(0.6167e-06)*t+(0.0000e+00)*t*t*t   nitrogen (not used)
```

Line 404 of the input file example sets NECHO to 1 to request echoing input, provides comments indicating that the forthcoming block is for Subroutine PROPS and the sets of conductivity polynomial coefficient arrays CCON0, CCON1, and CCON3. Line 405 of the input indicates that 8 (NMAT) properties sets are forthcoming. The subsequent line gives 40 characters of material labeling information, followed by a line with the three polynomial coefficients for the thermal conductivity of that material. Not all thermal conductivity property sets need be subsequently referenced. The fictitious high conductivity and low conductivity sets may be useful in setting fixed temperature or insulated surface boundary conditions, respectively. The polynomial assumes temperatures in degrees Kelvin.

The echoed input gives NMAT and the maximum value of NMAT currently allowed by dimensions (NMATP), followed by information on the conductivity polynomials and their labeling text in an informative form.

8.3.5 Parallel, Isotropic, and Orthotropic Conduction Models. PROPS Input Block 4

General Input Format

```
NECHO
MTMAX
SPECS(I),I=1,NSPECP
```

The entire dimensioned array SPECS is read. The user should construct it with MTMAX sets of entries, the sets being read end-to-end. Each set directs construction of an intermediate parameter set of index MT for subsequent referencing (in PROPS Input Block 6) in setting resistivities and film resistances on the cylindrical mesh. The form for a set for simple isotropic or orthotropic conduction or for parallel conduction is:

$$MT,MATS,MAT_1,WIDTH_1,MAT_2,WIDTH_2 \ldots MAT_{MATS},WIDTH_{MATS},$$

Unused entries in the SPECS array should be filled with zeros in the input.

General Input Description

These quantities are exactly as defined in Input Block 4 of PROP (Chapter 5.0) for use on the rectangular grid, but they form an independent set of information for use by PROPS on the cylindrical grid. Each intermediate parameter set constructed here has labeling index MT and includes three coefficients for a polynomial in Kelvin temperature for conductivity λ or a sum $\Sigma_i \lambda_i \delta W_i$.

Input File Example

```
422 1/props/specs def. 01 isotropic and 11 parallel
423 9
424 1.0,1.0,1.0,1.0,
425 2.0,1.0,2.0,1.0,
426 3.0,1.0,3.0,1.0,
427 4.0,1.0,4.0,1.0,
428 5.0,1.0,5.0,1.0,
429 6.0,1.0,6.0,1.0,
430 7.0,1.0,5.0,0.2259,
431 8.0,1.0,5.0,0.310,
432 9.0,1.0,5.0,0.5172,
433 64*0.0
```

Echoed Input File Example

```
665
666                                   maximum number of material types is currently  30
667                                   maximum array dimension of specs is currently 100
668
669                                ***composite definition 01 isotropic and 11 parallel***
670       props   mtmax=  9
671       props   specs                          mt   mats   mat    width
672                                              1     1     1   0.1000e+01
673                                              2     1     2   0.1000e+01
674                                              3     1     3   0.1000e+01
675                                              4     1     4   0.1000e+01
676                                              5     1     5   0.1000e+01
677                                              6     1     6   0.1000e+01
678                                              7     1     5   0.2259e+00
679                                              8     1     5   0.3100e+00
680                                              9     1     5   0.5172e+00
681
682                                    computed coefficients from specs array
683                                    mt      c0          c1          c3
684                                     1  0.1000e-20  0.0000e+00 0.0000e+00
685                                     2  0.1000e+20  0.0000e+00 0.0000e+00
686                                     3  0.5200e-03  0.3200e-05 0.0000e+00
687                                     4  0.9215e-01  0.1465e-03 0.0000e+00
688                                     5  0.5162e+00 -0.3205e-03 0.0000e+00
689                                     6  0.6880e-04  0.6340e-06 0.0000e+00
690                                     7  0.1166e+00 -0.7240e-04 0.0000e+00
691                                     8  0.1600e+00 -0.9936e-04 0.0000e+00
692                                     9  0.2670e+00 -0.1658e-03 0.0000e+00
```

Line 422 of the input file example requests echoing of input with NECHO = 1, then gives user comments indicating that the data is for Subroutine PROPS and directs construction of intermediate parameter sets for the simple conduction group 01 (ID = 01,02,03, or 04) or for the parallel conduction composite group 11 (ID = 11,12,13,14,15, or 16). Line 423 of the input says MTMAX = 9 directive sets for construction of intermediate parameter sets of the isotropic, orthotropic, or parallel conduction type are forthcoming. Lines 424 through 432 give the directive sets, each of which leads to the construction of polynomial coefficients for quantities of the form

$$\Sigma\lambda_i\delta W_i \text{ or } \Sigma_{MAT}\ \lambda(MAT)*WIDTH(MAT)$$

as described in Chapter 5.0. In the nine sets shown here, the number MATS of terms included in the sum is one for each case. The index MAT refers to sets of conductivity polynomial coefficients supplied in PROPS Input Block 3. Line 433 of the input fills out the unused entries in the SPECS array, which was dimensioned in this case to NSPECP = 100.

The echoed input first prints out a reminder that the largest value of MT is MTP, and that the length of the SPECS array for holding the directives for their construction is NSPECP. The sets of directives are themselves then printed, followed by the constructed polynomial coefficients C0(MT), C1(MT), and C3(MT) of degree 0, 1, and 3 in Kelvin temperature in response to those directive sets.

8.3.6 Series Conduction Models. PROPS Input Block 5

General Input Format

```
NECHO
MTMAX
SPECS(I),I=1,NSPECP
```

The entire dimensioned SPECS array is read. The user should construct it with MTMAX sets of entries, with the sets being read end-to-end. The entries are in floating point form, with some of them converted to integers. The input form for a series conduction set is:

```
MT,MAT,WIDTH,E1,E2,TWF(MT)
```

General Input Description

The definition and purpose of these input variables are the same as for the rectangular mesh. See Chapter 5.0, PROP Input Block 5.

Input File Example

```
434 1/props/specs def. 21 series
435 10
436 20.0,3.0,0.1,0.2,0.25,0.5,
437 21.0,3.0,0.15,0.2,0.25,0.5,
438 22.0,3.0,0.3,0.2,0.2,0.5,
439 23.0,3.0,5.0,0.2,0.2,0.5,
440 24.0,1.0,1.0,0.2,1.0,0.5,
```

```
441 25.0,6.0,0.1,0.2,0.25,0.5,
442 26.0,1.0,1.0,0.3,1.0,0.5,
443 27.0,1.0,1.0,0.96,1.0,0.5,
444 28.0,1.0,1.0,0.8,1.0,0.5,
445 29.0,3.0,0.001,0.2,0.25,0.5,
446 40*0.0
```

Echoed Input File Example

```
693
694                                   ***composite definition 21 series***
695     props   mtmax= 10
696     props   specs                 mt    mat   width        e1          e2          twf
697                                   20     3  0.1000e+00  0.2000e+00  0.2500e+00  0.5000e+00
698                                   21     3  0.1500e+00  0.2000e+00  0.2500e+00  0.5000e+00
699                                   22     3  0.3000e+00  0.2000e+00  0.2000e+00  0.5000e+00
700                                   23     3  0.5000e+01  0.2000e+00  0.2000e+00  0.5000e+00
701                                   24     1  0.1000e+01  0.2000e+00  0.1000e+01  0.5000e+00
702                                   25     6  0.1000e+00  0.2000e+00  0.2500e+00  0.5000e+00
703                                   26     1  0.1000e+01  0.3000e+00  0.1000e+01  0.5000e+00
704                                   27     1  0.1000e+01  0.9600e+00  0.1000e+01  0.5000e+00
705                                   28     1  0.1000e+01  0.8000e+00  0.1000e+01  0.5000e+00
706                                   29     3  0.1000e-02  0.2000e+00  0.2500e+00  0.5000e+00
707
708                                   computed coefficients from specs array
709                                   mt      c0          c1          c3
710                                   20   0.5200e-02  0.3200e-04  0.2835e-11
711                                   21   0.3467e-02  0.2133e-04  0.2835e-11
712                                   22   0.1733e-02  0.1067e-04  0.2520e-11
713                                   23   0.1040e-03  0.6400e-06  0.2520e-11
714                                   24   0.1000e-20  0.0000e+00  0.4536e-11
715                                   25   0.6880e-03  0.6340e-05  0.2835e-11
716                                   26   0.1000e-20  0.0000e+00  0.6804e-11
717                                   27   0.1000e-20  0.0000e+00  0.2177e-10
718                                   28   0.1000e-20  0.0000e+00  0.1814e-10
719                                   29   0.5200e+00  0.3200e-02  0.2835e-11
720
```

The MTMAX = 10 forthcoming sets of series type intermediate parameter set construction directives indicated on input example line 435 appear on lines 436 through 445. The remaining 40 entries of the NSPECP = 100 locations in SPECS are filled with zeros on line 446 of the input example. Line 436 directs construction of intermediate parameter set MT = 20 using the coefficient set MAT = 3, which was supplied on lines 410 and 411 of the input file example of PROPS Input Block 3. The thickness δL = WIDTH in the heat flow direction for the series layer is specified as 0.1 cm by the third entry on line 436. A radiation model for construction of C3(20) is requested by the next two entries of line 436 by the emittance values E1 = 0.2, E2 = 0.25. If the set MT = 20 is

used for a film resistance rather than as part of series layers for resistivity within a cell, the temperatures in the cells on the two sides of the interface will be equally weighted in forming a boundary temperature T_B at which to evaluate the polynomial for $\lambda/\delta L$, because TWF(20) is set to 0.5.

The other nine sets direct construction of additional $\lambda/\delta L$ polynomial (in Kelvin temperature) coefficient sets.

The echoed input repeats these specification sets and displays the polynomial coefficients actually constructed.

8.3.7 Assignment of Resistance to Cell Locations. PROPS Input Block 6

General Input Format

```
NECHO
NREG,NPAIR
INDEX(I),I=1,INDEXP
```

The entire array INDEX is read. The NREG sets of region resistance assignment directives stored end-to-end in index have the form:

$$IBEG,IEND,JBEG,JEND,KBEG,KEND,NPAIR,ID_1,MT_1,ID_2,MT_2,\ldots ID_{NPAIR},MT_{NPAIR}$$

The resistance assignments here on the cylindrical grid are analogous to those in PROP Input Block 7 for the rectangular grid, but the ranges apply to indices IS, JS, and K in the cylindrical grid, and the (ID,MT) pairs are those constructed in PROPS for the cylindrical grid rather than those constructed in PROP for the rectangular grid.

General Input Description

The definitions of the variables for assignment of resistances in the cylindrical grid are analogous to those in Subroutine PROP Input Block 7 for the rectangular grid (Chapter 5.0). Items to remember are:

- IBEG,IEND,JBEG,JEND,KBEG,KEND - Region limits for radial, azimuthal, and axial cell indices are, respectively,

  $IBEG \leq IS \leq IEND$

  $JBEG \leq JS \leq JEND$

  $KBEG \leq K \leq KEND$

- ID,MT - A pair of directives for modifying the thermal resistance arrays (refer to Chapter 5.0, PROP Input Block 7). The indices MT here refer to intermediate parameter sets set in PROPS, and the RESX, RESY, and RESZ (and corresponding RESFX, RESFY, and RESFZ) arrays refer to conduction in the R, θ, and Z directions. Table 5.3 still defines the actions requested for defined ID values, but one new value is added:

  ID = 53 - Add to radial film resistance RESFX at cask side according to cask side convection model and designated intermediate parameters set MT for radiation contribution.

Input File Example

```
447 1/props/index
448 21,30
449 1,1,2,63,2,30,1,1,1,
450 2,7,1,1,2,30,1,2,1,
451 2,7,64,64,2,30,1,2,1,
452 2,7,2,63,1,1,1,52,28,
453 2,2,2,63,2,3,1,4,5,
454 2,2,2,63,4,5,1,4,3,
455 2,2,2,63,6,24,2,4,4,41,29,
456 2,2,2,63,25,27,1,4,3,
457 2,2,2,63,28,28,2,4,4,41,20,
458 2,3,2,63,29,29,1,4,4,
459 4,7,2,63,27,29,1,4,5,
460 4,4,2,63,29,29,3,4,4,41,21,43,23,
461 3,3,2,63,2,28,1,4,5,
462 4,5,2,63,2,26,3,1,7,2,8,3,9,
463 6,7,2,63,2,26,1,4,5,
464 2,5,2,63,30,30,3,1,1,2,1,51,24,
465 5,5,2,63,30,30,1,41,25,
466 6,7,2,63,30,30,2,4,5,51,26,
467 7,7,2,63,2,5,1,53,26,
468 7,7,2,63,6,27,1,53,27,
469 7,7,2,63,28,30,1,53,26,
470 48*0
```

Echoed Input File Example

```
                                  ***available composite definitions***
                   group                             id
                   01 isotropic                       1 resx
                                                      2 resy
                                                      3 resz
                                                      4 resx,resy,resz
                   11 parallel                       11 resx,x-y plane
                                                     12 resx,x-z plane
                                                     13 resy,x-y plane
                                                     14 resy,y-z plane
                                                     15 resz,x-z plane
                                                     16 resz,y-z plane
                   21 series                         21 resx
                                                     22 resy
                                                     23 resz
                   41 film resistance                41 resfx
                                                     42 resfy
                                                     43 resfz
                   51 exterior convection            51 resfz for top of cask
                      and radiation                  52 resfz for bottom of cask
                                                     53 resfx for side of cask

props   nreg=   21   npair=   30   maximum current dimensions for nreg and npair are    25    40
props   index        cell location
               ibeg lend jbeg jend kbeg kend   npair     id   mt   id   mt   id   mt   id   mt   id   mt
                 1    1    2   63    2   30      1        1    1
                 2    7    1    1    2   30      1        2    1
                 2    7   64   64    2   30      1        2    1
                 2    7    2   63    1    1      1       52   28
                 2    2    2   63    2    3      1        4    5
                 2    2    2   63    4    5      1        4    3
                 2    2    2   63    6   24      2        4    4   41   29
                 2    2    2   63   25   27      1        4    3
                 2    2    2   63   28   28      2        4    4   41   20
                 2    3    2   63   29   29      1        4    4
                 4    7    2   63   27   29      1        4    5
                 4    4    2   63   29   29      3        4    4   41   21   43   23
                 3    3    2   63    2   28      1        4    5
                 4    5    2   63    2   26      3        1    7    2    8    3    9
                 6    7    2   63    2   26      1        4    5
                 2    5    2   63   30   30      3        1    1    2    1   51   24
                 5    5    2   63   30   30      1       41   25
                 6    7    2   63   30   30      2        4    5   51   26
                 7    7    2   63    2    5      1       53   26
                 7    7    2   63    6   27      1       53   27
                 7    7    2   63   28   30      1       53   26
```

The input file example asks for echoing of input on line 447 with NECHO = 1, then specifies 21 resistance assignment directive sets holding 30 (ID,MT) pairs on line 448. Lines 449 through 469 contain these resistance assignment directive sets.

Line 449 of the input file example sets radial resistivities (as indicated by ID = 1) to a large number (as indicated by MT = 1) on the inner radial cells (as indicated by the range $1 \leq IS \leq 1$, $2 \leq JS \leq 63$, $2 \leq K \leq 30$). That MT = 1 will get high resistivity can be seen by noting that the intermediate parameter set MT = 1 was constructed in PROPS Input Block 4, where the directive set on input file example line 424 referenced the input conductivity coefficient set

MAT = 1, which was for low conductivity. The set MAT = 1 was input on lines 406 and 407 of the input file example for PROPS Input Block 3. A high radial resistivity for IS = 1 is needed for proper communication between rectangular and cylindrical grid regions. The ID values are defined in Table 5.3.

Line 460 of the input file example specifies a region for its resistance array changes as (4 ≤ IS ≤ 4, 2 ≤ JS ≤ 63, 29 ≤ K ≤ 29). It requests implementation of resistance arrays changes there with three (ID,MT) pairs:

- (4,4) - Replace RESX, RESY, and RESZ in that region with values derived from intermediate parameter set 4.
- (41,21) - Add to radial film resistance RESFX the reciprocal of the $\lambda/\delta L$ determined from intermediate parameter set 21, which was set in PROPS Input Block 5. Parameter set MT = 21 specified a helium material with a gap radiation transfer model for setting C3.
- (43,23) - Add to axial film resistance RESFZ the reciprocal of the $\lambda/\delta L$ calculated from the intermediate parameter set MT = 23 set in PROPS Input Block 5 input file example line 439. The set MT = 23 described a 5-cm-wide helium filled gap with wall emittances 0.2 on both sides, with equal weighting of temperatures on either side requested [by TWF(23) = 0.5] in calculating a film temperature for properties evaluation.

The other resistance-assignment directive sets similarly implement one or more (ID,MT) pairs in filling out the resistance arrays. Unused locations in INDEX are set to zero values on line 470 of the input example. INDEX has INDEXP = 7*NREGP+2*NPAIRP dimensioned locations.

The echoed input first gives a summary table of the ID values and their requested actions. It then repeats the number NREG of region specifications forthcoming and the number NPAIR of (ID,MT) resistance-setting pairs they contain, and gives for user convenience the current dimension limits NREGP and NPAIRP for NREG and NPAIR, respectively. The echoed input gives a table of resistance assignment directives.

9.0 SUBROUTINE TSIDE

Subroutine TSIDE is used to solve the energy equation on the cylindrical grid region.

9.1 TSIDE FUNCTIONS

TSIDE reads input specifying initial temperatures, boundary temperatures, numerical procedure options, and printout options during initiation or restart of a simulation. If solution of the energy equation in the cylindrical grid region is requested, TSIDE is called at each time-step to advance the temperature solution.

The actions by TSIDE in the solution sequence include:

1. TSIDE sets the connector arrays for the energy equation on the cylindrical grid. These are the coefficients that relate heat flows to temperatures and heat sources.
2. TSIDE executes an algorithm that advances the temperature on the cylindrical grid through a time-step.
3. If requested, TSIDE prints monitoring information, including the location and magnitude of the greatest temperature change on the cylindrical grid for the current time-step, and also the temperatures in cells specified by the user for monitoring.
4. TSIDE makes a tentative adjustment in the time-step by comparing the maximum temperature change and a user-specified target maximum temperature change.

The algorithm used in TSIDE for advancing the temperature on the cylindrical grid through a time-step is discussed in Volume I - Equations and Numerics (McCann 1987). The imposition of continuity conditions between the rectangular and cylindrical grid regions, achieved with subroutine TBND supplementing TSIDE and THERM, is discussed in Chapter 2.0, Code Overview.

TSIDE is called at setup or restart to read input to guide the solution and to set or reset temperatures. Actions by TSIDE during setup or restart include:

1. reading certain numerical procedure options, printout options, and temperature monitoring options
2. reading and implementing options for setting or altering the initial temperature distribution and ambient temperature.

9.2 PARAMETER STATEMENT INFORMATION

Subroutine TSIDE requires specification of the following parameters, which were discussed in Chapter 4.0, Subroutine GRID:

IP,JP,KP,ISP,JSP,NEFAP,KBP,KTP

Subroutine TSIDE also requires specification of the parameter

- MONTSP - Number of cells in the cylindrical grid that can be specified by the user for monitoring the temperature during time-stepping.

9.3 INPUT FORMAT

9.3.1 Overview

The input read by TSIDE will be described in Section 9.3.2. Other input available to TSIDE includes the initial temperature for the cylindrical grid that was read in THERM.

9.3.2 TSIDE Input Block

General Input Format

```
NECHO
NEWTS,TSAMB,DTEMAX
NECHO
MONTS
IMONTS(M),JMONTS(M),KMONTS(M)  {Repeated for M=1 to MONTS+1, with
                               {IMONT(MONTS+1)=0
```

NECHO
NDELTA
DELTA(K),K=2,KP-1

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.

- NEWTS - An integer flag for initializing or resetting side (cask body or cylindrical grid) temperatures. If NEWTS = 1, cylindrical grid temperatures TS are set to the initial interface temperatures read in THERM. If NEWTS = 0, cylindrical grid temperatures are not reset.

- TSAMB - The cask-side ambient temperature. If resetting side ambient temperature is requested by NEWTA = 1 (set in MAIN) or NEWTS = 1, the cask-side ambient temperatures are set as:

  TS(IS,JS,K) = TSAMB

  for the cells defined by the ranges

  2≤JS≤JSP-1

  ISEND(K)+1≤IS≤ISP

  2≤K≤KP-1

  This is the region radially beyond the active computational cells.

- DTEMAX - The target maximum temperature change per time-step for the cylindrical grid. A tentative new time-step DTIMES is set as:

  DTIMES = 1.1*DTIME if DTMAX < DTEMAX

  DTIMES = DTIME*DTEMAX/DTMAX if DTMAX>DTEMAX

  DTIME is the current time-step, and DTMAX is the magnitude of the largest temperature change in the cylindrical grid in the current time-step.

- MONTS - The number of cells in the cylindrical grid region for which temperature monitoring is requested.

- IMONTS(M),JMONTS(M),KMONTS(M) - The radial, azimuthal and axial mesh indices IS, JS, and K, respectively, of the mth cell in the cylindrical grid for which temperature printout is desired during the time-stepping. IMONTS(MONTS+1) should be set = 0 to terminate the list.

- NDELTA - An integer flag for adding a K-plane dependent increment to the temperatures for the cylindrical grid interior cells. If NDELTA = 1, add DELTA(K) to the TS(IS,JS,K) for cells in the range

  $2 \leq K \leq KP-1$

  $2 \leq JS \leq JSP-1$

  $2 \leq IS \leq ISP-1$

  If NDELTA = 0, no DELTA increment is added. If ISEND(K) < ISP-2 and NDELTA = 1, the increment DELTA(K) will be added to the ambient temperature for that K-layer. In this case, reset the side ambient temperatures using NEWTA.

- DELTA(K) - Temperature increment to optionally add to the active computational cells of the kth plane of the cylindrical grid, either initially or in a restart. The DELTA array is read even if NDELTA = 0.

Input File Example

```
471 1/tside
472 0,297.0,1.0
473 1/tside/monitor/ts
474 4
475 7,63,6
476 7,63,15
477 7,63,18
478 7,63,26
479 0,0,0
480 1/tside/delta
481 0
482 29*0.0
```

Echoed Input File Example

```
768     tside   newts=0   tsamb=0.297e+03   dtemax=0.100e+01
769
770     tside   monitor cells= 4   maximum number currently allowed is  4
771                                                    m   i  j  k
772                                                    1   7 63  6
773                                                    2   7 63 15
774                                                    3   7 63 18
775                                                    4   7 63 26
776
777     tside   ndelta=0                    k    delta(k)
778                                         2   0.000e+00
779                                         3   0.000e+00
780                                         4   0.000e+00
781                                         5   0.000e+00
782                                         6   0.000e+00
783                                         7   0.000e+00
784                                         8   0.000e+00
785                                         9   0.000e+00
786                                        10   0.000e+00
787                                        11   0.000e+00
788                                        12   0.000e+00
789                                        13   0.000e+00
790                                        14   0.000e+00
791                                        15   0.000e+00
792                                        16   0.000e+00
793                                        17   0.000e+00
794                                        18   0.000e+00
795                                        19   0.000e+00
796                                        20   0.000e+00
797                                        21   0.000e+00
798                                        22   0.000e+00
799                                        23   0.000e+00
800                                        24   0.000e+00
801                                        25   0.000e+00
802                                        26   0.000e+00
803                                        27   0.000e+00
804                                        28   0.000e+00
805                                        29   0.000e+00
806                                        30   0.000e+00
807
```

The input file example requests echoing of input with NECHO = 1 on line 471. On line 472, the input file example sets NEWTS = 0, indicating that no new side (cask body) temperature is to be set. The ambient temperature for the cask side is to be set to 297°K or 24°C if such a resetting of side temperatures (cylindrical grid region) occurs. Line 472 sets target maximum temperature change per time-step for the cask body DTEMAX to 1.0°C. Line 473 resets NECHO, and serves to carry the user comments on what is forthcoming, which is

the list of cells to be monitored for the cask body. Line 474 specifies that monitoring of four temperatures is requested, and they are listed by their indices in lines 475 through 478. Line 479 terminates this list of monitored cells with its leading zero. Line 480 resets NECHO. Lines 481 and 482 set NDELTA to 0, then set the 29 entries (for K = 2 through 30 in a simulation with KP = 31) for DELTA(K) to zero, doubly indicating that no manual increment of the temperatures in the active computational cells of the cylindrical grid region is desired.

The output example echoes this input and also provides a reminder on line 770 of the number of monitor cells in the cylindrical grid region currently allowed by dimensioning.

10.0 SUBROUTINE TBND

Subroutine TBND provides the means to couple the solution of the energy equation within the interior of a cask to that of the exterior side of the cask body. A cartesian coordinate system is used for the interior of a cask and a cylindrical coordinate system is used for the side portion of the cask body. A cross section of a cask and the corresponding computational mesh is illustrated in Figure 4.1. Although the temperatures are determined implicitly within each region, the coupling between the two regions is explicit. This explicit coupling is done within subroutine TBND in such a way that temperature is continuous across the boundary and energy is conserved.

New-time temperatures are determined in the interior region using old-time boundary temperatures. Heat fluxes from the interior to the boundary are then determined. These heat fluxes are used as a boundary condition to calculate new-time exterior side temperatures. Finally, the temperatures on the boundary between the interior and exterior regions are updated to satisfy conservation of energy across the boundary. If there is no body to the cask, then neither subroutine TSIDE nor subroutine TBND is called.

10.1 PARAMETER STATEMENT INFORMATION

Subroutine TBND requires the specification of parameter IP, JP, KP, ISP, JSP, NEFAP, KBP, and KTP. These parameters define the overall computational mesh and are described in Chapter 4.0, Subroutine GRID. No additional parameters are needed for Subroutine TBND.

10.2 INPUT FORMAT

The operation of subroutine TBND is automatic, and input file specifications are not required.

11.0 SUBROUTINE RADC

HYDRA-II provides the user with three subroutines for use in modeling radiation heat transfer - RADC, RADP, and RADR. Subroutine RADC is described in this chapter. Subroutine RADP provides the user with a model for plate-to-plate radiation heat transfer. RADP is described in Chapter 12.0. The remaining subroutine, RADR, is described in Chapter 13.0 and is intended to model radiation heat transfer between the fuel rods of an assembly. The radiation heat transfer distribution computed in RADC is cumulative with that computed by the other radiation heat transfer routines, RADP and RADR.

Subroutine RADC allows simulation of radiation heat transfer between the cell surfaces making up an enclosure in the computational grid. Each surface is associated with a cell of the grid by using the cell's (I,J,K) index. For RADC, the surfaces of an enclosure must have the same K index. Therefore, RADC allows communication between only the surfaces of an enclosure that are on the same K-plane. Communication between surfaces at differing K-planes must be handled in RADP. Enclosures having the same configuration (i.e., the same set of (I,J) indices defining the surfaces, as well as the same heat transfer coefficients between those surfaces), but residing on different K-planes, form regions in RADC terminology.

The radiation heat transfer between surfaces of an enclosure is computed as:

$$\begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_m \\ \vdots \\ q_N \end{bmatrix} = DZ(K) \begin{bmatrix} H_{1,1} & H_{1,2} & H_{1,3} & \cdots & H_{1,N} \\ H_{2,1} & H_{2,2} & H_{2,3} & \cdots & H_{2,N} \\ & \vdots & \vdots & \vdots & \\ H_{m,1} & H_{m,2} & H_{m,3} & \cdots & H_{m,N} \\ & \vdots & \vdots & \vdots & \\ H_{N,1} & H_{N,2} & H_{N,3} & & H_{N,N} \end{bmatrix} \begin{bmatrix} T_1^4 \\ T_2^4 \\ \vdots \\ T_m^4 \\ \vdots \\ T_N^4 \end{bmatrix}$$

The radiation heat transfer received by the mth surface of the enclosure is represented by q_m. Each surface of the enclosure is assigned an index. These indices range sequentially from 1 to N. The correlation between these indices and the corresponding (I,J,K) indices of the computational cell is made in the input to RADC. The format for providing this information is discussed in Sections 11.2.3, 11.2.4, and 11.2.5.

DZ(K) represents the local DZ length segment which is common to all surfaces of this enclosure. It makes up half of the information necessary to compute the effective area of each of the surfaces. The other length segment is embedded in the radiation heat transfer coefficient, H.

The radiation heat transfer coefficients, $H_{m,n}$, are generated by the user and provided as input to RADC as discussed in Section 11.2.6. The constituent H's must include the effect of surface emissivity, shape factor, and Stefan-Boltzmann constant (σ = 5.67e-12 $W/cm^2 \cdot K^4$), in addition to carrying the other length segment representing the surface area. Since each enclosure of a RADC region has the same set of radiation heat transfer coefficients, there must be as many H matrices as there are regions in the RADC model. Each H matrix must be symmetric to ensure conservation of energy (i.e., $H_{m,n} = H_{n,m}$). The diagonal elements of these matrices account for reradiation from the receiving surface to the other surfaces of the region. Therefore, they must equal the negative of the sum of the off-diagonal row-element H's. More compactly stated,

$$H_{m,m} = - \sum_{\substack{n=1 \\ n \neq m}}^{N} H_{m,n}$$

As a general note, the information required to construct the H arrays can be very lengthy and dominates the RADC input section. Therefore, the user should configure the regions of the RADC model to take maximum advantage of any symmetries present in the geometry in an effort to reduce the number of H

arrays required. The effect of symmetries resulting from the application of boundary conditions requires special consideration. This is discussed in Section 11.2.7.

The temperatures used to represent the surfaces in the RADC computation are those of the corresponding (I,J,K) cells. These temperatures are actually located at the center of the cell. Therefore, the user must reference a cell surface to the cell that best represents the temperature of that surface. RADC is intended to model radiation heat transfer between solid surfaces, however. Consequently, the user must choose a cell that is consistent with both of these considerations.

11.1 PARAMETER STATEMENT INFORMATION

Aside from the overall grid specification information IP, JP, KP, KBP, and KTP (described in Chapter 4.0), RADC requires information pertaining to the limiting number of surfaces and regions in the model. The required data are as follows:

- NREGP - An array dimension greater than or equal to the maximum number of RADC regions in the model.
- KCELLP - An array dimension greater than or equal to the maximum number of K indices in a K-plane identifier.
- IDKP - An array dimension greater than or equal to the maximum number of K-plane identifiers in the model.
- NSURFP - An array dimension greater than or equal to the maximum number of surfaces in any region.
- IDIP - An array dimension greater than or equal to the maximum number of I-cell identifiers.
- IDJP - An array dimension greater than or equal to the maximum number of J-cell identifiers.
- IDHP - An array dimension greater than or equal to the maximum number of H identifiers.

Each of these parameters must be set, as a minimum, to a value of 1 (even when RADC is not used).

11.2 INPUT FORMAT

11.2.1 Overview

Generally speaking, the input to subroutine RADC can be divided into six subsections:

- set info switch
- define regions
- load K-plane identifiers
- load I-cell identifiers
- load J-cell identifiers
- load H array.

A detailed discussion of the input requirements for each of these subsections is provided in the following text. This discussion references the RADC radiation model for the sample problem presented previously in Chapter 4.0. The plan and elevation views illustrating the computational mesh and RADC regions are presented in Figures 11.1 and 11.2, respectively. The input for Region 4 will be discussed in detail. Therefore, an enlarged view of this region is provided in Figure 11.1.

11.2.2 Set INFO Switch

General Input Format

```
NECHO
INFO
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.

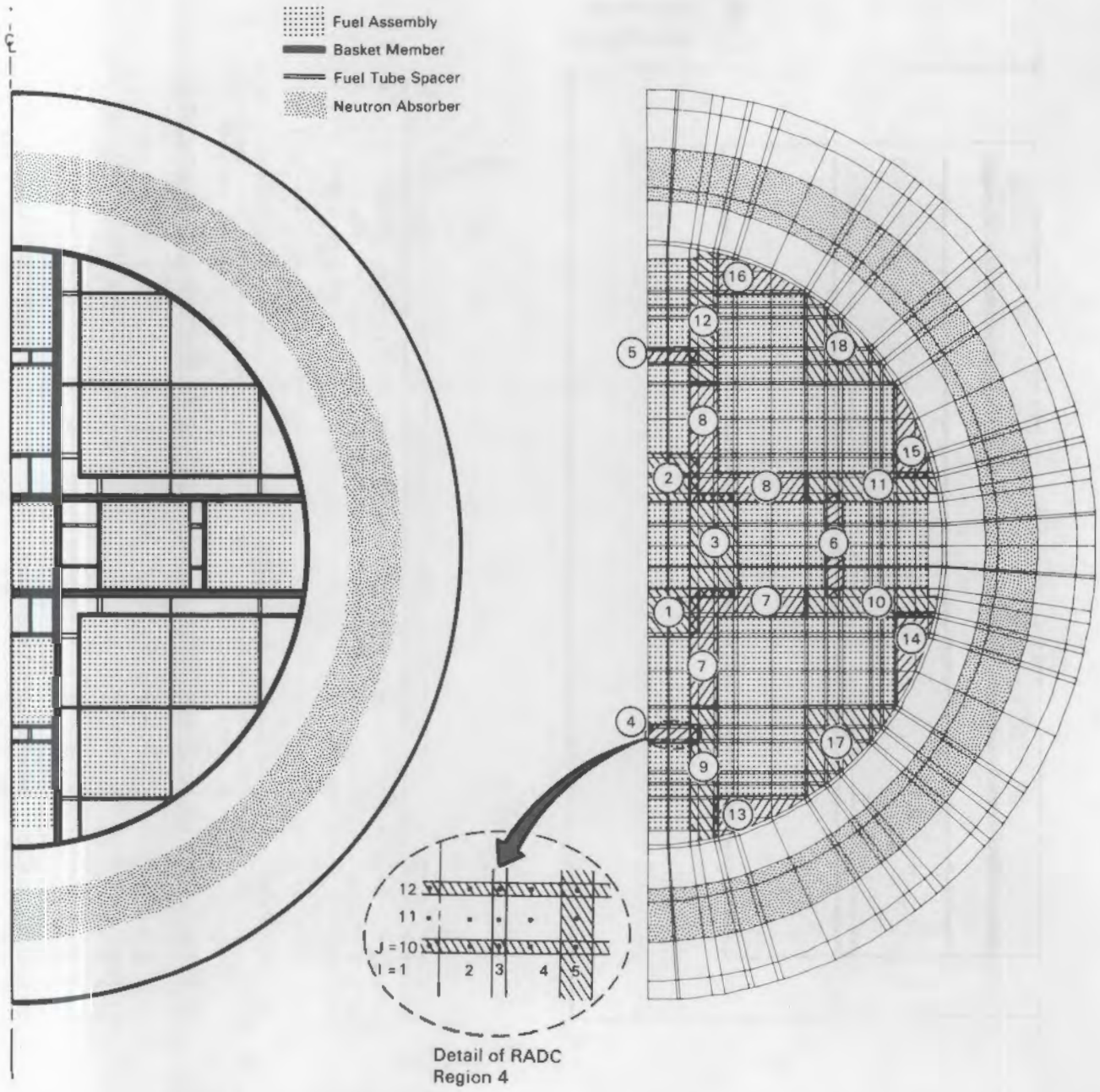


FIGURE 11.1. RADC Regions Superimposed on the Transverse Computational Mesh

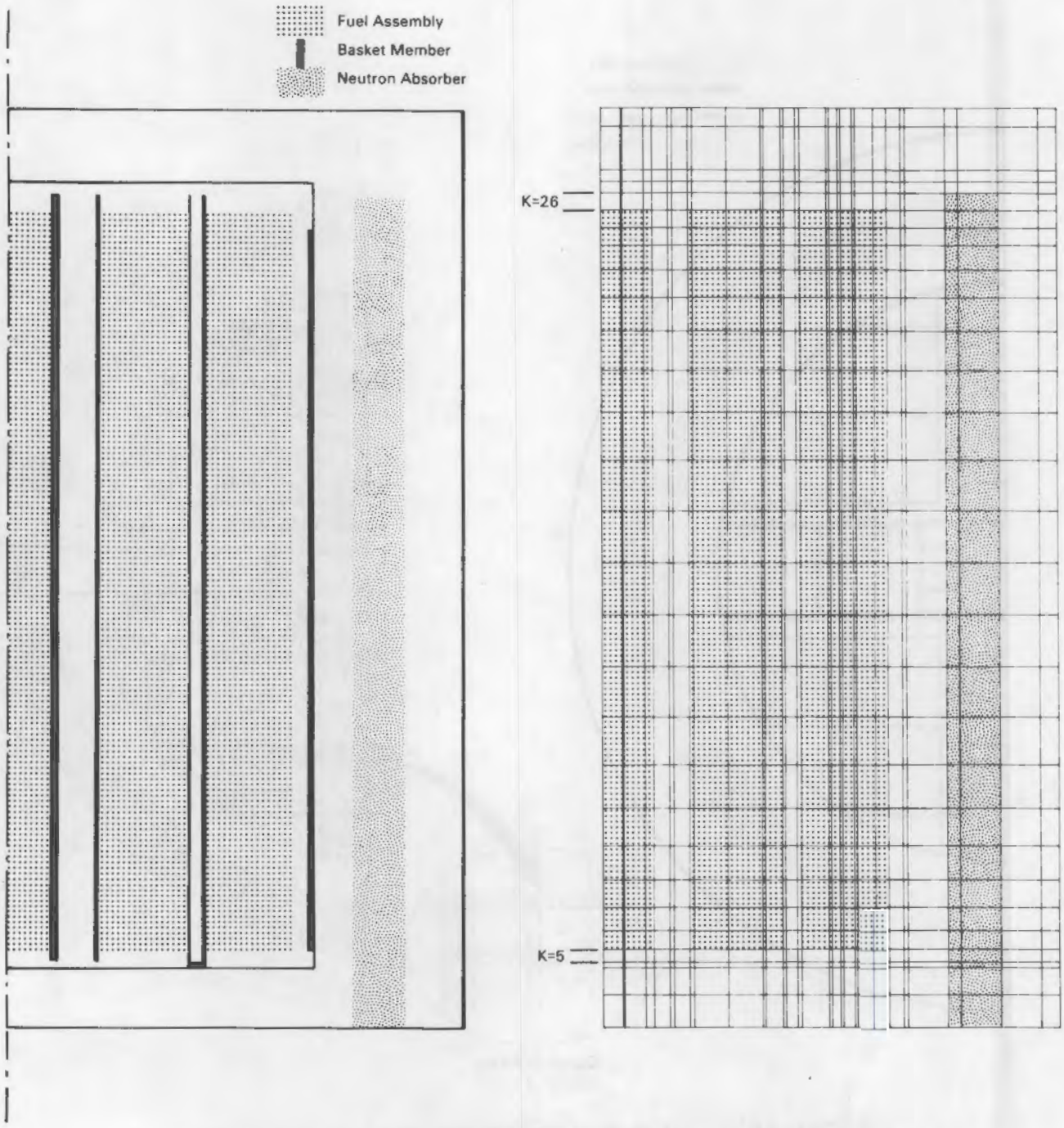


FIGURE 11.2. Axial Computational Mesh and Alignment of Mesh with Physical Cask Features

- INFO - With INFO = 1, the code will monitor all enclosures and indicate the one experiencing the largest (in magnitude) net radiation heat transfer. This is discussed further in the following echoed-input file example. Setting INFO = 0 bypasses this monitoring process. With INFO = 1, RADC will override all settings of NECHO < INFO in the input file for this subroutine.

Input File Example

```
483 1/radc
484 0
```

Echoed-Input File Example

```
808 radc Info=0
809
```

NECHO and INFO are input on lines 483 and 484, respectively. The corresponding echoed-input stream is presented as line 808. Setting INFO = 1 will allow the routine to monitor the net radiation heat transfer within an enclosure. In this case, RADC will print the net radiation heat transfer in the enclosure, the corresponding region number, and K-plane for the enclosure in which the maximum net radiation heat transfer has occurred. Note that the net radiation heat transfer in an enclosure should be 0. Therefore, this output provides a measure of sensitivity to truncation error as well as to inaccuracies in input data. When INFO = 1, all RADC input will be echoed in the output, regardless of the value of NECHO provided in the input. Setting INFO = 0 inhibits this echoing in the output.

11.2.3 Define Regions

General Input Format

```
NECHO
NREGS
NKCELL,IDK,NSURFS,IOI,IDJ,IDH   }
        .      .      .        }   repeated for each of the NREGS
        .      .      .        }   regions of the model
        .      .      .        }
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.
- NREGS - Number of regions in the RADC model (0 < NREGS < NREGP).
- NKCELL - Number of K-planes (enclosures) in this region.
- IDK - K-plane identifier for this region (1 < IDK < IDKP). This value will link with an IDK value input in Section 11.2.4.
- NSURFS - Number of radiating surfaces in an enclosure (1 < NSURFS < NSURFP).
- IDI - I-cell identifier for this region (1 < IDI < IDIP). This value will link with an IDI value input in Section 11.2.5.
- IDJ - J-cell identifier for this region (1 < IDJ < IDJP). This value will link with an IDJ value input in Section 11.2.6.
- IDH - H identifier for this region (1 < IDH < IDHP). This value will link with an IDH value input in Section 11.2.7.

Input File Example

```
485 1/radc/index
486 18
487 22,1,12,1,1,1
488 22,1,12,1,2,1
489 22,1,18,2,3,2
490 22,1,8,3,4,3
491 22,1,8,3,5,3
492 22,1,14,4,6,4
493 22,1,24,5,7,5
494 22,1,24,5,8,5
495 22,1,26,6,9,6
```

```
496 22,1,26,7,10,6
497 22,1,26,7,11,6
498 22,1,26,6,12,6
499 22,1,10,8,13,7
500 22,1,10,9,14,7
501 22,1,10,9,15,7
502 22,1,10,8,16,7
503 22,1,27,10,17,8
504 22,1,27,10,18,8
```

Echoed-Input File Example

```
 810  radc    nregs= 18   maximum current dimension for nregs is 18
 811  radc    index            region    number of    k-cell     numberof    i-cell     j-cell      h
 812                       number    k cells    identifier    surfaces    identifier    identifier    identifier
 813                          1         22          1           12           1           1           1
 814                          2         22          1           12           1           2           1
 815                          3         22          1           18           2           3           2
 816                          4         22          1            8           3           4           3
 817                          5         22          1            8           3           5           3
 818                          6         22          1           14           4           6           4
 819                          7         22          1           24           5           7           5
 820                          8         22          1           24           5           8           5
 821                          9         22          1           26           6           9           6
 822                         10         22          1           26           7          10           6
 823                         11         22          1           26           7          11           6
 824                         12         22          1           26           6          12           6
 825                         13         22          1           10           8          13           7
 826                         14         22          1           10           9          14           7
 827                         15         22          1           10           9          15           7
 828                         16         22          1           10           8          16           7
 829                         17         22          1           27          10          17           8
 830                         18         22          1           27          10          18           8
 831
```

Input lines 485 through 504 reflect the RADC input for the regional decomposition of the mesh. The corresponding echoed-input stream is presented in lines 810 through 830. NECHO is set to 1 on line 485 of this input section. As indicated in line 486 of the input and line 810 of the echoed-input, there are 18 RADC regions for this application. Further information for each of the 18 regions is provided in input lines 487 through 504 and echoed in output lines 811 through 830. The number of K-planes and surfaces present in each region are provided here, as are the I-cell, J-cell, K-plane, and H identifiers associated with each of these regions. The value of these identifiers provides the link between the surfaces of the region and the corresponding cell indices associated with each surface. In addition, the

value of the H identifier associates a matrix of radiation heat transfer coefficients with the surfaces of this region. These links are completed with the input from the following four sections, 11.2.4 through 11.2.7.

11.2.4 K-Cell Identifiers

General Input Format

```
NECHO
KCELLS,KCELL(1,IDK),KCELL(2,IDK), ... ,KCELL(KCELLS,IDK)   } repeated for
        .    .    .                                        } each K-plane
        .    .    .                                        } identifier
        .    .    .                                        }
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.
- KCELLS - Number of K-planes in this set ($1 \leq$ KCELLS $\leq$ KCELLP).
- KCELL - List of K-plane indices.
- IDK - K-plane identifier for this set ($1 \leq$ IDK $\leq$ IDKP). This value will link with an IDK value input in Section 11.2.3.

Input File Example

```
505 1/radc/kcell
506 22,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26
```

Echoed-Input File Example

```
832  radc    kcell    idk    k-cells:
833                     1      22    :  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
```

NECHO is set to one on line 505 of the input stream. The number and value of the K indices from the computational mesh are provided in input line 506. Since there is only one K-plane set in this model, the radiation heat transfer between the enclosure surfaces for the 18 regions will be computed for each of the 22 K-planes. These 22 K-planes span the range of K indices 5 through 26. Figure 11.2 illustrates their location in the model.

11.2.5 I-Cell Identifiers

General Input Format

```
NECHO
NSURFS,ICELL(1,IDI),ICELL(2,IDI), ... ,ICELL(NSURFS,IDI)   } repeated for each I-cell identifier
        .    .    .
        .    .    .
        .    .    .
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.
- NSURFS - Number of surfaces in this set ($1 \leq NSURFS \leq NSURFP$).
- ICELL - List of I-cell indices.
- IDI - I-cell identifier for this set ($1 \leq IDI \leq IDIP$). This value will link with an IDI value input in Section 11.2.3.

Input File Example

```
507 1/radc/icell
508 12,2,3,4,3*5,4,3,2,3*1
509 18,6,7,8,6*9,8,7,6,6*5
510 8,2,3,4,5,4,3,2,1
511 14,15,6*16,15,6*14
512 24,6,6*7,8,9,10,11,12,11,10,9,8,7,6,6*5
513 26,6,12*7,6,12*5
514 26,25,24,23,22,21,20,19,18,17,16,15,14,13,12,13,14,15,16,17,18,19,20,21,
515    22,23,24
516 10,8,9,10,11,11,10,9,8,7,7
517 10,2*25,24,23,4*22,23,24
518 27,13,14,15,16,17,18,19,20,21,21,20,19,18,17,16,15,14,13,9*12
```

Echoed-Input File Example

```
835     radc    icell   idi   i-cells:
836                      1     12   :  2  3  4  5  5  5  4  3  2  1  1  1
837                      2     18   :  6  7  8  9  9  9  9  9  9  8  7  6 5  5  5  5  5  5
838                      3      8   :  2  3  4  5  4  3  2  1
839                      4     14   : 15 16 16 16 16 16 16 15 14 14 14 14 14 14
840                      5     24   :  6  7  7  7  7  7  7  8  9 10 11 12 11 10  9  8  7  6  5  5  5  5  5  5
```

```
341                6    26   :  6  7  7  7  7  7  7  7  7  7  7  7  7  6  5  5  5  5  5  5  5  5  5  5  5
842                7    26   : 25 24 23 22 21 20 19 18 17 16 15 14 13 12 13 14 15 16 17 18 19 20 21 22 23 24
843                8    10   :  8  9 10 11 11 10  9  8  7  7
844                9    10   : 25 25 24 23 22 22 22 22 23 24
845               10    27   : 13 14 15 16 17 18 19 20 21 21 20 19 18 17 16 15 14 13 12 12 12 12 12 12 12 12 12
846
```

The information for each I-cell identifier is provided next in input lines 507 through 518. NECHO has again been set to 1 on line 507. The number of surfaces and mesh indices are provided for each of the 10 I-cell identifier sets (IDI) in lines 508 through 518. The echoed-input stream for this data is presented in lines 835 through 845. The number of surfaces represented in this I-cell set is presented first in a line of input (e.g., 8 surfaces will be represented by I-cell set 3 on input line 510). This is followed by the I-cell indices associated with each of the surfaces of the set (e.g., I = 2,3,4,... for I-cell set 3 on input line 510). Note that the IDI values for the I-cell groups are not explicitly provided in the input. HYDRA-II loads the value of NSURFS and each of the corresponding NSURFS I-cell indices into one IDI group before incrementing IDI and beginning to load the next IDI group.

11.2.6 J-Cell Identifiers

General Input Format

```
NECHO
NSURFS,JCELL(1,IDJ),JCELL(2,IDJ), ... ,JCELL(NSURFS,IDJ)  } repeated for
          .    .    .                                     } each J-cell
          .    .    .                                     } identifier
          .    .    .                                     }
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.
- NSURFS - Number of surfaces in this set ($1 \leq NSURFS \leq NSURFP$).
- JCELL - List of J-cell indices.

- IDJ - J-cell identifier for this set ($1 \leq IDJ \leq IDJP$). This value will link with an IDJ value input in Section 11.2.3.

Input File Example

```
519 1/radc/jcell
520 12,3*17,18,19,20,3*21,20,19,18
521 12,3*32,31,30,29,3*28,29,30,31
522 18,3*21,22,23,24,25,26,27,3*28,27,26,25,24,23,22
523 8,3*10,11,3*12,11
524 8,3*39,38,3*37,38
525 14,21,22,23,24,25,26,27,28,27,26,25,24,23,22
526 24,14,15,16,17,18,6*19,20,6*21,20,19,18,17,16,15
527 24,35,34,33,32,31,6*30,29,6*28,29,30,31,32,33,34
528 26,1,2,3,4,5,6,7,8,9,10,11,12,13,14,13,12,11,10,9,8,7,6,5,4,3,2
529 26,20,12*19,20,12*21
530 26,29,12*30,29,12*28
531 26,48,47,46,45,44,43,42,41,40,39,38,37,36,35,36,37,38,39,40,41,42,43,44,
532    45,46,47
533 10,1,1,2,3,4*4,3,2
534 10,18,17,16,15,15,16,17,18,19,19
535 10,31,32,33,34,34,33,32,31,30,30
536 10,48,48,47,46,4*45,46,47
537 27,5,6,7,8,9,10,11,12,13,9*14,13,12,11,10,9,8,7,6,5
538 27,44,43,42,41,40,39,38,37,36,9*35,36,37,38,39,40,41,42,43,44
```

Echoed-Input File Example

```
847      radc    jcell   idj   j-cells:
848                        1     12   : 17 17 17 18 19 20 21 21 21 20 19 18
849                        2     12   : 32 32 32 31 30 29 28 28 28 29 30 31
850                        3     18   : 21 21 21 22 23 24 25 26 27 28 28 28 27 26 25 24 23 22
851                        4      8   : 10 10 10 11 12 12 12 11
852                        5      8   : 39 39 39 38 37 37 37 38
853                        6     14   : 21 22 23 24 25 26 27 28 27 26 25 24 23 22
854                        7     24   : 14 15 16 17 18 19 19 19 19 19 19 20 21 21 21 21 21 21 20 19 18 17 16 15
855                        8     24   : 35 34 33 32 31 30 30 30 30 30 30 29 28 28 28 28 28 28 29 30 31 32 33 34
856                        9     26   :  1  2  3  4  5  6  7  8  9 10 11 12 13 14 13 12 11 10  9  8  7  6  5  4  3  2
857                       10     26   : 20 19 19 19 19 19 19 19 19 19 19 19 19 19 20 21 21 21 21 21 21 21 21 21 21 21 21
858                       11     26   : 29 30 30 30 30 30 30 30 30 30 30 30 30 30 29 28 28 28 28 28 28 28 28 28 28 28 28
859                       12     26   : 48 47 46 45 44 43 42 41 40 39 38 37 36 35 36 37 38 39 40 41 42 43 44 45 46 47
860                       13     10   :  1  1  2  3  4  4  4  4  3  2
861                       14     10   : 18 17 16 15 15 16 17 18 19 19
862                       15     10   : 31 32 33 34 34 33 32 31 30 30
863                       16     10   : 48 48 47 46 45 45 45 45 46 47
864                       17     27   :  5  6  7  8  9 10 11 12 13 14 14 14 14 14 14 14 14 14 13 12 11 10  9  8  7  6  5
865                       18     27   : 44 43 42 41 40 39 38 37 36 35 35 35 35 35 35 35 35 35 36 37 38 39 40 41 42 43 44
866
```

The J-cell identifier information is provided next in input lines 519 through 538. The format for this input is the same as that for the I-cell identifiers. That is, line 519 indicates NECHO has been set to a value of 1. Information for each of the 18 J-cell identifiers is provided next in input lines 520 through 538 and has been echoed in output lines 848 through 865. The number of surfaces and their corresponding J-cell indices are provided for each J-cell set in this input stream. For example, J-cell set 4 represents eight surfaces with J indices 10, 11, and 12. As with IDI in the previous section, the IDJ group identifier numbers are assigned internally in HYDRA-II.

At this point, the code has all the necessary index information to associate an (I,J,K) cell index with each of the surfaces modeled. For example, the (I,J,K) indices associated with the eight surfaces of region 4 are (2,10,K), (3,10,K), (4,10,K), (5,11,K), (4,12,K), (3,12,K), (2,12,K), and (1,11,K). As specified by the K-plane set provided on input line 506, K takes on the values 5 through 26 in this RADC model.

It remains to associate a radiation heat transfer coefficient with each of the interacting surface pairs of the model. This information is provided next.

11.2.7 H Array

General Input Format

```
NECHD
NSURFS
H(1,1,IDH),H(1,2,IDH), ... ,H(1,NSURFS,IDH),                    } repeated for
                .          .          .                         } each
                .          .          .                         } H-identifier
                .          .          .                         } set
H(NSURFS,1,IDH),H(NSURFS,2,IDH), ... ,H(NSURFS,NSURFS,IDH)      }
```

General Input Description

- NECHD - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.
- NSURFS - Number of surfaces represented in this H identifier set ($1 \leq NSURFS \leq NSURFP$).

- H - Matrix of radiation heat transfer coefficients for this set.
- IDH - H identifier for this H matrix (1 ≤ IDH ≤ IDHP).

Input File Example

```
539 0/radc/h
540 12
541  -.967992423084620e-11, .144545280611220e-12, .144593159843263e-11,
542   .133721620597627e-11, .389548549669991e-12, .154380651783190e-11,
543   .213480965409158e-11, .230612866749674e-12, .245345355748301e-11,
544  0.                    ,0.                    ,0.                    ,
545   .144545280611221e-12,-.112005588613371e-11, .145114180107132e-12,
546   .140265349851777e-12, .415585794368260e-13, .158065316055406e-12,
547   .236030481944205e-12, .238408757658562e-13, .230635822361273e-12,
548  0.                    ,0.                    ,0.                    ,
549   .144593159843263e-11, .145114180107131e-12,-.108314180956411e-10,
550   .223448481096404e-11, .436015483685137e-12, .152690761027124e-11,
551   .267210659730428e-11, .236019678319556e-12, .213483813655713e-11,
552  0.                    ,0.                    ,0.                    ,
553   .133721620597628e-11, .140265349851777e-12, .223448481096404e-11,
554  -.804166888540504e-11, .236067219282889e-12, .906119342226106e-12,
555   .150656347927900e-11, .156049296512796e-12, .152490318131222e-11,
556  0.                    ,0.                    ,0.                    ,
557   .389548549669995e-12, .415585794368262e-13, .436015483685141e-12,
558   .236067219282891e-12,-.220784085075826e-11, .238802877733071e-12,
559   .434383953042135e-12, .415548020670205e-13, .389909385841205e-12,
560  0.                    ,0.                    ,0.                    ,
561   .154380651783191e-11, .158065316055405e-12, .152690761027126e-11,
562   .906119342226099e-12, .238802877733070e-12,-.812834382046880e-11,
563   .225641498023646e-11, .142280625220507e-12, .135594655089405e-11,
564  0.                    ,0.                    ,0.                    ,
565   .213480965409158e-11, .236030481944201e-12, .267210659730428e-11,
566   .150656347927900e-11, .434383953042134e-12, .225641498023646e-11,
567  -.108318769033387e-10, .145123763252704e-12, .144644399418830e-11,
568  0.                    ,0.                    ,0.                    ,
569   .230612866749678e-12, .238408757658560e-13, .236019678319558e-12,
570   .156049296512798e-12, .415548020670205e-13, .142280625220508e-12,
571   .145123763252704e-12,-.112005839117282e-11, .144576483284708e-12,
572  0.                    ,0.                    ,0.                    ,
573   .245345355748303e-11, .230635822361273e-12, .213483813655713e-11,
574   .152490318131222e-11, .389909385841205e-12, .135594655089406e-11,
575   .144644399418831e-11, .144576483284708e-12,-.968070711192182e-11,
576  0.                    ,0.                    ,0.                    ,
577  0.                    ,0.                    ,0.                    ,
578  0.                    ,0.                    ,0.                    ,
579  0.                    ,0.                    ,0.                    ,
580  0.                    ,0.                    ,0.                    ,
581  0.                    ,0.                    ,0.                    ,
```

```
582  0.                    ,0.                    ,0.                    ,
583  0.                    ,0.                    ,0.                    ,
584  0.                    ,0.                    ,0.                    ,
585  0.                    ,0.                    ,0.                    ,
586  0.                    ,0.                    ,0.                    ,
587  0.                    ,0.                    ,0.                    ,
588  0.                    ,0.                    ,0.                    ,

                           .                      .                      .
                           .                      .                      .
                           .                      .                      .

698 8
699  -.877308748634275e-11, .185511143726041e-12, .133538878723581e-11,
700   .761243863764755e-12, .163568922689131e-11, .305931782435861e-12,
701   .454932268228895e-11,0.                    ,
702   .185511143726043e-12,-.111544670514729e-11, .178121837451535e-12,
703   .927571413452364e-13, .298914695728965e-12, .542101044596416e-13,
704   .305931782435858e-12,0.                    ,
705   .133538878723579e-11, .178121837451532e-12,-.100084944920911e-10,
706   .184258904621768e-11, .471779089856585e-11, .298914695728965e-12,
707   .163568922689129e-11,0.                    ,
708   .761243863764755e-12, .927571413452360e-13, .184258904621768e-11,
709  -.539318010265536e-11, .184258904621768e-11, .927571413452364e-13,
710   .761243863764749e-12,0.                    ,
711   .163568922689131e-11, .298914695728963e-12, .471779089856585e-11,
712   .184258904621768e-11,-.100084944920912e-10, .178121837451535e-12,
713   .133538878723578e-11,0.                    ,
714   .305931782435859e-12, .542101044596416e-13, .298914695728966e-12,
715   .927571413452364e-13, .178121837451534e-12,-.111544670514729e-11,
716   .185511143726041e-12,0.                    ,
717   .454932268228895e-11, .305931782435858e-12, .163568922689131e-11,
718   .761243863764749e-12, .133538878723579e-11, .185511143726041e-12,
719  -.877308748634275e-11,0.                    ,
720  0.                    ,0.                    ,0.                    ,
721  0.                    ,0.                    ,0.                    ,
722  0.                    ,0.                    ,

                           .                      .                      .
                           .                      .                      .
                           .                      .                      .

********************************* NOTE *********************************
*                                                                        *
*    Only part of the H input file (for H identifier = 1 and 3)          *
*    is shown for brevity                                                *
*                                                                        *
**************************************************************************
```

Part of the input file for the radiation heat transfer coefficients is provided in lines 539 through 588 and lines 698 through 722. This input is typically quite lengthy for enclosures having many surfaces. Therefore, only portions of it are presented here. Input line 539 indicates the setting of NECHO to zero for this section. Input lines 540 through 588 correspond to the data provided for the first H set (H identifier, IDH = 1). This array of radiation heat transfer coefficients represents a region composed of 12 surfaces (ref., input line 540). Therefore, there are 144 elements in this H array (12 x 12). The array is loaded by rows (i.e., updating the second index most rapidly). Consequently, the radiation heat transfer coefficients from the first through twelfth surfaces to the first surface are loaded first. Those from the first through twelfth surfaces to the second surface are loaded next, and so on. The H identifiers on input lines 487 and 488 (and in the echoed-input lines 813 and 814) indicate that this H array is used for regions 1 and 2 of the RADC model.

The regional input provided in lines 487 through 504 above indicated that there are eight such H arrays in this RADC model. Therefore, the input to this section must have eight corresponding sets of data similar in format to that provided in input lines 540 through 588.

Data for the third H array (H identifier, IDH = 3) are presented in input lines 698 through 722. Input line 698 indicates that this array represents the radiation heat transfer coefficients between eight surfaces. Therefore, this array contains 64 elements (8 x 8). As with the first H array, this array is loaded by rows.

The format for the H array input, as well as the connection between this input and the information provided for I-cell, J-cell, and K-plane specifications, is best illustrated by an example. Therefore, the following discussion pertains to region 4 of the model. The computational mesh associated with this region is illustrated in the detail of Figure 11.1.

Region 4 represents an eight-surface enclosure at each of the 22 K-planes corresponding to K indices 5 through 26. At each of these K-planes, radiation heat transfer will be computed between the eight surfaces represented by the I-cell and J-cell identifiers 3 and 4, respectively. The (I,J) pairs defining

the cells of this enclosure are identified by association with these I-cell and J-cell identifiers as (2,10), (3,10), (4,10), (5,11), (4,12), (3,12), (2,12), and (1,11). The H identifier is 3 for this region. Therefore, the corresponding radiation heat transfer coefficients for this region are provided in the third array of H data provided (input lines 698 through 722). The radiation heat transfer coefficient for reradiation from the surface associated with cell (2,10,K) to the seven other surfaces of this enclosure is input first. The radiation heat transfer coefficient for energy received by (2,10,K) from the surface associated with cell (3,10,K) is presented next in the input file, followed by that for (4,10,K) to (2,10,K), and so on. As indicated by the K index, these values are used for radiation heat transfer in this enclosure at each of the 22 K-planes of the model. The code internally scales these coefficients by the appropriate DZ(K). The other length scale of the area element must be incorporated in the radiation heat transfer coefficient.

To further illustrate the structure of the input file format, consider the specific interaction between nodes (5,11,K) and (3,10,K). The radiation heat transfer coefficient used for the energy radiated by the surface at (3,10,K) to the surface at (5,11,K) has the value 0.92757...e-13. Cell (5,11,K) represents the fourth surface element of an enclosure in region 4. Cell (3,10,K) represents the second surface element of an enclosure in region 4. Therefore, the radiation heat transfer coefficient for energy received by (5,11,K) from (3,10,K) is stored in $H_{4,2}$ (i.e., the second element of the fourth row in this H array). Since the array is loaded by rows, this corresponds to the twenty-sixth entry to the array (viz., the second entry on input line 708). To illustrate the symmetry required of the matrix of radiation heat transfer coefficients, this value must equal that representing transfer from (5,11,K) to (3,10,K). The value is stored in element $H_{2,4}$, the fourth element in the second row. This is the twelfth value entered in the H array, viz., the first entry on input line 703. Comparison of these two values indicates that they are equal. The radiation heat transfer coefficient used to model reradiation from (5,11,K) to the adjoining surfaces of the enclosure has the value -0.53931...e-11 (the diagonal element on the fourth row of this array, $H_{4,4}$). This value equals the negative of the sum of the other radiation heat transfer

coefficients from (5,11,K). These same coefficients are used for each of the 22 K-planes, 5 through 26 (with the appropriate rescaling by DZ(K)).

Frequently, symmetries are present in the problem configuration. The presence of these symmetries should be exploited in the model to reduce the amount of input and execution time required by the simulation. However, when invoking these symmetries, the user must be certain to include the effects of image cells (i.e., the reflection of model cells about a line of symmetry) when generating the input. In particular, the RADC radiation heat transfer coefficients must reflect the presence of these symmetries. A typical situation exhibiting this is illustrated in Figure 11.3. In this figure, the modeled section is represented on the right of the line-of-symmetry, and its image is to the left of the line-of-symmetry. The participating surfaces of the RADC enclosure and their images are indicated by the boxed numbers. To properly model the radiation heat transfer in this enclosure, the user must generate radiation heat transfer coefficients that include the presence of the image section. For example, the radiation heat transfer coefficient between surfaces 1 and 7 should also include the effect of radiation from the image of surface 7 (surface 7') to surface 1. Similarly, the interaction between surfaces 3 and 4 should include that between surfaces 3' and 4' also. Surfaces 1' through 7' are not, of course, explicitly included in the RADC model. Their effect is lumped into the surface in the modeled section and its corresponding radiation heat transfer coefficients.

11.2.8 Input Example When RADC Is Not Used

If routine RADC is not used in the simulation, then only lines 483 through 486, 505, 507, 519, and 539 need be provided in the input stream. The input might look like the following in this case:

```
483 1/radc
484 0
485 1/radc/index
486 0
505 0/radc/kcell
507 0/radc/icell
519 0/radc/jcell
539 0/radc/h
```

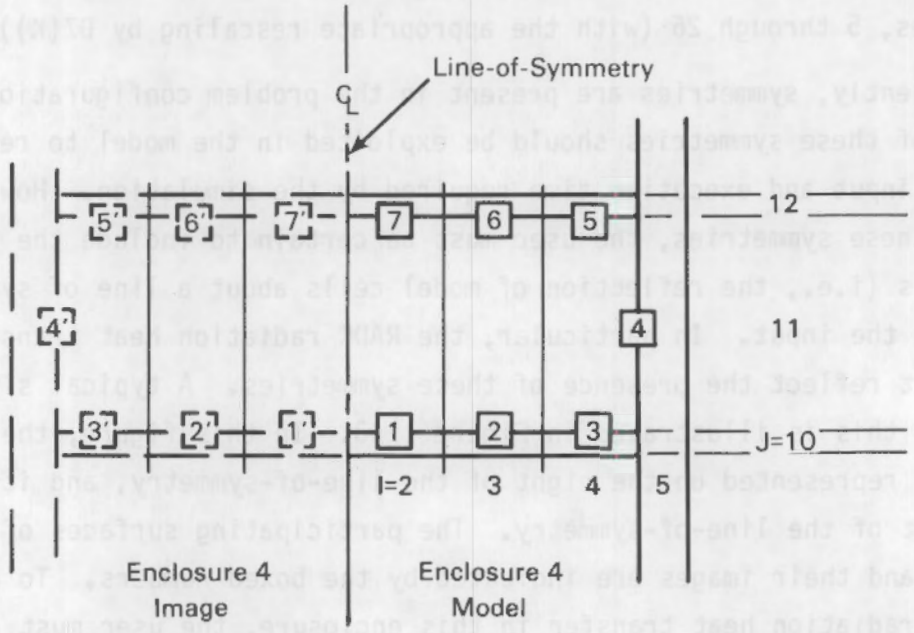


FIGURE 11.3. RADC Enclosure 4 Blow-up Showing Modeled and Image Sections (RADC Surfaces are Denoted by Boxed Numbers)

12.0 SUBROUTINE RAOP

HYDRA-II provides the user with three subroutines for radiation heat transfer - RADC, RADP, and RADR. Subroutine RADC is described in Chapter 11.0. RADC allows the user to simulate radiation heat transfer between the surfaces of an enclosure in the computational domain. The cells associated with these surfaces must share the same K index for RADC to be applicable. Subroutine RADP is described in this chapter. The remaining subroutine, RADR, is described in Chapter 13.0 and is intended to model radiation heat transfer between the fuel rods of an assembly. The radiation heat transfer distribution computed in RADP is cumulative with that computed by the other radiation heat transfer routines, RADC and RADR.

RADP computes the radiative heat transfer received by the mth cell surface from the nth cell surface using

$$q_{RADP}\ (m,n) = \frac{\sigma A_m \lfloor T_n^4 - T_m^4 \rfloor}{[(1/\varepsilon_2) - 1 + (1/\varepsilon_1)]}$$

where ε_1 and ε_2 are the emissivities of the two communicating cell surfaces, σ is the Stefan-Boltzmann constant (= 5.67e-12 $W/cm^2 \cdot K^4$), and A_m is the appropriate surface area of cell m. A shape factor of 1.0 is assumed between the two surfaces. Therefore, the radiation heat transfer is equivalent to that between two essentially infinite parallel planes.

RADP is designed to compute the radiation heat transfer between the cells on two computational mesh planes. These planes may be separated in any one of the three coordinate directions (viz., I, J, or K). Two of the three cell indices must be the same for any pair of communicating cells. Therefore, the transfer of energy is either between the cells associated with indices (I,J,K) and (L,J,K), between (I,J,K) and (I,M,K), or between (I,J,K) and (I,J,N). RADP will sweep over a user-specified range of the two variable indices, computing the radiation heat transfer between each pair of communicating cells in that range. The range of indices constitutes a region of the computational domain.

Radiation heat transfer is between two cell surfaces. Any one cell surface is shared by either of two cells. In addition, the temperatures T_m^4 and T_n^4 in the above relationship are those associated with the center of cells m and n. Therefore, care must be exercised when assigning cell indices to the surfaces exchanging energy. When the RADP model is set up, the participating cells should be chosen to accurately represent both the temperature and thermal properties of the interacting surfaces.

12.1 PARAMETER STATEMENT INFORMATION

Aside from the overall computational mesh specification information IP, JP, and KP, and the bottom- and top-side mesh information KBP and KTP (described in Chapter 4.0), RADP requires information pertaining to the limiting number of regions in the model. The required data are as follows:

- IREGP - An array dimension greater than or equal to the maximum number of IREG regions (see Section 12.2.2).
- JREGP - An array dimension greater than or equal to the maximum number of JREG regions (see Section 12.2.3).
- KREGP - An array dimension greater than or equal to the maximum number of KREG regions (see Section 12.2.4).

IREGP, JREGP, and KREGP must, as a minimum, be set to a value of one (even when RADP is not used).

12.2 INPUT FORMAT

12.2.1 Overview

Generally speaking, the input to subroutine RADP can be divided into three subsections:

- load arrays for heat transfer between cells separated in the I-direction
- load arrays for heat transfer between cells separated in the J-direction

- load arrays for heat transfer between cells separated in the K-direction.

A detailed discussion of the input requirements for each of these subsections is provided in the following text.

General Input Format

The general format for input to this routine is as follows:

```
input line  n              :  NECHO
input line (n+1)           :  NREGS
input line (n+2)           :  ε1, ε2, IBEG, IEND, JBEG, JEND, KBEG, KEND
                                        .    .    .
                                        .    .    .
                                        .    .    .
input line (n+2+NREGS-1):  ε1, ε2, IBEG, IEND, JBEG, JEND, KBEG, KEND.
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.
- NREGS - The number of regions modeled in this subsection.
- ε_1 and ε_2 - Emissivities of the communicating surfaces.
- IBEG - Beginning value for the I index range.
- IEND - Ending value for the I index range.
- JBEG - Beginning value for the J index range.
- JEND - Ending value for the J index range.
- KBEG - Beginning value for the K index range.
- KEND - Ending value for the K index range.

The pairs (IBEG,IEND), (JBEG,JENO), and (KBEG,KEND) represent the index ranges for the surfaces of this region. RADP will loop (in the FORTRAN sense) over any two of the three pairs of indices to compute the radiation heat transferred between the third pair of indices. The index for one cell is composed from the two running indices and the "BEG" value of the third index.

The index for the second cell of the pair is composed from the same two running indices and the "END" value of the third index. For example, consider two cells separated in the K-direction. Each cell has running indices I and J where IBEG ≤ I ≤ IEND and JBEG ≤ J ≤ JEND. Each pair of interacting cells will then have indices (I,J,KBEG) and (I,J,KEND). This configuration is illustrated in Figure 12.1.

This routine is perhaps best understood by means of an example problem. Therefore, the use of RADP in modeling the sample problem presented in Chapter 4.0 is discussed in Sections 12.2.2 through 12.2.4. Figures 12.2 and 12.3 illustrate the location of the regions modeled in the following input. The input line numbers are used to call out the location of the corresponding region on Figure 12.2.

12.2.2 I-Direction Radiation Heat Transfer Mode

Input File Example

```
1507 1/radp/iregs
1508 0
```

Echoed-Input File Example

```
867     radp    Iregs=  0   maximum current dimension for Iregs is  1
868
```

Those regions of the computational mesh for which the RADP surfaces are separated in the I-direction are input first. The corresponding input for the sample problem is shown here as input lines 1507 and 1508. On input line 1507, the value of NECHO is set to 1. Input line 1508 provides the value of the number of IREG regions in the RADP model. For this model, there are none, so 0 is entered. The echoed-input lines for this section are shown here as output lines 867 and 868.

12.2.3 J-Direction Radiation Heat Transfer Mode

Input File Example

```
1509 1/radp/jregs
1510 0
```

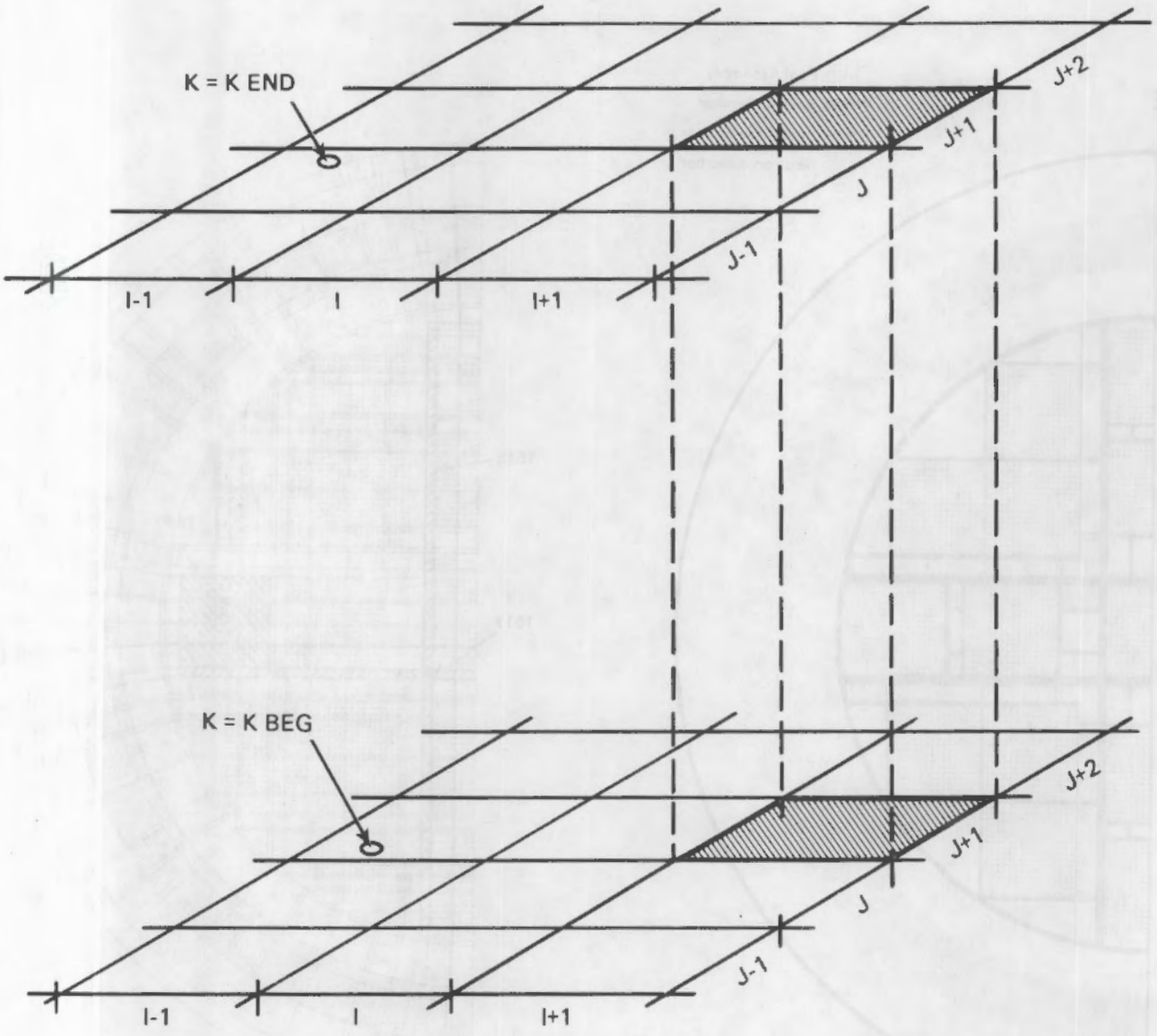


FIGURE 12.1. Typical RADP "Floating Region" Simulating Radiation Heat Transfer in the K-Direction

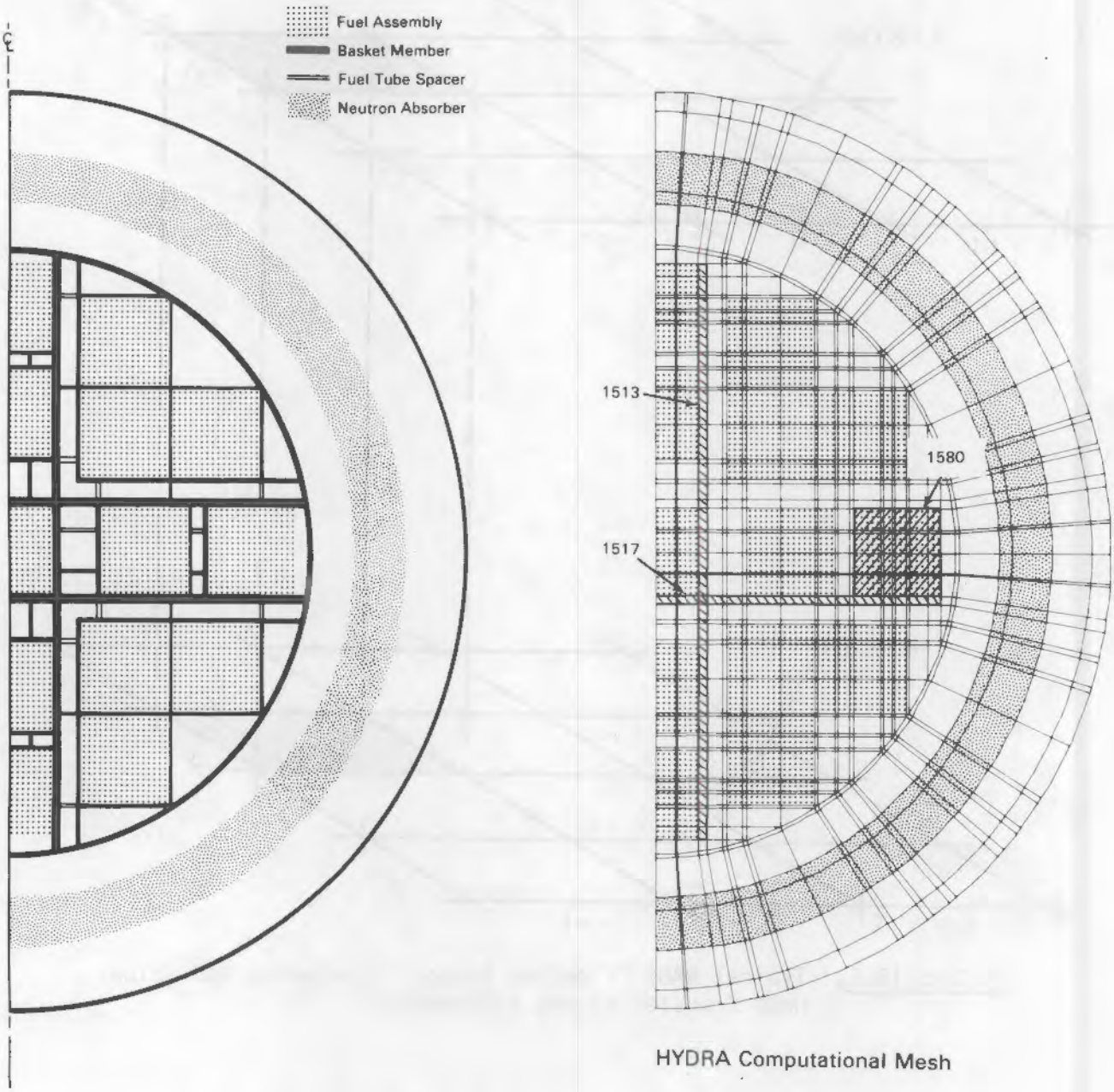


FIGURE 12.2. Transverse Computational Mesh and Alignment of Mesh with Physical Cask Features - RADP Regions Shown

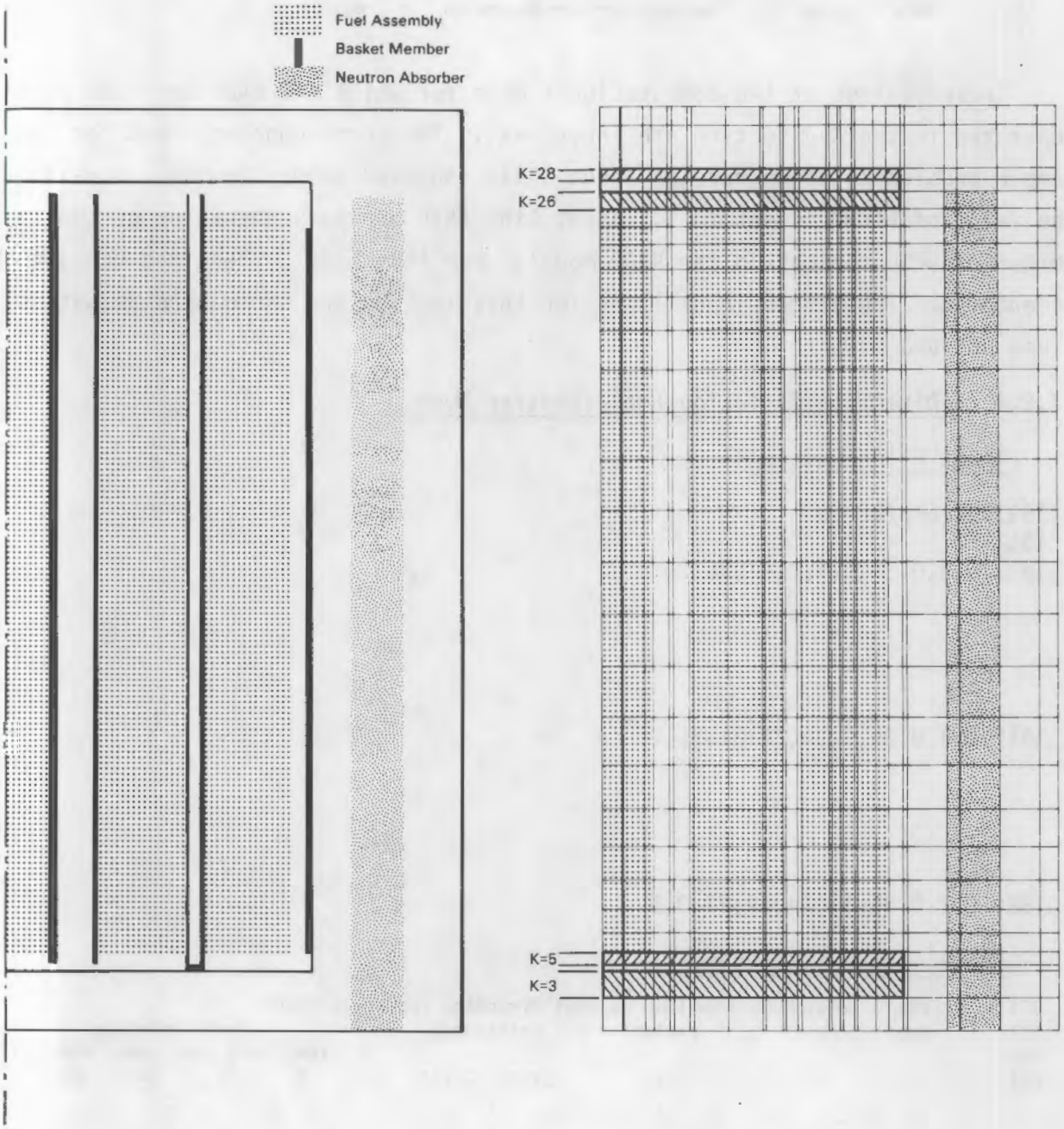


FIGURE 12.3. Axial Computational Mesh and Alignment of Mesh with Physical Cask Features - RADP KBEG and KEND Indices Shown

Echoed-Input File Example

```
869      radp    jregs=  0   maximum current dimension for jregs is  1
870
```

Those regions of the computational mesh for which the RADP surfaces are separated in the J-direction are input next. The corresponding input for the sample problem is shown here as input lines 1509 and 1510. On input line 1509, the value of NECHO is set to 1. Input line 1510 provides the value of the number of JREG regions in the RADP model. For this model, there are none, so 0 is entered. The echoed-input lines for this section are shown here as output lines 869 and 870.

12.2.4 K-Direction Radiation Heat Transfer Mode

Input File Example

```
1511 1/radp/kregs
1512 68
1513 0.4,0.25,5,5,2,47,26,28

          .   .   .
          .   .   .
          .   .   .

1517 0.4,0.25,2,24,21,21,26,28

          .   .   .
          .   .   .
          .   .   .

1580 0.8,0.25,17,24,22,27,3,5
```

Echoed-Input File Example

```
871      radp    kregs= 68   maximum current dimension for kregs is 68
872      radp                  region        emittances                cell location
873                                                          lbeg lend jbeg jend  kbeg kend
874                             1          0.400   0.250       5    5    2   47    26   28
                                .             .                          .
                                .             .                          .
                                .             .                          .
878                             5          0.400   0.250       2   24   21   21    26   28
                                .             .                          .
                                .             .                          .
                                .             .                          .
941                            68          0.800   0.250      17   24   22   27     3    5
```

Finally, those regions of the computational mesh for which the RADP surfaces are separated in the K-direction are input. The corresponding input for the example problem is shown as input lines 1511 through 1580. On input line 1511 the value of NECHO is set to 1. Input line 1512 indicates that there are 68 KREG regions in the RADP model. Input line 1580 is typical of the input lines in this routine. Here, ε_1 and ε_2 are set to a value of 0.8 and 0.25, respectively. Since this input is in the third subsection of input provided to this routine, the routine will sweep over the I and J index ranges, computing the radiation heat transfer between the surface pairs at (I,J,3) and (I,J,5) for each I and J in the ranges $17 \leq I \leq 24$ and $22 \leq J \leq 27$. The surface area, A, will be computed as DX(I)*DY(J). The echoed-input lines for these lines are shown in lines 871 through 874, line 878, and line 941.

12.2.5 Input Example When RADP Is Not Used

If routine RADP is not used in the simulation, the following input must still be provided:

```
1507 1/radp/iregs
1508 0
1509 1/radp/jregs
1510 0
1511 1/radp/kregs
1512 0
```

13.0 SUBROUTINE RADR

HYDRA-II provides the user with three subroutines for use in modeling radiation heat transfer - RADC, RADP, and RADR. Subroutine RADC is described in Chapter 11.0. RADC allows the user to simulate radiation heat transfer between the surfaces of an enclosure in the computational domain. The cells associated with these surfaces must share the same K index for RADC to be applicable. Subroutine RADP provides the user with a model for plate-to-plate radiation heat transfer. RADP is described in Chapter 12.0. Subroutine RADR is described in this chapter. The radiation heat transfer computed in RADR is cumulative with that computed by the other radiation heat transfer routines, RADC and RADP.

RADR provides the user with a method for computing rod-to-rod radiation heat transfer in a fuel assembly. Each computational cell of the RADR model contains only one spent fuel rod. The cell surfaces on any K-plane are configured so as not to "cut" the spent fuel rod boundaries; hence, the cell-to-cell nature of the radiation heat transfer mode in this routine (contrasted with the surface-to-surface structure of RADC). This idea is illustrated in Figure 13.1.

The routine is structured to compute the radiation heat transfer between the cell associated with index (I,J,K) and any of its 24 neighboring cells in the range $I\pm2$ and $J\pm2$. This region-of-influence is shown schematically in Figure 13.2. The center cell [index (I,J,K)] is the receiver cell. The "generic" cell in this region-of-influence is identified by the roman indices (I,J,K) to differentiate it from the center cell (I,J,K). The surrounding 24 cells of this region are the transmitter cells "seen" by the center cell. The region-of-influence "floats" over the range of cells specified in the RADR model. In addition, RADR computes the radiation heat transfer between these cells for a user-specified range of K-planes. As in the RADC subroutine, RADR does not allow radiation heat transfer between cells having different K-plane indices. This mode of exchange may be modeled using subroutine RADP.

In general, the proper computation of radiation heat transfer coefficients can get very involved. This is particularly true in cases where there are many

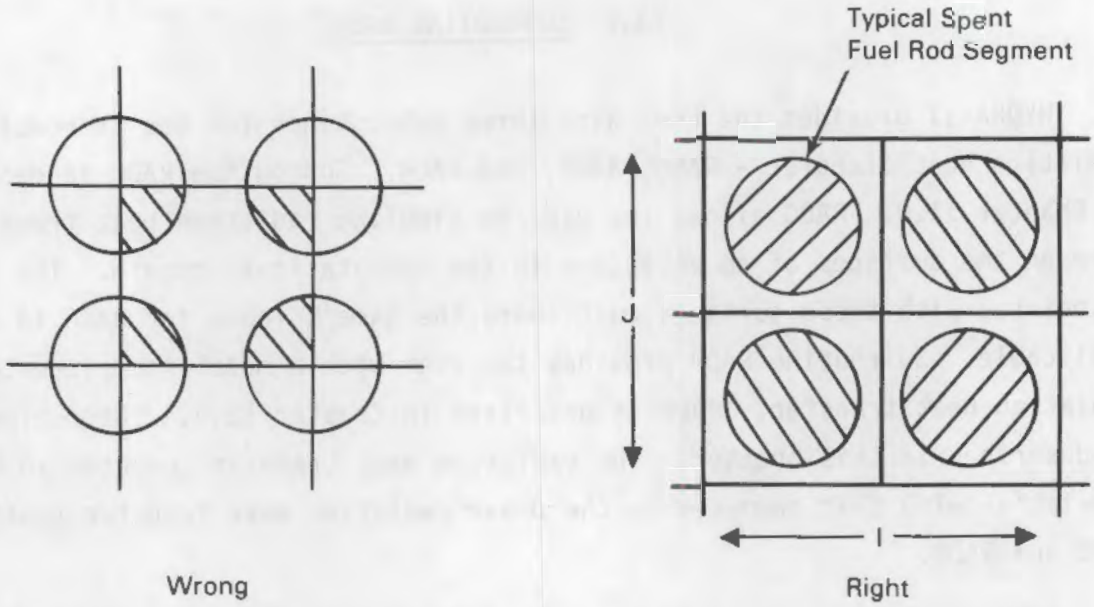


FIGURE 13.1. Placement of I and J Grid-Lines for HYDRA-II Cells When Spent Fuel Rods Are Modeled

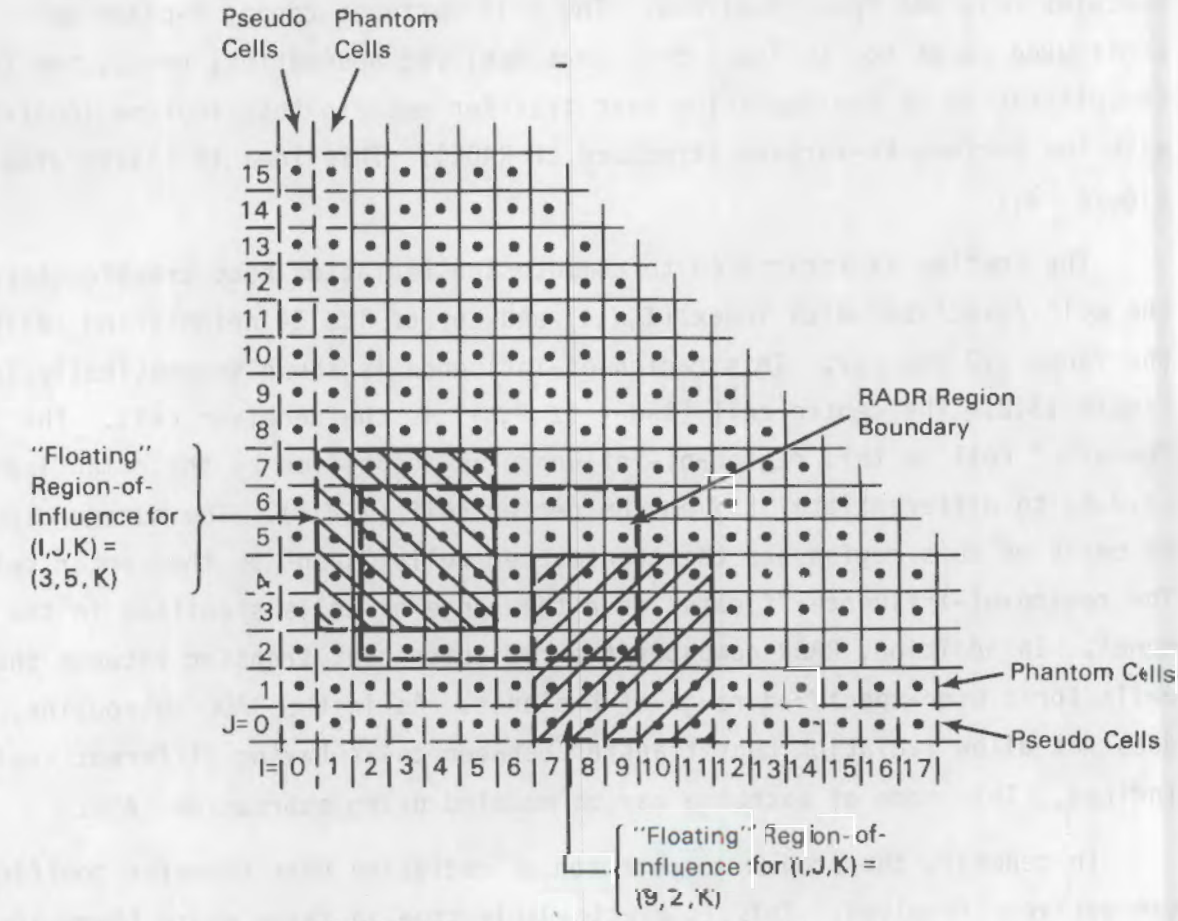


FIGURE 13.2. RADR Example Grid

interacting surfaces that can absorb, re-emit, and reflect radiation. The necessary radiation heat transfer coefficients have been tabulated for a variety of fuel rod assemblies by Cox (1977).

The radiation heat transfer from cell n to cell m is computed as

$$q_{RADR}\ (m,n) = \sigma\ H_{m,n}\ (T_n^4 - T_m^4)\ DZ(K)$$

The computational-cell index associated with the receiver cell m is (I,J,K); that for the transmitting cell is $(I-2 \leq I \leq I+2,\ J-2 \leq J \leq J+2,\ K)$ [excluding the combination (I,J,K)]. Note that the above definition for $q_{RADR}\ (m,n)$ has the DZ(K) portion of the area element explicitly included in the equation. The other length segment making up the surface area has been included in the specification of the radiation heat transfer coefficient, $H_{m,n}$. Note further that the Stefan-Boltzmann constant, σ (= 5.67e-12 $W/cm^2 \cdot K^4$), has been extracted from the radiation heat transfer coefficient in this expression. Therefore, the user must account for this when computing the radiation heat transfer coefficients for input to RADR.

13.1 PARAMETER STATEMENT INFORMATION

Aside from the overall grid specification information IP, JP, KP, KBP, and KTP (described in Chapter 4.0), RADR requires information pertaining to the limiting number of cells and radiation heat transfer coefficients in the model. The required data are as follows:

- NHP - An array dimension greater than or equal to the maximum number of RADR radiation heat transfer coefficient groups in the model.
- NREGP - An array dimension greater than or equal to the maximum number of computational cell regions in the model.

- NT4P - An array dimension greater than or equal to the maximum number of LT4 regions (to be defined in Section 13.2.5) in the model.

Each of these parameters must be set to a value of 1 as a minimum (even when RADR is not used).

13.2 INPUT FORMAT

13.2.1 Overview

Generally speaking, the input to subroutine RADR can be divided into four subsections:

- descriptive, introductory text
- the radiation heat transfer coefficient array, H
- regional description array, LREG
- array LT4 containing the T^4 values for the affected computational cells.

A detailed discussion of the input requirements for each of these subsections is provided in the following text.

13.2.2 Descriptive, Introductory Text Input

General Input Format

```
NECHO
NLINES
first line of TEXT
second line of TEXT
  .
  .
  .

ith line of TEXT
  .
  .
  .
(NLINES-1)th line of TEXT

(NLINES)th line of TEXT
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.
- NLINES - The number of lines of descriptive information to be read (NLINES > 0).
- TEXT - A line of descriptive information containing up to 48 characters.

Input File Example

```
324 1/radr/notes
325 2
326 emmitance of rods is 0.8
327 connectors confined to assembly
```

Echoed-Input File Example

```
555     radr     emittance of rods is 0.8
556     radr     connectors confined to assembly
```

Input variables NECHO and NLINES are provided on lines 324 and 325, respectively. This is followed by NLINES lines of descriptive text (herein provided on lines 326 and 327). The corresponding echoed-input file is presented as lines 555 through 556. NECHO is set to 1 here to generate an echo of the input. NLINES is set to 2 indicating there are two lines of text to follow. If no descriptive text is desired, set NLINES = 0.

13.2.3 H Array Input

General Input Format

```
NECHO
NH
1, H(1,1), H(2,1), ... , H(23,1), H(24,1)
2, H(1,2), H(2,2), ... , H(23,2), H(24,2)
     .    .    .
     .    .    .
     .    .    .
```

IDH, H(1,IDH), H(2,IDH), ... , H(23,IDH), H(24,IDH)

NH-1, H(1,NH-1), H(2,NH-1), ... , H(23,NH-1), H(24,NH-1)
NH, H(1,NH), H(2,NH), ... , H(23,NH), H(24,NH)

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.

- NH - Number of sets of radiation heat transfer coefficients ($0 < NH < NHP$).

- IDH - Identifier for this radiation heat transfer coefficient set ($1 < IDH < NH$).

- H - Array containing the radiation heat transfer coefficients. The first argument refers to the particular cell-to-cell connection. The second argument refers to the coefficient set identifier, IDH. Each coefficient refers to the communication between the cell at location (I,J,K) and one of its 24 neighboring cells. The input sequence follows a specific order indicating the indices of the transmitting cell as follows:

  H(1,IDH) => $(I+1,J,K)$ or h2e
  H(2,IDH) => $(I,J+1,K)$ or h2n
  H(3,IDH) => $(I-1,J,K)$ or h2w
  H(4,IDH) => $(I,J-1,K)$ or h2s
  H(5,IDH) => $(I+1,J+1,K)$ or h3ne
  H(6,IDH) => $(I-1,J+1,K)$ or h3nw
  H(7,IDH) => $(I-1,J-1,K)$ or h3sw
  H(8,IDH) => $(I+1,J-1,K)$ or h3se
  H(9,IDH) => $(I+2,J,K)$ or h4e
  H(10,IDH) => $(I,J+2,K)$ or h4n
  H(11,IDH) => $(I-2,J,K)$ or h4w

H(12,IDH) => $(I,J-2,K)$ or h4s
H(13,IDH) => $(I+2,J+1,K)$ or h5ene
H(14,IDH) => $(I+1,J+2,K)$ or h5nne
H(15,IDH) => $(I-1,J+2,K)$ or h5nnw
H(16,IDH) => $(I-2,J+1,K)$ or h5wnw
H(17,IDH) => $(I-2,J-1,K)$ or h5wsw
H(18,IDH) => $(I-1,J-2,K)$ or h5ssw
H(19,IDH) => $(I+1,J-2,K)$ or h5sse
H(20,IDH) => $(I+2,J-1,K)$ or h5ese
H(21,IDH) => $(I+2,J+2,K)$ or h6ne
H(22,IDH) => $(I-2,J+2,K)$ or h6nw
H(23,IDH) => $(I-2,J-2,K)$ or h6sw
H(24,IDH) => $(I+2,J-2,K)$ or h6se

All 24 radiation heat transfer coefficients must be provided for each coefficient set. If they are not used, the value should be set to 0. The units of H should be cm. RADR cells that connect with phantom-cells (e.g., those cells with I or J index of 1) and pseudo-cells (e.g., those cells with I or J index of 0) should have 0 entered for the radiation heat transfer coefficient between them. The modeler must ensure that transmission from image cells is accounted for when symmetry is exploited in a computational model to reduce the number of cells considered in the model. Further discussion of these subtleties is provided below in the example simulation.

The 24 coefficients are organized into five subsets labeled as h2x, h3x, h4x, h5x, and h6x. Compass positions [relative to the cell at (I,J,K)] are used to further identify the coefficient and, in so doing, define the neighboring cell to which this coefficient is related. The compass position (e.g., e, n, ene, ssw) is provided in the "x" suffix of the subset

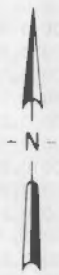
name. The subset and relative position of each coefficient is illustrated in Figure 13.3. As an example, the radiation heat transfer coefficient between cells (I,J,K) and $(I+1,J-2,K)$ is represented by the entry h5sse. The input sequence given in its general form above, can also be represented by the following sequence for each group:

IDH,h2e,h2n,h2w,h2s,
h3ne,h3nw,h3sw,h3se,
h4e,h4n,h4w,h4s,
h5ene,h5nne,h5nnw,h5wnw,h5wsw,h5ssw,h5sse,h5ese,
h6ne,h6nw,h6sw,h6se.

IDH (1 ≤ IDH ≤ NH) identifies the coefficient set. This data is provided, in its entirety, for each of the NH coefficient sets of the model.

Input File Example

```
328 1/radr/h
329 25
330 1.0,2*0.171,2*0.0,0.208,3*0.0,2*0.005,2*0.0,2*0.046,6*0.0,4*0.0,
331 2.0,0.171,0.388,0.171,0.0,2*0.208,2*0.0,0.005,0.010,2*0.0,3*0.046,5*0.0,
332  4*0.0,
333 3.0,0.388,0.171,0.0,0.171,0.208,2*0.0,0.208,0.010,0.005,2*0.0,2*0.046,
334 5*0.0,0.046,4*0.0,
335 4.0,0.171,0.342,0.171,0.0,2*0.208,2*0.0,0.005,0.010,0.005,0.0,4*0.046,
336  4*0.0,4*0.0,
337 5.0,0.342,0.171,0.0,0.171,0.208,2*0.0,0.208,0.010,0.005,0.0,0.005,2*0.046,
338  4*0.0,2*0.046,4*0.0,
339 6.0,0.171,0.342,0.171,0.0,2*0.208,2*0.0,0.0,0.010,0.005,0.0,0.0,3*0.046,
340  4*0.0,4*0.0,
341 7.0,0.342,0.171,0.0,0.171,0.208,2*0.0,0.208,0.010,2*0.0,0.005,0.046,5*0.0,
342  2*0.046,4*0.0,
343 8.0,0.0,0.342,0.171,0.0,0.0,0.208,2*0.0,0.0,0.010,0.005,0.0,2*0.0,2*0.046,
344  4*0.0,4*0.0,
345 9.0,0.342,2*0.0,0.171,3*0.0,0.208,0.010,2*0.0,0.005,6*0.0,2*0.046,4*0.0,
346 10.0,4*0.388,4*0.208,2*0.010,2*0.0,3*0.046,4*0.0,0.046,4*0.0,
347 11.0,0.388,0.342,0.388,0.342,4*0.208,3*0.010,0.0,5*0.046,2*0.0,0.046,4*0.0,
348 12.0,0.342,0.388,0.342,0.388,4*0.208,2*0.010,0.0,0.0[0,3*0.046,2*0.0,
```



J+2	6/NW	5/NNW	4/N	5/NNE	6/NE	
J+1	5/WNW	3/NW	2/N	3/NE	5/ENE	
J	4/W	2/W		2/E	4/E	
J-1	5/WSW	3/SW	2/S	3/SE	5/ESE	
J-2	6/SW	5/SSW	4/S	5/SSE	6/SE	
	I-2	I-1	I	I+1	I+2	

FIGURE 13.3. RADR Heat Transfer Coefficient Notation

```
 3*0.046,4*0.0,
13.0,0.388,0.342,0.388,0.342,4*0.208,0.0,2*0.010,0.0,0.0,4*0.046,3*0.0,
 4*0.0,
14.0,0.342,0.388,0.342,0.388,4*0.208,0.010,2*0.0,0.010,0.046,4*0.0,3*0.046,
 4*0.0,
15.0,0.0,0.342,0.388,0.342,0.0,2*0.208,0.0,0.0,2*0.010,0.0,2*0.0,3*0.046,
 3*0.0,4*0.0,
16.0,0.342,0.0,0.342,0.388,2*0.0,2*0.208,0.010,2*0.0,0.010,5*0.0,3*0.046,
 4*0.0,
17.0,4*0.342,4*0.208,4*0.010,8*0.046,4*0.0,
18.0,4*0.342,4*0.208,0.0,3*0.010,0.0,6*0.046,0.0,4*0.0,
19.0,4*0.342,4*0.208,0.010,0.0,2*0.010,0.046,2*0.0,5*0.046,4*0.0,
20.0,4*0.342,4*0.208,2*0.0,2*0.010,3*0.0,4*0.046,0.0,4*0.0,
21.0,0.0,3*0.342,0.0,2*0.208,0.0,0.0,3*0.010,2*0.0,4*0.046,2*0.0,4*0.0,
22.0,0.342,0.0,2*0.342,2*0.0,2*0.208,0.010,0.0,2*0.010,4*0.0,4*0.046,4*0.0,
23.0,0.0,3*0.342,0.0,2*0.208,0.0,2*0.0,2*0.010,3*0.0,3*0.046,2*0.0,4*0.0,
24.0,0.342,0.0,2*0.342,2*0.0,2*0.208,2*0.0,2*0.010,4*0.0,3*0.046,0.0,4*0.0,
25.0,2*0.0,2*0.342,2*0.0,0.208,0.0,2*0.0,2*0.010,4*0.0,2*0.046,2*0.0,4*0.0
```

Echoed-Input File Example

```
radr    nh= 25   maximum current dimension for nh is  25
radr    h
                nh   h2e(nh)    h2n(nh)    h2w(nh)    h2s(nh)    h3ne(nh)   h3nw(nh)   h3sw(nh)   h3se(nh)
                 1 0.1710e+00 0.1710e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.0000e+00 0.0000e+00 0.0000e+00
                 2 0.1710e+00 0.3880e+00 0.1710e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00 0.0000e+00
                 3 0.3880e+00 0.1710e+00 0.0000e+00 0.1710e+00 0.2080e+00 0.0000e+00 0.0000e+00 0.2080e+00
                 4 0.1710e+00 0.3420e+00 0.1710e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00 0.0000e+00
                 5 0.3420e+00 0.1710e+00 0.0000e+00 0.1710e+00 0.2080e+00 0.0000e+00 0.0000e+00 0.2080e+00
                 6 0.1710e+00 0.3420e+00 0.1710e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00 0.0000e+00
                 7 0.3420e+00 0.1710e+00 0.0000e+00 0.1710e+00 0.2080e+00 0.0000e+00 0.0000e+00 0.2080e+00
                 8 0.0000e+00 0.3420e+00 0.1710e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.0000e+00 0.0000e+00
                 9 0.3420e+00 0.0000e+00 0.0000e+00 0.1710e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.2080e+00
                10 0.3880e+00 0.3880e+00 0.3880e+00 0.3880e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                11 0.3880e+00 0.3420e+00 0.3880e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                12 0.3420e+00 0.3880e+00 0.3420e+00 0.3880e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                13 0.3880e+00 0.3420e+00 0.3880e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                14 0.3420e+00 0.3880e+00 0.3420e+00 0.3880e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                15 0.0000e+00 0.3420e+00 0.3880e+00 0.3420e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00
                16 0.3420e+00 0.0000e+00 0.3420e+00 0.3880e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.2080e+00
                17 0.3420e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                18 0.3420e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                19 0.3420e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                20 0.3420e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                21 0.0000e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00
                22 0.3420e+00 0.0000e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.2080e+00
                23 0.0000e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00
                24 0.3420e+00 0.0000e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.2080e+00
                25 0.0000e+00 0.0000e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.0000e+00

                nh   h4e(nh)    h4n(nh)    h4w(nh)    h4s(nh)
                 1 0.5000e-02 0.5000e-02 0.0000e+00 0.0000e+00
                 2 0.5000e-02 0.1000e-01 0.0000e+00 0.0000e+00
                 3 0.1000e-01 0.5000e-02 0.0000e+00 0.0000e+00
                 4 0.5000e-02 0.1000e-01 0.5000e-02 0.0000e+00
                 5 0.1000e-01 0.5000e-02 0.0000e+00 0.5000e-02
                 6 0.0000e+00 0.1000e-01 0.5000e-02 0.0000e+00
                 7 0.1000e-01 0.0000e+00 0.0000e+00 0.5000e-02
                 8 0.0000e+00 0.1000e-01 0.5000e-02 0.0000e+00
                 9 0.1000e-01 0.0000e+00 0.0000e+00 0.5000e-02
                10 0.1000e-01 0.1000e-01 0.0000e+00 0.0000e+00
                11 0.1000e-01 0.1000e-01 0.1000e-01 0.0000e+00
                12 0.1000e-01 0.1000e-01 0.0000e+00 0.1000e-01
                13 0.0000e+00 0.1000e-01 0.1000e-01 0.0000e+00
                14 0.1000e-01 0.0000e+00 0.0000e+00 0.1000e-01
                15 0.0000e+00 0.1000e-01 0.1000e-01 0.0000e+00
                16 0.1000e-01 0.0000e+00 0.0000e+00 0.1000e-01
                17 0.1000e-01 0.1000e-01 0.1000e-01 0.1000e-01
                18 0.0000e+00 0.1000e-01 0.1000e-01 0.1000e-01
                19 0.1000e-01 0.0000e+00 0.1000e-01 0.1000e-01
                20 0.0000e+00 0.0000e+00 0.1000e-01 0.1000e-01
                21 0.0000e+00 0.1000e-01 0.1000e-01 0.1000e-01
                22 0.1000e-01 0.0000e+00 0.1000e-01 0.1000e-01
                23 0.0000e+00 0.0000e+00 0.1000e-01 0.1000e-01
                24 0.0000e+00 0.0000e+00 0.1000e-01 0.1000e-01
                25 0.0000e+00 0.0000e+00 0.1000e-01 0.1000e-01

                nh   h5ene(nh)  h5nne(nh)  h5nnw(nh)  h5wnw(nh)  h5wsw(nh)  h5ssw(nh)  h5sse(nh)  h5ese(nh)
                 1 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
                 2 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
                 3 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01
                 4 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
                 5 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01
                 6 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
                 7 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01
                 8 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
                 9 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01
                10 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01
                11 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.4600e-01
```

```
526                 12 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01
527                 13 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00
528                 14 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01
529                 15 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00
530                 16 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01
531                 17 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01
532                 18 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00
533                 19 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01
534                 20 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00
535                 21 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00
536                 22 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.4600e-01
537                 23 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00
538                 24 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01 0.0000e+00
539                 25 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.0000e+00 0.0000e+00
540
541                 nh   h6ne(nh)   h6nw(nh)   h6sw(nh)   h6se(nh)
542                  1 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
543                  2 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
544                  3 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
545                  4 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
546                  5 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
547                  6 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
548                  7 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
549                  8 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
550                  9 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
551                 10 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
552                 11 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
553                 12 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
554                 13 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
555                 14 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
556                 15 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
557                 16 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
558                 17 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
559                 18 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
560                 19 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
561                 20 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
562                 21 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
563                 22 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
564                 23 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
565                 24 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
566                 25 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
```

Radiation heat transfer coefficient information is provided next in the input file. In this model, NECHO is set to 1 on input line 328. Thus, the input to this section will be echoed in the output listing.

The radiation heat transfer coefficient information is divided into sets of 24 coefficients corresponding to the 24 neighboring cells. The number of sets provided in the model, NH ($0 < NH < NHP$), is entered next in the input. For this model, input line 329 indicates that there are 25 such sets. The echoed input is provided in line 558 of the output listing.

Each set represents the exchange between a typical computational cell location identified by indices (I,J,K) and its 24 neighboring cells located

within the range (I-2 ≤ I ≤ I+2, J-2 ≤ J ≤ J+2, K). In this way, several regions of the model can reference the same set of heat transfer coefficients without having to be retyped as input.

Radiation heat transfer coefficients representing communication of a computational cell with phantom and/or pseudo cells should be assigned a zero value. This situation is typically encountered in those cells residing within a distance of two cells from a symmetry condition or computational-mesh boundary. The temperature associated with these phantom and pseudo cells may be fictitious. Consequently, these cells must be effectively excluded from the computation. In models exploiting a symmetry condition of the problem, the RADR radiation heat transfer coefficients must include the effect of heat transfer with the image cells residing outside the computational domain. This same concern is discussed in detail in Section 11.2.7.

Lines 330 through 366 of the input present the radiation heat transfer coefficient information for this model. The echoed input generated is presented in output lines 559 through 666.

13.2.4 LREG Array Input Section

General Input Format

```
NECHO
NREG
1,IDH,IBEG,IEND,JBEG,JEND,KBEG,KEND
2,IDH,IBEG,IEND,JBEG,JEND,KBEG,KEND
        .   .   .
        .   .   .
        .   .   .
IREG,IDH,IBEG,IEND,JBEG,JEND,KBEG,KEND
        .   .   .
        .   .   .
        .   .   .
NREG-1,IDH,IBEG,IEND,JBEG,JEND,KBEG,KEND
NREG,IDH,IBEG,IEND,JBEG,JEND,KBEG,KEND
```

General Input Description

- NREG - The number of RADR regions in the model (0 ≤ NREG ≤ NREGP).
- IREG - Region identifier (1 ≤ IREG ≤ NREG).

- IDH - Radiation heat transfer coefficient set identifier ($1 \leq IDH \leq NH$).
- IBEG - Beginning I index of the region for which IDH applies.
- IEND - Ending I index of the region for which IDH applies.
- JBEG - Beginning J index of the region for which IDH applies.
- JEND - Ending J index of the region for which IDH applies.
- KBEG - Beginning K index of the plane.
- KEND - Ending K index of the plane.

Input File Example

```
367 1/radr/lreg
368 25
369 1,1,2,2,2,2,2,23,
370 2,2,3,3,2,2,2,23,
371 3,3,2,2,3,3,2,23,
372 4,4,4,7,2,2,2,23,
373 5,5,2,2,4,7,2,23,
374 6,6,8,8,2,2,2,23,
375 7,7,2,2,8,8,2,23,
376 8,8,9,9,2,2,2,23,
377 9,9,2,2,9,9,2,23,
378 10,10,3,3,3,3,2,23,
379 11,11,4,7,3,3,2,23,
380 12,12,3,3,4,7,2,23,
381 13,13,8,8,3,3,2,23,
382 14,14,3,3,8,8,2,23,
383 15,15,9,9,3,3,2,23,
384 16,16,3,3,9,9,2,23,
385 17,17,4,7,4,7,2,23,
386 18,18,8,8,4,7,2,23,
387 19,19,4,7,8,8,2,23,
388 20,20,8,8,8,8,2,23,
389 21,21,9,9,4,7,2,23,
390 22,22,4,7,9,9,2,23,
391 23,23,9,9,8,8,2,23,
392 24,24,8,8,9,9,2,23,
393 25,25,9,9,9,9,2,23
```

Echoed-Input File Example

```
 668     radr    nreg= 25   maximum current dimension for nreg is  25
 669     radr    ireg         region    radiation                cell location
 670                          number    type (nh)      ibeg iend  jbeg jend  kbeg kend
 671                            1          1            2    2     2    2     2   23
 672                            2          2            3    3     2    2     2   23
 673                            3          3            2    2     3    3     2   23
 674                            4          4            4    7     2    2     2   23
 675                            5          5            2    2     4    7     2   23
 676                            6          6            8    8     2    2     2   23
 677                            7          7            2    2     8    8     2   23
 678                            8          8            9    9     2    2     2   23
 679                            9          9            2    2     9    9     2   23
 680                           10         10            3    3     3    3     2   23
 681                           11         11            4    7     3    3     2   23
 682                           12         12            3    3     4    7     2   23
 683                           13         13            8    8     3    3     2   23
 684                           14         14            3    3     8    8     2   23
 685                           15         15            9    9     3    3     2   23
 686                           16         16            3    3     9    9     2   23
 687                           17         17            4    7     4    7     2   23
 688                           18         18            8    8     4    7     2   23
 689                           19         19            4    7     8    8     2   23
 690                           20         20            8    8     8    8     2   23
 691                           21         21            9    9     4    7     2   23
 692                           22         22            4    7     9    9     2   23
 693                           23         23            9    9     8    8     2   23
 694                           24         24            8    8     9    9     2   23
 695                           25         25            9    9     9    9     2   23
```

The portions of the model over which RADR radiation heat transfer is simulated are segregated into regions. Each region is assigned a number, NREG ($1 \leq NREG \leq NREGP$), as well as an identifier for the set of heat transfer coefficients IDH ($1 \leq IDH \leq NHP$). In addition, an index range is provided in this input file to identify the indices I, J, and K to which the coefficient set associated with IDH applies. For each K-plane in the specified K-range, RADR will sweep (in the FORTRAN sense) over the I and J index ranges using the radiation heat transfer coefficients in set IDH to compute the radiation energy transferred between each (I,J,K) cell and its 24 neighboring cells. The regions and participating cells of this model are illustrated in Figures 13.4 and 13.5.

The input required by RADR to effect this result is provided in this section. An example of this input is provided in Section 13.2.3 as input lines

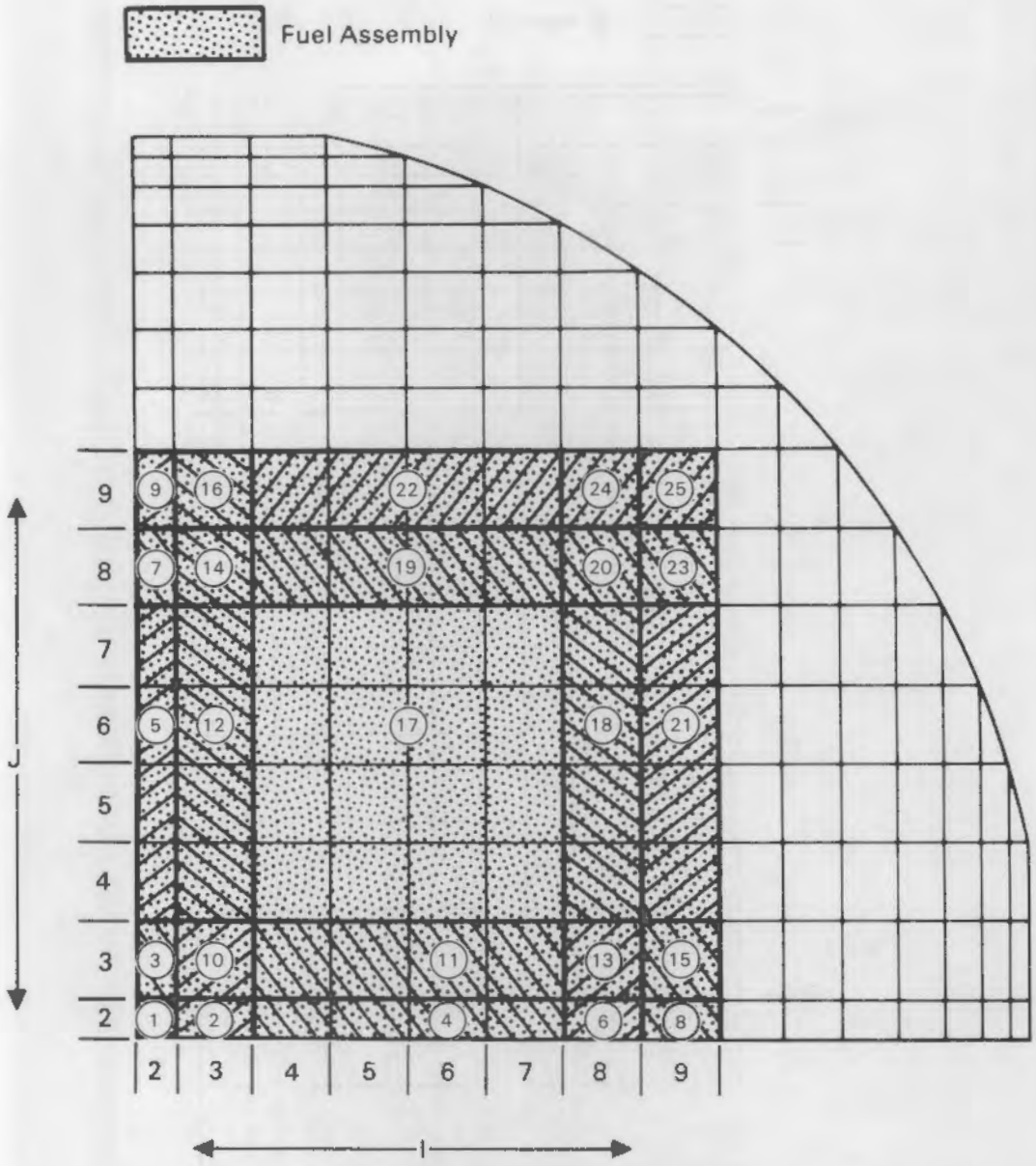


FIGURE 13.4. Transverse Computational Mesh Illustrating I-Cell and J-Cell Levels of the RADR Model (Encircled numbers indicate model region numbers)

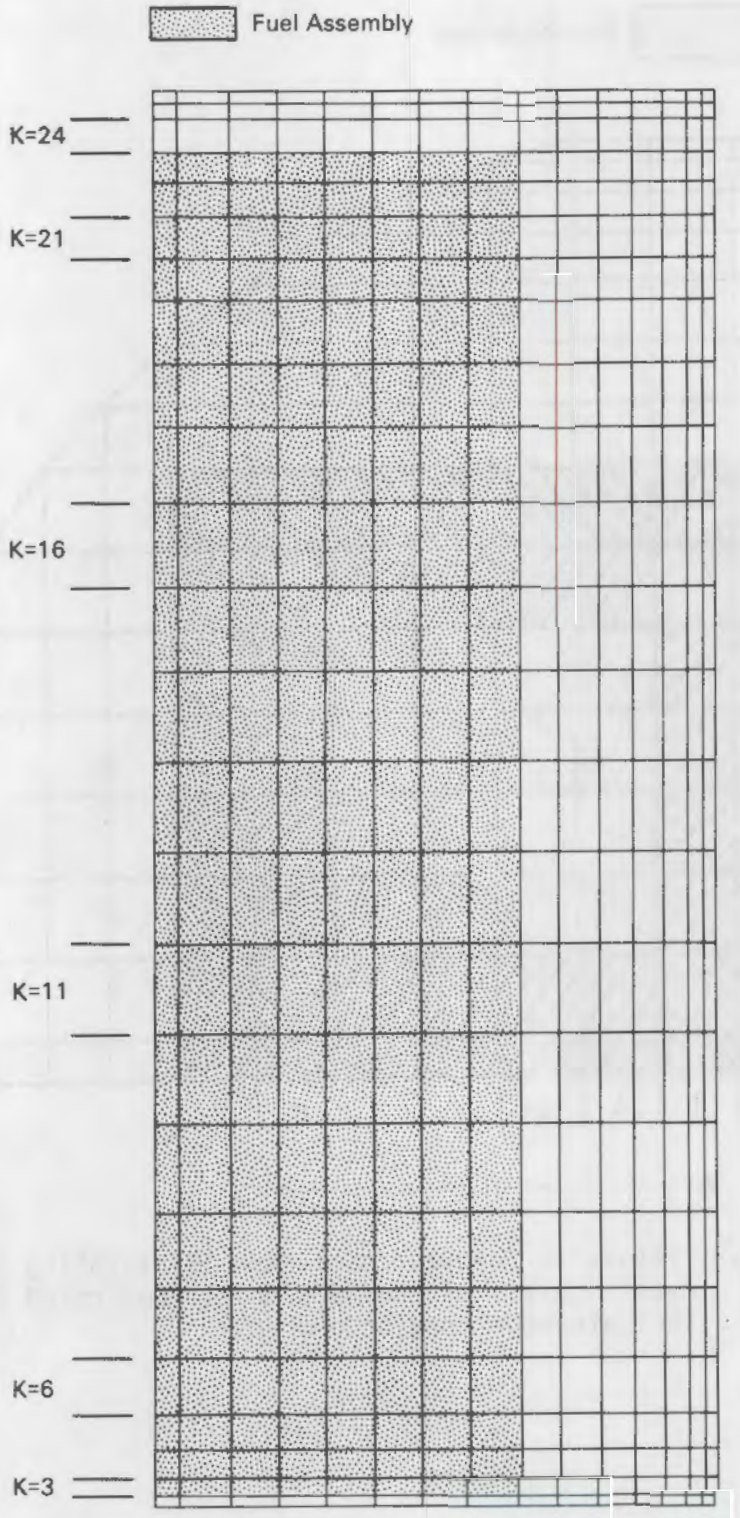


FIGURE 13.5. Axial Computational Mesh Illustrating K-Cell Levels of the RADR Model

367 through 393. The input to this section is initiated by assigning a value to NECHO. For the input file example, this is done on input line 367.

The number of regions in the model, NREG (0 < NREG < NREGP), is provided next in the input file (input line 368 for this example). As indicated, the remaining input to this section follows the general format:

IREG,NH,IBEG,IEND,JBEG,JEND,KBEG,KEND.

Input variable IREG identifies the region number (1 < IREG < NREG). The cells assigned to this region of the RADR model will use the radiation heat transfer coefficients identified in coefficient set NH. The I, J, and K ranges are next provided as indicated above. Note that, since RADR sweeps over the cells in this range in the FORTRAN sense, radiation heat transfer will be computed for every cell in this range.

13.2.5 LT4 Array Input

For computational reasons, subroutine RADR computes the T^4 terms for all participating cells in the radiation model. As with the input of the preceeding section, the participating cells are divided into regions. The cell indices associated with these regions are loaded into the LT4 array. The cells of a region in this input section are not constrained to share a common set of radiation heat transfer coefficients. Therefore, the number of cells in an LT4 region can be greatly increased. This reduces the amount of input required. The cells identified in this input must, however, "cover" every participating cell of the RADR model.

General Input Format

```
NECHO
NT4
1,IT4BEG,IT4END,JT4BEG,JT4END,KT4BEG,KT4END
2,IT4BEG,IT4END,JT4BEG,JT4END,KT4BEG,KT4END
                  .  .  .
                  .  .  .
                  .  .  .
IT4,IT4BEG,IT4END,JT4BEG,JT4END,KT4BEG,KT4END
                  .  .  .
                  .  .  .
                  .  .  .
```

NT4-1,IT4BEG,IT4END,JT4BEG,JT4END,KT4BEG,KT4END
NT4,IT4BEG,IT4END,JT4BEG,JT4END,KT4BEG,KT4END

General Input Description

- NT4 - Number of T4 regions in the model (0 < NT4 < NT4P).
- IT4 - T4 region identifier (1 < IT4 < NT4).
- IT4BEG - Beginning I index of the T4 region.
- IT4END - Ending I index of the T4 region.
- JT4BEG - Beginning J index of the T4 region.
- JT4END - Ending J index of the T4 region.
- KT4BEG - Beginning K index of the T4 region.
- KT4ENO - Ending K index of the T4 region.

Input File Example

```
394 1/radr/lt4
395 1
396 1,2,9,2,9,2,23
```

Echoed-Input File Example

```
697    radr   nt4=  1  maximum current dimension for nt4 is  1
698    radr   lt4                    region              cell location
699                                  number     ibeg iend  jbeg jend  kbeg kend
700                                    1          2   9      2   9      2   23
```

NECHO is set to a value of 1 on input line 394. The index ranges for the participating cells of the RADR model are stored in array LT4. NT4, the number of regions into which the RADR model is subdivided for loading LT4, is provided next in the input file. For this model, NT4 is set to 1 on input line 395. This is reflected in the echoed input on output line 697.

As indicated above, the remaining input to this section has the general form

IT4,IBEG,IEND,JBEG,JEND,KBEG,KEND.

IT4 (1 ≤ IT4 ≤ NT4) is the region number for this set of indices comprising the computational cells (I,J,K) where IBEG ≤ I ≤ IEND, JBEG ≤ J ≤ JEND, and KBEG ≤ K ≤ KEND. This input is presented in input line 396 for the model discussed herein. The corresponding echoed input is presented in output lines 698 through 700.

13.2.6 Discussion of Input Example

To aid understanding of the interconnection between the input sections of this routine, consider LREG region number 1 in Figure 13.4. This region represents a portion of the computational domain swept-out by cells (2,2,2 ≤ K ≤ 23) - essentially a pencil of cells located at (I = 2, J = 2) and covering K planes 2 through 23. RADR will compute the radiation heat transfer between each of the neighboring 24 cells in the range (0 ≤ I ≤ 4, 0 ≤ J ≤ 4, K) and the cell at (2,2,K) for each of the 22 K-planes. The radiation heat transfer coefficients used in these computations are carried in the first coefficient set (NH = 1). Thus, for example, the radiation heat transfer coefficient used for communication between cells (2,4,K) and (2,2,K) is identified as h4n(1) = 0.005; that between cells (4,4,K) and (2,2,K) is h6ne = 0. Initialization of the T^4 temperatures for the participating cells of this region are "covered" in LT4 region number 1. Note that the phantom cells (index I or J = 1) and some pseudo-cells (index I or J = 0) are included in the LREG region. These cells are not "covered" by the LT4 region. The "temperature" for each of these cells is therefore set to zero by the initialization procedure. However, their effect is excluded from the RADR model by the zero entries in the radiation heat transfer coefficients h2w(1), h2s(1), h3nw(1), h3sw(1), h3se(1), h4w(1), h4s(1), h5nnw(1), h5wnw(1), h5wsw(1), h5ssw(1), h5sse(1), h5ese(1), h6nw(1), h6sw(1), and h6se(1). Due to the quarter symmetry exploited in this problem, some of these cell locations do coincide with image cells. For example, coefficient h3ne(1) must include the effect of the communication between cell (3,3,K) and (2,2,K) and its image energy-flow path, (1,1,K) and (2,2,K).

As in subroutine RADC, the matrix of heat transfer coefficients must be symmetric to ensure energy conservation. For example, the radiation heat transfer coefficient used in computing the energy received by the cell at

(8,8,K) from the cell at (7,6,K) [h5ssw(20) = 0.046] must equal that used in computing the energy received by cell (7,6,K) from cell (8,8,K) [h5nne(17) = 0.046].

13.2.7 Input Example When RADR Is Not Used

If subroutine RADR is not used in the simulation, then only the following lines of input are required:

```
1/radr
0
1/radr/h
0
1/radr/lreg
0
1/radr/lt4
0
```

14.0 SUBROUTINE REBA

Subroutine REBA provides an optional procedure for acceleration of the energy equation solution when a steady state is sought.

14.1 REBA FUNCTIONS

REBA solves steady-state energy balance equations on a coarse mesh made up of three regions in each of the KP-2 active computational K-planes. The three regions at a given K-plane are the rectangular grid region, the interface cells, and the cylindrical grid region.

The merits and constraints of a coarse-mesh solution of the energy equation in accelerating progress toward steady state were discussed in Chapter 7.0, Subroutine REBT. Some admonitions there are also applicable to use of REBA. Use of REBA should be deferred until enough time-steps are taken that properties and flows have "settled down" somewhat to near-physical values. The axially coupled three-radial-region solutions in REBA are sufficiently effective, however, in achieving a rough temperature distribution that its use is recommended for simulations that use both the rectangular and cylindrical grid features.

The pattern of calls to REBA is set in Program MAIN by input variables REBAON, NREB, and NREBN. The user may find it advantageous to monitor the progress toward the steady-state solution before and after use of REBA by looking at the maximum temperature change per time-step, and also by looking at power balance information that can be calculated and printed by Subroutine QINFO. See Chapters 15.0 and 29.0 for the QINFO features.

A feature provided in REBA to avoid potential overcompensation is a maximum allowable magnitude for the temperature change from the REBA coarse-mesh solution. If in a given K-plane a temperature change $\delta T'$ is calculated for one of the three regions, the amount of temperature change δT added to the evolving temperatures for that region is

$$\delta T = \text{SIGN}(\text{MIN}(\text{ABS}(\delta T'),\text{DTMAX}),\delta T')$$

where the FORTRAN SIGN function gives the algebraic sign of the second argument ($\delta T'$ in this case) to the magnitude of the first argument (the smaller of $|\delta T'|$ and DTMAX, in this case).

A printout option in REBA allows displaying "divergence error" quantities. In REBA, a divergence error for a cell is calculated by net heat flow into the cell, which should be zero in steady state. The divergence error quantities printable in REBA are the sums of divergence errors over the regions (rectangular, boundary, and cylindrical) of a K-plane. The largest sum for any K-plane for each region can be printed.

14.2 PARAMETER STATEMENT INFORMATION

Parameters appearing in subroutine REBA that were discussed in Chapter 4.0, Subroutine GRID, include:

IP,JP,KP,ISP,JSP,KBP,KTP

Additional dimensioning parameters in subroutine REBA that are discussed in Chapter 25.0, Subroutine CROUT, include:

ICRP,JCRP

14.3 INPUT FORMAT

14.3.1 Overview

The schedule for calls to REBA is set in Program MAIN. The input here sets a maximum allowable temperature change from the coarse grid solution, and also sets the level of printout desired.

14.3.2 REBA Input Block

General Input Format

NECHD
DTMAX,INFO

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- DTMAX - The upper bound on the magnitude of the temperature change to add for any of the three regions at a K-plane from the coarse-mesh solution.
- INFO - An integer flag variable for printout of results. If INFO = 1, REBA will report the K-plane at which the divergence error sum is largest for each of the three regions (rectangular grid, interface cells, cylindrical grid) and the value of that divergence error sum. Note that calculating this information takes some (though not major) effort, so it should be done only as needed. If INFO = 0, this information is not reported.

Input File Example

```
1591     1/reba
1592     20.0,1
```

Echoed Input File Example

```
949
950     reba     dtmax=0.200e+02     info=1
951
```

The input file asks for echoing (line 1591), sets maximum temperature change in a region to 20°C (line 1592), and asks for a printout of divergence error information with INFO = 1 on line 1592. A typical line of divergence error information printed in response to INFO = 1 on a call to REBA is:

```
reba    info=1   dtmax=-0.371e-01   dimax= 0.402e-01   ki=30   dbmax=0.133e-01   kb=15   dsmax= 0.386e-08   ks= 3
```

This REBA printout line gives the maximum temperature change DTMAX that actually occurred in the current call to REBA, the maximum divergence error DIMAX for the interior (rectangular grid) region, the K-plane KI = 30 where it occurred, the maximum divergence error DBMAX for the boundary or interface

region, the K-plane KB = 15 where it occurred, the maximum divergence DSMAX on the side or cylindrical grid region, and the K-plane KS = 3 where it occurred.

15.0 SUBROUTINE QINFO

At the conclusion of a run, a user may optionally print net heat flows to various portions of the cask and heat fluxes in the inside of the cask. Subroutine QINFO implements the process of determining heat flows using geometrical information and current temperatures and thermal resistances.

15.1 PARAMETER STATEMENT INFORMATION

Subroutine QINFO requires the specification of parameters IP, JP, KP, KBP, and KTP. These parameters define the overall computational mesh and are described in Chapter 4.0, Subroutine GRIO. No additional parameters are needed in Subroutine QINFO.

15.2 INPUT FORMAT

Subroutine QINFO does not read information from the input file. No user attention is required other than selecting appropriate input file options as described in Chapter 3.0, Program MAIN.

16.0 SUBBROUTINE HYDRO

This subroutine serves as a gateway to all other subroutines required for the solution of the fluid momentum and continuity equations. Subroutine HYDRO is always called in the initialization phase of a run to set a number of constants and arrays. If a momentum solution is desired, then this subroutine is called once each time-step to update temperature-dependent properties, call other subroutines, and provide diagnostic information.

The first operation undertaken in this subroutine is to read the input file. The information contained on the input file includes:

- minimum and maximum allowed values of the momentum time-step
- reference pressure, temperature, and density for the gas within the cask
- gravitational vector orientation with respect to the cask
- temperature dependence of gas viscosity
- viscosity specifications to account for fluid flow obstructions and free-slip boundary conditions
- provision to monitor selected mass fluxes during a run.

The above information must be on the input file even if a momentum solution is not desired, to satisfy list-directed read requirements. If no momentum solution is desired, such as for a conduction-only application, then the information on the input file need not represent a physically realizable system.

There are certain other control parameters on the input file that relate to simulating transient applications. This documented version of the code is, however, intended for only steady-state applications. To allow for potential future extension of the code and its documentation, input specifications relating to a transient mode of operation have been retained. In the general input descriptions in this chapter, parameters related to the transient mode are identified, a brief indication of the function given, and the appropriate value to be used is provided.

If a solution to the momentum and continuity equations is desired (enabled by setting NOVEL = 0 in Program MAIN), then subroutine HYDRO will call the appropriate subroutines once each time-step. The calling sequence is:

- subroutine MOMX, MOMY, and MOMZ (Chapter 19.0) for solution of tilde mass fluxes - Tilde mass fluxes are tentative mass fluxes that do not yet satisfy continuity because they are based on old-time pressures.
- subroutine PDG (Chapter 20.0) for computation of the divergence error of the tilde mass fluxes and construction of the discrete form of the continuity equation
- subroutine PITER (Chapter 21.0), which directs the solution of the continuity equation expressed in terms of pressure changes.

After satisfaction of the pressure (continuity) equation, the pressure changes are returned to subroutine HYDRO to update the tilde mass fluxes so that they satisfy conservation of mass. The next momentum time-step is computed automatically based on the current time-step, the tilde mass-flux continuity error, and the computational effort required to satisfy the pressure (continuity) equation. The new time-step may be adjusted up or down to meet the specified optimum tilde mass-flux continuity error and specified optimum computational cycles for the pressure equation. Finally, those mass fluxes designated for monitoring are sent to the output file.

16.1 PARAMETER STATEMENT INFORMATION

Subroutine HYDRO requires the specification of parameters IP, JP, KP, KBP, and KTP. These parameters define the overall computational mesh and are described in Chapter 4.0, Subroutine GRID. Four additional parameters, local to this subroutine, are required for specification of fluid viscosities and printing options:

- NREGP - This parameter is used to dimension an array that holds information about regions of computational cells requiring special treatment of viscosity. The details of this special treatment are given in Section 16.2.3. NREGP should be greater than or equal

to the number of regions. If no special regions are required, then NREGP should equal 1.

- MONMXP, MONMYP, MONMZP - Three parameters, each greater than or equal to 1, that allow storage for mass fluxes mx, my, and/or mz to be monitored at designated computational cells. For example, if MONMXP = 4, then it is possible to print mass fluxes in the x-direction every time-step at up to four different locations. See Section 16.2.2 for further details.

16.2 INPUT FORMAT

16.2.1 Run Control Information

This section of input provides some of the information needed for operation of the momentum solution. Basic gas properties and gravitational vector orientation are also specified here. The input file must be constructed as shown, to satisfy list-directed read requirements--even if no momentum solution is required.

General Input Format

```
NECHO
CONVEK,EPSCON,MITMAX,THETAM,WM,ESTPF
NDTYME,DTYMEN,DTYMAX
NEWGAS,NEWVEL,EXTRAV
PFREF,TFREF,DFREF
GX,GY,GZ
CVISA,CVISB
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- CONVEK - The convection of momentum terms may be deleted from the linear momentum equations if desired. The terms deleted are $\nabla\cdot(\vec{v}\dot{m})$ where $\vec{v}$ is the velocity and $\dot{m}$ is

the mass flux. The terms are included if CONVEK = 1.0; they are deleted if CONVEK = 0.0.

- EPSCON - The maximum allowable continuity error to be permitted if both momentum and continuity equations are to be satisfied each time-step. This option is intended for transient applications; therefore, EPSCON should be set equal to 0.0.

- MITMAX - The maximum number of solution cycles permitted to satisfy both momentum and continuity equations each time-step. This option is intended for transient applications; therefore, MITMAX should be set equal to 0.

- THETAM - New-time tilde mass fluxes may be computed based on a mixture of old-time mass fluxes and new-time tilde mass fluxes. THETAM sets the relative weighting and should have the value of 0.5 for steady-state applications.

- WM - A weighting factor in the momentum equations intended for switching between transient and steady-state modes of operation. A value of 1.0 is to be used for the steady-state mode.

- ESTPF - This constant is used to estimate new-time pressures according to the expression

$$p = p + estpf * \frac{\delta t}{\delta t_{old}} (p - p_{old})$$

The momentum equations and the continuity (pressure) equation are not solved simultaneously; thus, the coupling is explicit. Slight underrelaxation is, at times, beneficial for stability. The value shown on

the input file example for estpf, -0.05, is usually satisfactory. A best value is application-specific, and, if necessary, is determined by trial.

- NDTYME - If a new momentum time-step is desired at the start of a run, then ndtyme = 1; otherwise, ndtyme = 0. If the run is started without a restart tape, then ndtyme = 1.
- DTYMEN - The value of the new initial momentum time-step.
- DTYMAX - The maximum value of the momentum time-step. DTYMAX will normally not exceed 1.0, and may be less for steady-state applications.
- NEWGAS - A switch that enables changing gas properties at the start of a run for transient applications. NEWGAS should be set to 0 for steady-state applications.
- NEWVEL - This constant, if equal to 1, will set all mass fluxes to zero at the start of any run. No action is taken if NEWVEL equals 0.
- EXTRAV - If EXTRAV has a value different from 1.0, then all mass fluxes are reset at the start of any run according to the expression m = EXTRAV * m. The new mass fluxes still satisfy continuity.
- PFREF, TFREF, DFREF - Reference pressure, temperature, and density for the gas, used in the code to compute density according to an equation of state,

$$\rho = \left(\frac{\rho T}{p}\right)_{ref} \frac{p}{T}$$

- GX, GY, GZ - The components (direction cosines) of the gravitational vector along the three cartesian coordinate axes. The cartesian coordinate system is fixed relative to the cask body.

- CVISA, CVISB - The constants in the temperature-dependent equation for the viscosity of the gas,

$$\mu = CVISA + CVISB * T$$

Input File Example

```
1593 1/hydro
1594 1.0,0.2e-7,0,0.5,1.0,-0.05
1595 0,0.1e-3,0.1
1596 0,0,1.0
1597 0.65e+6,483.0,0.6472e-4
1598 0.0,0.0,-1.0
1599 0.7e-4,0.4e-6
```

Echoed Input File Example

```
952     hydro   convek=1.0   epscon=0.200e-07   mitmax= 0   thetam=0.5   wm=1.0   estpf=-.500e-01
953     hydro   ndtyme=0   dtymen=0.100e-03   dtymax=0.100e+00
954     hydro   newgas=0   newvel=0   extrav=0.100e+01
955     hydro   pfref=0.6500000e+06   tfref=0.483e+03   dfref=0.64720e-04
956     hydro   gx= 0.000000   gy= 0.000000   gz=-1.000000
957     hydro   cvisa=0.700e-04   cvisb=0.400e-06
```

16.2.2 Monitor Cells for Mass Flux

Mass fluxes at selected I,J,K locations may be written to the output file while the run is in progress. Printing a few carefully chosen mass fluxes periodically may aid in monitoring the performance of the code toward a steady-state solution.

General Input Format

```
NECHO
MONMX
I,J,K
  .
  .
  .
I,J,K
```

```
0,0,0
NECHO
MONMY
I,J,K
  .
  .
  .
I,J,K
0,0,0
NECHO
MONMZ
I,J,K
  .
  .
  .
I,J,K
0,0,0
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- MONMX,MONMY MONMZ - The number of monitor cells for mass fluxes in the x-, y-, and z-directions, respectively.
- I,J,K - The I,J,K location of each cell.
- 0,0,0 - The I,J,K sequence for MONMX, MONMY, and MONMZ must terminate with 0,0,0.

Input File Example

```
1600 1/hydro/monitor/mx
1601 4
1602 12,13,2
1603 12,20,2
1604 5,20,2
1605 9,20,25
1606 0,0,0
1607 1/hydro/monitor/my
1608 0
1609 0,0,0
1610 1/hydro/monitor/mz
1611 4
1612 2,20,16
1613 8,20,16
1614 23,20,16
1615 2,24,16
1616 0,0,0
```

Echoed Input File Example

```
959     hydro   monitor mx cells= 4   maximum number currently allowed is 4
960                                          m   i   j   k
961                                          1  12  13   2
962                                          2  12  20   2
963                                          3   5  20   2
964                                          4   9  20  25
965
966     hydro   monitor my cells= 0   maximum number currently allowed is 4
967
968     hydro   monitor mz cells= 4   maximum number currently allowed is 4
969                                          m   i   j   k
970                                          1   2  20  16
971                                          2   8  20  16
972                                          3  23  20  16
973                                          4   2  24  16
```

In the example shown, four cells were selected for mass fluxes in the x-direction, none in the y-direction, and four in the z-direction. These mass fluxes will be written to the output file while the run is in progress.

16.2.3 Viscosity Specifications

The viscosity is specified automatically for those cells that contain a fluid. However, certain boundary (phantom) cells and those internal cells not containing a fluid need to be identified on the input file. A single cell or a region of contiguous cells forming a rectangular parallelpiped may be identified by a single specification. In either case, the cell or region of cells is indicated by an I,J,K range: IBEG, IEND, JBEG, JEND, KBEG, and KEND.

The most common flow boundary condition is a no-slip condition. Consequently, the viscosity in all cells is initialized to a large value (1.De+20). The input file then identifies those boundary cells (regions) requiring a different viscosity.

Some internal cells may be occupied by a solid material. These cells may be conveniently identified by a large viscosity.

General Input Format

```
NECHO/HYDRO/SPECS VIS BOUNDARY
NREG
VIS,IBEG,IEND,JBEG,JEND,KBEG,KEND
```

```
          .   .   .
          .   .   .
          .   .   .
NECHO/HYDRO/SPECS VIS INSIDE
NREG
XVIS,IBEG,IEND,JBEG,JEND,KBEG,KEND
          .   .   .
          .   .   .
          .   .   .
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- NREG - The number of regions specified in the section of input that follows (either boundary or inside cells).
- VIS - Viscosity in boundary (phantom) cells. A very low value would indicate a free-slip condition.
- XVIS - A number that multiplies the normal fluid viscosity for interior cells. A solid obstruction would be represented by multiplying the fluid viscosity by a large XVIS for those cells.
- IBEG,IEND, JBEG,JEND, KBEG,KEND - The beginning and ending I,J,K indices for a parallelpiped. If a single cell is to be identified, then IBEG = IEND, etc. IBEG,...KEND are input as real numbers.

Input File Example

```
1617 1/hydro/specs vis boundary
1618 1
1619 0.1e-19,1.0,1.0,2.0,47.0,2.0,25.0,
1620 189*0.0
1621 1/hydro/specs vis inside
1622 27
1623 0.1e+10,2.0,4.0,10.0,10.0,3.0,24.0,
1624 0.1e+10,2.0,4.0,12.0,12.0,3.0,24.0,
1625 0.1e+10,2.0,4.0,17.0,17.0,3.0,24.0,
1626 0.1e+10,2.0,4.0,32.0,32.0,3.0,24.0,
          .   .   .
1645 0.1e+10,14.0,14.0,22.0,27.0,3.0,24.0,
```

```
1646 0.1e+10,16.0,16.0,22.0,27.0,3.0,24.0,
1647 0.1e+10,2.0,3.0,10.0,12.0,2.0,2.0,
1648 0.1e+10,2.0,3.0,37.0,39.0,2.0,2.0,
1649 0.1e+10,14.0,16.0,23.0,26.0,2.0,2.0,
1650 7*0.0
```

Echoed Input File Example

```
974
975     hydro   nreg=  1   maximum current dimension for nreg is  28
976     hydro   specs         region          viscosity                cell location
977                                                          ibeg  iend  jbeg  jend   kbeg  kend
978                             1             0.100e-19        1     1     2    47      2    25
979
980     hydro   nreg= 27   maximum current dimension for nreg is  28
981     hydro   specs         region          viscosity                cell location
982                                           multiplier         ibeg  iend  jbeg  jend   kbeg  kend
983                             1             0.100e+10        2     4    10    10      3    24
984                             2             0.100e+10        2     4    12    12      3    24
985                             3             0.100e+10        2     4    17    17      3    24
986                             4             0.100e+10        2     4    32    32      3    24
      .   .   .
1005                           23             0.100e+10       14    14    22    27      3    24
1006                           24             0.100e+10       16    16    22    27      3    24
1007                           25             0.100e+10        2     3    10    12      2     2
1008                           26             0.100e+10        2     3    37    39      2     2
1009                           27             0.100e+10       14    16    23    26      2     2
```

For the example shown on the input file, there is one boundary region (line 1618) that includes the J-K plane with I equal to 1 (line 1619) that has a viscosity of 0.1e-19 (a free-slip condition). The array that holds the above information is, in this example, dimensioned to 196 (28 regions * 7 items/region) therefore 189 additional items of the list are provided (line 1620) but are not used in the code. The echoed input file example reflects this information on lines 975 through 978.

For the example shown on the input file, there are 27 internal regions (line 1622). The following 27 lines (lines 1623 to 1649) each contain a viscosity multiplier and the six constants specifying the I,J,K range of the region. The viscosity multiplier (0.1e+10 in the example) shown on each line is used to multiply the regular fluid viscosity in the indicated range of cells. The array that holds the above information is the same one used for boundary viscosity information and is dimensioned for 28 regions. Line 1650 provides the additional dummy items of the list.

17.0 SUBROUTINE PINIT

Subroutine PINIT initializes the pressure field assuming a static (zero velocity) flow field within the domain. Consequently, the equation for the pressure (obtained by setting each of the velocity component terms in the momentum equations to zero), is solved initially. This equation is

$$- \nabla p + \rho \vec{g} = 0 \qquad (17.1)$$

PINIT sets up the matrix and vector components for the discrete form of this equation. The actual solution for the pressure is performed in subroutines PITER and PILES. Typically, HYDRA-II computes the gas properties using an equation of state to relate pressure, density, and temperature. However, for the purposes of the pressure initialization process in this routine only, the fluid density is assumed constant.

HYDRA-II provides two options for setting the average pressure:

1. Set the desired average pressure directly.
2. Set the fluid mass in the domain.

Option 1 uses the reference fluid density, DFREF, specified as input to subroutine HYDRO in the computation for the pressure field. After Equation (17.1) is solved, each nodal pressure is adjusted by a constant amount so that the average pressure over the field equals FIXEDP if a value FIXEDP > 0.0 is input to subroutine AVG. If the mass of the system is set as the constraint (option 2 above - invoked when FIXEDM > 0.0 is input to subroutine AVG), the cell density is adjusted to produce this specified mass. The cell pressures are subsequently adjusted to be consistent with this density and the specified initial temperature. In this case, the presence of any porous media, which have been specified by the user to occupy some or all of the fluid cells (through the input to subroutine PRDPM), is accounted for to reduce the effective volume of the domain.

The pressure field resulting from this initialization process is a function of, among other things, the orientation of the gravitational field vector,

$\vec{g}$, relative to the computational domain's coordinate system. The direction cosines defining the orientation of the gravitational field vector are GX, GY, and GZ. These direction cosines are provided by the user as input to subroutine HYDRO. Vector $\vec{g}$ is then defined as

$$\vec{g} = (GX\ \hat{i} + GY\ \hat{j} + GZ\ \hat{k})\ |\vec{g}| \qquad (17.2)$$

where $\hat{i}$, $\hat{j}$, and $\hat{k}$ are the unit vectors in the x-, y-, and z-directions of the coordinate system, respectively, and $|\vec{g}|$ is the magnitude of the acceleration due to gravity (= 980.665 cm/sec^2 in HYDRA-II).

Subroutine PINIT is not accessed in the event of:

1. a restart run (NREAD = 1 as input to MAIN)
2. no momentum-equation solution desired (NOVEL = 1 as input to MAIN).

In the first event, the pressure field is obtained from restart data. The pressure field is irrelevant for the second event.

17.1 PARAMETER STATEMENT INFORMATION

Subroutine PINIT requires the specification of parameters IP, JP, KP, KBP, and KTP. These data define the overall computational mesh and are described in Chapter 4.0.

17.2 INPUT FORMAT

Subroutine PINIT does not require input data.

18.0 SUBROUTINE PROPM

The grid information has been provided in subroutine GRID, and much of the thermo-fluid property information obtained through input to subroutine HYDRO. Therefore, solution of the momentum equations in HYDRA-II requires only some additional input regarding embedded flow obstructions. This information pertains to area blockages, cell porosities, and cell permeabilities. Two models are available to the user for representing subgrid scale flow obstructions. Flow paths in which a permeable substance is present may be modeled using a Darcy-flow relationship. This Darcy-flow model may be used to represent the entire range of permeability, from virtually unobstructed to essentially plugged paths. For those flow paths occupied in part by an impermeable obstruction, HYDRA-II allows the user to reduce the effective flow area to simulate an orifice-induced pressure gradient.

Flow through porous media can be modeled by using any one of the PERMO, PERMX, PERMY, and/or PERMZ input options provided in this routine. The pressure gradient experienced from cell-to-cell as a result of the presence of this porous media is modeled using the Darcy-flow relationship,

$$\nabla p = \frac{-\mu}{\rho * PERMI} \vec{m} \qquad (18.1)$$

where p, μ, and ρ are the pressure, viscosity, and density of the fluid in the cell, respectively, $\vec{m}$ is the mass flux vector, and PERMI is the permeability coefficient (with I = X, Y, or Z representing pressure gradients in the x-, y-, or z-direction, respectively). Orthotropic permeability can be modeled by specifying different values for the PERMX, PERMY, and PERMZ coefficients associated with a given cell. The permeability for each physical cell of the computational mesh is initialized to the input value PERMO. This value applies to PERMX, PERMY, and PERMZ. Therefore, each cell is initially isotropic. The prescribed permeability may then be overwritten with input to PERMX, PERMY, and/or PERMZ as desired, to introduce directional preference in the model. An impermeable cell is represented by a very small permeability coefficient. Conversely, a very porous cell is represented by a large permeability coefficient.

The appropriate value to be assigned to PERMI at input may be estimated from an order-of-magnitude analysis of the affected terms in the momentum equations. For example, an order-of-magnitude study of the ratio of Darcy-flow induced pressure gradient to the viscous shear-stress gradient indicates that these two terms will be of comparable importance if the permeability, PERMI, is on the order of the square of the mesh size. Mathematically stated,

$$\text{PERMI} \sim \delta^2 \tag{18.2}$$

where δ is the characteristic cell size. Therefore, for cases in which Darcy-flow modeling is desired, the permeability coefficient, PERMI, should be set to a value on the order of the square of the local mesh size. To model both virtually-impermeable and very permeable cells with this Darcy-flow model, PERMI should be represented as follows:

- PERMI $<< \delta^2$ (or $<< (\delta|_{min})^2$ in the global case) for virtually impermeable cells.
- PERMI $>> \delta^2$ for permeable cells (or $>> (\delta|_{max})^2$ for globally very permeable cells.

"Plugging" of cells may be instituted either by the above process (i.e., specifying PERMI $<< \delta^2$) or by setting the cell viscosity to a relatively large value. There is a subtle, but important, difference in these two approaches. When using the cell viscosity to "plug" a cell, the blockage is assumed to occur over the entire cell. The no-slip condition will then be effectively applied at the cell faces. On the other hand, using the permeability coefficient to "plug" a cell results in an induced drag that affects the mass flow rates across the cell interfaces. The "no-slip" condition is therefore effectively applied at the location of the mass flow rates, and is centered on the surface of the cell interfaces. This amounts to adding an additional half-a-cell width to the location of the "no-slip" condition. These ideas are illustrated in Figure 18.1. PERMI may be used to "plug" a cell in any or all of the coordinate directions independently. On the other hand, using viscosity to "plug" a cell precludes flow through the cell in any direction.

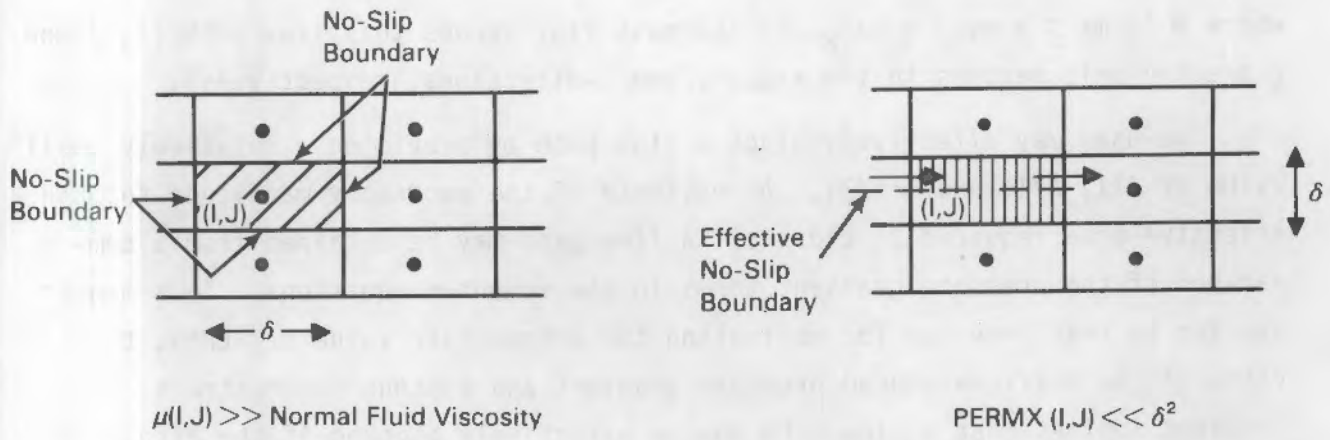


FIGURE 18.1. Cellular Locations for No-Slip Boundary Conditions

Area blockages at the interface between two cells (e.g., orifice plates or sudden expansions and contractions) are modeled with input to arrays AXI, AYI, and/or AZI. The entries to these arrays represent the effective cross-sectional area fraction between communicating cells available for fluid flow. Input variables AXI, AYI, and AZI represent effective fractional flow areas in the x-, y-, and z-directions, respectively. Those elements of the arrays corresponding to faces of the physical cells in the computational mesh are initialized to 1.0, representing no flow obstruction. Therefore, only the interfaces in which an obstruction is present need to be modified via the input to this subroutine. Array element AXI(I,J,K) represents a flow obstruction for the flow path between cells (I,J,K) and (I+1,J,K). Similarly, array element AYI(I,J,K) represents a flow obstruction for the flow path between cells (I,J,K) and (I,J+1,K), as does AZI(I,J,K) for flow between cells (I,J,K) and (I,J,K+1).

The loss coefficient associated with these obstructions is modeled as $(1 - A^2)/A^2$, where A is the effective flow area fraction for this flow path. This produces an additional pressure gradient across the flow path. The pressure gradient is included in the appropriate component of the momentum equation as

$$\nabla P = -\frac{1}{2\rho}\left[\left(\frac{1-AXI^2}{AXI^2}\frac{|mx|mx}{\Delta x}\right)\hat{i} + \left(\frac{1-AYI^2}{AYI^2}\frac{|my|my}{\Delta y}\right)\hat{j} + \left(\frac{1-AZI^2}{AZI^2}\frac{|mz|mz}{\Delta z}\right)\hat{k}\right] \quad (18.3)$$

where $\vec{m}$ (= mx $\hat{i}$ + my $\hat{j}$ + mz $\hat{k}$) is the mass flux across this flow path ($\hat{i}$, $\hat{j}$ and $\hat{k}$ are the unit vectors in the x-, y-, and z-directions, respectively).

The user may effectively block a flow path by providing a relatively small value of AXI, AYI, and/or AZI. An estimate of the necessary magnitude for the effective area required to close off a flow path may be obtained from a comparison of the pressure gradient terms in the momentum equations. In a manner similar to that provided for estimating the appropriate value of PERMI, the ratio of the orifice-induced pressure gradient and viscous shear-stress gradient implies that a flow path may be effectively blocked if the effective flow area (e.g., AXI) satisfies

$$AXI^2 << Re_\delta/(1+Re_\delta) \qquad (18.4)$$

where Re_δ is an estimate of the cell Reynolds number ($Re_\delta = \rho u\delta/\mu$). This ignores the difference in scales associated with the pressure and viscous shear-stress gradients, but does provide a rough estimate.

A typical situation in which non-unity AXI is required to simulate the flow obstruction is depicted in Figure 18.2. Here, obstructions are present between the cells at (I,J) = (2,1) and (3,1), and between (2,2) and (3,2).

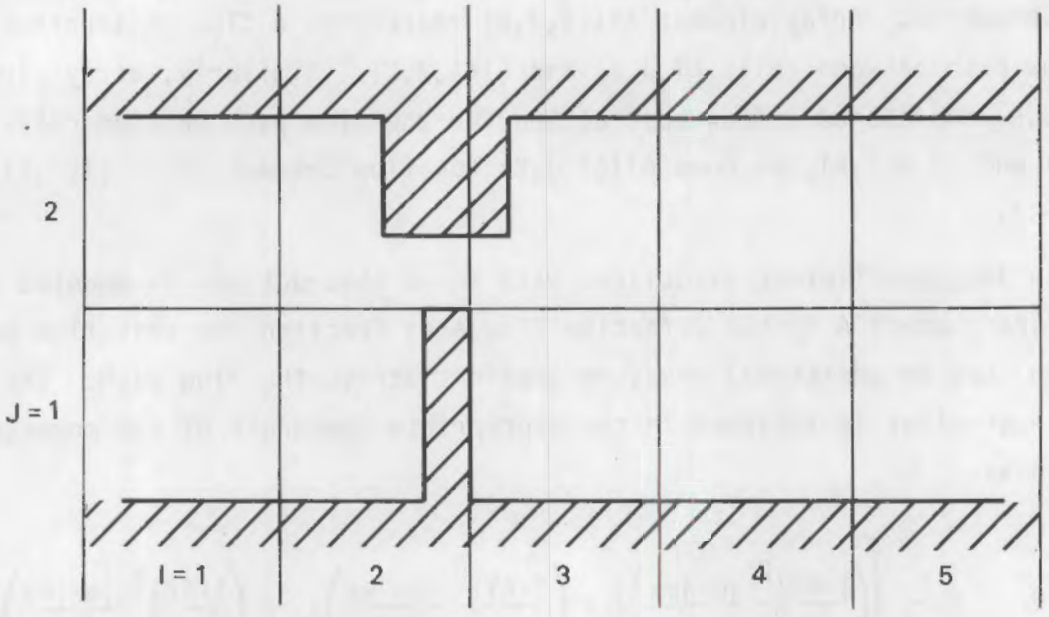


FIGURE 18.2. Obstructed Flow Path

These obstructions reduce the effective flow area by 100% and 60%, respectively. The corresponding input would be 10^{-6} (an entry of 0.0 would produce a division-by-zero error) for the AXI associated with the path (2,1) ↔ (3,1), and 0.4 for the AXI associated with the path (2,2) ↔ (3,2).

With regard to the input variables AXI, AYI, and AZI, the presence of a flow obstruction implies that:

- a restriction to flow exists in one or more of the coordinate directions
- a no-slip condition be imposed for flow in directions parallel to the obstruction surface.

The first item is addressed by specifying values for AXI, AYI, and/or AZI that are in the range 0 < AXI, AYI, AZI < 1. The second item is addressed in the coding of HYDRA-II. The momentum equation viscous-stress terms representing drag to the flow in directions parallel to the obstruction surface are scaled in the code to represent the no-slip condition imposed by the obstruction. For example, when AXI ≠ 1.0, the flow rates in the y- and z-directions will experience an additional drag at the cell interface due to the presence of this obstruction.

The free-volume fraction of a cell can be modified from its default value with the input to array POR. Values of 0.0 ≤ POR(I,J,K) ≤ 1.0 indicate that the effective free volume of the cell associated with index (I,J,K) is

$$VOL(I,J,K) = POR(I,J,K)*DX(I)*DY(J)*DZ(K) \qquad (18.5)$$

where DX, DY, and DZ are the mesh sizes for the cell. For steady-state applications, the volume influences the results for only those cases in which a fixed mass is specified for the computational domain (FIXEDM > 0 as input to subroutine AVG). When the average pressure is specified for the computational domain (FIXEDP > 0 as input to subroutine AVG), POR has no effect on the computation. Array POR is initialized to 0.0 for those cells outside the hydrodynamic portion of the computational domain, to 0.5 for those cells lying on the interface between the cartesian and cylindrical meshes (to simulate the

cells whose volumes are partially occupied by the domain enclosure), and to 1.0 for those cells located entirely within the hydrodynamic portion of the computational domain.

As a final note, the effective loss coefficient for pressure-drop calculations is independent of flow speed (or, equivalently, flow rate) in the porous-media model. On the other hand, the effective loss coefficient in modeling flow obstructions with AXI, for example, is linearly dependent on the flow speed. Therefore, by judiciously combining the two models and their coefficients, the user may simulate a segment of the drag curve for flow around a body (e.g., cylinder or sphere). Attempts can then be made to match the coefficients to produce the experimentally observed drag coefficient variation in the Reynolds number range of interest.

18.1 PARAMETER STATEMENT INFORMATION

Only the overall grid specification information IP, JP, KP, KBP, and KTP (described in Chapter 4.0) is required as PARAMETER information in PROPM.

18.2 INPUT FORMAT

18.2.1 Overview

Generally speaking, the input to subroutine PROPM can be divided into two subsections:

- "global" setting of the PERMX, PERMY, and PERMZ arrays
- loading of arrays AX, AY, AZ, AXI, AYI, AZI, and POR, as well as the resetting of arrays PERMX, PERMY, and PERMZ by mesh blocks.

The input requirements for each of these subsections is provided in Section 18.2.2.

18.2.2 "Global" Setting of PERMX, PERMY, and PERMZ

General Input Format

```
NECHO
PERMO
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.

- PERMO - Value to which the elements of arrays PERMX, PERMY, and PERMZ will be set. A value must be provided for the input.

Input File Example

```
1651 1/propm
1652 10.0
```

Echoed Input File Example

```
1011     propm  perm0=0.100e+02
1012
```

NECHO is set to 1 on input line 1651. The value of PERMO is set to 10.0 on input line 1652. This is reflected in the output as line 1011. As a result, PERMX, PERMY, and PERMZ are set to 10.0 for every element of the arrays associated with a "physical" cell of the computational domain (i.e., those cells of the computational mesh which are neither phantom nor pseudo-cells).

18.2.3 Block Loading Arrays AX, AY, AZ, AXI, AYI, AZI, POR, PERMX, PERMY, and PERMZ

General Input Format

```
NECHO
INFO
VALUE,IBEG,IEND,JBEG,JEND,KBEG,KEND
          .    .    .    .    .
          .    .    .    .    .
          .    .    .    .    .

VALUE,IBEG,IEND,JBEG,JEND,KBEG,KEND
 -1.0, 6*0
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.

- INFO - Switch to print the output file for the entire contents of the array associated with this input section (e.g., AXI or PERMY). Setting INFO = 1 will generate this output listing; INFO = 0 will not.

- *VALUE* - Quantity to be loaded into this block of AX, AY, AZ, AXI, AYI, AZI, POR, PERMX, PERMY, or PERMZ. A block is defined as those cells covered by a sweep through the I, J, and K index ranges. Loading is terminated for a set of blocks with the sequence -1.0, 6*0. Up to 1000 blocks may be loaded in each set. The AX set of blocks is loaded first, followed by the AY, AZ, AXI, AYI, AZI, POR, PERMX, PERMY, and PERMZ sets. Loading in this order is essential. Input to arrays AX, AY, and AZ has no significance to the steady-state solution obtained by HYDRA-II. Therefore, no input is provided to these arrays. As indicated in the sample input presented in this section, only the terminator sequence is provided as input to these arrays. The input variable *"VALUE"* corresponds to a multiplier when loading array POR. The affected elements of array POR are set equal to the product of the input value of POR multiplied by the cell volume

  POR(I,J,K) = *VALUE**DX(I)*DY(J)*DZ(K).

  The volumes of those hydrodynamic cells lying on the interface between cartesian and cylindrical meshes are halved to account for the cell bisection produced by this interface.

- IBEG - Beginning I index of the block.
- IEND - Ending I index of the block.
- JBEG - Beginning J index of the block.
- JEND - Ending J index of the block.
- KBEG - Beginning K index of the block. The values specified for these K indices refer to the momentum equation grid. This distinction was discussed in Section 4.1.
- KEND - Ending K index of the block. The values specified for these K indices refer to the momentum equation grid. This distinction was discussed in Section 4.1.

Input File Example

```
1653 1/propm/ax
1654 0
1655 -1.0,6*0
1656 1/propm/ay
1657 0
1658 -1.0,6*0
1659 1/propm/az
1660 0
1661 -1.0,6*0
1662 1/propm/axi
1663 0
1664 0.67,1,23,2,47,2,2
1665 0.62,1,23,2,47,25,25
1666 0.65,2,3,11,11,3,24
1667 0.65,2,3,18,20,3,24
1668 0.65,2,3,29,31,3,24
1669 0.65,2,3,38,38,3,24
1670 0.65,8,9,20,20,3,24
1671 0.65,8,9,29,29,3,24
1672 0.65,21,22,20,20,3,24
1673 0.65,21,22,29,29,3,24
1674 -1.0,6*0
1675 1/propm/ayi
1676 0
1677 0.67,2,23,2,46,2,2
1678 0.62,2,23,2,46,25,25
1679 0.65,6,6,3,4,3,24
1680 0.65,6,6,16,17,3,24
1681 0.65,6,6,31,32,3,24
1682 0.65,6,6,44,45,3,24
1683 0.65,6,8,22,23,3,24
```

```
1684 0.65,6,8,25,26,3,24
1685 0.65,15,15,22,23,3,24
1686 0.65,15,15,25,26,3,24
1687 -1.0,6*0
1688 1/propm/azi
1689 0
1690 0.1e-6,2,4,9,13,2,2
1691 0.1e-6,2,4,36,40,2,2
1692 0.1e-6,13,17,22,27,2,2
1693 0.1e-6,2,4,2,2,2,2,
1694 0.1e-6,2,4,47,47,2,2
1695 0.1e-6,24,24,22,27,2,2
1696 0.1e-6,2,4,16,16,2,2
1697 0.1e-6,2,4,33,33,2,2
1698 0.1e-6,10,10,22,27,2,2
1699 0.1e-4,2,4,22,22,2,2
1700 0.1e-4,2,4,27,27,2,2

    .   .   .
    .   .   .
    .   .   .

1755 0.45,8,10,20,20,3,24
1756 0.45,8,10,29,29,3,24
1757 0.4,6,6,3,7,3,24
1758 0.4,6,6,42,46,3,24
1759 0.4,19,23,20,20,3,24
1760 0.4,19,23,29,29,3,24
1761 -1.0,6*0
1762 1/propm/por
1763 0
1764 -1.0,6*0
1765 1/propm/permx
1766 0
1767 0.5e-2,2,4,2,9,4,23
1768 0.5e-2,2,4,13,16,4,23
1769 0.5e-2,2,4,22,27,4,23
1770 0.5e-2,2,4,33,36,4,23
1771 0.5e-2,2,4,40,47,4,23
1772 0.5e-2,8,11,5,13,4,23
1773 0.5e-2,8,11,15,18,4,23
1774 0.5e-2,8,11,31,34,4,23
1775 0.5e-2,8,11,36,44,4,23
1776 0.5e-2,13,21,15,18,4,23
1777 0.5e-2,13,21,31,34,4,23
1778 0.5e-2,10,13,22,27,4,23
1779 0.5e-2,17,24,22,27,4,23
1780 -1.0,6*0
1781 1/propm/permy
1782 0
1783 0.5e-2,2,4,2,9,4,23
```

```
1784 0.5e-2,2,4,13,16,4,23
1785 0.5e-2,2,4,22,27,4,23
1786 0.5e-2,2,4,33,36,4,23
1787 0.5e-2,2,4,40,47,4,23
1788 0.5e-2,8,11,5,13,4,23
1789 0.5e-2,8,11,15,18,4,23
1790 0.5e-2,8,11,31,34,4,23
1791 0.5e-2,8,11,36,44,4,23
1792 0.5e-2,13,21,15,18,4,23
1793 0.5e-2,13,21,31,34,4,23
1794 0.5e-2,10,13,22,27,4,23
1795 0.5e-2,17,24,22,27,4,23
1796 -1.0,6*0
1797 1/propm/permz
1798 0
1799 0.1e-1,2,4,2,9,4,23
1800 0.1e-1,2,4,13,16,4,23
1801 0.1e-1,2,4,22,27,4,23
1802 0.1e-1,2,4,33,36,4,23
1803 0.1e-1,2,4,40,47,4,23
1804 0.1e-1,8,11,5,13,4,23

      .    .    .
      .    .    .
      .    .    .

1825 0.1e-4,22,22,29,29,3,24
1826 0.1e-4,15,15,23,23,3,24
1827 0.1e-4,15,15,26,26,3,24
1828 -1.0,6*0
```

Echoed Input File Example

```
1013     propm   info=0   region      ax                cell location
1014                                                ibeg iend  jbeg jend  kbegkend
1015
1016     propm   info=0   region      ay                cell location
1017                                                ibeg iend  jbeg jend  kbegkend
1018
1019     propm   info=0   region      az                cell location
1020                                                ibeg iend  jbeg jend  kbegkend
1021
1022     propm   info=0   region      axl               cell location
1023                                                ibeg iend  jbeg jend  kbegkend
1024                        1   0.670000e+00          1   23     2   47     2   2
1025                        2   0.620000e+00          1   23     2   47    25  25
1026                        3   0.650000e+00          2    3    11   11     3  24
1027                        4   0.650000e+00          2    3    18   20     3  24
1028                        5   0.650000e+00          2    3    29   31     3  24
1029                        6   0.650000e+00          2    3    38   38     3  24
1030                        7   0.650000e+00          8    9    20   20     3  24
1031                        8   0.650000e+00          8    9    29   29     3  24
1032                        9   0.650000e+00         21   22    20   20     3  24
1033                       10   0.650000e+00         21   22    29   29     3  24
1034
```

```
1035    propm   info=0  region      ayi                cell location
1036                                              ibeg iend  jbeg jend  kbegkend
1037                      1    0.670000e+00         2   23     2   46    2   2
1038                      2    0.620000e+00         2   23     2   46   25  25
1039                      3    0.650000e+00         6    6     3    4    3  24
1040                      4    0.650000e+00         6    6    16   17    3  24
1041                      5    0.650000e+00         6    6    31   32    3  24
1042                      6    0.650000e+00         6    6    44   45    3  24
1043                      7    0.650000e+00         6    8    22   23    3  24
1044                      8    0.650000e+00         6    8    25   26    3  24
1045                      9    0.650000e+00        15   15    22   23    3  24
1046                     10    0.650000e+00        15   15    25   26    3  24
1047
1048    propm   info=0  region      azl                cell location
1049                                              ibeg iend  jbeg jend  kbegkend
1050                      1    0.100000e-06         2    4    9   13    2   2
1051                      2    0.100000e-06         2    4   36   40    2   2
1052                      3    0.100000e-06        13   17   22   27    2   2
1053                      4    0.100000e-06         2    4    2    2    2   2
1054                      5    0.100000e-06         2    4   47   47    2   2
1055                      6    0.100000e-06        24   24   22   27    2   2
1056                      7    0.100000e-06         2    4   16   16    2   2
1057                      8    0.100000e-06         2    4   33   33    2   2
1058                      9    0.100000e-06        10   10   22   27    2   2
1059                     10    0.100000e-04         2    4   22   22    2   2
1060                     11    0.100000e-04         2    4   27   27    2   2
          .                        .                                      .
          .                        .                                      .
          .                        .                                      .

1115                     66    0.450000e+00         8   10   20   20    3  24
1116                     67    0.450000e+00         8   10   29   29    3  24
1117                     68    0.400000e+00         6    6    3    7    3  24
1118                     69    0.400000e+00         6    6   42   46    3  24
1119                     70    0.400000e+00        19   23   20   20    3  24
1120                     71    0.400000e+00        19   23   29   29    3  24
1121
1122    propm   info=0  region      por                cell location
1123                                              ibeg iend  jbeg jend  kbegkend
1124
1125    propm   info=0  region      permx              cell location
1126                                              ibeg iend  jbeg jend  kbegkend
1127                      1    0.500000e-02         2    4    2    9    4  23
1128                      2    0.500000e-02         2    4   13   16    4  23
1129                      3    0.500000e-02         2    4   22   27    4  23
1130                      4    0.500000e-02         2    4   33   36    4  23
1131                      5    0.500000e-02         2    4   40   47    4  23
1132                      6    0.500000e-02         8   11    5   13    4  23
1133                      7    0.500000e-02         8   11   15   18    4  23
1134                      8    0.500000e-02         8   11   31   34    4  23
1135                      9    0.500000e-02         8   11   36   44    4  23
1136                     10    0.500000e-02        13   21   15   18    4  23
1137                     11    0.500000e-02        13   21   31   34    4  23
1138                     12    0.500000e-02        10   13   22   27    4  23
1139                     13    0.500000e-02        17   24   22   27    4  23
1140
```

```
1141    propm   info=0   region     permy                cell location
1142                                                ibeg iend  jbeg jend  kbegkend
1143                        1    0.500000e-02        2    4     2    9     4   23
1144                        2    0.500000e-02        2    4    13   16     4   23
1145                        3    0.500000e-02        2    4    22   27     4   23
1146                        4    0.500000e-02        2    4    33   36     4   23
1147                        5    0.500000e-02        2    4    40   47     4   23
1148                        6    0.500000e-02        8   11     5   13     4   23
1149                        7    0.500000e-02        8   11    15   18     4   23
1150                        8    0.500000e-02        8   11    31   34     4   23
1151                        9    0.500000e-02        8   11    36   44     4   23
1152                       10    0.500000e-02       13   21    15   18     4   23
1153                       11    0.500000e-02       13   21    31   34     4   23
1154                       12    0.500000e-02       10   13    22   27     4   23
1155                       13    0.500000e-02       17   24    22   27     4   23
1156
1157    propm   info=0   region     permz                cell location
1158                                                ibeg iend  jbeg jend  kbegkend
1159                        1    0.100000e-01        2    4     2    9     4   23
1160                        2    0.100000e-01        2    4    13   16     4   23
1161                        3    0.100000e-01        2    4    22   27     4   23
1162                        4    0.100000e-01        2    4    33   36     4   23
1163                        5    0.100000e-01        2    4    40   47     4   23
1164                        6    0.100000e-01        8   11     5   13     4   23

          .                          .                                      .
          .                          .                                      .
          .                          .                                      .

1185                       27    0.100000e-04       22   22    29   29     3   24
1186                       28    0.100000e-04       15   15    23   23     3   24
1187                       29    0.100000e-04       15   15    26   26     3   24
```

NECHO is set to 1 on input line 1653; INFO is set to 0 on line 1654. Arrays AX, AY, and AZ have no significance to the steady-state solution produced by HYDRA-II. Therefore, their input sections are effectively bypassed by providing only the terminator line of input. Consequently, the array elements are loaded with the default value 1.0.

Ten blocks of array AXI are loaded with the input from lines 1664 through 1673. The input follows the standard format. For example, input line 1668 results in the array elements of AXI(I,J,K) for $2 \leq I \leq 3$, $29 \leq J \leq 31$, and $3 \leq K \leq 24$ being loaded with the value 0.65. This particular input is echoed in line 1028 of the output. Input to array AXI is terminated by the input on line 1674. The echoed input for the complete section is provided in output lines 1022 through 1033. Those "physical" cells not explicitly loaded will contain the default value 1.0. The elements of AXI associated with the remaining cells outside of the hydrodynamic region will contain the default value

0.0. Ten blocks of array AYI are loaded with the input from lines 1677 through 1686. Input to this array is terminated with the information provided on line 1687. The echoed input for this section is provided in lines 1035 through 1046. The same defaults apply here as for array AXI.

Seventy-one blocks of array AZI are loaded with the input from lines 1690 through 1761. The corresponding echoed-input is provided in lines 1048 through 1120. Again, the same default values apply here as for array AXI. The POR array multiplier is loaded next in the sequence. However, in this example the default values are sufficient (defaults to 1.0). Therefore, only the section terminator line is provided, input line 1764.

PERMX, PERMY, and PERMZ are loaded next. Input lines 1765 through 1828 reflect the values specified for each block. For example, the array elements PERMX(I,J,K) for $10 \leq I \leq 13$, $22 \leq J \leq 27$, and $4 \leq K \leq 23$ are loaded with the value 0.005 on line 1778 of the input. Those "physical" cells not covered in the input to these sections are defaulted to PERMO.

19.0 SUBROUTINES MOMX, MOMY, AND MOMZ

The terms of the momentum equations are evaluated in subroutines MOMX, MOMY, and MOMZ using the methods discussed in Volume I - Equations and Numerics (McCann 1987). Subroutine MOMX evaluates the terms of the x-component momentum equation; MOMY, the y-component; and MOMZ the z-component. The x-, y-, and z-momentum equation terms are evaluated using pressures obtained from the previous time-step. Consequently, the momentum subroutines produce a mass-flux field that will not, in general, satisfy continuity. For this reason, these mass fluxes are tentative and are denoted by a tilde, $\tilde{m}$. This part of the calculation is thus termed the "tilde phase." Mass conservation is enforced by subsequently modifying the pressure field using the tilde-phase mass-flux field. The final mass fluxes for this time-step are then computed using the tilde-phase mass fluxes and the modified pressure field.

19.1 PARAMETER STATEMENT INFORMATION

Subroutines MOMX, MOMY, and MOMZ require the specification of parameters IP, JP, KP, KBP, KTP, and NEFAP. These data define the overall computational mesh and are described in the discussion of subroutine GRID in Chapter 4.0. No additional parameters are needed for these three subroutines.

19.2 INPUT FORMAT

Subroutines MOMX, MOMY, and MOMZ do not require input data.

20.0 SUBROUTINE PDG

Subroutine PDG performs two functions. First, PDG sets up the coefficient matrix required to obtain a solution for the pressure-correction field. The elements comprising this coefficient matrix are identified in Chapter 9.0 of Volume I - Equations and Numerics (McCann 1987). This matrix is used in obtaining a first-pass solution in PDG. It is also employed in subroutines PILES, REBS, REBQ, and AF to obtain a solution to the pressure-correction field. The first-pass solution is generated in PDG using a variant of the Douglas and Gunn algorithm (1964). The modification to this algorithm employs a user-supplied weighting parameter, WP. This parameter is used to artificially weight the diagonal elements of the coefficient matrix. The effect of this weighting is to enhance the convergence properties of the algorithm.

Subroutine PDG also allows the user to monitor the cell mass imbalance during the solution process. Monitoring is controlled by switch NSINFO (set in MAIN). This constant controls the printing frequency of diagnostic information and monitored variables. For example, if NSINFO = 20, then information will be printed for time-steps 1, 21, 41, etc. Information is always printed for the first and last time-steps of a run. The output provided in this process is:

- the time-step number
- the momentum time-step
- the I, J, and K indices of the cell experiencing the largest tilde-phase mass imbalance
- the tilde-phase mass imbalance for this cell.

In addition, the largest component mass-flux corrections and their corresponding computational-mesh indices are provided in the output.

The magnitude of the largest continuity error is used to suggest a momentum time-step adjustment to subroutine HYDRO. This is done in an effort to maintain the optimum tilde-phase continuity error for the next time-step.

20.1 PARAMETER STATEMENT INFORMATION

Subroutine PDG requires the specification of parameters, IP, JP, KP, KBP, KTP, and NEFAP. These data define the overall computational mesh and are described in the discussion of subroutine GRID in Chapter 4.0.

20.2 INPUT FORMAT

20.2.1 Overview

Very little input is required by subroutine PDG. Only three variables are read: NECHO, WP, and OPTCON. The input sequence and definition are provided below.

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.
- WP - A weight parameter used to weight the diagonal elements of the coefficient matrix. The appropriate value depends on the nature of the desired solution, i.e., time-dependent or steady state. For steady-state solutions, set WP = 0.8.
- OPTCON - A weight factor allowing the user a measure of control in achieving the "optimum continuity" error. Subroutine PDG will suggest scaling the new momentum time-step using

$$\Delta t_m = (1.5 - 0.5*|ERRCON|/OPTCON)*\Delta t$$

where the subscript m refers to the suggested momentum time-step and ERRCON is the largest cell mass imbalance.

General Input Format

```
NECHO
WP,OPTCON
```

Input File Example

```
1829 1/pdg
1830 0.8,0.5e-5
```

Echoed-Input File Example

```
1189    pdg    wp=0.80    optcon=0.500e-05
1190
```

NECHO has been set to 1 on input line 1829. Input line 1830 indicates that WP has been set to a value of 0.8 and OPTCON to a value of 0.5e-5.

21.0 SUBROUTINE PITER

Subroutine PITER serves as a traffic control routine directing program flow to the various methods available for solving the Poisson equation for the pressure-correction field. HYDRA-II provides the user with a number of approaches to generate the solution to the Poisson equation:

- Coarse-mesh subroutines REBS and REBQ adjust the interim pressure-correction field solution to reduce long-wavelength errors. These routines are discussed in Chapters 23.0 and 24.0.
- Subroutine AF uses an approximate-factorization technique. AF is discussed in Chapter 26.0.
- Subroutine PILES performs line successive relaxation iterations. PILES is discussed in Chapter 22.0.

Subroutine PITER allows the user to tailor the solution scheme to suit the requirements of the specific problem at hand. PITER starts with the pressure-correction field estimate obtained in subroutine PDG. An optimum sequence for solving the pressure equation cannot be prescribed a priori for a particular simulation. The user can cautiously try using REBQ along with PILES, and possibly AF or REBS in a sequence found workable for similar problems. The use of REBQ, REBS, or AF should be interspersed with the use of PILES with, at least initially, setting the printout option INFO = 1 in PILES. The divergence error, DMAX, for each direction of line-successive-relaxation sweeps in PILES should be examined, and the maximum number of three-direction line-successive-relaxation sweeps (NMAX) in PILES should be set to ensure that:

1. the short wavelength error is being reduced sufficiently in PILES so that the divergence error is smaller than it was before the call to REBQ or to a combination of REBQ, AF, and REBS
2. the iterations within PILES are not continuing past a point of diminishing returns (i.e., the divergence error is no longer being removed effectively).

In some cases it may be desirable to systematically explore the efficacy of REBS, REBQ, and AF patterns, with PILES in the pressure correction solution. This can be done with a sequence as follows:

1. Run HYDRA-II through some number of time-steps, possibly using only PILES or some previously successful combination of PILES, REBS, REBQ, and AF, but terminating with PILES. Create a restart file.

2. Run a succession of restart cases from this restart file in which one of the routines REBS, REBQ, or AF is called, followed by a call to PILES with a fairly high number of inner iterations (NMAX) and with INFO = 1 to get divergence error printouts. Consider the pattern of divergence errors (printed in PILES), noting which of the routines preceding the call to PILES are effective in reducing the divergence error. Note that some routines (particularly REBS and REBQ) may initially increase the divergence error by increasing short wavelength error while reducing long wavelength error. PILES is effective for reducing short wavelength error.

3. Select some of the more promising routines from among REBS, REBQ, and AF, based on the tests in Step 2. Use them in combinations, with or without calls to PILES between them, and do further comparisons of divergence error patterns. PILES should be called in the sequence, of course, since only it, and possibly AF, can produce converged solutions on the fine mesh. Always note the number of iterations in PILES needed to show a net improvement in the divergence error, paying particular attention to the diminishing returns phenomenon. Select a pattern of calls to PILES, REBS, REBQ, and AF for further use in seeking convergence, along with a number of iterations in PILES (NMAX).

4. With the sequence (specified in NORDER in the input to PITER) chosen by this procedure, and with the selected number of inner iterations in PILES (NMAX), advance the simulation through additional time-steps, stopping and restarting as appropriate. Reduce the level of printout when confidence is gained that the sequence of procedures is effective.

The number of techniques employed to obtain the interim solutions are completely specified by the user with input variable NORDA. The sequence in which each technique is employed in the process is specified by the user with input to array NORDER(I) for I = 1,2, ... ,NORDA. The following is a list of allowable NORDER settings and the corresponding routines invoked:

NORDER(I)	Routine Invoked
1	line successive relaxation - PILES
2	coarse-mesh solver - REBS
3	coarse-mesh solver - REBQ
4	approximate factorization - AF

Subroutine PITER sweeps through the first NORDA elements of array NORDER; therefore, the solution technique associated with the value of NORDER(1) will be employed first. This is followed by invocation of the scheme associated with NORDER(2), and so on up to NORDER(NORDA).

Convergence is not necessarily assured with one passage through the set of schemes invoked by NORDER. Therefore, PITER allows the user to specify, via the input variable NMAX, the number of times this set of schemes will be called by subroutine PITER during each pass through PITER.

21.1 PARAMETER STATEMENT INFORMATION

Subroutine PITER requires the specification of one parameter, NORDAP. This parameter sets the maximum number of elements which can be contained in array NORDER. The elements of NORDER specify which methods are employed in the calling sequence of subroutine PITER.

21.2 INPUT FORMAT

21.2.1 Overview

The input to subroutine PITER serves primarily to direct the calling sequence to the various solution algorithms available.

General Input Format

```
NECHO
NOPT,NMAX
REBSON,REBQON,AFON
NECHO
NORDA
NORDER(1),NORDER(2), ... , NOROER(NORDA)
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.

- NOPT - The desired optimum number of passes through subroutine PITER. Subroutine PITER will suggest appropriate scaling of the momentum time-step to the calling routine, HYDRO, based on the convergence history of the pressure solution. The scaling is based on the number of PITER passes required for convergence, ITER. ITER is set to the value NMAX if no convergence is obtained in this pass through subroutine PITER. The suggested time-step is computed as

  Δt_p = MAX(1.5 - 0.5*REAL(ITER)/REAL(NOPT),0.1)*Δt

  NOPT should be set to a value less than or equal to NMAX. Therefore, the suggested time-step scaling can range from 0.1 for difficult convergence situations to an asymptote of 1.5.

- NMAX - Maximum iterations allowed in each pass through PITER.

- REBSON, REBQON AFON - Initialization switches for subroutines REBS, REBQ, and AF, respectively. If any of these routines are to be employed in the set of iteration schemes, the

corresponding switch for that routine should be set to 1.0. Otherwise, set the switch to 0.0.

- NORDA - Total number of routines employed in each pass through PITER. If one routine is used more than once in the set, it should be counted as many times as it is invoked.

- NORDER - Array containing the identification numbers for the solution schemes. Their storage order corresponds to the sequence in which the routines will be invoked in the iteration. The identification number for the various routines is provided in the above text. There must be NORDAP entries provided in the input - even if NORDA < NORDAP. NORDER(I) for I = NORDA+1, NORDA+2, ..., NORDAP may be set to any value.

Input File Example

```
1831 1/piter
1832 4,20
1833 0.0,1.0,1.0
1834 1/piter/norder
1835 3
1836 3,4,1,0
```

Echoed-Input File Example

```
1191    piter    nopt=4    nmax=20
1192    piter    rebson=0.0   rebqon=1.0    afon=1.0
1193
1194    piter    norda= 3   maximum current dimension for norda is 4
1195    piter    norder     3  4  1  0
```

NECHO has been set to 1 on input line 1831. On input line 1832, NOPT is set to 4 and NMAX is set to 20. Therefore, there will be a maximum of 20 iterations allowed in each pass through PITER.

Input line 1833 indicates that, of the three switchable schemes, only REBQ and AF will be employed in this set. Subroutine PILES will be the last subroutine invoked in this set of schemes. NECHO has been set to 1 on input line 1834. Input line 1835 indicates that there will be three schemes employed in the set; therefore, each scheme (viz., REBQ, AF, and PILES) will be invoked

only once per iteration. The sequence in which these schemes are employed is provided on input line 1836. This line indicates that REBQ will be invoked first, followed by AF and PILES. Note that four entries are provided for array NORDER, even though only three are non-zero. With NORDAP = 4 and NORDA = 3, four entries are required for input, but only the first three are used. The remaining one is ignored.

This input sequence has been echoed in output lines 1191 through 1195.

22.0 SUBROUTINE PILES

Subroutine PILES solves the Poisson equation for the pressure correction field using a line-successive-relaxation iteration scheme. This Poisson equation is obtained by seeking the pressure-field correction that will produce a mass balance for each cell of the computational mesh.

The line-successive-relaxation iteration is performed in three passes--one corresponding to each of the three coordinate directions. If the user-specified value for INFO is > 1, the routine searches for the largest solution residual (in magnitude) and its (I,J,K) index location at the beginning of the first two of the three passes. PILES always searches for these values at the beginning of the third step, regardless of the value of INFO. If INFO is set to a value greater than 0, PILES will print the iteration count, together with the largest residual and its (I,J,K) index location at the first and second passes in the iteration. The time-step number (NS, updated in MAIN) and switch NSINFO (also set in MAIN) control whether or not this printout is produced at the end of the third pass. For example, if NSINFO = 20, then information will be printed at time-steps 1, 21, 41, etc. Information is always printed for the first and last time-steps of a run, NS = 1 and NSTEP, respectively.

Convergence is tested at the conclusion of the third pass in each iteration. When the largest residual (in magnitude) is less than the user-specified convergence criterion, EPSD, the algorithm has converged. PILES will then return to subroutine PITER. If no convergence is obtained after NMAX iterations have been performed, PILES will set a flag before returning to PITER. This flag indicates to subroutine PITER, the lack of convergence in PILES. HYDRA-II uses this information to determine whether momentum time-step adjustment is required.

The iteration scheme requires the user to specify a relaxation parameter, OMEGA. This relaxation parameter may assume a value in the range

$$0 < \text{OMEGA} < 2$$

OMEGA < 1 corresponds to underrelaxation; OMEGA > 1 corresponds to overrelaxation. As with the familiar successive overrelaxation (SOR) methods, there exists a value for OMEGA which will produce the largest asymptotic reduction in error. Unfortunately, the exact value for this optimal OMEGA is very problem-specific and is usually determined by numerical experiment in most simulations.

22.1 PARAMETER STATEMENT INFORMATION

Subroutine PILES requires the specification of parameters IP, JP, KP, KBP, KTP, and NEFAP. These data define the overall computational mesh and are described in the discussion of subroutine GRID in Chapter 4.0.

22.2 INPUT FORMAT

22.2.1 Overview

The input to subroutine PILES sets the parameters of the line successive-relaxation scheme. Specifically, the convergence criterion (EPSD), relaxation factor (OMEGA), and number of iterations per pass through PILES (NMAX), are defined by the user through the input to this routine.

General Input Format

```
NECHO
EPSD,OMEGA,NMAX,INFO
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in output; if NECHO = 0, this echoing will not be provided.
- EPSD - Convergence criterion. The appropriate value to use is problem-dependent. A "loose" convergence criterion effectively produces sources and sinks of mass in the problem. These mass sources and sinks are amplified

by the enthalpy terms in the energy equation and are, therefore, commonly manifested as spurious trends in the temperature field.

- OMEGA - Relaxation parameter. OMEGA is constrained to a value in the range 0 < OMEGA < 2. Values of OMEGA < 1 correspond to underrelaxation; OMEGA > 1 corresponds to overrelaxation. The optimal value for OMEGA is problem-dependent. This value must be determined from numerical test cases. Problems that are "stiff" in the numerical sense (e.g., problems in which the gas region is represented by a disparate range of mesh sizes) typically require a relaxation parameter close to 1 (e.g., OMEGA = 1.1). Conversely, those problems that are not "stiff" will allow greater over-relaxation (e.g., OMEGA = 1.8).

- NMAX - The maximum number of line-successive-relaxation iterations to be performed in each pass through subroutine PILES.

- INFO - Residual-monitor and print flag.

Input File Example

```
1837 1/piles
1838 0.2e-8,1.1,4,0
```

Echoed-Input File Example

```
1197    piles    epsd=0.200e-08    omega=1.10    nmax= 4    info=0
1198
```

NECHO has been set to 1 on input line 1837. Convergence will be achieved if the absolute value of the largest residual is less than the specified value of EPSD, 0.2E-8. The second entry on input line 1838 indicates that an over-relaxation factor of 1.1 will be used in this simulation for each of the maximum of four iterations per pass through PILES. The last entry on input line 1838 specifies INFO = 0.

23.0 SUBROUTINE REBS

Subroutine REBS is one member of the set of subroutines (PILES, REBS, REBQ, and AF) that can be called upon by subroutine PITER to solve a Poisson equation for the pressure correction field.

23.1 REBS FUNCTIONS

If requested for use, REBS solves the Poisson equation three times on slab representations of the rectangular grid, for slabs lying in planes of constant I, J, and K in turn. The $\delta P(I)$ calculated for the I-slab case is applied to computational cells in that I-plane, and similarly for the J-plane and K-plane solutions.

REBS does not read input, and it executes rapidly. It is used without user control in setting up the static pressure field when initiating a simulation. REBS is effective for numerically-easy problems. Its effectiveness in the pressure-correction equation solution sequence can be monitored by noting the divergence error for the pressure equation as printed by PILES before and after REBS application. REBS will generally introduce some short-wavelength error (which PILES is effective in removing) while reducing long-wavelength error. Allow enough line-successive-relaxation sweeps in PILES between REBS calls to ensure that the short-wavelength error is reduced and net progress toward a solution is made.

23.2 PARAMETER STATEMENT INFORMATION

Dimensioning parameters set in REBS include IP,JP,KP. These were defined in Chapter 4.0, subroutine GRID, and have the same meanings and should have the same values here. Also set are KBP,KTP which were discussed in Chapter 4.0 and defined in Chapter 6.0, subroutine THERM.

23.3 INPUT FORMAT

Subroutine REBS does not read input.

24.0 SUBROUTINE REBQ

Subroutine REBQ is another member of the set of subroutines (PILES, REBS, REBQ, and AF) that can be called by subroutine PITER to aid in solving a Poisson equation for the pressure correction field.

24.1 REBQ FUNCTIONS

REBQ solves the pressure correction equation on three different user-defined coarse partitions of the rectangular grid. These coarse mesh solutions are used to improve the estimate of the pressure correction field on the fine mesh. REBQ has proved an effective tool for expediting convergence in the pressure correction field, even for difficult simulations with intricate flow patterns. It is effective in removing long-wavelength error, and it should be interspersed with techniques like those of subroutine PILES or AF that are effective against short-wavelength error.

REBQ is noteworthy for the flexibility and ease with which the coarse mesh can be defined. For the first of the three coarse meshes (the KREG mesh), the X-Y boundaries are defined identically for each K-plane. The coarse mesh can be a fairly arbitrary set of rectangles bounded by X- and Y-grid lines. Such a set is shown in Figure 24.1. The user must define the X-Y bounds of the cells. The flow computational region with phantom planes extends from K = 1 to K = KP-KBP-KTP.

The second of the three coarse meshes (the JREG mesh) is defined identically for each J-plane. The coarse cells within a J-plane are a fairly arbitrary set of rectangles bounded by X- and Z-grid lines, with the user defining the bounds and interfaces. An example of a partition of a J-plane is shown in Figure 24.2. Similarly, for the third or IREG simulation, each coarse cell defined within a single I-plane is bounded by Y- and Z-grid lines.

The specification of any of these three coarse meshes requires identifying:

1. the bounds of the coarse cells within a single plane
2. the other coarse cells with which each one has an interface

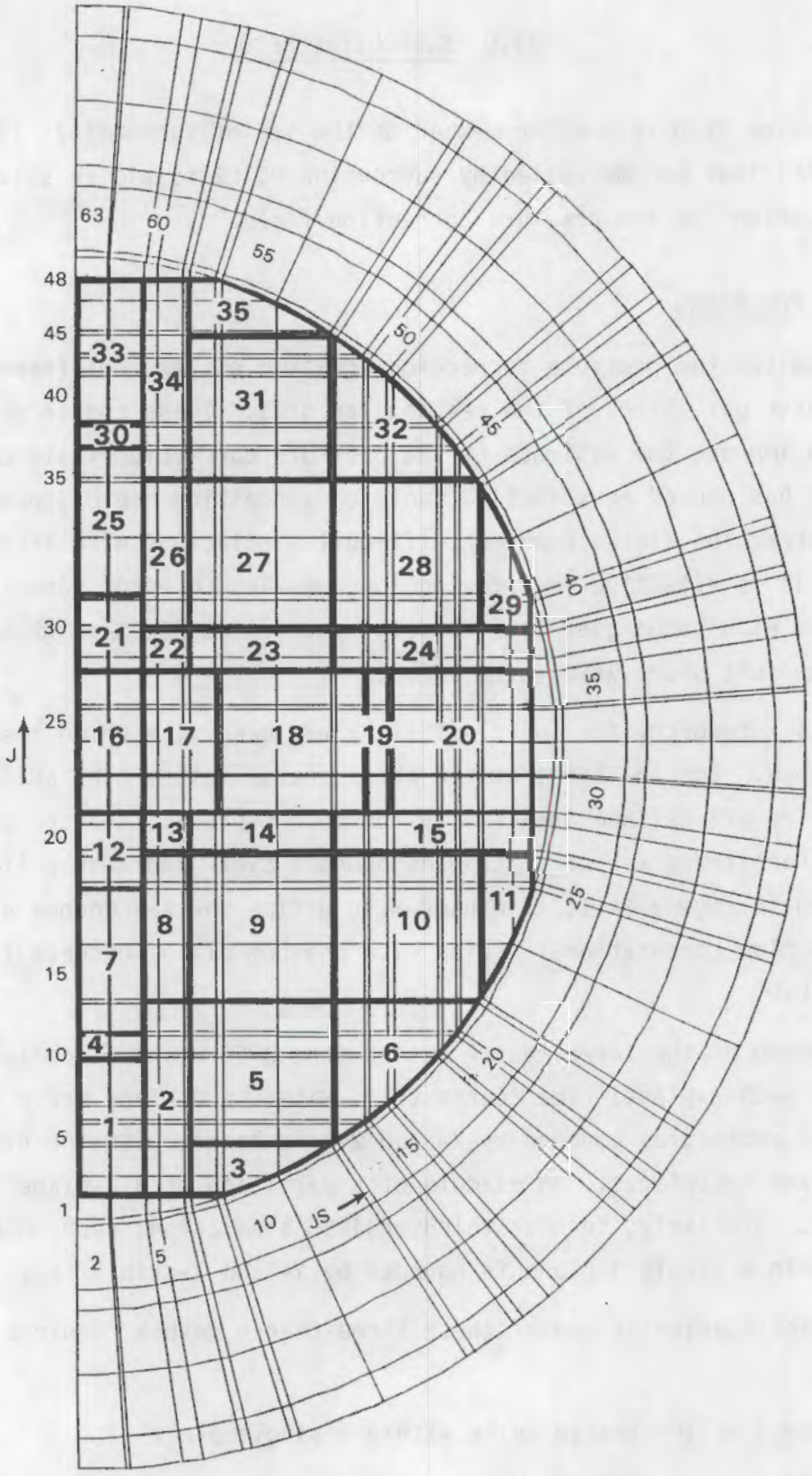


FIGURE 24.1. Coarse Mesh for a K-Plane

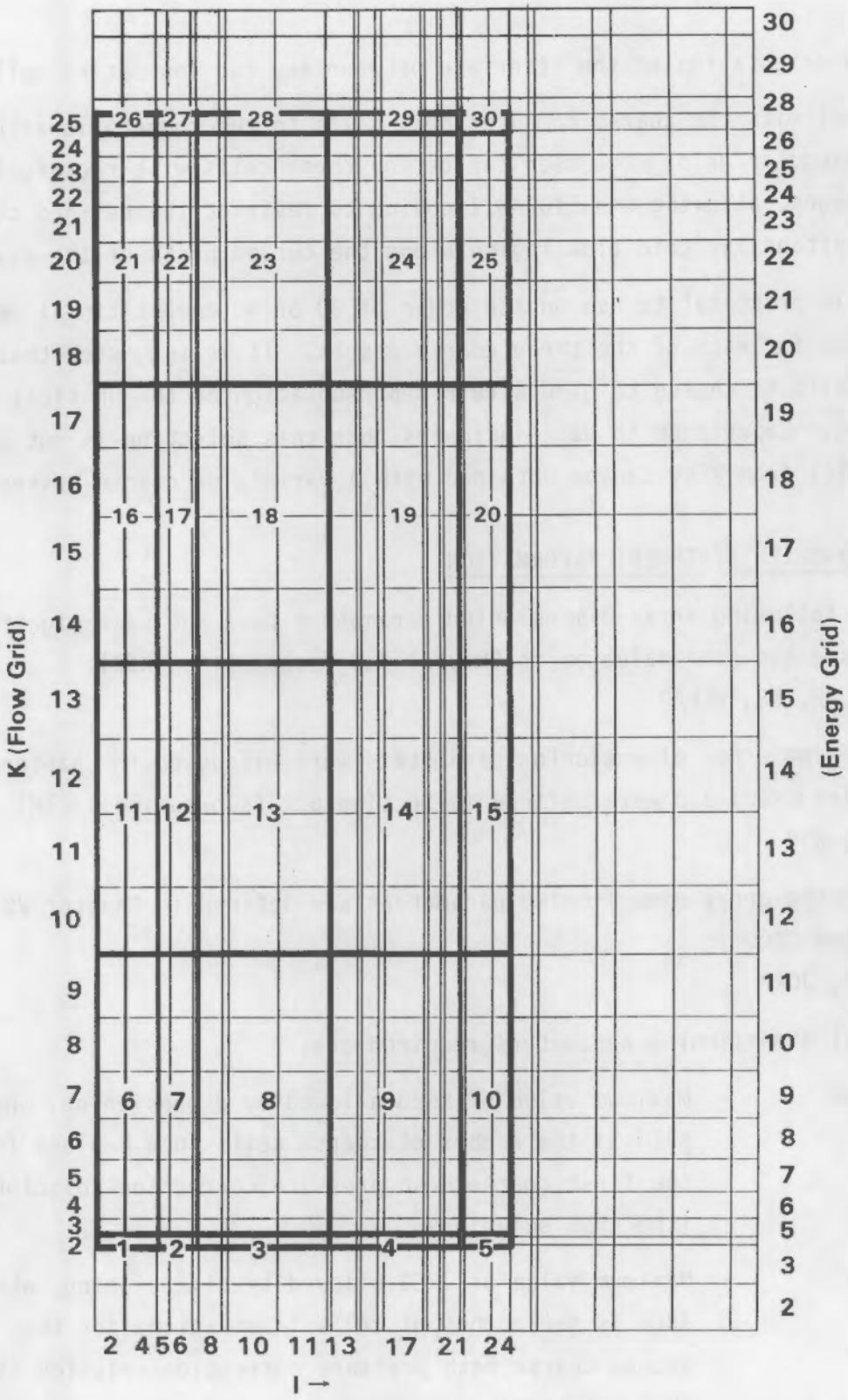


FIGURE 24.2. Coarse Mesh for a J-Plane

3. the orientation of the interface between any two contacting cells.

The code limits the coarse computational cells to the computational region of the rectangular grid. The user can define these cells with rectangular grid index ranges, allowing the HYDRA-II coding to restrict the defined coarse cells to the rectangular grid flow region along the curved parts of the boundary.

It is practical to use on the order of 30 or 40 computational cells in each plane for each of the three coarse meshes. It is suggested that the coarse cells be chosen to give a fair representation of the physical phenomena occurring. Experience to date indicates that this selection is not critical, as benefits from REBQ can be obtained with a variety of coarse meshes.

24.2 PARAMETER STATEMENT INFORMATION

The following array-dimensioning parameters have the same significance and should have the same value as in Chapter 4.0 (subroutine GRID):

- IP, JP, KP, NEFAP

The following array dimensioning parameters were discussed in Chapter 4.0 (subroutine GRID) and were defined in Section 6.2 (subroutine THERM):

- KBP, KTP

The following array dimensioning parameters are defined in Chapter 25.0 (subroutine CROUT):

- ICRP, JCRP

Additional dimensioning parameters required are:

- KREGP - Maximum value of KREG allowed by dimensioning, where KREG is the number of coarse cells in a K-plane for the first coarse mesh pressure correction solution (the KREG solution).
- JREGP - Maximum value of JREG allowed by dimensioning, where JREG is the number of cells in a J-plane for the second coarse mesh pressure correction solution (the JREG solution).

- IREGP - Maximum value of IREG allowed by dimensioning, where IREG is the number of cells in an I-plane for the third coarse mesh pressure correction solution (the IREG solution).
- KBIDAP - The length of the array KBID, used to store the cell interface information for the KREG partition. The KBID array stores, for each coarse cell of the KREG mesh, a list of pairs of numbers for interfaces with other coarse cells not already specified. The pair for an interface comprises the neighbor cell number and a number specifying the orientation of their interface plane.
- JBIDAP - The length of the array JBID, used to store the cell interface information for the JREG partition, analogous to KBIDAP for the KREG partition.
- IBIDAP - The length of the array IBID, used to store the cell interface information for the IREG partition, analogous to KBIDAP for the KREG partition.

24.3 INPUT FORMAT

24.3.1 Overview

The REBQ input can be considered in four blocks:

1. specifications on the level of printout and execution options for the pressure correction solutions on the REBQ type partitions of the flow region
2. cell geometry and interfaces in the I-J planes (planes of constant K) for the KREG partition
3. cell geometry and interfaces in the I-K planes (planes of constant J) for the JREG partition
4. cell geometry and interfaces in the J-K planes (planes of constant I) for the IREG partition.

24.3.2 Printout and Execution Options

General Input Format

```
NECHO
NMAX, INFO
KBOUND, JBOUND, IBOUND
AKKMIN, AJJMIN, AIIMIN
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- NMAX - Number of times to cycle through the approximate solution on the three coarse region partitions on a call to REBQ. The preferred value is simulation-dependent, and should be chosen by setting NMAX initially to 3 with INFO set to 1. Observe the printed divergence error and adjust the value of NMAX if necessary to an observed point of diminishing returns on the divergence error reduction.
- INFO - Flag for the level of printout desired. If INFO = 1, print divergence error maxima and location before each of the three coarse partition solutions at each of the NMAX iterations. If INFO = 2, print divergence error maxima and location before and after each of these coarse partition solutions at each of the NMAX iterations. If INFO = 3, print also the coefficient matrices for the coarse partitions. If INFO = 0, bypass printing. After choosing and verifying a satisfactory value of NMAX, it is desirable to set INFO = 0.
- KBOUND, JBOUND IBOUND - Index of a phantom (boundary) plane related to inflow and outflow conditions. This version of HYDRA-II is restricted to no-flow boundaries; therefore, KBOUND, JBOUND, and IBOUND should each be equal to 1.

- AKKMIN, AJJMIN, AIIMIN - Minimum values of the coarse mesh coefficient matrix related to inflow and outflow conditions. This version of HYDRA-II is restricted to no-flow boundaries; therefore, AKKMIN, AJJMIN, and AIIMIN should each have the value of 0.1E-20.

Input File Example

```
1849 1/rebq
1850 3,0
1851 1,1,1
1852 0.1e-20,0.1e-20,0.1e-20
```

Echoed Input File Example

```
1216      rebq    nmax=3        info=0
1217      rebq    kbound= 1   jbound= 1    ibound= 1
1218      rebq    akkmin=0.100e-20   ajjmin=0.100e-20   aiimin=0.100e-20
1219
```

The input file example requests echoing on line 1849 with NECHO = 1, sets number of solutions on the three partitions to NMAX = 3 on line 1850, and suppresses diagnostic printout with INFO = 0. A value NMAX = 3 was set (for this application) after inspection of patterns of divergence error, so INFO = 0 is appropriate to obtain no further divergence error information from the calls to REBQ.

24.3.3 KREG Partition Specifications

General Input Format

```
NECHO
KREG
KRID(L), L = 1, KRIDAP
NECHO
KBIDA
KBID(L), L = 1, KBIDAP
```

The array KRID contains KREG sets of X-Y region specifications end-to-end, each set having six entries in the form:

KREGNO, NBND, IBEG, IEND, JBEG, JEND

The array KBID contains data sets stored end-to-end, each set having the form:

$$KREGA, KREGB_1, MBTYP_1, KREGB_2, MBTYP_2, \ldots, KREGB_{NBND(KREGA)}, MBTYP_{NBND(KREGA)}$$

Each set in KBID has as a leading entry a region number KREGA that was one of the regions KREGNO specified in KRID. This is followed by NBND(KREGA) pairs of integers, where NBND(KREGA) was the second entry for set KREGA in KRID. Each pair ($KREGB_i$, $MBTYP_i$) of these integers has as first entry a number KREGB of another region in the X-Y plane that adjoins region KREGA, and as second entry a number MBTYP (-1, +1, -2, or +2) that tells whether region KREGB is in the -X (MBTYP = -1), +X (MBTYP = +1), -Y (MBTYP = -2), or +Y (MBTYP = +2) direction from region KREGA. An interface should be specified only once. If region KREGB is specified as adjoining region KREGA, then KREGA should not be included in the list of regions adjoining KREGB.

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- KREG - Number of coarse computational cells in an X-Y plane at each K-plane.
- KRID - Array defining the coarse cells in the X-Y plane for each K-plane. The data entries for the regions follow each other end-to-end, the six entries for each region being:

  KREGNO, NBND, IBEG, IEND, JBEG, JEND
- KREGNO - Number of a region in the X-Y plane for the KREG computation. The region numbers and their accompanying six-entry data sets must appear consecutively with indices KREGNO running 1 through KREG without omissions.

- NBND - Number of interfaces in the I-J plane for cell KREGNO not previously specified for some other cell. See forthcoming discussion for (KREGB, MBTYP) pairs.

- IBEG, IEND, JBEG, JEND - The beginning and end in the I-direction, followed by the beginning and end in the J-direction, of the included fine mesh cells for cell KREGNO in the coarse KREG partition of the X-Y plane. The KREG coarse cells are further restricted to the active computational region for the momentum equations defined the IMEND, JMBEG, and JMEND arrays.

- KBIDA - The number of active entries (individual numbers) forthcoming in the KBID array (which is dimensioned to KBIDAP).

- KBID - The array of sets of information on the interfaces of the cells of the KREG partition, stored end-to-end as previously indicated, each set having the form:

  KREGA, $KREGB_1$, $MBTYP_1$, $KREGB_2$, $MBTYP_2$, ...,
  $KREGB_{NBND(KREGA)}$, $MBTYP_{NBND(KREGA)}$

- KREGB, MBTYP - The index of a cell having an interface with cell KREGA, and a specification of its relative position. The values of MBTYP and their meanings are:

MBTYP	Direction of KREGB From KREGA	Interface Plane
-1	-X	Y-Z
+1	+X	Y-Z
-2	-Y	X-Z
+2	+Y	X-Z

  The interface between two regions should be specified only once in the KBID array, which is achieved if the region index KREGB is always greater than KREGA in the sets in KBID.

Input File Example

```
1853 1/rebq/krid
1854 35
1855 1,2,2,4,2,9,
1856 2,5,5,7,2,13,
1857 3,1,8,12,2,4,
1858 4,1,2,4,10,12,
1859 5,2,8,12,5,13,
1860 6,1,13,21,5,13,
1861 7,2,2,4,13,16,
1862 8,3,5,7,14,18,
1863 9,2,8,12,14,18,
1864 10,2,13,21,14,18,
1865 11,1,22,24,14,18,
1866 12,2,2,4,17,21,
1867 13,2,5,7,19,21,
1868 14,3,8,12,19,21,
1869 15,3,13,24,19,21,
1870 16,2,2,4,22,27,
1871 17,3,5,9,22,27,
1872 18,3,10,13,22,27,
1873 19,2,14,16,22,27,
1874 20,1,17,24,22,27,
1875 21,3,2,4,28,32,
1876 22,2,5,7,28,30,
1877 23,2,8,12,28,30,
1878 24,2,13,24,28,30,
1879 25,3,2,4,33,36,
1880 26,2,5,7,31,35,
1881 27,2,8,12,31,35,
1882 28,2,13,21,31,35,
1883 29,0,22,24,31,35,
1884 30,2,2,4,37,39,
1885 31,3,8,12,36,44,
1886 32,0,13,21,36,44,
1887 33,1,2,4,40,47,
1888 34,1,5,7,36,47,
1889 35,0,8,12,45,47
1890 1/rebq/kbid
1891 168
1892 1,2,1,4,2,
1893 2,3,1,4,-1,5,1,7,-1,8,2,
1894 3,5,2,
1895 4,7,2,
1896 5,6,1,9,2,
1897 6,10,2,
1898 7,8,1,12,2,
1899 8,9,1,12,-1,13,2,
1900 9,10,1,14,2,
1901 10,11,1,15,2,
```

```
1902 11,15,2,
1903 12,13,1,16,2,
1904 13,14,1,17,2,
1905 14,15,1,17,2,18,2,
1906 15,18,2,19,2,20,2,
1907 16,17,1,21,2,
1908 17,18,1,22,2,23,2,
1909 18,19,1,23,2,24,2,
1910 19,20,1,24,2,
1911 20,24,2,
1912 21,22,1,25,2,26,1,
1913 22,23,1,26,2,
1914 23,24,1,27,2,
1915 24,28,2,29,2,
1916 25,26,1,30,2,34,1,
1917 26,27,1,34,2,
1918 27,28,1,31,2,
1919 28,29,1,32,2,
1920 30,33,2,34,1,
1921 31,32,1,34,-1,35,2,
1922 33,34,1,
1923 34,35,1
```

Echoed Input File Example

```
1220    rebq    kreg= 35   maximum current dimension for kreg is  35
1221    rebq    krid              kreg      boundary          celllocation
1222                                        surfaces      lbeg  lend  jbeg  jend
1223                              1           2             2     4     2     9
1224                              2           5             5     7     2    13
1225                              3           1             8    12     2     4
1226                              4           1             2     4    10    12
1227                              5           2             8    12     5    13
1228                              6           1            13    21     5    13
1229                              7           2             2     4    13    16
1230                              8           3             5     7    14    18
1231                              9           2             8    12    14    18
1232                             10           2            13    21    14    18
1233                             11           1            22    24    14    18
1234                             12           2             2     4    17    21
1235                             13           2             5     7    19    21
1236                             14           3             8    12    19    21
1237                             15           3            13    24    19    21
1238                             16           2             2     4    22    27
1239                             17           3             5     9    22    27
1240                             18           3            10    13    22    27
1241                             19           2            14    16    22    27
1242                             20           1            17    24    22    27
1243                             21           3             2     4    28    32
1244                             22           2             5     7    28    30
1245                             23           2             8    12    28    30
1246                             24           2            13    24    28    30
1247                             25           3             2     4    33    36
1248                             26           2             5     7    31    35
1249                             27           2             8    12    31    35
1250                             28           2            13    21    31    35
1251                             29           0            22    24    31    35
1252                             30           2             2     4    37    39
```

```
1253                              31          3                    8   12   36   44
1254                              32          0                   13   21   36   44
1255                              33          1                    2    4   40   47
1256                              34          1                    5    7   36   47
1257                              35          0                    8   12   45   47
1258
1259      rebq    kbida=168   maximum current dimension for kbida is 168
1260      rebq    kbid              kreg       sees plane   sees plane   sees plane   sees plane   sees plane
1261                                          kreg type    kreg type    kreg type    kreg type    kreg type
1262                                 1          2    1       4    2
1263                                 2          3    1       4   -1       5    1       7   -1       8    2
1264                                 3          5    2
1265                                 4          7    2
1266                                 5          6    1       9    2
1267                                 6         10    2
1268                                 7          8    1      12    2
1269                                 8          9    1      12   -1      13    2
1270                                 9         10    1      14    2
1271                                10         11    1      15    2
1272                                11         15    2
1273                                12         13    1      16    2
1274                                13         14    1      17    2
1275                                14         15    1      17    2      18    2
1276                                15         18    2      19    2      20    2
1277                                16         17    1      21    2
1278                                17         18    1      22    2      23    2
1279                                18         19    1      23    2      24    2
1280                                19         20    1      24    2
1281                                20         24    2
1282                                21         22    1      25    2      26    1
1283                                22         23    1      26    2
1284                                23         24    1      27    2
1285                                24         28    2      29    2
1286                                25         26    1      30    2      34    1
1287                                26         27    1      34    2
1288                                27         28    1      31    2
1289                                28         29    1      32    2
1290                                30         33    2      34    1
1291                                31         32    1      34   -1      35    2
1292                                33         34    1
1293                                34         35    1
```

This input file example requests the partition shown in Figure 24.1 for the KREG coarse region computation.

The input file example requests echoing on line 1853 with NECHO = 1, then states on line 1854 that 35 (KREG) regions in each K-plane will be used. Lines 1855 through 1889 specify those 35 regions. For example, line 1855 indicates that region 1 (first entry) has two specified interfaces in the X-Y plane, and has X-Y extent $2 \leq I \leq 4$, $2 \leq J \leq 9$. Line 1856 indicates that region 2 has five not previously specified interfaces in the X-Y plane (the interface with region 1 not being included in this list).

Line 1890 of the input example introduces the forthcoming KBID array data by again setting NECHO to 1 with accompanying comments. Line 1891 promises 168 forthcoming numbers to specify the interfaces between the KREG type cells, and these 168 entries in the KBID array appear in lines 1892 through 1923. Line 1892 indicates that cell 1 (first number) sees cell 2 (second number) on its positive X side (as specified by the third number, 1), and sees cell 4 (fourth number) on its +Y side (as specified by the fifth number, 2). Recall that two pairs of bounding cells for cell 1 had been specified by the second entry NBND = 2 for cell 1 on line 1855. Line 1893 gives five new interfaces for cell 2, but does not give the 1-2 interface, which was specified on line 1892. No trailing zeros appear in this KBID array data because the array was dimensioned exactly to KBIDAP = 168.

The echoed input gives the KREG information in tabular form.

24.3.4 JREG Partition Specifications

General Input Format

```
NECHO
JREG
JRID(L), L = 1, JRIDAP
NECHO
JBIDA
JBID(L), L = 1, JBIDAP
```

General Input Description

- NECHO - Echoing switch for this section of input, if input is to be echoed, then NECHO = 1; otherwise, 0.
- JREG - Number of coarse computational cells in the X-Z plane for each J-plane.
- JRID - Array defining the coarse cells in the X-Z plane for each J-plane. The data entries for the regions follow consecutively end-to-end, with the six entries for each region being

  JREGNO, NBND, IBEG, IEND, KBEG, KEND

- JREGNO - Number of a region in the X-Z plane for the JREG computation. Region numbers run 1 through JREG consecutively.
- NBND - Number of interfaces in the I-K plane for cell JREGNO not previously specified for some other cell. See forthcoming discussion for (JREGB, MBTYP) pairs.
- IBEG, IEND, KBEG, KEND - The beginning and end in the I-direction, followed by the beginning and end in the K-direction, of the fine mesh cells included in the coarse mesh cell JREGNO. The JREG coarse cells are further restricted in the code to the active computational region for the momentum equations defined by the IMENO, JMBEG, and JMEND arrays.
- JBIDA - The number of active entries (individual numbers) forthcoming in the JBID array (which is dimensioned to JBIDAP).
- JBID - The array of sets of information on the interfaces of the cells of the JREG partition, stored end-to-end, with each set having the form:

  $JREGA, JREGB_1, MBTYP_1, JREGB_2, MBTYP_2,$
  $\ldots JREGB_{NBND(JREGA)}, MBTYP_{NBND(JREGA)}$
- JREGB, MBTYP - The index of a cell having an interface with cell JREGA, and a specification of their relative position. The values of MBTYP and their meanings are:

MBTYP	Direction of KREGB From KREGA	Interface Plane
-1	-X	Y-Z
+1	+X	Y-Z
-3	-Z	X-Y
+3	+Z	X-Y

Input File Example

```
1924 1/rebq/jrid
1925 30
```

```
1926 1,2,2,4,2,2,
1927 2,2,5,7,2,2,
1928 3,2,8,12,2,2,
1929 4,2,13,21,2,2,
1930 5,1,22,24,2,2,
1931 6,2,2,4,3,9,
1932 7,2,5,7,3,9,
1933 8,2,8,12,3,9,
1934 9,2,13,21,3,9,
1935 10,1,22,24,3,9,
1936 11,2,2,4,10,13,
1937 12,2,5,7,10,13,
1938 13,2,8,12,10,13,
1939 14,2,13,21,10,13,
1940 15,1,22,24,10,13,
1941 16,2,2,4,14,17,
1942 17,2,5,7,14,17,
1943 18,2,8,12,14,17,
1944 19,2,13,21,14,17,
1945 20,1,22,24,14,17,
1946 21,2,2,4,18,24,
1947 22,2,5,7,18,24,
1948 23,2,8,12,18,24,
1949 24,2,13,21,18,24,
1950 25,1,22,24,18,24,
1951 26,1,2,4,25,25,
1952 27,1,5,7,25,25,
1953 28,1,8,12,25,25,
1954 29,1,13,21,25,25,
1955 30,0,22,24,25,25
1956 1/rebq/jbid
1957 127
1958 1,2,1,6,3,
1959 2,3,1,7,3,
1960 3,4,1,8,3,
1961 4,5,1,9,3,
1962 5,10,3,
1963 6,7,1,11,3,
1964 7,8,1,12,3,
1965 8,9,1,13,3,
1966 9,10,1,14,3,
1967 10,15,3,
1968 11,12,1,16,3,
1969 12,13,1,17,3,
1970 13,14,1,18,3,
1971 14,15,1,19,3,
1972 15,20,3,
1973 16,17,1,21,3,
1974 17,18,1,22,3,
1975 18,19,1,23,3,
1976 19,20,1,24,3,
```

```
1977 20,25,3,
1978 21,22,1,26,3,
1979 22,23,1,27,3,
1980 23,24,1,28,3,
1981 24,25,1,29,3,
1982 25,30,3,
1983 26,27,1,
1984 27,28,1,
1985 28,29,1,
1986 29,30,1
```

Echoed Input File Example

```
1294
1295     rebq    jreg= 30   maximum current dimension for jreg is  30
1296     rebq    jrid             jreg       boundary                  celllocation
1297                                         surfaces              ibeg iend kbeg kend
1298                               1            2                   2    4    2    2
1299                               2            2                   5    7    2    2
1300                               3            2                   8   12    2    2
1301                               4            2                  13   21    2    2
1302                               5            1                  22   24    2    2
1303                               6            2                   2    4    3    9
1304                               7            2                   5    7    3    9
1305                               8            2                   8   12    3    9
1306                               9            2                  13   21    3    9
1307                              10            1                  22   24    3    9
1308                              11            2                   2    4   10   13
1309                              12            2                   5    7   10   13
1310                              13            2                   8   12   10   13
1311                              14            2                  13   21   10   13
1312                              15            1                  22   24   10   13
1313                              16            2                   2    4   14   17
1314                              17            2                   5    7   14   17
1315                              18            2                   8   12   14   17
1316                              19            2                  13   21   14   17
1317                              20            1                  22   24   14   17
1318                              21            2                   2    4   18   24
1319                              22            2                   5    7   18   24
1320                              23            2                   8   12   18   24
1321                              24            2                  13   21   18   24
1322                              25            1                  22   24   18   24
1323                              26            1                   2    4   25   25
1324                              27            1                   5    7   25   25
1325                              28            1                   8   12   25   25
1326                              29            1                  13   21   25   25
1327                              30            0                  22   24   25   25
1328
1329     rebq    jbida=127  maximum current dimension for jbida is 127
1330     rebq    jbid             jreg       sees plane   sees plane   sees plane   sees plane   sees plane
1331                                         jreg type    jreg type    jreg type    jreg type    jreg type
1332                               1            2    1       6    3
1333                               2            3    1       7    3
1334                               3            4    1       8    3
1335                               4            5    1       9    3
1336                               5           10    3
1337                               6            7    1      11    3
1338                               7            8    1      12    3
1339                               8            9    1      13    3
1340                               9           10    1      14    3
```

```
1341      10    15   3
1342      11    12   1    16   3
1343      12    13   1    17   3
1344      13    14   1    18   3
1345      14    15   1    19   3
1346      15    20   3
1347      16    17   1    21   3
1348      17    18   1    22   3
1349      18    19   1    23   3
1350      19    20   1    24   3
1351      20    25   3
1352      21    22   1    26   3
1353      22    23   1    27   3
1354      23    24   1    28   3
1355      24    25   1    29   3
1356      25    30   3
1357      26    27   1
1358      27    28   1
1359      28    29   1
1360      29    30   1
```

This example requests the partition shown in Figure 24.2 for the JREG coarse region computation. The section shown in Figure 24.2 is the plane of constant Y passing through the cask axis.

The input file example requests echoing on line 1924 with NECHO = 1, then indicates on line 1925 that 30 (JREG) regions in each J-plane will be used. Lines 1926 through 1955 specify those 30 regions. Line 1926 indicates that region 1 (first number) has two (second number) specified interfaces in the X-Z plane, and has a fine mesh extent $2 \leq I \leq 4$, $2 \leq K \leq 2$. Note that the K indices are in the momentum equations grid, whose indices in the K-direction are offset from those of the energy equation grid by KBP. Line 1927 indicates region 2 has two not-previously specified interfaces and has a fine mesh extent $5 \leq I \leq 7$, $2 \leq K \leq 2$.

Line 1956 of the input file example resets NECHO to 1 while serving to introduce with comments the specification of the interfaces for the JREG partition in the forthcoming JBID array. Line 1957 specifies that 127 data entries are forthcoming to specify those interfaces. Because the JBID array was dimensional to JBIDAP = 127 for this simulation, the 127 entries on lines 1958 through 1986 fill that array and no filling of unused locations with zeros is needed. Line 1958 specifies the two interfaces for region 1 (first entry) that were alluded to on line 1926, the interfaces being specified by the data pairs (2,1) and (6,3). The (2,1) pair states that region 2 is in the +X

direction from region 1, while the (6,3) pair states that region 6 is in the +Z direction from region 1 in the JREG partition.

Line 1959 of the input file example specifies the two not-previously specified interfaces of JREG cell 2. Cell 2 (first number) has an interface with cell 3 (second number) on its +X (third number, +1) side, and with cell 7 (fourth number) on its +Z (fifth number, +3) side.

The echoed input summarizes the information on the JREG partition and interfaces in tabular form.

24.3.5 IREG Partition Specifications

General Input Format

```
NECHO
IREG
IRID(L), L = 1, IRIOAP
NECHO
IBIOA
IBID(L), L = 1, IBIDAP
```

General Input Description

- NECHO - Echoing switch for this section of input. If input is to be echoed, then NECHO = 1; otherwise, 0.
- IREG - Number of coarse computational cells in a Y-Z plane at each I-plane.
- IRID - Array defining the coarse cells in a Y-Z plane for each I-plane. The data entries for the regions follow consecutively end-to-end, the six entries for each region being:

  IREGNO, NBND, JBEG, JEND, KBEG, KEND
- IREGNO - Number of a region in the Y-Z plane for the IREG computation. Region numbers run 1 through IREG consecutively.
- NBND - Number of interfaces in the J-K plane for cell IREGNO not previously specified for some other cell. See forthcoming discussion of (IREG, MBTYP) pairs.

- JBEG, JEND, KBEG, KEND - The beginning and end in the J-direction, followed by the beginning and end in the K-direction, of the fine mesh cells to include in the coarse mesh cell IREGNO. The IREG coarse cells are further restricted in the code to the active computational region for the momentum equations defined by the IMEND, JMBEG, and JMEND arrays.

- IBIDA - The number of active entries (individual numbers) forthcoming in the IBID array (which is dimensioned to IBIDAP).

- IBID - The array of sets of information on the interfaces of the cells of the IREG partition, stored end-to-end, with each set having the form:

  $$IREGA, IREGB_1, MBTYP_1, IREGB_2, MBTYP_2, \ldots IREGB_{NBND(IREGA)}, MBTYP_{NBND(IREGA)}$$

- IREGB, MBTYP - The index of an IREG type cell having an interface with cell IREGA, and a specification of its relative position. The values of MBTYP and their meanings are:

MBTYP	Direction of KREGB From KREGA	Interface Plane
-2	-Y	X-Z
+2	+Y	X-Z
-3	-Z	X-Y
+3	+Z	X-Y

Input File Example

```
1987 1/rebq/irid
1988 35
1989 1,2,2,10,2,4,
1990 2,2,11,16,2,4,
1991 3,2,17,20,2,4,
1992 4,2,21,28,2,4,
1993 5,2,29,32,2,4,
1994 6,2,33,38,2,4,
1995 7,1,39,47,2,4,
1996 8,2,2,10,5,10,
1997 9,2,11,16,5,10,
1998 10,2,17,20,5,10,
```

```
1999 11,2,21,28,5,10,
2000 12,2,29,32,5,10,
2001 13,2,33,38,5,10,
2002 14,1,39,47,5,10,
2003 15,2,2,10,11,15,
2004 16,2,11,16,11,15,
2005 17,2,17,20,11,15,
2006 18,2,21,28,11,15,
2007 19,2,29,32,11,15,
2008 20,2,33,38,11,15,
2009 21,1,39,47,11,15,
2010 22,2,2,10,16,22,
2011 23,2,11,16,16,22,
2012 24,2,17,20,16,22,
2013 25,2,21,28,16,22,
2014 26,2,29,32,16,22,
2015 27,2,33,38,16,22,
2016 28,1,39,47,16,22,
2017 29,1,2,10,23,25,
2018 30,1,11,16,23,25,
2019 31,1,17,20,23,25,
2020 32,1,21,28,23,25,
2021 33,1,29,32,23,25,
2022 34,1,33,38,23,25,
2023 35,0,39,47,23,25
2024 1/rebq/ibid
2025 150
2026 1,2,2,8,3,
2027 2,3,2,9,3,
2028 3,4,2,10,3,
2029 4,5,2,11,3,
2030 5,6,2,12,3,
2031 6,7,2,13,3,
2032 7,14,3,
2033 8,9,2,15,3,
2034 9,10,2,16,3,
2035 10,11,2,17,3,
2036 11,12,2,18,3,
2037 12,13,2,19,3,
2038 13,14,2,20,3,
2039 14,21,3,
2040 15,16,2,22,3,
2041 16,17,2,23,3,
2042 17,18,2,24,3,
2043 18,19,2,25,3,
2044 19,20,2,26,3,
2045 20,21,2,27,3,
2046 21,28,3,
2047 22,23,2,29,3,
2048 23,24,2,30,3,
2049 24,25,2,31,3,
```

```
2050 25,26,2,32,3,
2051 26,27,2,33,3,
2052 27,28,2,34,3,
2053 28,35,3,
2054 29,30,2,
2055 30,31,2,
2056 31,32,2,
2057 32,33,2,
2058 33,34,2,
2059 34,35,2
```

Echoed Input File Example

```
1362    rebq    lreg= 35   maximum current dimension for lreg is  35
1363    rebq    lrid             lreg      boundary                    celllocation
1364                                       surfaces                jbeg jend kbeg kend
1365                              1          2                      2   10   2    4
1366                              2          2                     11   16   2    4
1367                              3          2                     17   20   2    4
1368                              4          2                     21   28   2    4
1369                              5          2                     29   32   2    4
1370                              6          2                     33   38   2    4
1371                              7          1                     39   47   2    4
1372                              8          2                      2   10   5   10
1373                              9          2                     11   16   5   10
1374                             10          2                     17   20   5   10
1375                             11          2                     21   28   5   10
1376                             12          2                     29   32   5   10
1377                             13          2                     33   38   5   10
1378                             14          1                     39   47   5   10
1379                             15          2                      2   10  11   15
1380                             16          2                     11   16  11   15
1381                             17          2                     17   20  11   15
1382                             18          2                     21   28  11   15
1383                             19          2                     29   32  11   15
1384                             20          2                     33   38  11   15
1385                             21          1                     39   47  11   15
1386                             22          2                      2   10  16   22
1387                             23          2                     11   16  16   22
1388                             24          2                     17   20  16   22
1389                             25          2                     21   28  16   22
1390                             26          2                     29   32  16   22
1391                             27          2                     33   38  16   22
1392                             28          1                     39   47  16   22
1393                             29          1                      2   10  23   25
1394                             30          1                     11   16  23   25
1395                             31          1                     17   20  23   25
1396                             32          1                     21   28  23   25
1397                             33          1                     29   32  23   25
1398                             34          1                     33   38  23   25
1399                             35          0                     39   47  23   25
1400
1401    rebq    lbida=150  maximum current dimension for lbida is 150
1402    rebq    lbid             lreg      sees plane   sees plane   sees plane   sees plane   sees plane
1403                                       lreg type    lreg type    lreg type    lreg type    lreg type
1404                              1          2    2       8    3
1405                              2          3    2       9    3
1406                              3          4    2      10    3
1407                              4          5    2      11    3
1408                              5          6    2      12    3
```

```
1409        6        7    2        13    3
1410        7       14    3
1411        8        9    2        15    3
1412        9       10    2        16    3
1413       10       11    2        17    3
1414       11       12    2        18    3
1415       12       13    2        19    3
1416       13       14    2        20    3
1417       14       21    3
1418       15       16    2        22    3
1419       16       17    2        23    3
1420       17       18    2        24    3
1421       18       19    2        25    3
1422       19       20    2        26    3
1423       20       21    2        27    3
1424       21       28    3
1425       22       23    2        29    3
1426       23       24    2        30    3
1427       24       25    2        31    3
1428       25       26    2        32    3
1429       26       27    2        33    3
1430       27       28    2        34    3
1431       28       35    3
1432       29       30    2
1433       30       31    2
1434       31       32    2
1435       32       33    2
1436       33       34    2
1437       34       35    2
```

This input is quite analogous to that for the KREG partition and the JREG partition, defining the regions in a J-K layer in lines 1988 through 2023, then defining their interfaces in lines 2025 through 2059.

25.0 SUBROUTINE CROUT

Subroutine CROUT employs a direct method for the solution of linear matrix equations associated with subroutines REBA and REBQ. The Crout method is used to solve matrix equations of the form

$$AX = B$$

where A is an m by m square matrix and X and B each have m rows and n columns. A discussion of the Crout method may be found in Westlake (1968).

25.1 PARAMETER STATEMENT INFORMATION

The dimension of arrays A and B are specified by two parameters:

- ICRP - Row and column dimension of A and rows of B. If subroutine REBA is used, then ICRP = 3. If subroutine REBQ is used, then ICRP = MAX(IREG,JREG,KREG). If both subroutines are used, then ICRP must equal the largest of the above two dimensions.
- JCRP - Number of columns of B. If subroutine REBA is used, then JCRP = 4. If subroutine REBQ is used, then JCRP = ICRP. If both subroutines are used, then JCRP must equal the largest of the above two dimensions.

25.2 INPUT FORMAT

Subroutine CROUT does not read the input file.

26.0 SUBROUTINE AF

Subroutine AF solves a Poisson equation (derived in Volume I - Equations and Numerics, Chapter 9.0) for the pressure-correction field. It is one of the set of subroutines (viz., PILES, REBS, REBQ, and AF) that can be called upon by subroutine PITER to produce this solution. The method employed in this routine is effectively an approximate factorization of the pressure-correction-field matrix operator. Since the factorization is approximate, the exact solution is not obtained in one pass through the algorithm. The user must specify the number of times the routine will cycle through the algorithm in each pass through the subroutine. This is done with input variable NMAX.

Subroutine AF also allows the user to monitor the convergence history of this algorithm. By setting input variable INFO = 1, AF will print the following information: iteration count, the value of the current pressure-correction at the (I,J,K) mesh location corresponding to the cell experiencing the largest right-hand-side residual (in absolute value), the right-hand-side residual at cell (I,J,K), and the I, J, and K cell indices for this "worst-case" cell. With INFO = 1, this information is provided after entering AF just prior to commencement of the iteration (for which case the iteration count and the largest right-hand-side residual are printed as having values of 0), and once again for each of the NMAX iterations. If this output is not desired, specify INFO = 0 in the input.

26.1 PARAMETER STATEMENT INFORMATION

Subroutine AF requires the specification of parameters IP, JP, KP, KBP, and KTP. These data define the overall computational mesh and are described in the discussion of subroutine GRID in Chapter 4.0.

26.2 INPUT FORMAT

26.2.1 Overview

Very little input is required by subroutine AF. Only three variables are read--NECHO, NMAX, and INFO. The input sequence and definition is provided below.

General Input Format

NECHO
NMAX,INFO

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.
- NMAX - Maximum number of iterations per pass through subroutine AF. The appropriate setting for NMAX is very problem-specific if one wishes to optimally employ the pressure-iteration scheme in HYORA-II. NMAX should be set in this routine after factoring in the convergence history of AF relative to that realized when subroutine PILES is employed. A more detailed discussion of this is provided in Chapter 21.0 of the User's Manual.
- INFO - Convergence history print-out switch. INFO = 0 precludes output; INFO = 1 produces convergence history output as described in the above text. Scanning the pressure-correction field to locate the "worst-case" residual is a relatively expensive process. Therefore, this switch should be set to zero unless a resetting of NMAX is desired.

Input File Example

```
2060 1/af
2061 5,0
```

Echoed-Input File Example

```
1439    af    nmax= 5    info=0
```

NECHO is set to 1 on input line 2060. NMAX and INFO are set to 5 and 0, respectively, on input line 2061. With NECHO set to 1, these input data are echoed in the output on line 1439.

27.0 SUBROUTINE AVG

Subroutine AVG computes the pressure adjustment required to satisfy the user-specified constraint of either fixed total fluid mass or fixed average pressure for the system. In either case, AVG takes advantage of the indeterminacy of the pressure field defined by the momentum equations. This indeterminacy allows the pressure field to be shifted by a spatially-uniform amount in every cell of the computational mesh to effect the desired mass or average-pressure constraint.

The choice of one or the other is determined by the user with a positive input for FIXEDM (for fixed total system mass) or FIXEDP (for fixed average system pressure). If either of the options is NOT desired, the corresponding input should be zero.

27.1 PARAMETER STATEMENT INFORMATION

Subroutine AVG requires the specification of parameters IP, JP, KP, KBP, and KTP. These data define the overall computational mesh and are described in the discussion of subroutine GRID in Chapter 4.0.

27.2 INPUT FORMAT

27.2.1 Overview

Very little input is required by subroutine AVG. Only three variables are read--NECHO, FIXEDM, and FIXEDP. The input sequence and definition is provided below.

General Input Format

```
NECHO
FIXEDM,FIXEDP
```

General Input Description

- NECHO - Echoing switch for this section of input. If NECHO = 1, an echo of the input for this section will be provided in the output; if NECHO = 0, this echoing will not be provided.

- FIXEDM - Flag to indicate whether or not the system mass is fixed and, if so, at what value. If this option is not to be used, set FIXEDM = 0.0; otherwise, set FIXEDM = desired system mass in grams.
- FIXEDP - Flag to indicate whether or not the system is operating at fixed average pressure. If this option is not to be used, set FIXEDP = 0.0; otherwise, set FIXEDP = desired average system pressure in dyn/cm^2.

Input File Example

```
2062 1/avg
2063 0.0,0.496e+6
```

Echoed-Input File Example

```
1441    avg    fixedm=0.0000000e+00    fixedp=0.4960000e+06
```

NECHO is set to 1 on input line 2062. FIXEDM and FIXEDP have been set to 0 grams and 496000 dyn/cm^2, respectively. Therefore, this simulation will operate with a fixed average pressure.

28.0 SUBROUTINE PRINTL

Subroutine PRINTL is called from numerous locations to print array variables, according to user options or code defaults. PRINTL prints the triply-dimensioned variable in its call list. No user attention to PRINTL is required except to the dimensioning parameters.

28.1 PARAMETER STATEMENT INFORMATION

Subroutine PRINTL requires the specification of parameters IP and JP that define the computational mesh and are described in Chapter 4.0, Subroutine GRID. Two additional parameters, NPLA1P and NPLA2P, are required for specification of printing options. These are described in Chapter 3.0, Program MAIN.

28.2 INPUT FORMAT

Subroutine PRINTL does not read user input.

29.0 SAMPLE PROBLEM

This chapter presents a relatively simple sample problem with many of the characteristics of a typical spent fuel cask. The configuration is still sufficiently detailed, however, so that many of the input options available in HYDRA-II can be exercised. General observations on code setup and operation, and on output interpretation, are made and illustrated by means of this sample problem. The complete input and output file obtained from the execution of this sample problem is provided in Appendixes A and B. This, together with the source code and restart tape available in the HYDRA-II package, should provide the necessary checkpoints for the user to get comfortable with the input to the code.

In this chapter, the physical characteristics of the sample problem are first presented. Having oriented the user to the configuration, the following sections of this chapter will discuss some of the salient points in the modeling of this sample problem and the corresponding HYDRA-II input. The model and corresponding results are not intended to be representative of an actual spent fuel cask configuration. Nor are the details of the model (e.g., nodalization) necessarily intended to represent those suitable for design and licensing purposes.

29.1 CONFIGURATION

A cutaway view of the sample problem (Figure 29.1) illustrates the overall arrangement of the cask body and its internal components. Figures 29.2 and 29.3 present the corresponding elevation views of this cask. The overall dimensions of the cask are:

- outside height = 118 cm
- outside diameter = 29 cm
- inside diameter = 21 cm
- top lid thickness = 4 cm
- bottom lid thickness = 4 cm.

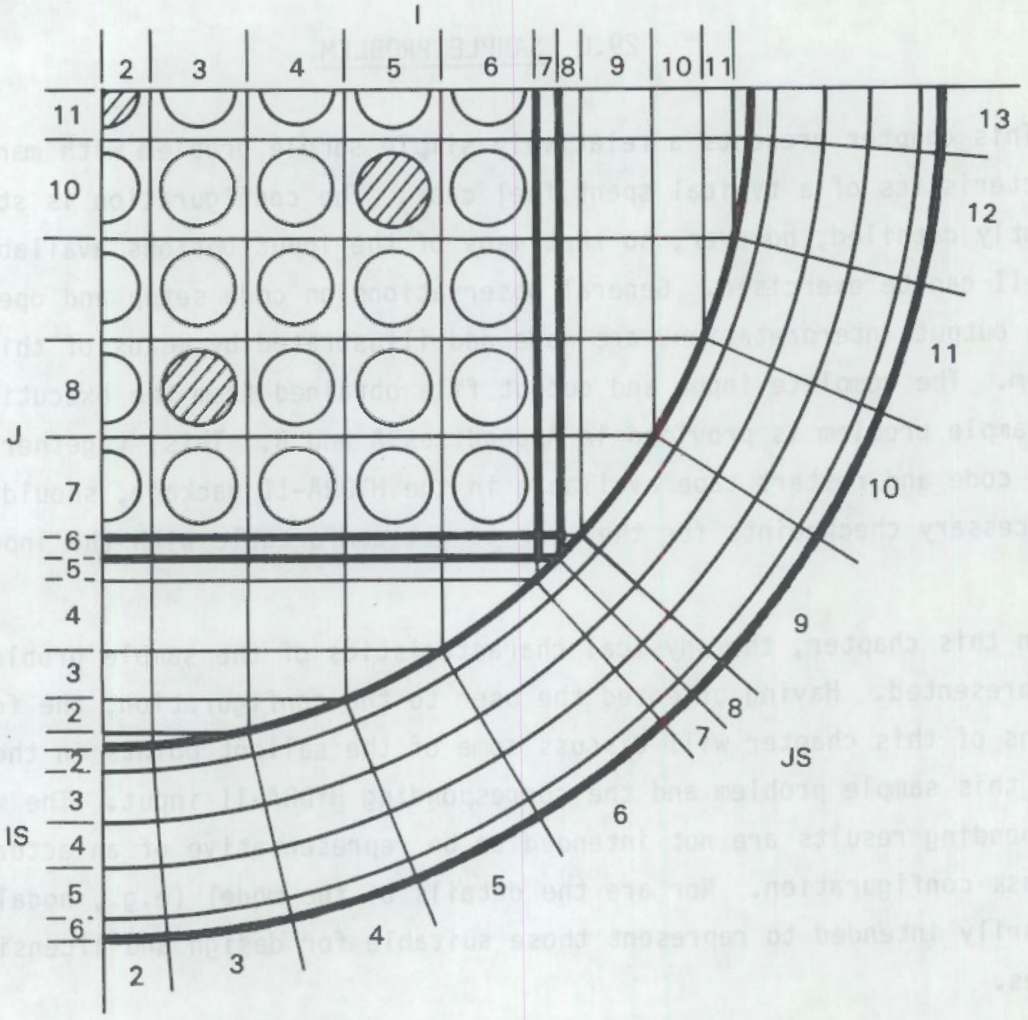


FIGURE 29.1. Sample Problem Computational Mesh - Plan View

The top and bottom lids are welded to the side of the cask, leaving a slight 1-mm gap between the lid and cask side, as shown in the detail drawing of Figure 29.4. The entire cask body is constructed of nodular cast iron.

Spent fuel rods are stored in a 9x9 square array within the cask. The physical parameters for this array are:

- rod diameter = 1.072 cm
- pitch-to-diameter ratio = 1.334
- rod height = 100 cm.

The modeled portion of the rod array generates 290 watts of decay heat. Therefore, the full rod array produces 1160 watts (4 x 290) of decay heat. The relative activity profile for each rod is presented in Figure 29.5. Several of

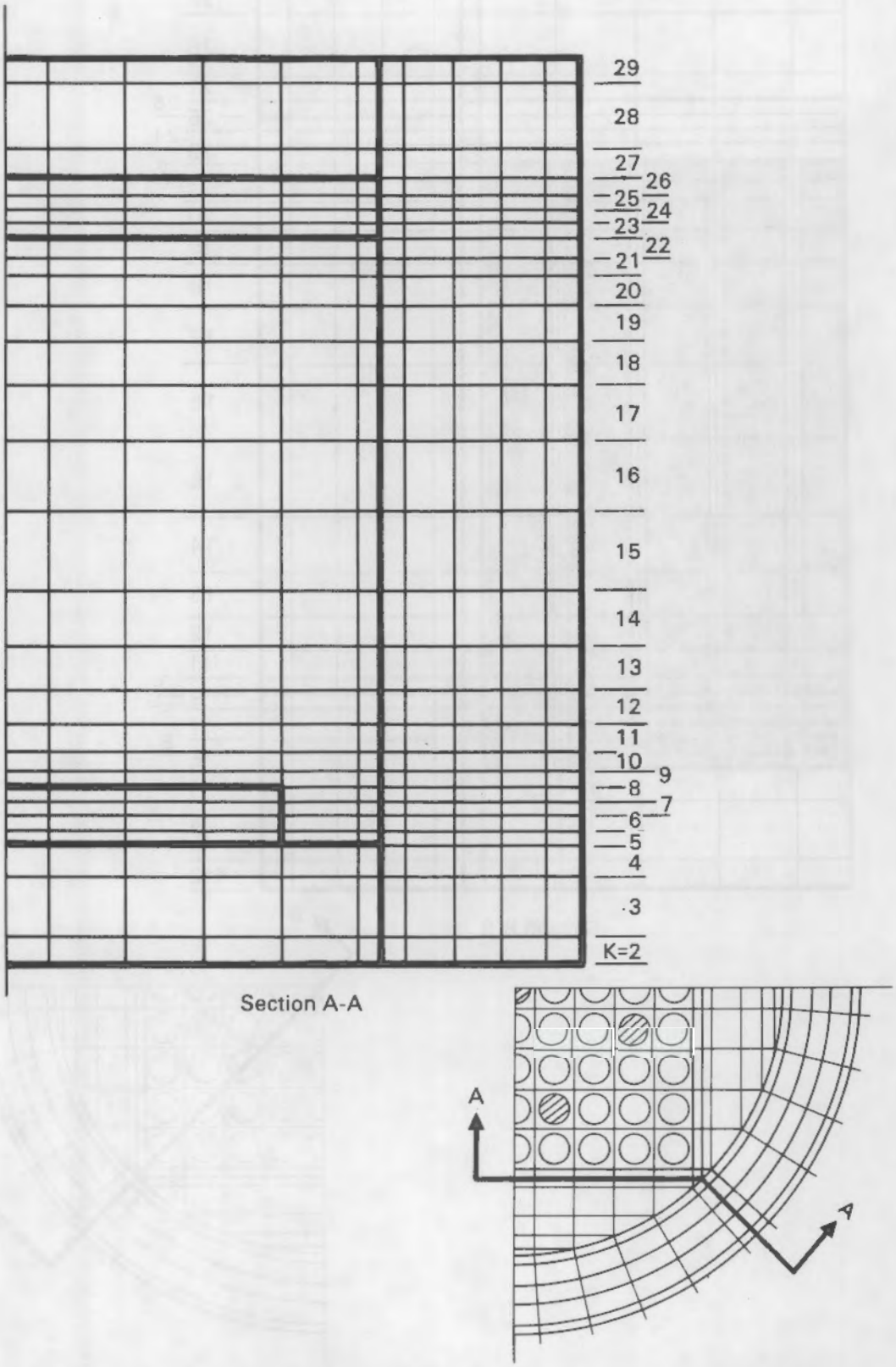
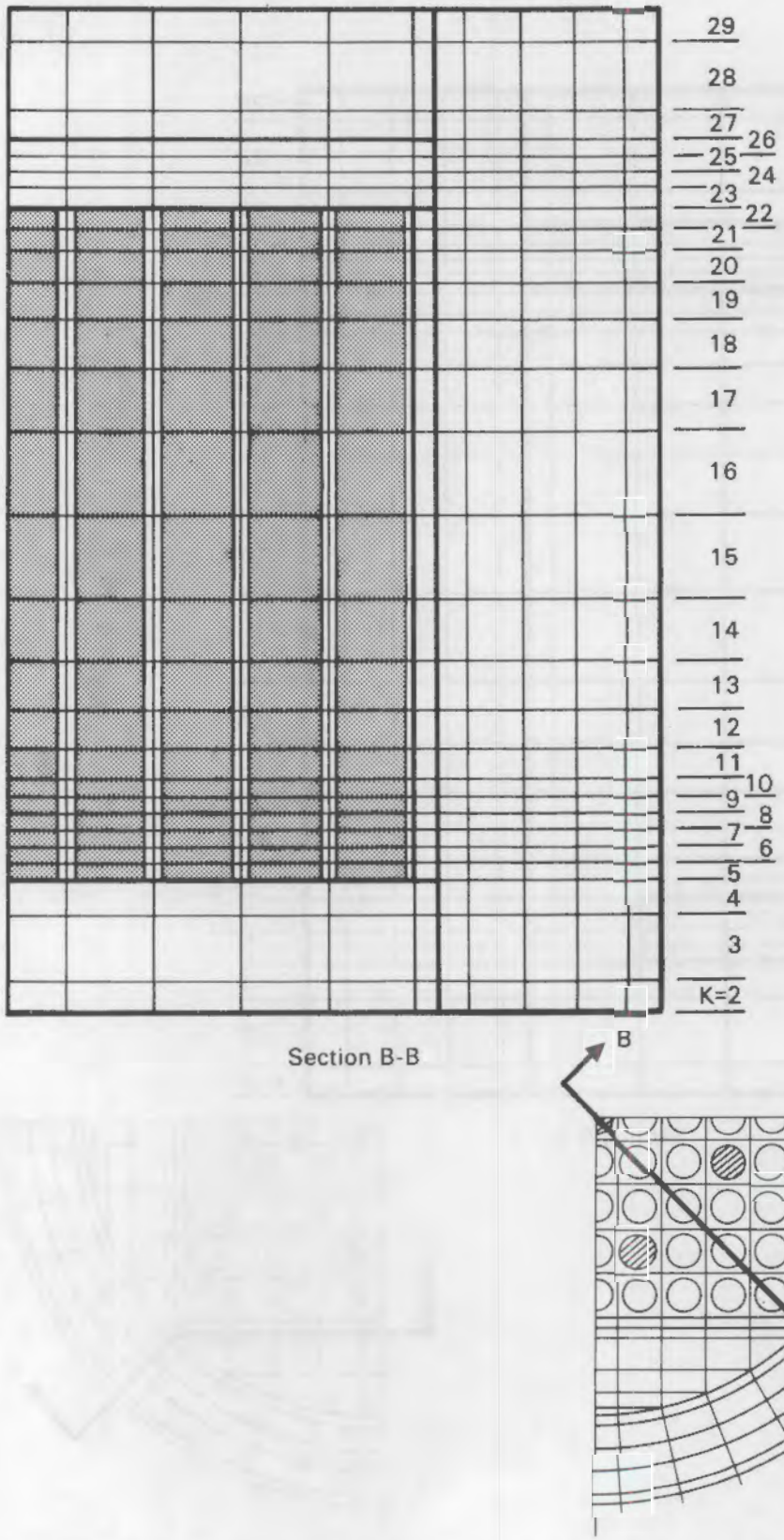


FIGURE 29.2. Sample Problem Computational Mesh - Elevation View



Section B-B

FIGURE 29.3. Sample Problem Computational Mesh - Elevation View

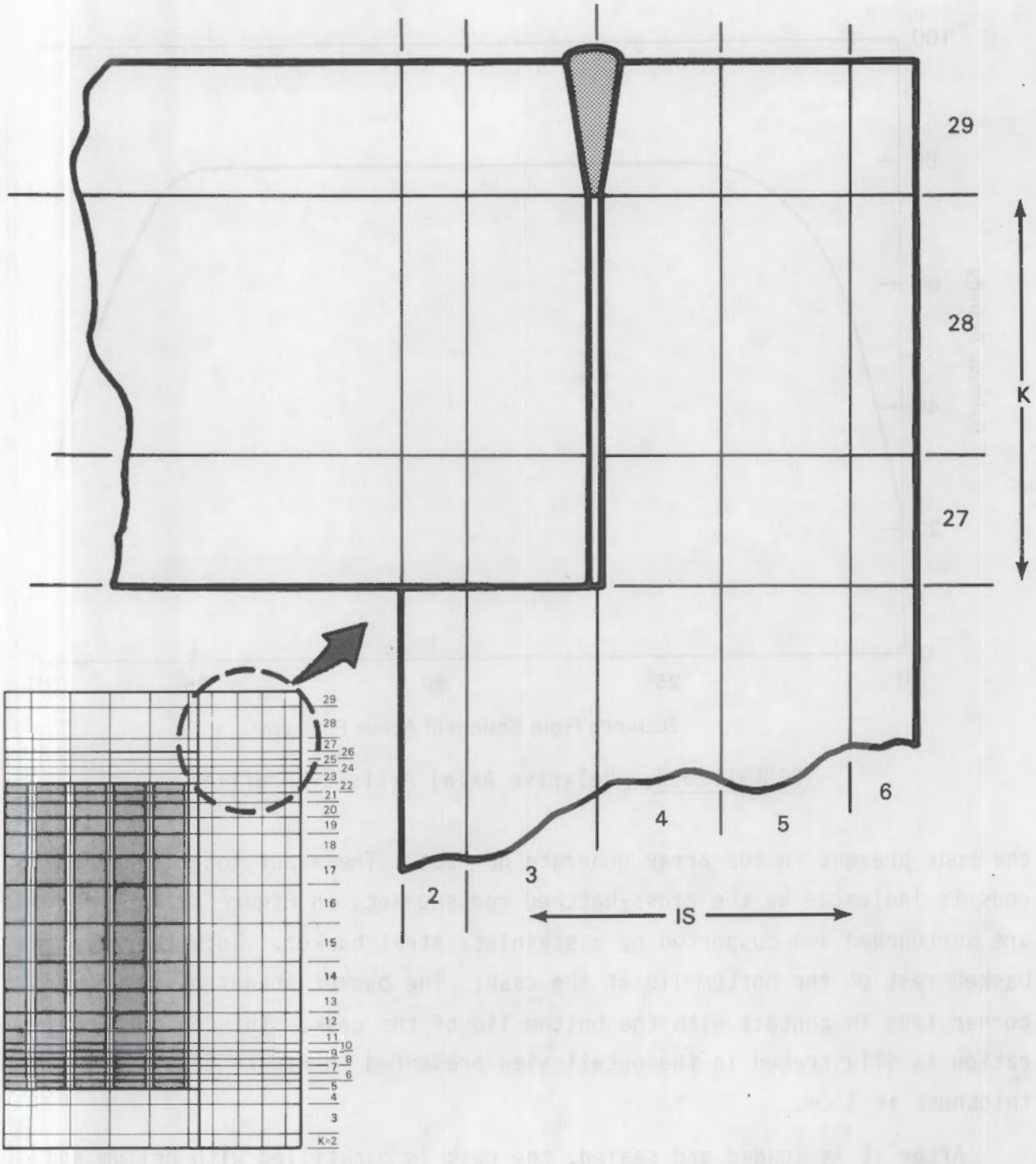


FIGURE 29.4. Cask Lid-to-Body Interface

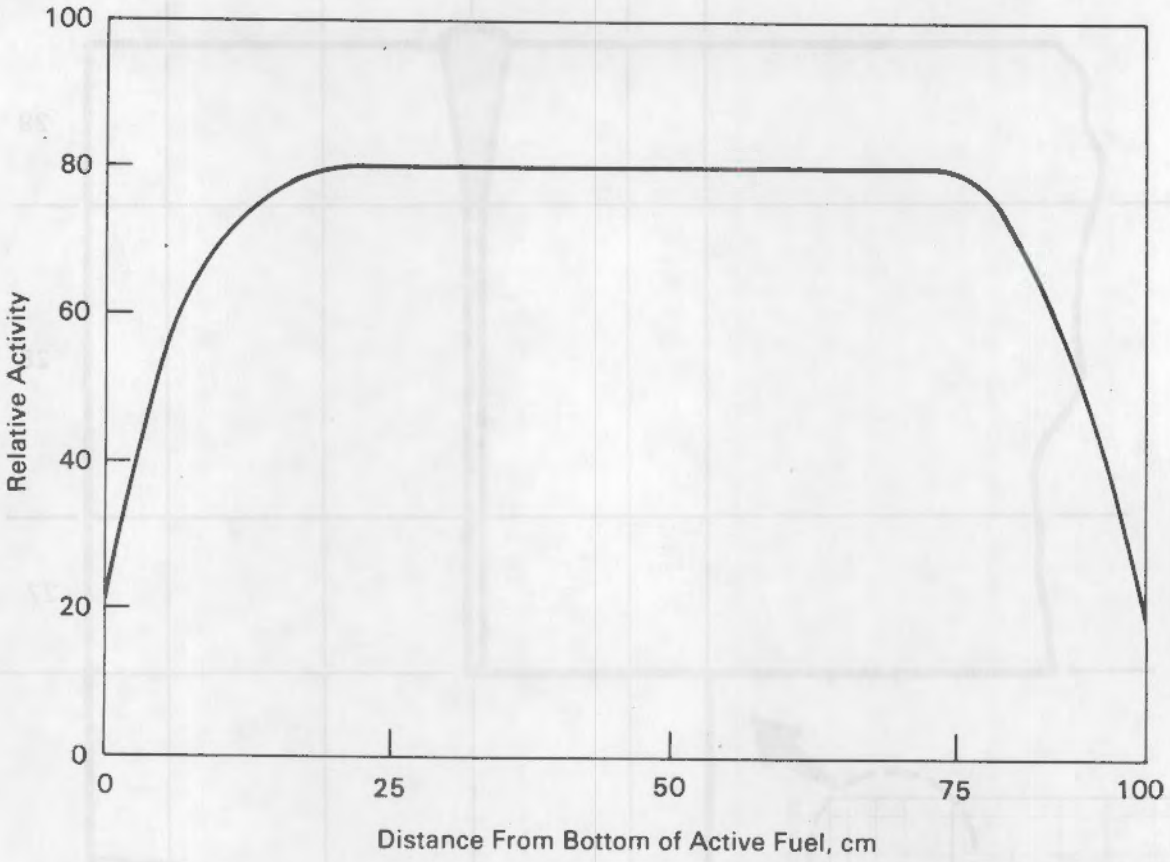


FIGURE 29.5. Relative Axial Activity Profile

the rods present in the array generate no heat. The exact location of these rods is indicated by the cross-hatched rod segments in Figure 29.1. The rods are surrounded and supported by a stainless steel basket. Both the rods and basket rest on the bottom lid of the cask. The basket stands on its four corner legs in contact with the bottom lid of the cask. This support configuration is illustrated in the detail view presented in Figure 29.6. The basket thickness is 1 cm.

After it is loaded and sealed, the cask is backfilled with helium and maintained at an absolute pressure of 496,000 dyn/cm^2. The cask stands in a vertical orientation on an insulated foundation in this simulation. The outside surfaces of the cask are exposed to the ambient environment whose temperature is maintained at a constant temperature of 300 K.

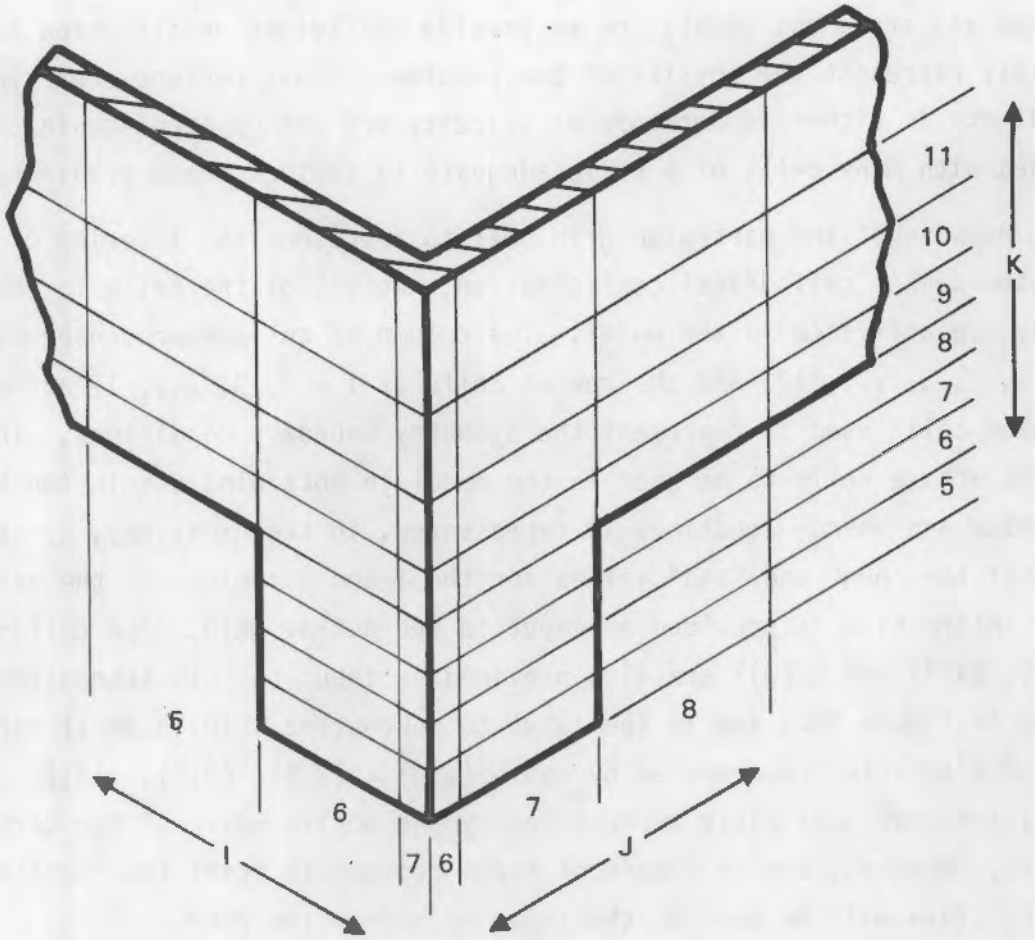


FIGURE 29.6. Basket Support Configuration

29.2 COMPUTATIONAL MODEL

The computational mesh chosen to represent this cask is illustrated in the plan and elevation views of Figures 29.1 and 29.2, respectively. Symmetry should be exploited wherever appropriate to reduce the number of cells required to represent the problem. For this sample problem, only one quarter of the cask need be modeled; hence, the quarter symmetry of the computational grid presented in Figure 29.1. Each K-plane of the computational domain is divided into a 12x12 array of cells representing the I and J directions. In the fuel rod region of the domain, the cell size is chosen so that each cell contains only one rod segment per cell. The remaining cell boundaries are defined either by the interfaces present between regions of dissimilar materials (e.g.,

helium and stainless steel), or to provide sufficient nodalization to adequately represent the physics of the problem. Thus, regions where large gradients in either temperature or velocity are anticipated should be represented with many cells of a scale adequate to capture these gradients.

Because of the cartesian grid used to represent the interior of the cask and the cask's cylindrical configuration, not all of the cells in the 12x12 array are activated in the model. The column of cells represented by I = 1 and J = 1, 2, 3, ..., 12, and the row of cells at I = 2, 3, ..., 12 and J = 12 are phantom cells used to represent the symmetry boundary conditions. The extent of the active cells to be used in the model in obtaining a solution to the momentum and energy equations is represented, in the usual way, by specification of the "beg" and "end" values for the I and J indices of the active cells. This information is provided as input to subroutine GRID. The cell sizes (viz., DX(I) and DY(J)) are also provided as input to this subroutine. As noted in Figure 29.1 and in the input to subroutine GRID, a small portion of the cask interior represented by cells (I,J) = (2,1), (3,1), (12,10), and (12,11) is not explicitly represented by the active cells of the cartesian region. However, the influence of these regions is still incorporated in the model. This will be done in the input to subroutine PROP.

The azimuthal cell spacing in the cylindrical grid is set by the points-of-intersection of the cartesian-region computational grid lines with the cask body inner surface. Phantom cells for this region of the model are represented by the row of cells at IS = 1 and JS = 1, 2, 3, ..., 14 as well as IS = 7, JS = 1, 2, 3, ..., 14. The fact that the outside of the cask has constant radius at all elevations is represented by the uniformity of input to array ISEND(K) for K= 1 through 30. As with the cartesian-grid information, this data is provided in the input to subroutine GRID.

The input pertaining to material properties of the cartesian region is provided as input to subroutine PROP. For the most part, this input is relatively straightforward and reflects the information necessary to set the thermal resistances represented by the cells. However, the thermal resistance of the regions represented by the cells at (I,J) = (2,1), (3,1), (12,10), and (12,11) are incorporated as equivalent film resistances in the input to this

subroutine. RESFY values are assigned to cells (2,1) and (3,1) to model the effective resistance represented by these regions for heat transfer between the active cells (I,J) = (2,2) and (3,2) of the cartesian region and cells (IS,JS) = (2,2) and (2,3) of the cylindrical region. While cartesian-region cells (2,1) and (3,1) are phantom cells, they may still have resistances assigned to them. The effective thermal resistance must be assigned to these cells because HYDRA-II assumes that RESFY(I,J,K) represents a resistance to heat flow between the cell at (I,J,K) and (I,J+1,K). The input to subroutine PROP indicates that these resistances are computed using the series-resistance properties assigned to MT = 41, 42, 43, or 44. MT = 41 and 43 are used to represent the thermal resistance of these cells in the bottom and top lids of the cask. The material making up these cells as well as the adjoining cells in the lids is nodular cast iron (MAT = 5 in the input). PROP has been directed to use the average of the temperature in cell (2,2,K) and that in (2,1,K) for RESFY(2,1,K) when K = 2, 3, 4, 27, 28, and 29. Similarly, HYDRA-II will use the average temperature of cell (3,2,K) and that of cell (3,1,K) in the computation of RESFY(3,1,K) for K = 2, 3, 4, 27, 28, and 29. This has been done by specifying TWF = 0.5 for MT = 41 and 43. For the cells at K = 5 through 26, however, the material making up the interior cells and the walls of the cask are dissimilar. The region excluded from the active cells of the cartesian region is backfill gas (in this case helium) and, for the sake of illustration, is assumed to be more closely represented by the temperature of the cell at either (I,J) = (2,2) or (3,2) rather than that at the cask inner wall. Therefore, by specifying TWF = 0 for MT = 42 and 44, RESFY will be computed using the temperature of the cell at either (I,J,K) = (2,2,K) or (3,2,K) for the cells at K = 5 through 26.

A similar approach has been employed in modeling the thermal resistance present in the communication between the cells at (I,J,K) = (11,10,K), (11,11,K) and the cask-body inner surface. However, since RESFX(I,J,K) represents a thermal resistance between the cells at (I,J,K) and (I+1,J,K), these RESFX's are assigned to the cells at (11,10,K) and (11,11,K). TWF has been set to 0.5 for the RESFX's located in the bottom and top lids (K = 2, 3, 4, 27, 28, and 29), and to 1.0 for the remaining cells (K = 5 through 26). Thus, HYDRA-II will use an average temperature to compute RESFX in the heads (MT = 41 or 43),

and the temperature at either of cells (11,10,K) or (11,11,K) for those cells representing a gas-to-solid film resistance (MT = 45 or 46).

Information pertaining to the heat load presented by the spent fuel rods is provided as part of the input to subroutine THERM. The weighting factors assigned to each rod or rod portion in the model are provided in the "q weighting factor" input section. Note that those cells containing half a rod (viz., along I = 2 and J = 11) have a weight factor of 0.5. The rods without heat generation are located in cells (I,J) = (2,11), (3,8), and (5,10). The corresponding q weighting factor assigned to these cells is 0.0. The remaining cells in which the spent fuel rods are located are assigned a unity q weighting factor. The q-weighting-factor array is initialized to zero for each column of cells of the computational mesh (representing 144 cells in this sample problem - 12x12). Therefore, inputting nonzero q weighting factors serves to "turn-on" power generation in that column. The input to this array illustrates the usage of the overwriting capabilities frequently available during the input to HYDRA-II. For example, note that the cells in the range $3 \leq I \leq 6$ and $7 \leq J \leq 10$ have been assigned a q weighting factor of one. These values are subsequently overwritten with a value of zero to identify those cells within this (I,J) index range for which there is no heat generation. The K-dependence of the rod's heat generation rate is provided next in the input. The values input here reflect the profile illustrated in Figure 29.5.

The next major input section involves that for subroutine PROPS. The thermal resistance represented by the 1-mm gap in the lid-to-side interfaces at both the top and bottom of the cask is represented by means of film resistances. Here, the gap is modeled as a film resistance between the cylindrical-region cells at (IS,JS,K) = (3,JS,K) and (4,JS,K) for JS = 2 through 13, and K = 3, 4, 27, and 28. The gap is specified in the input as having the properties associated with MT = 42. As such, the gap is assumed to be filled with helium gas at a temperature equal to the average of the two adjoining cylindrical-region cells (TWF = 0.5 will use IS = 3 and 4). Moreover, radiation across this gap is accounted for in this model, with both surfaces having emissivities of 0.4.

The symmetry conditions are imposed by specifying very small values for the fluid viscosity (e.g., 10^{-20}) in the input to HYDRO. Conversely, very large values of viscosity (viz. 10^{20}) are used in this simulation to indicate the presence of solids. This input is also provided to subroutine HYDRO. Note that the K-values specified in the input to HYDRO correspond to those of the momentum-solution grid. That is, they are offset by KBP from the K-values used in the formation of the grid and illustrated in Figure 29.1.

Alternatively, very small values (e.g., 10^{-6}) may be provided for the AXI, AYI, and/or AZI quantities in subroutine PROPM, to indicate the presence of the impermeable flow obstruction represented by the solid. This method was also used in this simulation and is provided in the input to PROPM. Specifying the presence of solids by both large viscosities and small area-fractions is redundant, however. It is done in this model for illustration only. Note that, in specifying a very small value for flow-path area-fraction,

- AXI(I,J,K) applies to flow between cells (I,J,K) and (I+1, J,K).
- AYI(I,J,K) applies to flow between cells (I,J,K) and (I,J+1,K).
- AZI(I,J,K) applies to flow between cells (I,J,K) and (I,J,K+1).

As in the input to HYDRO, the K-values specified here correspond to those of the momentum-solution grid.

This simulation reflects a FIXEDP > 0 condition (specified later by the input to subroutine AVG). Therefore, the values loaded in the POR array in the input to subroutine HYDRO will have no impact on the momentum solution. However, they are provided for consistency. Very small values (e.g., 10^{-6}) are loaded into array POR to represent those cells entirely occupied by solids. On the other hand, cells partially occupied by solids have a corresponding free-volume fraction that is a significant fraction of 1. This is the case for the cells representing the fuel assembly region (i.e., $2 < I < 6$, $7 < J < 11$, and $2 < K < 19$). Again, the K-values represented are those of the momentum-solution grid.

Flow through the fuel assemblies will be represented using the Darcy-flow model. Consequently, the permeabilities in each of the flow directions are

provided to arrays PERMX, PERMY, and PERMZ. As with the other input to subroutine PROPM, the K-values listed in this input reflect those of the momentum-solution grid.

Skipping down to the input to REBQ, the model employed for this mode of rebalance is illustrated in Figures 29.7, 29.8, and 29.9. These figures indicate the manner in which the cells of the cartesian-region portion of the model have been collected into coarse cells. The corresponding input follows directly from the information provided in these figures and the discussion of input provided in Chapter 24.0.

29.3 COMPUTER SIMULATIONS

A HYDRA-II input file was generated to simulate this sample problem. A base-case run was first executed using this input. This case serves as a starting point for a series of parametric runs. The changes made in each of these parametric runs are discussed in the following subsections. The intent here is to assess the effectiveness of some routines in obtaining a converged solution.

29.3.1 Base Case Run

Appendix A presents the input file used in the base case run. The salient features of this simulation are as follows:

- no rebalance schemes employed in the energy equation solution
- the pressure iteration scheme employed utilizes REBQ, AF, and PILES, in that order
- run for time-steps 0 to 1000.

The results generated by this run are presented in the output listing provided in Appendix B. A walk-through of the output file follows.

Lines 1 through 839 present an echo of the input file. The results from the simulation are presented in the remainder of the output, lines 841 through 1868. The static pressure field is initialized as indicated in lines 841 through 846. The iteration count, together with the maximum residual and its corresponding (I,J,K) location, are provided in output lines 845 through 846.

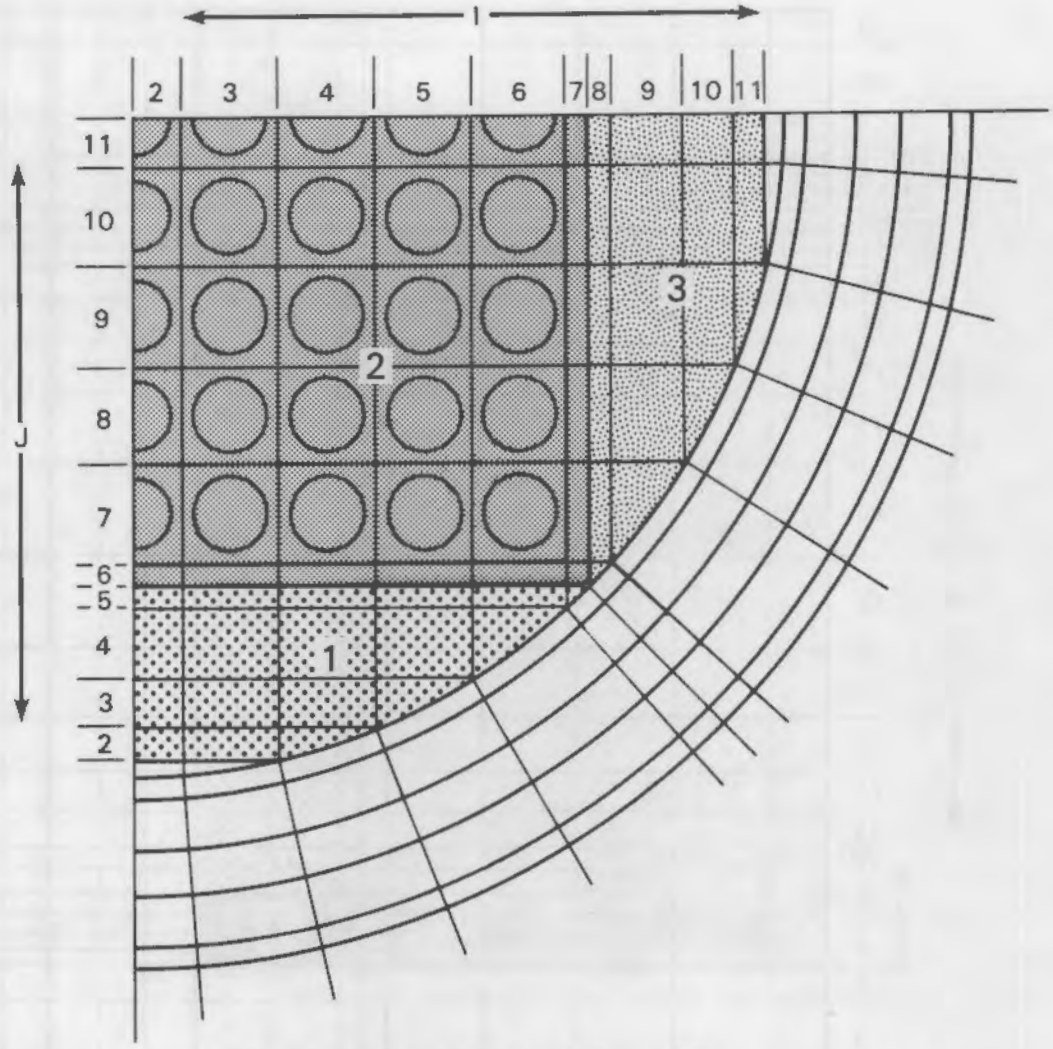


FIGURE 29.7. REBQ Model - KREG

The time-step number, thermal time-step, and maximum inside temperature change are presented next in the output (line 848). As indicated here, HYDRA-II starts with the thermal time-step set to value DTIMEN provided in the input. The maximum inside temperature change (here 1.38 degrees) must be considered in relation to this time-step. The ratio of the maximum inside temperature change to the thermal time-step provides one measure of convergence in the solution. This information is immediately followed by the cell temperatures at the locations requested in the monitoring information provided to subroutine THERM (echoed in lines 222 through 229 of the output). These locations should be chosen to indicate the temperature in particularly

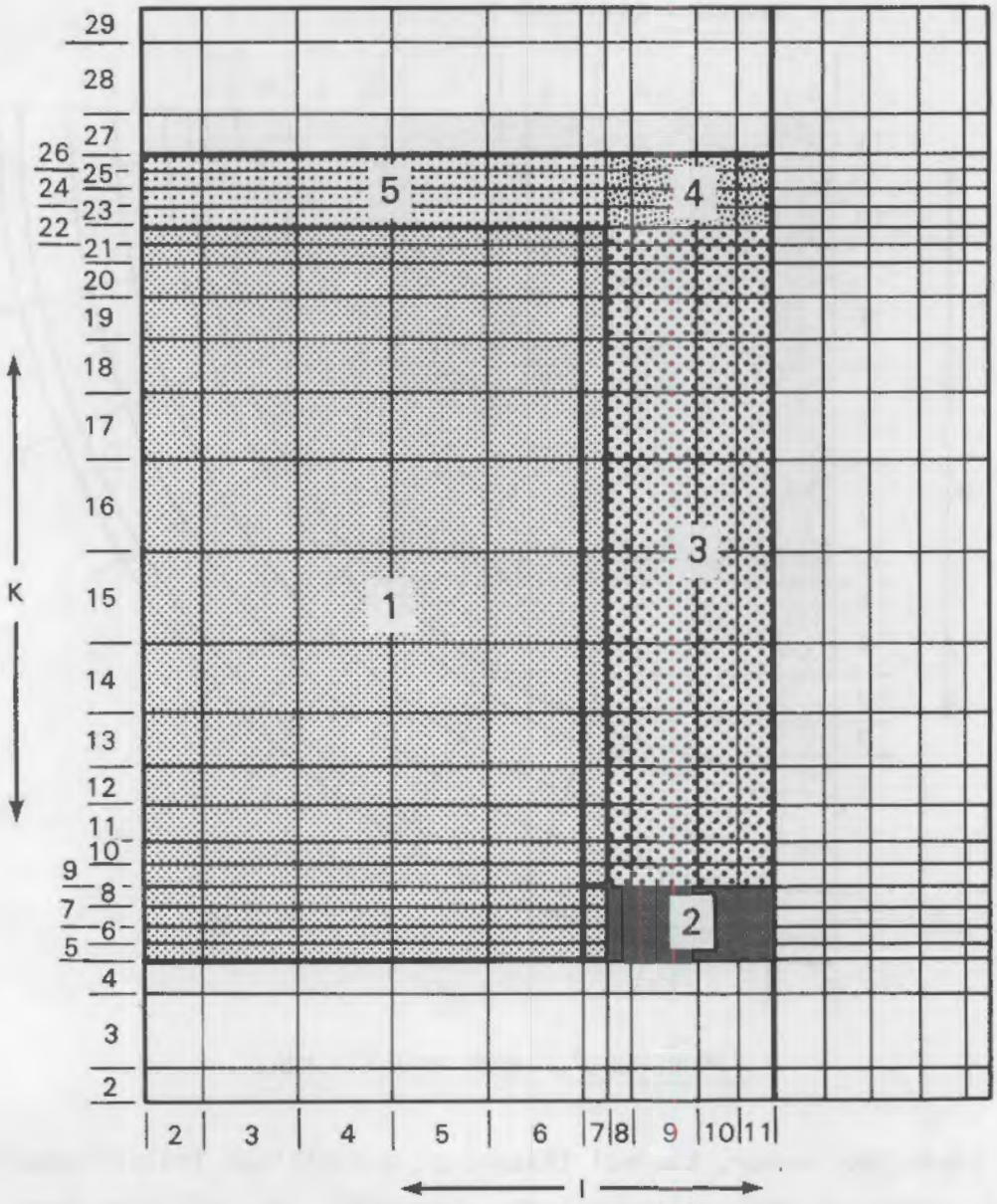


FIGURE 29.8. REBQ Model - JREG

sensitive cells or to illustrate symmetries which are in the model, and should be reflected in the results. For example, the sample problem considered here is symmetric both geometrically and physically (with respect to the energy and momentum equations) about a radial line at -45 degrees from the horizontal (J equal constant) line. Consequently, the cells chosen for temperature

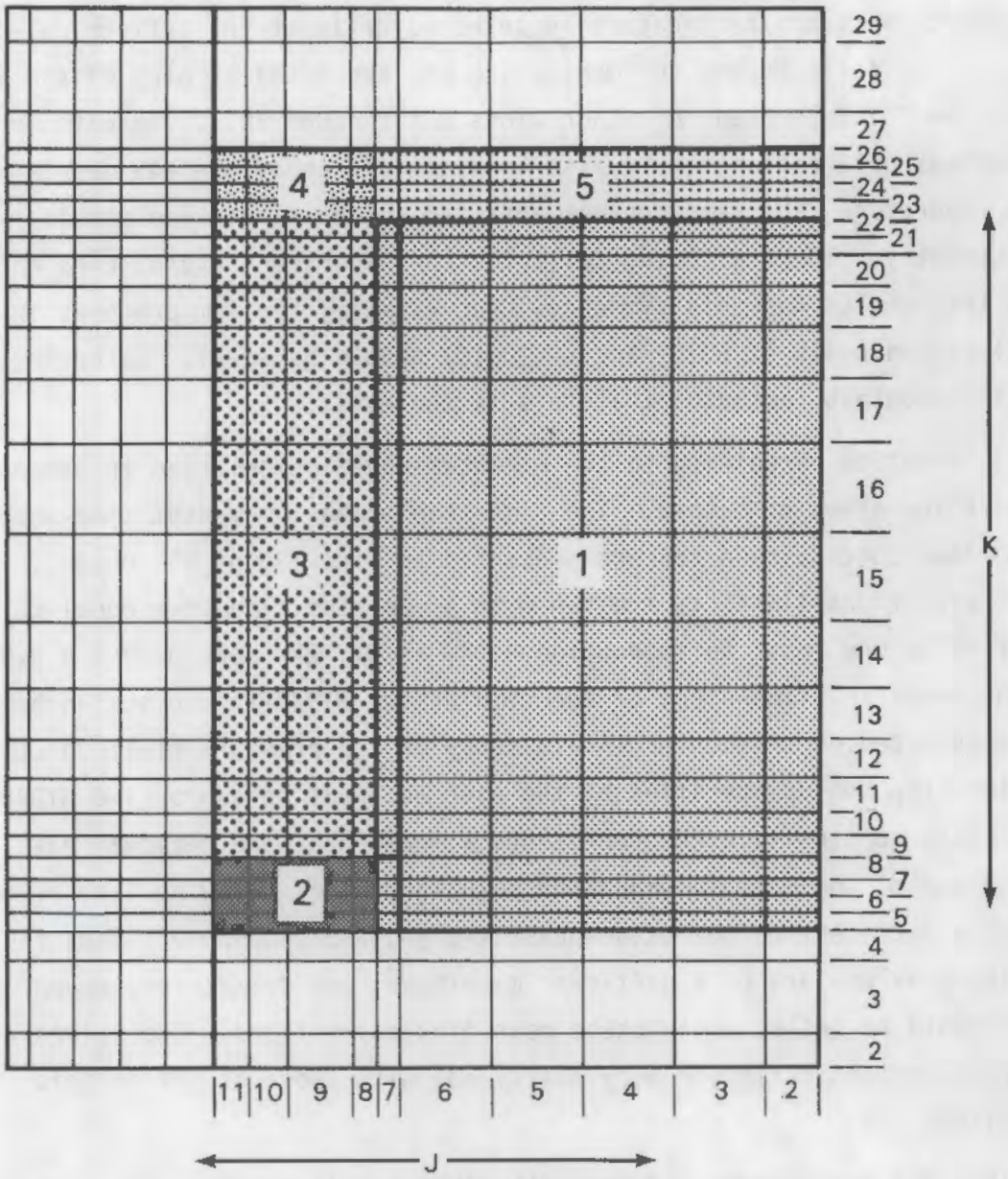


FIGURE 29.9. REBQ Model - IREG

monitoring in this simulation should exhibit this symmetry. The temperatures listed on lines 849 and 850 of the output do exhibit this symmetry [e.g., T(3,4,10) = T(9,10,10)].

The maximum temperature change in the cylindrical-grid region of the model is listed next in the output. The ratio of this value to the thermal time-step provides a measure of the convergence of the solution. The following line of

the output lists the temperature in selected cells of the cylindrical-grid region. The cells chosen for monitoring are specified as part of the input to subroutine TSIDE (echoed in output lines 851 through 852). Results for the cylindrical-grid region should also be symmetric about the -45 degree radial line. Therefore, the temperatures obtained in the simulation should reflect this symmetry. The monitoring cells for the side temperatures were chosen to check the results for this symmetry. For example, the temperatures in cylindrical-region cells (2,5,10) and (2,10,10) should be equal. Referring to line 852 of the output indicates that this is the case.

Information pertaining to the momentum-equation solution is presented in the next few lines of output. The time-step number, momentum time-step, and tilde-phase continuity error are presented in line 853 of the output. As indicated here, HYORA-II starts the run with a momentum time-step equal to that specified in the input to subroutine HYDRO as OTYMEN (here OTYMEN = 0.0001). For the remaining time-steps of the simulation, HYDRA-II chooses an appropriate time-step based on the convergence history of the pressure-field solution and the time-step bounds specified by the user as input to subroutine HYDRO. The tilde-phase continuity error represents a measure of the residual mass in the tilde phase of the momentum-equation solution. The following line of output lists the increment to the tilde-phase x-, y-, and z-component mass fluxes. When these values are of significant magnitude, any symmetries present in the model should be reflected in these mass-flux corrections. The values of DMX should be antisymmetric (or very nearly so) with those of DMY in this simulation.

INFO has been turned off for both PILES and AF in this run. Had they been turned on, however, a more detailed listing of the convergence history would have been provided in the output. For example, the expanded listing of the PILES convergence history presented in lines 873 through 876 in the output appears as follows:

```
206
207                          maximum
208     piles      n          residual   i   j   k
209                1       -0.259e-08   9  11  18
210                1       -0.458e-08   9  10  18
211                1       -0.333e-08   9  10  18
212                2       -0.292e-08   9  10  18
```

```
213              2    -0.308e-08  9 10 18
214              2    -0.265e-08  9  9 18
215              3    -0.239e-08  9 10 18
216              3    -0.244e-08  9 10 18
217              3    -0.228e-08  9  9 18
218              4    -0.201e-08  9 10 18
219              4    -0.203e-08  9 10 18
220              4    -0.209e-08  9  8 17
```

Similarly, when INFO is set at one in AF, the detailed listing appears as

```
33
34
                          pressure          maximum
35      af          n     correction        residual      I  J  k
36                  0   0.0000e+00     -0.1684e-04       7  7 20
37                  1   -0.2102e-03     0.1959e-05       6  7 23
38                  2   -0.5179e-03    -0.8487e-06       3 10 23
39                  3    0.1057e-03     0.4336e-06       3 10 21
40                  4    0.5252e-03     0.2126e-06       9 10 23
41                  5   -0.1227e-03    -0.1352e-06       4  5 18
```

Here, the iteration count is presented along with the pressure correction and (I,J,K) indices corresponding to the cell experiencing the maximum residual in the Poisson equation for the pressure correction field. The maximum residual is the appropriate item to key on with regard to the rate of convergence of the routine. In the listing for AF it appears we have reached the "point of diminishing returns" with regard to the convergence rate. That is, with NMAX= 5 in AF, the "payoff" in the last few iterations is diminishing. Therefore, some computer time may be saved by reducing the allowed number of iterations (NMAX).

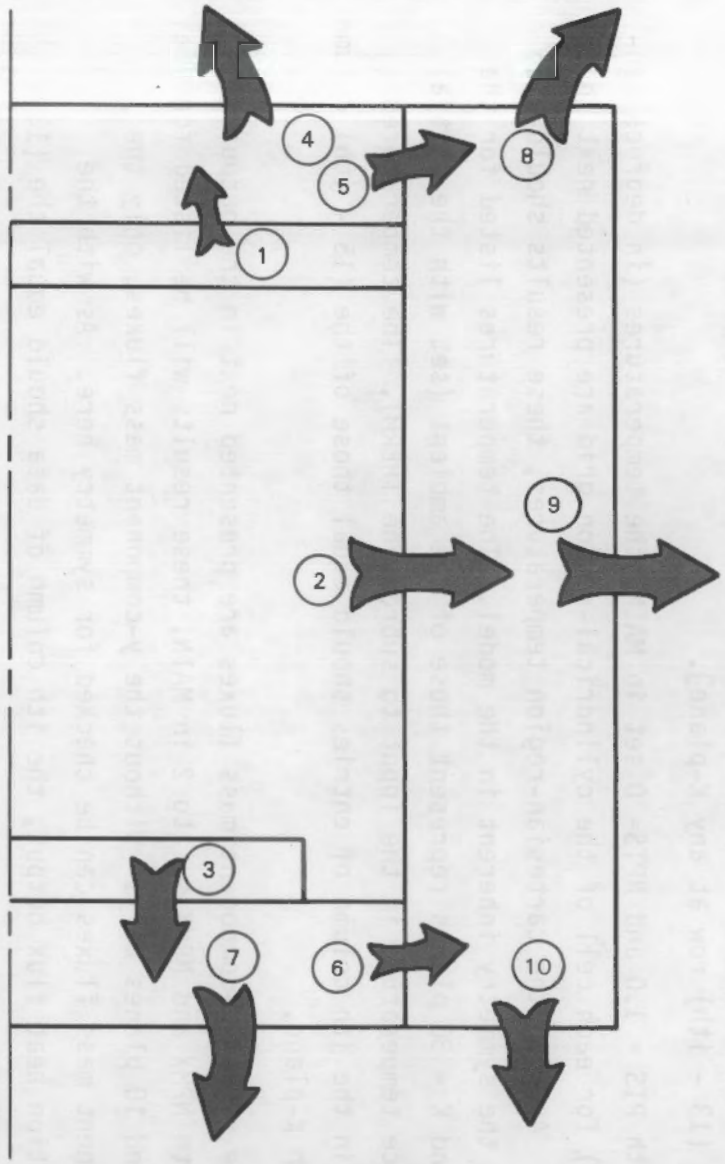
Following the call to PILES (to obtain the final pressure correction field at this time-step) and its usual output, HYDRA-II lists the component mass fluxes at the cell locations specified in the input to subroutine HYDRO (this input has been echoed in lines 691 through 708 of the output). As with the temperatures, these locations should be chosen to exhibit the mass fluxes in particularly sensitive cells or to aid in verifying solution symmetry. Lines 861 and 862 indicate the antisymmetry expected in the solution (when the mass fluxes are of significant magnitude).

Finally, the average pressure (in atmospheres) and continuity error are presented. This average pressure should equal that specified as input to subroutine AVG for the case when FIXEDP > 0 is desired. Otherwise, this value will reflect the average pressure required to obtain the desired FIXEDM

specified in the input to subroutine AVG. The continuity error presented in this line of output represents that of the final mass-flux field at this time-step. This value should be acceptably low, as not only does it represent the presence of a source or sink in the fluid mass, but its effect gets amplified in the solution of the energy equation due to the multiplicative enthalpy term. In fact, often times continuity errors will be manifest first as spurious temperatures, but are actually traceable to the fluid portion of the simulation.

The above output is provided at the first, last, and each of the specified intermediate time-steps of the simulation. Following this, when PQBND has been set to 1.0 in the input to MAIN, HYDRA-II will provide a summary output section in which the heat balances (or lack thereof) for the constituent portions of the model are presented. This section provides an excellent source of information for checking the convergence of the solution. For the most part, the descriptive text provided with each entry in this section is self-explanatory. Some key values in this output section are the "EXCESS POWER ..." entries. These values represent macro-balances on the cask cavity and body. In a converged solution, they should all be zero (or very nearly so). The first value (EXCESS POWER LEAVING CAVITY) represents the difference between the power supplied to the cavity via the decay-heat section of the input to subroutine THERM (echoed in output lines 231 through 274) and the sum of the thermal power from the cavity to the top, side, and bottom of the cask body (output lines 988 through 992). These thermal powers are based on the temperature distribution at the final time-step of this run. The remaining three macro-balances represent the difference between the "THERMAL POWER FROM CAVITY TO ..." and the "THERMAL POWER FROM ... TO AMBIENT (or SIDE)." Figure 29.10 illustrates the location and orientation of each of the energy flow paths listed in this section of the output.

The remainder of the output presents the cell heat fluxes, temperatures, mass fluxes, and pressure corrections at the locations specified by the input to MAIN (echoed in output lines 1020 through 1866). In this simulation, the I- and J-direction heat fluxes for the K = 8 plane (PQI = 1.0 and NPQI = 1 in the input to MAIN) are presented in output lines 1020 through 1050. These values



Index	Descriptor
1	Thermal power from cavity to top
2	Thermal power from cavity to side
3	Thermal power from cavity to bottom
4	Thermal power from top to ambient
5	Thermal power from top to side
6	Thermal power from bottom to side
7	Thermal power from bottom to ambient
8	Thermal power from top of side to ambient
9	Thermal power from side to ambient
10	Thermal power from bottom of side to ambient

FIGURE 29.10. Sample Problem Energy Flow Paths

provide and excellent check of the symmetry properties that should result from this simulation. The I-component heat-flux matrix should be antisymmetric with the J-component heat-flux matrix in this simulation. Therefore, the I = 7 output column for the I-direction heat flux values should equal the negative of J = 5 output column for the J-direction heat flux values (recall that the heat flux in the ith column of output for the I-direction heat flux component represents the heat flux between the cells at I and I+1; those in the jth row of output for the J-direction heat flux component represent that between the cells at J and J+1). The K-direction heat fluxes for the K = 8 plane are provided next in the output (lines 1053 through 1066). These results should be symmetric. For example, the I = 9 column of results should equal the results presented in the J = 4 column.

The cartesian-region temperatures are presented next in the output (output lines 1069 through 1519). This results from setting PT = 1.0 in the input to MAIN. With NPT = 0, the cell temperatures (in degrees Centigrade) are printed for each (I,J,K) value in the cartesian-region grid. These results should also exhibit the symmetry inherent in the model [e.g., the ith column should equal the J = (13 - ith) row at any K-plane].

With PTS = 1.0 and NPTS= 0 set in MAIN, the temperatures (in degrees Centigrade) for each cell of the cylindrical-region grid are presented next in the output. As with the cartesian-region temperatures, these results should also exhibit the symmetry inherent in the model. The temperatures listed for the K = 1 and K = 30 planes represent those of the ambient (set with the initial interface temperature in the input to subroutine THERM). The temperatures listed in the jth column of entries should equal those of the (15 - jth) column for each K-plane.

The x- and z-component mass fluxes are presented next in the output file. With both NPMX and NPMY set to 2 in MAIN, these results will be listed for the K = 2 and 10 planes only. Without the y-component mass fluxes, only the z-component mass fluxes can be checked for symmetry here. As with the K-direction heat flux output, the ith column of data should equal the (13 - ith) row of data for symmetry.

Finally, the pressure change results are presented. These values represent the amount of correction applied to the pressure field in the last time-step.

29.3.2 Base-Case Run Extension

The results from the preceeding base-case run indicated that convergence was not obtained in the first 1000 time-steps (EXCESS POWER LEAVING CAVITY = -78.7 watts). Therefore, for this case the same model and simulation parameters (e.g., no energy-equation rebalance routines invoked) were utilized to extend the run an additional 1000 time steps (i.e., time steps 1001 through 2000) using the restart tape generated by the base-case run. This involved changes to the following variables in the input file and the corresponding routine in which they appear:

*NREAD = 1 in MAIN
*NEWTA = 0 in MAIN
*NDTIME = 0 in MAIN

*NEWT = 0 in THERM
*NEWTC = 0 in THERM

*NEWTS = 0 in TSIDE

*NDTYME = 0 in HYDRO.

This simulation produced the following "EXCESS POWER" values:

- EXCESS POWER LEAVING CAVITY -0.507e+02
- EXCESS POWER LEAVING TOP -0.353e+02
- EXCESS POWER LEAVING SIDE -0.586e+03
- EXCESS POWER LEAVING BOTTOM -0.558e+02.

Clearly, with this iteration scheme, the problem still has not converged.

29.3.3 Invoke REBA

This simulation represents an extension to the base-case run for 1000 time-steps (i.e., time-steps 1001 through 2000) as was done for the preceeding case. However, in this simulation the REBA routine was invoked (by setting

REBAON = 1.0 in MAIN). With REBA switched on and INFO already set to one in the input to REBA, the simulation will produce the following information in the output every time REBA is invoked:

```
839  reba  Info=1  dtmax=0.200e+02  dimax=0.541e+01  ki=3  dbmax=0.934e+00  kb=15  dsmax=0.132e+02  ks=15
```

This line indicates the maximum temperature change was 20 degrees Centigrade. The maximum divergence error for the cartesian region was 5.41 occurring on the third K-plane, the maximum divergence error for the interface region was 0.934 and occurred on the fifteenth K-plane, and the maximum divergence error in the cylindrical region was 13.2 occurring, again, on the fifteenth K-plane.

The simulation produced the following "EXCESS POWER" values:

- EXCESS POWER LEAVING CAVITY 0.558e-01
- EXCESS POWER LEAVING TOP 0.337e-02
- EXCESS POWER LEAVING SIDE 0.346e-02
- EXCESS POWER LEAVING BOTTOM -0.611e-01.

This solution appears to be very close to convergence. The "excess power" values are only one measure of convergence, however. One must also check to ensure that quantities such as the "maximum inside change," "maximum side change," and "continuity error" are sufficiently small.

REBA appears to have been very effective in producing a converged solution for this problem. Other problems may not be as responsive to the implementation of REBA. They may well require an entirely different rebalance scheme (e.g., REBT) to accelerate convergence. In any case, a sufficient number of time-steps should be executed before any rebalance scheme is invoked. This allows the solution to "settle-down" from that provided as the (assumed erroneous) initial guess and reduces the possibility for over-correction brought on by invoking a rebalance routine.

29.3.4 Invoke REBT

This simulation is similar to that presented in the preceeding section 29.3.3 except that REBT is invoked in place of REBA. This is effected by setting REBON = 1.0 in the input to THERM. NREB and NREBN have been set to 100 and 1, respectively, to facilitate comparison with the preceeding cases. The simulation is then extended 1000 time-steps from the base-case run (i.e.,

time-steps 1001 through 2000). With REBT turned on and INFO = 1 specified in the input to REBT, subroutine REBT produces the following output at specified intervals during the run:

76	rebt	info=1	n	dimax	id	djmax	jd	dkmax	kd
77			1	0.437e+01	7	-0.633e+01	2	-0.251e+01	28
78			2	-0.432e+01	11	-0.448e+01	2	0.235e-01	26
79			3	-0.348e+01	11	-0.318e+01	2	0.165e-01	26
80			4	-0.260e+01	11	-0.228e+01	2	0.119e-01	26
81			5	-0.192e+01	11	-0.165e+01	2	0.866e-02	26
82			6	-0.140e+01	11	-0.120e+01	2	0.630e-02	26
83			7	-0.102e+01	11	-0.874e+00	2	0.459e-02	26
84			8	-0.744e+00	11	-0.636e+00	2	0.334e-02	26
85			9	-0.542e+00	11	-0.463e+00	2	0.243e-02	26
86			10	-0.395e+00	11	-0.337e+00	2	0.177e-02	26
87			11	-0.288e+00	11	-0.246e+00	2	0.129e-02	26
88			12	-0.210e+00	11	-0.179e+00	2	0.940e-03	26

These results indicate the iteration number, maximum divergence error in the I-, J-, and K-direction passes, and the corresponding planes on which this error occurred. It appears from these data that more iterations may be required because there is still a substantial reduction in divergence error obtained between the eleventh and twelfth iterations.

The simulation produced the following "EXCESS POWER" values:

- EXCESS POWER LEAVING CAVITY -0.194e+02
- EXCESS POWER LEAVING TOP -0.283e+02
- EXCESS POWER LEAVING SIDE -0.618e+03
- EXCESS POWER LEAVING BOTTOM -0.470e+02.

These values indicate that the run is still far from convergence.

To test the effect of increasing the number of REBT iterations, an additional study was performed in which the above-discussed case was rerun with NMAX changed from 12 to 17. This simulation was again run using the restart tape from the base-case run and carrying the case out an additional 1000 time-steps. A typical REBT output produced by this run is as follows:

123	rebt	info=1	n	dimax	id	djmax	jd	dkmax	kd
124			1	0.114e+02	7	-0.106e+02	2	-0.605e+01	28
125			2	-0.707e+01	11	-0.776e+01	2	0.435e-01	26
126			3	-0.600e+01	11	-0.550e+01	2	0.295e-01	26
127			4	-0.451e+01	11	-0.396e+01	2	0.214e-01	26
128			5	-0.332e+01	11	-0.287e+01	2	0.156e-01	26
129			6	-0.243e+01	11	-0.209e+01	2	0.113e-01	26
130			7	-0.178e+01	11	-0.152e+01	2	0.827e-02	26
131			8	-0.130e+01	11	-0.111e+01	2	0.603e-02	26
132			9	-0.946e+00	11	-0.808e+00	2	0.439e-02	26
133			10	-0.690e+00	11	-0.589e+00	2	0.320e-02	26

134	11	-0.503e+00	11	-0.430e+00	2	0.234e-02	26
135	12	-0.367e+00	11	-0.313e+00	2	0.170e-02	26
136	13	-0.267e+00	11	-0.228e+00	2	0.124e-02	26
137	14	-0.195e+00	11	-0.167e+00	2	0.906e-03	26
138	15	-0.142e+00	11	-0.121e+00	2	0.661e-03	26
139	16	-0.104e+00	11	-0.886e-01	2	0.482e-03	26
140	17	-0.756e-01	11	-0.646e-01	2	0.351e-03	26

Extending the number of iterations by five appears to have reduced the divergence errors by roughly a factor of five. However, as the following "EXCESS POWER" values show, little improvement was realized in the overall energy balance.

- EXCESS POWER LEAVING CAVITY -0.193e+02
- EXCESS POWER LEAVING TOP -0.282e+02
- EXCESS POWER LEAVING SIDE -0.619e+03
- EXCESS POWER LEAVING BOTTOM -0.469e+02.

29.3.5 Timing Runs

In an effort to assess the computational expense incurred when invoking any of the various energy-equation and pressure-field iterative schemes, the base-case run was extended for 10 time-steps. The CPU time spent in each of the various acceleration-scheme subroutines was computed. These times will vary from one machine to another, as well as from one simulation to another. The results presented here have been normalized in an effort to enable generalizing somewhat from the findings of this single simulation. However, the significance of these results will vary on a case-by-case basis. Keep in mind that, while some of the acceleration schemes appear relatively expensive and perhaps ineffective in producing a converged solution for this simulation, they may be very effective under different simulation conditions and, therefore, well worth the added computational expense.

In comparing the relative merits of using REBA or REBT, the results discussed in Section 29.3.3 obtained from invoking REBA are compared with a case in which REBT is invoked. This REBT case differs from that presented in Section 29.3.4 in that NMAX has been changed from 12 to 1. In this way, one can compare the cost per pass through either REBA or REBT. Normalizing on the REBA times, one pass through REBT requires ~25% of the computational time for one REBA pass. NREB and NREBN were set to 100 and 1, respectively, for both of these simulations. Rerunning the REBT simulation with NMAX = 12 results in

each REBT pass costing ~1.6 times one REBA pass. Invoking REBA proved to be very effective in producing a converged solution in the above studies. Its added cost (relative to one REBT pass) was more than offset by the reduced number of total time-steps required to produce a converged solution.

Timings were also performed for the various pressure-field acceleration schemes to assess their relative costs. In this study, each of the four schemes (REBS, REBQ, AF, and PILES) was invoked once per pass with NMAX = 1 where appropriate. Normalizing on the sum of the time spent in each subroutine during one pass through the pressure-iteration scheme, REBS required ~6% of the total, REBQ (with the REBQ model presented in the base-case run) required ~46%, AF required ~14%, and PILES required 34%. INFO was switched off for each of these subroutine passes (and INFONS was less than one in PILES) so that no time was spent generating monitoring information. In the sample problem, the tilde-phase momentum solution had an inconsequential contribution to the total time. However, these timings are still valid and should provide some assistance to the user in setting up an iteration scheme for different simulations. Again however, the user may well encounter situations in which the relative expense of invoking REBQ, for example, may pay big dividends in reducing the number of iterations required to produce a convergent momentum-equation solution. Typically these situations are encountered in large-scale simulations with a high contrast among connectors and where the fluid is experiencing rather significant eddying motion.

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APPENDIX A

SAMPLE PROBLEM INPUT

APPENDIX A

SAMPLE PROBLEM INPUT

```
 1 1 /MAIN - necho
 2 3
 3 HYDRA User's Manual
 4 Appendix Problem Input
 5 Use quarter symmetry
 6 1,1000,200 /MAIN - nrun,nstep,nsinfo
 7 0,1,1000,0 /MAIN - nread,nwrite,ndump,ngraph
 8 1,0,0,0 /MAIN - steady,nobody,notemp,novel
 9 1 /MAIN - newta
10 1,0.1,1.0,0.01 /MAIN - ndtime,dtimen,dtimax,dtimin
11 1,1,1 /MAIN - radcon,radpon,radron
12 0,100,1 /MAIN - rebaon,nreb,nrebn
13 1 /MAIN - necho
14 2 /MAIN - npla2
15 1,8 /MAIN - plane 1 option
16 2,2,10,16 /MAIN - plane 2 option
17 1 /MAIN - necho
18 0,0 /MAIN - pti,npti
19 0,0 /MAIN - ptsi,nptsi
20 1 /MAIN - pqbnd
21 1,1 /MAIN - pqi,npqi
22 0,0 /MAIN - pqrad,npqrad
23 0,0 /MAIN - ptsl,nptsl
24 1,0 /MAIN - pt,npt
25 1,0 /MAIN - pts,npts
26 1,2 /MAIN - pmx,npmx
27 0,0 /MAIN - pmy,npmy
28 1,2 /MAIN - pmz,npmz
29 1,1 /MAIN - pdpf,npdpf
30 D,0 /MAIN - ppf,nppf
31 1 /GRID - necho
```

```
32 1,3,11,10,11 /GRID - symtry,iflatm,iflatp,jflatm,jflatp
33 1 /GRID - necho,ieend
34 1,3,4,5,6,7,8,9,10,11,11,11
35 1 /GRID - inco
36 2,2,2,3,4,5,6,7,8,9,10 /GRID - jebeg
37 1 /GRID - inco
38 11*11 /GRID - jeend
39 1 /GRID - inco
40 4,4,5,6,7,8,9,10,4*11 /GRID - imend
41 1 /GRID - inco
42 4*2,3,4,5,6,7,8,9 /GRID - jmbeg
43 1 /GRID - inco
44 11*11 /GRID - jmend
45 1 /GRID - inco
46 2,3,4,5,6,7,8,9,10,11,2*12 /GRID - icart
47 1 /GRID - inco
48 2*1,2,3,4,5,6,7,8,9,10,11 /GRID - jcart
49 1 /GRID - inco
50 30*6 /GRID - isend
51 1 /GRID - necho
52 1, 0.71501, 4*1.43002, 1, 0.8806025934102, 0.9314908108106,
53    0.6412008982674, 0.4053017678801, 1 /GRID - dx
54 1 /GRID - inco
55 1, 0.4053017678801, 0.6412008982674, 0.9314908108106,
56 0.8806025934102, 1, 4*1.43002, 0.71501, 1 /GRID - dy
57 1 /GRID - inco
58 1, 1, 2, 1, 5*2.5, 3.25, 4.25, 5.5, 7.25, 9.5, 12.75, 12.75,
59 9.5, 7.25, 5.5, 4.25, 3.25, 5*2.5, 1, 2, 1, 1 /GRID - dz
60 1 /GRID - inco
61 10.51480511546, 0.5, 3*1, 0.5, 1 /GRID - dr
62 1 /PROP - necho
63 0, 0, 0, 0, 0, 0, 0 /PROP - nsx,nsfx,nsy,nsfy,nsz,nsfz,info
64 1, 26.1, 0, 0.14, 0.333 /PROP - toph,topl,topv,topc,topn
65 0, 26.1, 0, 0, 0.25 /PROP - both,botl,botv,botc,botn
```

```
1 /PROP - necho
6 /PROP - nmat
low conductivity                          /PROP - text
0.1e-20, 0, 0                             /PROP - ccon(0),ccon(1),ccon(3)
high conductivity                         /PROP - text
0.1e+20, 0, 0                             /PROP - ccon(0),ccon(1),ccon(3)
helium ( backfill gas )                   /PROP - text
0.52e-3, 0.32e-5, 0                       /PROP - ccon(0),ccon(1),ccon(3)
stainless steel                           /PROP - text
0.09215, 0.0001465, 0                     /PROP - ccon(0),ccon(1),ccon(3)
nodular cast iron                         /PROP - text
0.5162, -0.3205e-3, 0                     /PROP - ccon(0),ccon(1),ccon(3)
air ( not used )                          /PROP - text
0.6880e-4, 0.6340e-6, 0                   /PROP - ccon(0),ccon(1),ccon(3)
1 /PROP - necho ( specs def. 01 isotropic and 11 parallel )
5 /PROP - mtmax
1, 1, 1, 1,
2, 1, 2, 1,
3, 1, 3, 1,
4, 1, 4, 1,
5, 1, 5, 1,
30*0 /PROP - specs
1 /PROP - necho ( specs def. 21 series )
7 /PROP - mtmax
40, 1, 1, 0.2, 1, 0.5
41, 5, 0.016, 0, 0, 0.5
42, 3, 0.016, 0, 0, 0.0
43, 5, 0.107, 0, 0, 0.5
44, 3, 0.107, 0, 0, 0.0
45, 3, 0.016, 0, 0, 1
46, 3, 0.107, 0, 0, 1
4*0 /PROP - specs
1 /PROP - necho ( specs def. 31 fuel assembly )
1 /PROP - mtmax
```

```
100 47, 3, 0.9484, 1.072, 1.43002, 0.0209, 0.115, 0, 0
101 41*0 /PROP - specs
102 1 /PROP - necho
103 24, 24 /PROP - nreg,npair
104 1,1, 2,11, 2,29, 1,1,1,
105 2,11, 12,12, 2,29, 1,2,1,
106 2,11, 2,11, 5,26, 1,4,3,
107 2,7, 6,6, 5,22, 1,4,4,
108 7,7, 7,11, 5,22, 1,4,4,
109 2,5, 6,6, 5,8, 1,4,3,
110 7,7, 8,11, 5,8, 1,4,3,
111 2,6, 7,11, 5,22, 1,31,47,
112 2,11, 2,11, 2,4, 1,4,5,
113 2,11, 2,11, 27,29, 1,4,5,
114 2,11, 2,11, 1,1, 1,3,1,
115 2,11, 2,11, 29,29, 1,51,40,
116 2,2, 1,1, 2,4, 1,42,41
117 2,2, 1,1, 5,26, 1,42,42
118 2,2, 1,1, 27,29, 1,42,41
119 3,3, 1,1, 2,4, 1,42,43
120 3,3, 1,1, 5,26, 1,42,44
121 3,3, 1,1, 27,29, 1,42,43
122 11,11, 10,10, 2,4, 1,41,43
123 11,11, 10,10, 5,26, 1,41,46
124 11,11, 10,10, 27,29, 1,41,43
125 11,11, 11,11, 2,4, 1,41,41
126 11,11, 11,11, 5,26, 1,41,45
127 11,11, 11,11, 27,29, 1,41,41
128 791*0 /PROP - index
129 1 /THERM - necho
130 0.5, 5.234, 0.5 /THERM - theta,sphtf,dtemax
131 0, 100, 50 /THERM - rebon,nreb,nrebn
132 1 /THERM - necho
133 8 /THERM - mont
```

```
2,2,10
3,4,10
5,6,10
5,7,10
11,11,10
9,10,10
7,8,10
6,8,10
0,0,0 /THERM - (i,j,k) locations
1 /THERM - necho
0.5, 2,2,7,11
0.5, 3,6,11,11
1, 3,6,7,10
0, 2,2,11,11
0, 3,3,8,8
0, 5,5,10,10
0, 4*0 /THERM - q weighting factor,ibeg,iend,jbeg,jend
1 /THERM - necho
290., 2,6,7,11
0.,0,0,0,0,0 /THERM - group power,ibeg,iend,jbeg,jend
1 /THERM - necho
3*0, 29.5, 44.5, 57, 65, 71, 75, 78, 6*80,
78.5, 69, 55, 39, 24.5, 7*0 /THERM -  relact(k)
1 /THERM - necho
0 /THERM - pqgen
1 /THERM - necho
1,11.5
321, 323, 325, 356, 398, 433, 456, 473, 484, 492,
6*498, 494, 467, 428, 383, 342, 337, 332, 328,
324, 320, 315, 310 /THERM - newt,cenj,tcen(k)
1 /THERM - necho
1, 0
12*300, 336*320, 12*300 /THERM - newtc,cenj,tsl(j,k)
1 /THERM - necho
```

```
168 0 /THERM - ndelta
169 2,6,2,13 /THERM - loc
170 29*0 /THERM -  delta
171 1 /REBT - necho
172 0.1e+6, 12, 1 /REBT - xdtime,nmax,info
173 1 /PROPS - necho
174 0, 0, 0, 0, 0, 0, 0  /PROPS - nsx,nsfx,nsy,nsfy,nsz,nsfz,info
175 1, 26.1, 0, 0.14, 0.333 /PROP - toph,topl,topv,topc,topn
176 0, 26.1, 0, 0, 0.25 /PROP - both,botl,botv,botc,botn
177 1, 118.0, 0, 0.10, 0.333 /PROPS - sideh,sidel,sidev,sidec,siden
178 1 /PROPS - necho
179 6 /PROPS - nmat
180 low conductivity                          /PROPS - text
181 0.1e-20, 0, 0                           /PROPS - ccon0,ccon1,ccon3
182 high conductivity                       /PROPS - text
183 0.1e+20, 0, 0                           /PROPS - ccon0,ccon1,ccon3
184 helium ( backfill gas )                 /PROPS - text
185 0.52e-3, 0.32e-5, 0                     /PROPS - ccon0,ccon1,ccon3
186 stainless steel                         /PROPS - text
187 0.09215, 0.0001465, 0                   /PROPS - ccon0,ccon1,ccon3
188 nodular cast iron                       /PROPS - text
189 0.5162, -0.3205e-3, 0                   /PROPS - ccon0,ccon1,ccon3
190 air ( not used )                        /PROPS - text
191 0.6880e-4, 0.6340e-6, 0                 /PROPS - ccon0,ccon1,ccon3
192 1 /PROPS - necho
193 5 /PROPS - mtmax ( specs def. 01 isotropic and 11 parallel )
194 1, 1, 1, 1,
195 2, 1, 2, 1,
196 3, 1, 3, 1,
197 4, 1, 4, 1,
198 5, 1, 5, 1,
199 80*0 /PROPS - specs
200 1 /PROPS - necho
201 2 /PROPS - mtmax ( specs def. 21 series )
```

```
202 41, 1, 1, 0.2, 1, 0.5
203 42, 3, 0.1, 0.4, 0.4, 0.5
204 88*0 /PROPS - specs
205 1 /PROPS - necho
206 9,9 /PROPS - nreg,npair
207 2,6, 2,13, 2,29, 1,4,5
208 1,1, 2,13, 2,29, 1,1,1
209 2,6, 1,1, 2,29, 1,2,1
210 2,6, 14,14, 2,29, 1,2,1
211 6,6, 2,13, 2,29, 1,53,41
212 2,6, 2,13, 1,1, 1,3,1
213 2,6, 2,13, 29,29, 1,51,41
214 3,3, 2,13, 27,28, 1,41,42
215 3,3, 2,13, 3,4, 1,41,42
216 174*0 /PROPS - index
217 1 /TSIDE - necho
218 1, 300, 5 /TSIDE - newts,tsamb,dtemax
219 1 /TSIDE - necho
220 4 /TSIDE - monts
221 2, 5, 10
222 2, 10, 10
223 4, 5, 10
224 4, 10, 10
225 0, 0, 0 /TSIDE - inco1,inco2,inco3
226 1 /TSIDE - necho
227 0
228 28*0 /TSIDE - ndelta,delta
229 1 /RADC - necho
230 0 /RADC - info
231 1 /RADC - necho
232 2 /RADC - nregs
233 18,1,12,1,1,1
234 18,1,12,2,2,1 /RADC - nkcell,idk,nsurfs,idi,idj,idh
235 1 /RADC - necho
```

```
18, 5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22 /RADC - kcells,kcell,idk
1 /RADC - necho
12, 2,3,4,5,6,7,7,6,5,4,3,2 /RADC - nsurfs,icell(*,1)
12, 6*7,8,9,10,11,2*12 /RADC - nsurfs,icell(*,2)
1 /RADC - necho
12, 6*6,5,4,3,2,2*1 /RADC - nsurfs,jcell(*,1)
12, 11,10,9,8,7,6,6,7,8,9,10,11 /RADC - nsurfs,jcell(*,2)
1 /RADC - necho
12 /RADC - nsurfs
  -1.9315045692589e-12,   1.7814174953191e-13,   1.4676974094935e-13,
   1.0922176415065e-13,   7.4006341878091e-14,   3.3356405994197e-14,
   5.0253274575751e-14,   1.2031398337844e-13,   1.9416884735737e-13,
   3.0864550228951e-13,   4.3775113556598e-13,   2.7887582358759e-13,
   1.7814174953191e-13,  -3.7133637277021e-12,   2.962943649003e-13,
   2.3030898670503e-13,   1.5758935284123e-13,   6.9428148011471e-14,
   1.0569095369594e-13,   2.6880575245861e-13,   4.5921549645403e-13,
   6.9273903046315e-13,   8.1680503895927e-13,   4.3834485368104e-13,
   1.4676974094936e-13,   2.9629436490029e-13,  -3.7607747156819e-12,
   2.6124382424036e-13,   1.9084872556432e-13,   7.9638816576821e-14,
   1.2631628926698e-13,   3.9130616188361e-13,   6.8319780127815e-13,
   7.3024192016115e-13,   5.9565067832659e-13,   2.5926639253403e-13,
   1.0922176415065e-13,   2.3030898670502e-13,   2.6124382424036e-13,
  -3.7649985826716e-12,   2.6203843744515e-13,   1.0928846605724e-13,
   1.9581318305493e-13,   7.6226577648453e-13,   8.0621286265921e-13,
   5.0848068315119e-13,   3.6532275159017e-13,   1.5480184713297e-13,
   7.4006341878094e-14,   1.5758935284123e-13,   1.9084872556433e-13,
   2.6203843744515e-13,  -3.7138156110638e-12,   2.2620983572389e-13,
   6.0877889258035e-13,   1.1130978871075e-12,   4.7003581272239e-13,
   2.8037622095288e-13,   2.2970032442227e-13,   1.0113377982547e-13,
   3.33564059942e-14,     6.9428148011475e-14,   7.9638816576823e-14,
   1.0928846605724e-13,   2.2620983572389e-13,  -2.4867927816087e-12,
   1.2067655762691e-12,   3.2389558541632e-13,   1.5345365652446e-13,
   1.2136129618654e-13,   1.1243369400613e-13,   5.0961300842421e-14,
   5.0253274575752e-14,   1.0569095369594e-13,   1.2631628926699e-13,
```

```
 1.9581318305493e-13,   6.0877889258036e-13,   1.2067655762691e-12,
-3.2096362674751e-12,   3.3513657881041e-13,   2.0146062162007e-13,
 1.6159819783848e-13,   1.4787255007166e-13,   6.9950149691289e-14,
 1.2031398337844e-13,   2.6880575245863e-13,   3.9130616188361e-13,
 7.6226577648454e-13,   1.1130978871075e-12,   3.2389558541632e-13,
 3.3513657881041e-13,  -4.33824795969e-12,     3.6672146643102e-13,
 2.8727032822821e-13,   2.5147402795549e-13,   1.1796041153554e-13,
 1.9416884735739e-13,   4.5921549645397e-13,   6.8319780127817e-13,
 8.0621286265922e-13,   4.7003581272239e-13,   1.5345365652449e-13,
 2.0146062162004e-13,   3.6672146643102e-13,  -4.086691328908e-12,
 3.2052904844429e-13,   2.918754201466e-13,    1.3982029527023e-13,
 3.0864550228951e-13,   6.9273903046317e-13,   7.3024192016117e-13,
 5.084806831512e-13,    2.8037622095288e-13,   1.213612961865e-13,
 1.6159819783847e-13,   2.8727032822825e-13,   3.2052904844429e-13,
-3.8909369156429e-12,   3.2164379379074e-13,   1.5805089413644e-13,
 4.3775113556601e-13,   8.1680503895927e-13,   5.9565067832661e-13,
 3.6532275159019e-13,   2.2970032442223e-13,   1.1243369400614e-13,
 1.478725500717e-13,    2.5147402795551e-13,   2.9187542014654e-13,
 3.2164379379077e-13,  -3.7377436677138e-12,   1.6721425287865e-13,
 2.7887582358759e-13,   4.38344853681e-13,     2.59266392534e-13,
 1.5480184713297e-13,   1.0113377982548e-13,   5.0961300842396e-14,
 6.995014969128e-14,    1.179604115355e-13,    1.3982029527028e-13,
 1.5805089413639e-13,   1.6721425287866e-13,  -1.9363800011156e-12
1 /RADP - necho
2 /RADP - iregs
0.4, 0.25, 7,8, 6,6, 5,8
0.4, 0.25, 7,9, 7,7, 5,8
1 /RADP - necho
2 /RADP - jregs
0.25, 0.4, 6,6, 4,6, 5,8
0.25, 0.4, 7,7, 5,6, 5,8
1 /RADP - necho
5 /RADP - kregs
0.4, 0.25, 2,7, 6,6, 22,27
```

```
0.4, 0.25, 7,7, 7,11, 22,27
0.8, 0.25, 2,6, 7,11, 22,27
0.25, 0.4, 2,5, 6,6, 4,9
0.25, 0.4, 7,7, 8,11, 4,9 /RADP - e1,e2,ibeg,iend,jbeg,jend,kbeg,kend
1 /RADR - necho
2
RADR Input Section
Rod Emittance is 0.8
1 /RADR - necho
25 /RADR - nh, h
  1.000000      0.1710000     0.0000000E+00 0.0000000E+00 0.1710000
  0.0000000E+00 0.0000000E+00 0.0000000E+00 0.2080000     4.9999999E-03
  0.0000000E+00 0.0000000E+00 4.9999999E-03 0.0000000E+00 0.0000000E+00
  0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 4.6000000E-02
  4.6000000E-02 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
  2.000000      0.1710000     0.0000000E+00 0.1710000     0.3880000
  0.0000000E+00 0.0000000E+00 0.2080000     0.2080000     4.9999999E-03
  0.0000000E+00 0.0000000E+00 9.9999998E-03 0.0000000E+00 0.0000000E+00
  0.0000000E+00 0.0000000E+00 0.0000000E+00 4.6000000E-02 4.6000000E-02
  4.6000000E-02 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
  3.000000      0.3880000     0.1710000     0.0000000E+00 0.1710000
  0.2080000     0.0000000E+00 0.0000000E+00 0.2080000     9.9999998E-03
  0.0000000E+00 0.0000000E+00 4.9999999E-03 4.6000000E-02 0.0000000E+00
  0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 4.6000000E-02
  4.6000000E-02 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
  4.000000      0.1710000     0.0000000E+00 0.1710000     0.3420000
  0.0000000E+00 0.0000000E+00 0.2080000     0.2080000     4.9999999E-03
  0.0000000E+00 4.9999999E-03 9.9999998E-03 0.0000000E+00 0.0000000E+00
  0.0000000E+00 0.0000000E+00 4.6000000E-02 4.6000000E-02 4.6000000E-02
  4.6000000E-02 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
  5.000000      0.3420000     0.1710000     0.0000000E+00 0.1710000
  0.2080000     0.0000000E+00 0.0000000E+00 0.2080000     9.9999998E-03
  4.9999999E-03 0.0000000E+00 4.9999999E-03 4.6000000E-02 4.6000000E-02
  0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 4.6000000E-02
```

338	4.6000000E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
339	6.000000	0.1710000	0.0000000E+00	0.1710000	0.3420000
340	0.0000000E+00	0.0000000E+00	0.2080000	0.2080000	0.0000000E+00
341	0.0000000E+00	4.9999999E-03	9.9999998E-03	0.0000000E+00	0.0000000E+00
342	0.0000000E+00	0.0000000E+00	4.6000000E-02	4.6000000E-02	4.6000000E-02
343	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
344	7.000000	0.3420000	0.1710000	0.0000000E+00	0.1710000
345	0.2080000	0.0000000E+00	0.0000000E+00	0.2080000	9.9999998E-03
346	4.9999999E-03	0.0000000E+00	0.0000000E+00	4.6000000E-02	4.6000000E-02
347	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
348	4.6000000E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
349	8.000000	0.0000000E+00	0.0000000E+00	0.1710000	0.3420000
350	0.0000000E+00	0.0000000E+00	0.2080000	0.0000000E+00	0.0000000E+00
351	0.0000000E+00	4.9999999E-03	9.9999998E-03	0.0000000E+00	0.0000000E+00
352	0.0000000E+00	0.0000000E+00	4.6000000E-02	4.6000000E-02	0.0000000E+00
353	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
354	9.000000	0.3420000	0.1710000	0.0000000E+00	0.0000000E+00
355	0.2080000	0.0000000E+00	0.0000000E+00	0.0000000E+00	9.9999998E-03
356	4.9999999E-03	0.0000000E+00	0.0000000E+00	4.6000000E-02	4.6000000E-02
357	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
358	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
359	10.00000	0.3880000	0.3880000	0.3880000	0.3880000
360	0.2080000	0.2080000	0.2080000	0.2080000	9.9999998E-03
361	0.0000000E+00	0.0000000E+00	9.9999998E-03	4.6000000E-02	0.0000000E+00
362	0.0000000E+00	0.0000000E+00	0.0000000E+00	4.6000000E-02	4.6000000E-02
363	4.6000000E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
364	11.00000	0.3880000	0.3420000	0.3880000	0.3420000
365	0.2080000	0.2080000	0.2080000	0.2080000	9.9999998E-03
366	0.0000000E+00	9.9999998E-03	9.9999998E-03	4.6000000E-02	0.0000000E+00
367	0.0000000E+00	4.6000000E-02	4.6000000E-02	4.6000000E-02	4.6000000E-02
368	4.6000000E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
369	12.00000	0.3420000	0.3880000	0.3420000	0.3880000
370	0.2080000	0.2080000	0.2080000	0.2080000	9.9999998E-03
371	9.9999998E-03	0.0000000E+00	9.9999998E-03	4.6000000E-02	4.6000000E-02

372	4.6000000E-02	0.0000000E+00	0.0000000E+00	4.6000000E-02	4.6000000E-02
373	4.6000000E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
374	13.00000	0.3880000	0.3420000	0.3880000	0.3420000
375	0.2080000	0.2080000	0.2080000	0.2080000	0.0000000E+00
376	0.0000000E+00	9.9999998E-03	9.9999998E-03	0.0000000E+00	0.0000000E+00
377	0.0000000E+00	4.6000000E-02	4.6000000E-02	4.6000000E-02	4.6000000E-02
378	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
379	14.00000	0.3420000	0.3880000	0.3420000	0.3880000
380	0.2080000	0.2080000	0.2080000	0.2080000	9.9999998E-03
381	9.9999998E-03	0.0000000E+00	0.0000000E+00	4.6000000E-02	4.6000000E-02
382	4.6000000E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
383	4.6000000E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
384	15.00000	0.0000000E+00	0.3420000	0.3880000	0.3420000
385	0.0000000E+00	0.2080000	0.2080000	0.0000000E+00	0.0000000E+00
386	0.0000000E+00	9.9999998E-03	9.9999998E-03	0.0000000E+00	0.0000000E+00
387	0.0000000E+00	4.6000000E-02	4.6000000E-02	4.6000000E-02	0.0000000E+00
388	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
389	16.00000	0.3420000	0.3880000	0.3420000	0.0000000E+00
390	0.2080000	0.2080000	0.0000000E+00	0.0000000E+00	9.9999998E-03
391	9.9999998E-03	0.0000000E+00	0.0000000E+00	4.6000000E-02	4.6000000E-02
392	4.6000000E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
393	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
394	17.00000	0.3420000	0.3420000	0.3420000	0.3420000
395	0.2080000	0.2080000	0.2080000	0.2080000	9.9999998E-03
396	9.9999998E-03	9.9999998E-03	9.9999998E-03	4.6000000E-02	4.6000000E-02
397	4.6000000E-02	4.6000000E-02	4.6000000E-02	4.6000000E-02	4.6000000E-02
398	4.6000000E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
399	18.00000	0.3420000	0.3420000	0.3420000	0.3420000
400	0.2080000	0.2080000	0.2080000	0.2080000	0.0000000E+00
401	9.9999998E-03	9.9999998E-03	9.9999998E-03	0.0000000E+00	4.6000000E-02
402	4.6000000E-02	4.6000000E-02	4.6000000E-02	4.6000000E-02	4.6000000E-02
403	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
404	19.00000	0.3420000	0.3420000	0.3420000	0.3420000
405	0.2080000	0.2080000	0.2080000	0.2080000	9.9999998E-03

```
406   9.9999998E-03  9.9999998E-03  0.0000000E+00  4.6000000E-02  4.6000000E-02
407   4.6000000E-02  4.6000000E-02  4.6000000E-02  0.0000000E+00  0.0000000E+00
408   4.6000000E-02  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
409  20.00000        0.3420000      0.3420000      0.3420000      0.3420000
410   0.2080000      0.2080000      0.2080000      0.2080000      0.0000000E+00
411   9.9999998E-03  9.9999998E-03  0.0000000E+00  0.0000000E+00  4.6000000E-02
412   4.6000000E-02  4.6000000E-02  4.6000000E-02  0.0000000E+00  0.0000000E+00
413   0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
414  21.00000        0.0000000E+00  0.3420000      0.3420000      0.3420000
415   0.0000000E+00  0.2080000      0.2080000      0.0000000E+00  0.0000000E+00
416   9.9999998E-03  9.9999998E-03  9.9999998E-03  0.0000000E+00  0.0000000E+00
417   4.6000000E-02  4.6000000E-02  4.6000000E-02  4.6000000E-02  0.0000000E+00
418   0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
419  22.00000        0.3420000      0.3420000      0.3420000      0.0000000E+00
420   0.2080000      0.2080000      0.0000000E+00  0.0000000E+00  9.9999998E-03
421   9.9999998E-03  9.9999998E-03  0.0000000E+00  4.6000000E-02  4.6000000E-02
422   4.6000000E-02  4.6000000E-02  0.0000000E+00  0.0000000E+00  0.0000000E+00
423   0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
424  23.00000        0.0000000E+00  0.3420000      0.3420000      0.3420000
425   0.0000000E+00  0.2080000      0.2080000      0.0000000E+00  0.0000000E+00
426   9.9999998E-03  9.9999998E-03  0.0000000E+00  0.0000000E+00  0.0000000E+00
427   4.6000000E-02  4.6000000E-02  4.6000000E-02  0.0000000E+00  0.0000000E+00
428   0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
429  24.00000        0.3420000      0.3420000      0.3420000      0.0000000E+00
430   0.2080000      0.2080000      0.0000000E+00  0.0000000E+00  0.0000000E+00
431   9.9999998E-03  9.9999998E-03  0.0000000E+00  0.0000000E+00  4.6000000E-02
432   4.6000000E-02  4.6000000E-02  0.0000000E+00  0.0000000E+00  0.0000000E+00
433   0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
434  25.00000        0.0000000E+00  0.3420000      0.3420000      0.0000000E+00
435   0.0000000E+00  0.2080000      0.0000000E+00  0.0000000E+00  0.0000000E+00
436   9.9999998E-03  9.9999998E-03  0.0000000E+00  0.0000000E+00  0.0000000E+00
437   4.6000000E-02  4.6000000E-02  0.0000000E+00  0.0000000E+00  0.0000000E+00
438   0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
439 1 /RADR - necho
```

```
440 25 /RADR - nreg,lreg
441 1,1, 2,2, 11,11, 5,22
442 2,2, 3,3, 11,11, 5,22
443 3,3, 2,2, 10,10, 5,22
444 4,4, 4,4, 11,11, 5,22
445 5,5, 2,2, 9,9, 5,22
446 6,6, 5,5, 11,11, 5,22
447 7,7, 2,2, 8,8, 5,22
448 8,8, 6,6, 11,11, 5,22
449 9,9, 2,2, 7,7, 5,22
450 10,10, 3,3, 10,10, 5,22
451 11,11, 4,4, 10,10, 5,22
452 12,12, 3,3, 9,9, 5,22
453 13,13, 5,5, 10,10, 5,22
454 14,14, 3,3, 8,8, 5,22
455 15,15, 6,6, 10,10, 5,22
456 16,16, 3,3, 7,7, 5,22
457 17,17, 4,4, 9,9, 5,22
458 18,18, 5,5, 9,9, 5,22
459 19,19, 4,4, 8,8, 5,22
460 20,20, 5,5, 8,8, 5,22
461 21,21, 6,6, 9,9, 5,22
462 22,22, 4,4, 7,7, 5,22
463 23,23, 6,6, 8,8, 5,22
464 24,24, 5,5, 7,7, 5,22
465 25,25, 6,6, 7,7, 5,22
466 1 /RADR - necho
467 1 /RADR - nt4
468 1, 2,6, 7,11, 5,22 /RADR - lt4
469 1 /REBA - necho
470 20, 1 /REBA - dtmax,info
471 1 /HYDRO - necho
472 1,0,0,0.5,1,-0.5 /HYDRO - convek,epscon,mitmax,thetam,estpf
473 1,0.0001,0.1 /HYDRO - ndtyme,dtymen,dtymax
```

```
474 0,0,1 /HYDRO - newgas,newvel,extrav
475 0.65e+6, 483, 0.6472e-4 /HYDRO - pfref,tfref,dfref
476 0,0,-1 /HYDRO - gx,gy,gz
477 0.7e-4, 0.4e-6 /HYDRO - cvisa,cvisb
478 1 /HYDRO - necho
479 3 /HYDRO - monmx
480 7,9,3 /HYDRO - i,j,k location for monitoring mx
481 4,4,12
482 9,9,12
483 0,0,0
484 1 /HYDRO - necho
485 3 /HYDRO - monmy
486 4,5,3 /HYDRO - i,j,k location for monitoring my
487 9,8,12
488 4,3,12
489 0,0,0
490 1 /HYDRO - necho
491 4 /HYDRD - monmz
492 7,9,3 /HYDRO - i,j,k location for monitoring mz
493 4,6,3
494 4,4,12
495 9,9,12
496 0,0,0
497 1 /HYDRO - necho
498 2 /HYDRO - nreg
499 0.1e-19, 1,1, 2,11, 2,23
500 0.1e-19, 2,11, 12,12, 2,23
501 28*0
502 1 /HYDRO - necho
503 4 /HYDRO - nreg
504 0.1e+21, 6,7, 6,6, 2,5
505 0.1e+21, 2,7, 6,6, 6,19
506 0.1e+21, 7,7, 7,7, 2,5
507 0.1e+21, 7,7, 7,11, 6,19
```

```
508 14*0
509 1 /PROPM - necho
510 10 /PROPM - perm0
511 1 /PROPM - necho
512 0 /PROPM - info
513 -1, 6*0 /PROPM - ax
514 1 /PROPM - necho
515 0 /PROPM - info
516 -1, 6*0 /PROPM - ay
517 1 /PROPM - necho
518 0 /PROPM - info
519 -1, 6*0 /PROPM - az
520 1 /PROPM - necho
521 0 /PROPM - info
522 0.1e-5, 6,7, 6,11, 6,19 /PROPM - axi,ibeg,iend,jbeg,jend,kbeg,kend
523 0.1e-5, 1,6, 6,6, 6,19
524 0.1e-5, 5,7, 6,6, 2,5
525 0.1e-5, 6,7, 7,7, 2,5
526 -1, 6*0
527 1 /PROPM - necho
528 0 /PROPM - info
529 0.1e-5, 2,7, 5,6, 6,19 /PROPM - ayi,ibeg,iend,jbeg,jend,kbeg,kend
530 0.1e-5, 7,7, 7,11, 6,19
531 0.1e-5, 6,7, 5,6, 2,5
532 0.1e-5, 7,7, 7,7, 2,5
533 -1, 6*0
534 1 /PROPM - necho
535 0 /PROPM - info
536 0.1e-5, 2,7, 6,6, 5,19 /PROPM - azi,ibeg,iend,jbeg,jend,kbeg,kend
537 0.1e-5, 7,7, 7,11, 5,19
538 0.1e-5, 6,7, 6,6, 2,5
539 0.1e-5, 7,7, 7,7, 2,5
540 -1, 6*0
541 1 /PROPM - necho
```

```
0 /PROPM - info
0.1e-5, 2,7, 6,6, 6,19 /PROPM - por,ibeg,iend,jbeg,jend,kbeg,kend
0.1e-5, 7,7, 7,11, 6,19
0.1e-5, 6,7, 6,6, 2,5
0.1e-5, 7,7, 7,7, 2,5
0.559, 2,6, 7,11, 2,19
-1, 6*0
1 /PROPM - necho
0 /PROPM - info
0.00466, 2,6, 7,11, 2,19 /PROPM - permx,ibeg,iend,jbeg,jend,kbeg,kend
-1, 6*0
1 /PROPM - necho
0 /PROPM - info
0.00466, 2,6, 7,11, 2,19 /PROPM - permy,ibeg,iend,jbeg,jend,kbeg,kend
-1, 6*0
1 /PROPM - necho
0 /PROPM - info
0.0098, 2,6, 7,11, 2,19 /PROPM - permz,ibeg,iend,jbeg,jend,kbeg,kend
-1, 6*0
1 /PDG - necho
0.8, 0.5e-5 /PDG - wp,optcon
1 /PITER - necho
4, 20 /PITER - nopt,nmax
0, 1, 1 /PITER - rebson,rebqon,afon
1 /PITER - necho
3 /PITER - norda
3,4,1,0 /PITER - norder
1 /PILES - necho
0.2e-8, 1.1, 4, 0 /PILES - epsd,omega,nmax,info
1 /REBQ - necho
2,0 /REBQ - nmax,info
1,1,1 /REBQ - kbound,jbound,ibound
0.1e-20, 0.1e-20, 0.1e-20 /REBQ - akkmin,ajjmin,aiimin
1 /REBQ - necho
```

```
576 3 /REBQ - kreg
577 1,1, 2,7, 2,5
578 2,1, 2,7, 6,11
579 3,0, 8,11, 6,11 /REBQ - krid
580 1 /REBQ - necho
581 6 /REBQ - kbida
582 1, 2,2
583 2, 3,1 /REBQ - kbid
584 1 /REBQ - necho
585 5 /REBQ - jreg
586 1,3, 2,7, 2,19
587 2,1, 8,11, 2,5
588 3,1, 8,11, 6,19
589 4,1, 8,11, 20,23
590 5,0, 2,7, 20,23 /REBQ - jrid
591 1 /REBQ - necho
592 16 /REBQ - jbida
593 1, 2,1, 3,1, 5,3
594 2, 3,3
595 3, 4,3
596 4, 5,-1 /REBQ - jbid
597 1 /REBQ - necho
598 5 /REBQ - ireg
599 1,3, 2,7, 2,19
600 2,1, 8,11, 2,5
601 3,1, 8,11, 6,19
602 4,1, 8,11, 20,23
603 5,0, 2,7, 20,23 /REBQ - irid
604 1 /REBQ - necho
605 16 /REBQ - ibida
606 1, 2,2, 3,2, 5,3
607 2, 3,3
608 3, 4,3
609 4, 5,-2
```

```
 610 1 /AF - necho
 611 5,0 /AF - nmax,info
 612 1 /AVG - necho
 613 0, 0.496e+6 /AVG - fixedm,fixedp
*
```

APPENDIX B

SAMPLE PROBLEM OUTPUT

APPENDIX B

SAMPLE PROBLEM OUTPUT

```
                                Appendix Problem Input
                                Use quarter symmetry
                                                    run number   1

main    nrun= 1   nstep=1000   nsinfo= 200
main    nread=0   nwrite=1   ndump=1000
main    steady=1.0   nobody=0   notemp=0   novel=0
main    newta=1
main    ndtime=1   dtimen=0.100e+00   dtimax=0.100e+01   dtimin=0.100e-01
main    radcon=1.0   radpon=1.0   radron=1.0
main    rebaon=0.0   nreb=100   nrebn=  1

main    print plane options are  2 maximum allowed is  4 with  5 planes per option
        option  1:  8
        option  2:  2 10

main    print arrays or info
        pti=0.0   npti= 0
        ptsi=0.0   nptsi= 0
        pqbnd=1.0
        pqi=1.0   npqi= 1
        pqrad=0.0   npqrad= 0
        ptsi=0.0   nptsi= 0
        pt=1.0   npt= 0
        pts=1.0   npts= 0
        pmx=1.0   npmx= 2
        pmy=0.0   npmy= 0
        pmz=1.0   npmz= 2
        pdpf=1.0   npdpf= 1
        ppf=0.0   nppf= 0

grid    symtry=1.0   iflatm= 3   iflatp=11   jflatm=10   jflatp=11

grid                ieend(j)   jebeg(i)   jeend(i)   imend(j)   jmbeg(i)   jmend(i)   icart(js)   jcart(js)   isend(k)
                1         1          2         11          4          2         11          **          **          6
                2         3          2         11          4          2         11          2           1           6
                3         4          2         11          5          2         11          3           1           6
                4         5          3         11          6          2         11          4           2           6
                5         6          4         11          7          3         11          5           3           6
                6         7          5         11          8          4         11          6           4           6
                7         8          6         11          9          5         11          7           5           6
                8         9          7         11         10          6         11          8           6           6
```

46		9	10	8	11	11	7	11	9	7	6
47		10	11	9	11	11	8	11	10	8	6
48		11	11	10	11	11	9	11	11	9	6
49		12	11	**	**	11	**	**	12	10	6
50		13	**	**	**	**	**	**	12	11	6
51		14	**	**	**	**	**	**	**	**	6
52		15	**	**	**	**	**	**	**	**	6
53		16	**	**	**	**	**	**	**	**	6
54		17	**	**	**	**	**	**	**	**	6
55		18	**	**	**	**	**	**	**	**	6
56		19	**	**	**	**	**	**	**	**	6
57		20	**	**	**	**	**	**	**	**	6
58		21	**	**	**	**	**	**	**	**	6
59		22	**	**	**	**	**	**	**	**	6
60		23	**	**	**	**	**	**	**	**	6
61		24	**	**	**	**	**	**	**	**	6
62		25	**	**	**	**	**	**	**	**	6
63		26	**	**	**	**	**	**	**	**	6
64		27	**	**	**	**	**	**	**	**	6
65		28	**	**	**	**	**	**	**	**	6
66		29	**	**	**	**	**	**	**	**	6
67		30	**	**	**	**	**	**	**	**	6
68											
69	grid		dx(i)		dy(j)		dz(k)		dr(is)		dtheta(js)
70		1	0.100000000e+01		0.100000000e+01		0.100000000e+01		0.105148051e+02		0.389913964e+01
71		2	0.715010000e+00		0.405301768e+00		0.100000000e+01		0.500000000e+00		0.389913964e+01
72		3	0.143002000e+01		0.641200898e+00		0.200000000e+01		0.100000000e+01		0.787188093e+01
73		4	0.143002000e+01		0.931490811e+00		0.100000000e+01		0.100000000e+01		0.810594772e+01
74		5	0.143002000e+01		0.880602593e+00		0.250000000e+01		0.100000000e+01		0.854765268e+01
75		6	0.143002000e+01		0.100000000e+01		0.250000000e+01		0.500000000e+00		0.930983760e+01
76		7	0.100000000e+01		0.143002000e+01		0.250000000e+01		0.100000000e+01		0.726554143e+01
77		8	0.880602593e+00		0.143002000e+01		0.250000000e+01		**********		0.726554143e+01
78		9	0.931490811e+00		0.143002000e+01		0.250000000e+01		**********		0.930983760e+01
79		10	0.641200898e+00		0.143002000e+01		0.325000000e+01		**********		0.854765268e+01
80		11	0.405301768e+00		0.715010000e+00		0.425000000e+01		**********		0.810594772e+01
81		12	0.100000000e+01		0.100000000e+01		0.550000000e+01		**********		0.787188093e+01
82		13	**********		**********		0.725000000e+01		**********		0.389913964e+01
83		14	**********		**********		0.950000000e+01		**********		0.389913964e+01
84		15	**********		**********		0.127500000e+02		**********		**********
85		16	**********		**********		0.127500000e+02		**********		**********
86		17	**********		**********		0.950000000e+01		**********		**********
87		18	**********		**********		0.725000000e+01		**********		**********
88		19	**********		**********		0.550000000e+01		**********		**********
89		20	**********		**********		0.425000000e+01		**********		**********
90		21	**********		**********		0.325000000e+01		**********		**********
91		22	**********		**********		0.250000000e+01		**********		**********

```
                23     **************     **************     0.250000000e+01     **************     **************
                24     **************     **************     0.250000000e+01     **************     **************
                25     **************     **************     0.250000000e+01     **************     **************
                26     **************     **************     0.250000000e+01     **************     **************
                27     **************     **************     0.100000000e+01     **************     **************
                28     **************     **************     0.200000000e+01     **************     **************
                29     **************     **************     0.100000000e+01     **************     **************
                30     **************     **************     0.100000000e+01     **************     **************
                                                                                                     0.900000000e+02

 prop    nsx=  0   nsfx=  0   nsy=  0   nsfy=  0   nsz=  0   nsfz=  0   info=0

 prop    toph=1.0   topi=0.261e+02   topv=0.000e+00   topc=0.140e+00   topn=0.333e+00
 prop    both=0.0   boti=0.261e+02   botv=0.000e+00   botc=0.000e+00   botn=0.250e+00

 prop    nmat=  6   maximum current dimension for nmat is  10
 prop    ccon0,ccon1,ccon3                  material thermal conductivity, w/cm-k
                          k(mat)=  ccon0(mat)+  ccon1(mat)*t+  ccon3(mat)*t*t*t
                             1   (0.1000e-20)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   low conductivity
                             2   (0.1000e+20)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   high conductivity
                             3   (0.5200e-03)+(0.3200e-05)*t+(0.0000e+00)*t*t*t   helium ( backfill gas )
                             4   (0.9215e-01)+(0.1465e-03)*t+(0.0000e+00)*t*t*t   stainless steel
                             5   (0.5162e+00)+(-.3205e-03)*t+(0.0000e+00)*t*t*t   nodular cast iron
                             6   (0.6880e-04)+(0.6340e-06)*t+(0.0000e+00)*t*t*t   air ( not used )

                               maximum number of material types is currently  50
                               maximum array dimension of specs is currently  50

                            ***composite definition 01 isotropic and 11 parallel***
 prop    mtmax=  5
 prop    specs                                  mt   mats   mat     width
                                                 1     1     1    0.1000e+01
                                                 2     1     2    0.1000e+01
                                                 3     1     3    0.1000e+01
                                                 4     1     4    0.1000e+01
                                                 5     1     5    0.1000e+01

                                          computed coefficients from specs array
                                          mt      c0          c1          c3
                                           1  0.1000e-20  0.0000e+00  0.0000e+00
                                           2  0.1000e+20  0.0000e+00  0.0000e+00
                                           3  0.5200e-03  0.3200e-05  0.0000e+00
                                           4  0.9215e-01  0.1465e-03  0.0000e+00
                                           5  0.5162e+00 -0.3205e-03  0.0000e+00

                                           ***composite definition 21 series***
```

```
 prop    mtmax=  7
 prop    specs                    mt    mat   width        e1           e2           twf
                                  40     1  0.1000e+01  0.2000e+00  0.1000e+01  0.5000e+00
                                  41     5  0.1600e-01  0.0000e+00  0.0000e+00  0.5000e+00
                                  42     3  0.1600e-01  0.0000e+00  0.0000e+00  0.0000e+00
                                  43     5  0.1070e+00  0.0000e+00  0.0000e+00  0.5000e+00
                                  44     3  0.1070e+00  0.0000e+00  0.0000e+00  0.0000e+00
                                  45     3  0.1600e-01  0.0000e+00  0.0000e+00  0.1000e+01
                                  46     3  0.1070e+00  0.0000e+00  0.0000e+00  0.1000e+01

                                       computed coefficients from specs array
                                       mt     c0          c1          c3
                                       40  0.1000e-20  0.0000e+00  0.4536e-11
                                       41  0.3226e+02 -0.2003e-01  0.0000e+00
                                       42  0.3250e-01  0.2000e-03  0.0000e+00
                                       43  0.4824e+01 -0.2995e-02  0.0000e+00
                                       44  0.4860e-02  0.2991e-04  0.0000e+00
                                       45  0.3250e-01  0.2000e-03  0.0000e+00
                                       46  0.4860e-02  0.2991e-04  0.0000e+00

                                    ***composite definition 31 fuel assembly***
 prop    mtmax=  1
 prop    specs    mt    mta   fuelod      cladod      pitch       cfuel       cclad       erod        egap
                  47     3  0.9484e+00  0.1072e+01  0.1430e+01  0.2090e-01  0.1150e+00  0.0000e+00  0.0000e+00

                                       computed coefficients from specs array
                  mt     c0          c1          c3          x1          x2          z1          z2          z3
                  47  0.5200e-03  0.3200e-05  0.0000e+00  0.1130e+01  0.1701e+01  0.3455e+00  0.9591e-01  0.5586e+00

                                       ***available composite definitions***
                                     group                 id
                                  01 isotropic              1 resx
                                                            2 resy
                                                            3 resz
                                                            4 resx,resy,resz
                                  11 parallel              11 resx, x-y plane
                                                           12 resx, x-z plane
                                                           13 resy, x-y plane
                                                           14 resy, y-z plane
                                                           15 resz, x-z plane
                                                           16 resz, y-z plane
                                  21 series                21 resx
                                                           22 resy
                                                           23 resz
                                  31 fuel assembly         31 resx,resy,resz for rod array
                                  41 film resistance       41 resfx
```

```
                                                                  42 resfy
                                                                  43 resfz
                                        51 exterior convection    51 resfz for top of cask
                                           and radiation          52 resfz for bottom of cask

 prop    nreg=  24   npair=  24   maximum current dimensions for nreg and npair are    25    30
 prop    index          cell location
                ibeg iend  jbeg jend  kbeg kend   npair     id   mt     id   mt     id   mt     id   mt     id   mt
                  1    1     2   11     2   29       1      1    1
                  2   11    12   12     2   29       1      2    1
                  2   11     2   11     5   26       1      4    3
                  2    7     6    6     5   22       1      4    4
                  7    7     7   11     5   22       1      4    4
                  2    5     6    6     5    8       1      4    3
                  7    7     8   11     5    8       1      4    3
                  2    6     7   11     5   22       1     31   47
                  2   11     2   11     2    4       1      4    5
                  2   11     2   11    27   29       1      4    5
                  2   11     2   11     1    1       1      3    1
                  2   11     2   11    29   29       1     51   40
                  2    2     1    1     2    4       1     42   41
                  2    2     1    1     5   26       1     42   42
                  2    2     1    1    27   29       1     42   41
                  3    3     1    1     2    4       1     42   43
                  3    3     1    1     5   26       1     42   44
                  3    3     1    1    27   29       1     42   43
                 11   11    10   10     2    4       1     41   43
                 11   11    10   10     5   26       1     41   46
                 11   11    10   10    27   29       1     41   43
                 11   11    11   11     2    4       1     41   41
                 11   11    11   11     5   26       1     41   45
                 11   11    11   11    27   29       1     41   41

 therm   theta=0.5   sphtf=0.5234e+01   dtemax=0.500e+00
 therm   rebon=0.0   nreb=100   nrebn= 50

 therm   monitor cells= 8   maximum number currently allowed is 12
                                                m   i  j  k
                                                1   2  2 10
                                                2   3  4 10
                                                3   5  6 10
                                                4   5  7 10
                                                5  11 11 10
                                                6   9 10 10
                                                7   7  8 10
                                                8   6  8 10
```

therm	q weighting factor	ibeg	iend	jbeg	jend
	0.5000e+00	2	2	7	11
	0.5000e+00	3	6	11	11
	0.1000e+01	3	6	7	10
	0.0000e+00	2	2	11	11
	0.0000e+00	3	3	8	8
	0.0000e+00	5	5	10	10

(cell location: ibeg, iend, jbeg, jend)

therm	group power	ibeg	iend	jbeg	jend
	0.2900e+03	2	6	7	11

(cell location: ibeg, iend, jbeg, jend)

therm	k	relact(k)
	2	0.0000e+00
	3	0.0000e+00
	4	0.0000e+00
	5	0.2950e+02
	6	0.4450e+02
	7	0.5700e+02
	8	0.6500e+02
	9	0.7100e+02
	10	0.7500e+02
	11	0.7800e+02
	12	0.8000e+02
	13	0.8000e+02
	14	0.8000e+02
	15	0.8000e+02
	16	0.8000e+02
	17	0.8000e+02
	18	0.7850e+02
	19	0.6900e+02
	20	0.5500e+02
	21	0.3900e+02
	22	0.2450e+02
	23	0.0000e+00
	24	0.0000e+00
	25	0.0000e+00
	26	0.0000e+00
	27	0.0000e+00
	28	0.0000e+00
	29	0.0000e+00

total generated power=0.116000e+04, watts

```
 276
 277      therm   pqgen=0.0
 278
 279      therm   newt=1   cenj=11.5     k     tcen(k)
 280                                      2   0.321e+03
 281                                      3   0.323e+03
 282                                      4   0.325e+03
 283                                      5   0.356e+03
 284                                      6   0.398e+03
 285                                      7   0.433e+03
 286                                      8   0.456e+03
 287                                      9   0.473e+03
 288                                     10   0.484e+03
 289                                     11   0.492e+03
 290                                     12   0.498e+03
 291                                     13   0.498e+03
 292                                     14   0.498e+03
 293                                     15   0.498e+03
 294                                     16   0.498e+03
 295                                     17   0.498e+03
 296                                     18   0.494e+03
 297                                     19   0.467e+03
 298                                     20   0.428e+03
 299                                     21   0.383e+03
 300                                     22   0.342e+03
 301                                     23   0.337e+03
 302                                     24   0.332e+03
 303                                     25   0.328e+03
 304                                     26   0.324e+03
 305                                     27   0.320e+03
 306                                     28   0.315e+03
 307                                     29   0.310e+03
 308
 309      therm   newtc=1   info=0                  * * * Initial Interface Temp., deg. K * * *
 310
 311      therm   ndelta=0
 312      therm   ibeg= 2   iend= 6   jbeg= 2   jend=13
 313                                      k    delta(k)
 314                                      2   0.000e+00
 315                                      3   0.000e+00
 316                                      4   0.000e+00
 317                                      5   0.000e+00
 318                                      6   0.000e+00
 319                                      7   0.000e+00
 320                                      8   0.000e+00
 321                                      9   0.000e+00
```

```
322                                    10   0.000e+00
323                                    11   0.000e+00
324                                    12   0.000e+00
325                                    13   0.000e+00
326                                    14   0.000e+00
327                                    15   0.000e+00
328                                    16   0.000e+00
329                                    17   0.000e+00
330                                    18   0.000e+00
331                                    19   0.000e+00
332                                    20   0.000e+00
333                                    21   0.000e+00
334                                    22   0.000e+00
335                                    23   0.000e+00
336                                    24   0.000e+00
337                                    25   0.000e+00
338                                    26   0.000e+00
339                                    27   0.000e+00
340                                    28   0.000e+00
341                                    29   0.000e+00
342
343     rebt    xdtime=0.100e+06   nmax=12   info=1
344
345     props   nsx=  0   nsfx=  0   nsy=  0   nsfy=  0   nsz=  0   nsfz=  0   info=0
346
347     props   toph=1.0   topl=0.261e+02   topv=0.000e+00   topc=0.140e+00   topn=0.333e+00
348     props   both=0.0   botl=0.261e+02   botv=0.000e+00   botc=0.000e+00   botn=0.250e+00
349     props   sideh=1.0   sidel=0.118e+03   sidev=0.000e+00   sidec=0.100e+00   siden=0.333e+00
350
351     props   nmat=  6   maximum current dimension for nmat is  20
352     props   ccon0,ccon1,ccon3                material thermal conductivity, w/cm-k
353                             k(mat)=  ccon0(mat)+  ccon1(mat)*t+  ccon3(mat)*t*t*t
354                                1   (0.1000e-20)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   low conductivity
355                                2   (0.1000e+20)+(0.0000e+00)*t+(0.0000e+00)*t*t*t   high conductivity
356                                3   (0.5200e-03)+(0.3200e-05)*t+(0.0000e+00)*t*t*t   helium ( backfill gas )
357                                4   (0.9215e-01)+(0.1465e-03)*t+(0.0000e+00)*t*t*t   stainless steel
358                                5   (0.5162e+00)+(-.3205e-03)*t+(0.0000e+00)*t*t*t   nodular cast iron
359                                6   (0.6880e-04)+(0.6340e-06)*t+(0.0000e+00)*t*t*t   air ( not used )
360
361                                   maximum number of material types is currently  30
362                                   maximum array dimension of specs is currently 100
363     .
364                                  ***composite definition 01 isotropic and 11 parallel***
365     props   mtmax=  5
366     props   specs                                  mt   mats   mat     width
367                                                     1     1     1    0.1000e+01
```

```
                                    2     1     2    0.1000e+01
                                    3     1     3    0.1000e+01
                                    4     1     4    0.1000e+01
                                    5     1     5    0.1000e+01

                                  computed coefficients from specs array
                                  mt      c0          c1          c3
                                   1  0.1000e-20  0.0000e+00  0.0000e+00
                                   2  0.1000e+20  0.0000e+00  0.0000e+00
                                   3  0.5200e-03  0.3200e-05  0.0000e+00
                                   4  0.9215e-01  0.1465e-03  0.0000e+00
                                   5  0.5162e+00 -0.3205e-03  0.0000e+00

                                   ***composite definition 21 series***
 props   mtmax=  2
 props   specs                mt    mat   width        e1          e2          twf
                              41     1  0.1000e+01  0.2000e+00  0.1000e+01  0.5000e+00
                              42     3  0.1000e+00  0.4000e+00  0.4000e+00  0.5000e+00

                                  computed coefficients from specs array
                                  mt      c0          c1          c3
                                  41  0.1000e-20  0.0000e+00  0.4536e-11
                                  42  0.5200e-02  0.3200e-04  0.5670e-11

                                  ***available composite definitions***
                                    group                    id
                                 01 isotropic                 1 resx
                                                              2 resy
                                                              3 resz
                                                              4 resx,resy,resz
                                 11 parallel                 11 resx, x-y plane
                                                             12 resx, x-z plane
                                                             13 resy, x-y plane
                                                             14 resy, y-z plane
                                                             15 resz, x-z plane
                                                             16 resz, y-z plane
                                 21 series                   21 resx
                                                             22 resy
                                                             23 resz
                                 41 film resistance          41 resfx
                                                             42 resfy
                                                             43 resfz
                                 51 exterior convection      51 resfz for top of cask
                                    and radiation            52 resfz for bottom of cask
                                                             53 resfx for side of cask
```

```
 414    props   nreg=    9   npair=    9   maximum current dimensions for nreg and npair are    25    40
 415    props   index          cell location
 416                    lbeg  iend   jbeg  jend   kbeg  kend    npair      id   mt      id   mt      id   mt      id   mt      id   mt
 417                      2     6      2    13      2    29        1       4    5
 418                      1     1      2    13      2    29        1       1    1
 419                      2     6      1     1      2    29        1       2    1
 420                      2     6     14    14      2    29        1       2    1
 421                      6     6      2    13      2    29        1      53   41
 422                      2     6      2    13      1     1        1       3    1
 423                      2     6      2    13     29    29        1      51   41
 424                      3     3      2    13     27    28        1      41   42
 425                      3     3      2    13      3     4        1      41   42
 426
 427    tside   newts=1   tsamb=0.300e+03   dtemax=0.500e+01
 428
 429    tside   monitor cells= 4   maximum number currently allowed is  4
 430                                                    m   i   j   k
 431                                                    1   2   5  10
 432                                                    2   2  10  10
 433                                                    3   4   5  10
 434                                                    4   4  10  10
 435
 436    tside   ndelta=0                 k    delta(k)
 437                                     2   0.000e+00
 438                                     3   0.000e+00
 439                                     4   0.000e+00
 440                                     5   0.000e+00
 441                                     6   0.000e+00
 442                                     7   0.000e+00
 443                                     8   0.000e+00
 444                                     9   0.000e+00
 445                                    10   0.000e+00
 446                                    11   0.000e+00
 447                                    12   0.000e+00
 448                                    13   0.000e+00
 449                                    14   0.000e+00
 450                                    15   0.000e+00
 451                                    16   0.000e+00
 452                                    17   0.000e+00
 453                                    18   0.000e+00
 454                                    19   0.000e+00
 455                                    20   0.000e+00
 456                                    21   0.000e+00
 457                                    22   0.000e+00
 458                                    23   0.000e+00
 459                                    24   0.000e+00
```

```
                                        25   0.000e+00
                                        26   0.000e+00
                                        27   0.000e+00
                                        28   0.000e+00
                                        29   0.000e+00

     radc    info=0

     radc    nregs=  2   maximum current dimension for nregs is  2
     radc    index            region   number of     k-cell     number of     i-cell      j-cell      h
                              number    k cells    identifier   surfaces    identifier  identifier  identifier
                                 1         18           1          12           1           1           1
                                 2         18           1          12           2           2           1

     radc    kcell   idk   k-cells:
                      1     18   :  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22

     radc    icell   idl   i-cells:
                      1     12   :  2  3  4  5  6  7  7  6  5  4  3  2
                      2     12   :  7  7  7  7  7  7  8  9 10 11 12 12

     radc    jcell   idj   j-cells:
                      1     12   :  6  6  6  6  6  6  5  4  3  2  1  1
                      2     12   : 11 10  9  8  7  6  6  7  8  9 10 11

     radc    h

                                                  * * * idh= 1   nsurfs=12 * * *

1    -0.193150e-11   0.178142e-12   0.146770e-12   0.109222e-12   0.740063e-13   0.333564e-13   0.502533e-13   0.120314e-12   0.194169e-12
      0.308646e-12   0.437751e-12   0.278876e-12
2     0.178142e-12  -0.371336e-11   0.296294e-12   0.230309e-12   0.157589e-12   0.694281e-13   0.105691e-12   0.268806e-12   0.459215e-12
      0.692739e-12   0.816805e-12   0.438345e-12
3     0.146770e-12   0.296294e-12  -0.376077e-11   0.261244e-12   0.190849e-12   0.796388e-13   0.126316e-12   0.391306e-12   0.683198e-12
      0.730242e-12   0.595651e-12   0.259266e-12
4     0.109222e-12   0.230309e-12   0.261244e-12  -0.376500e-11   0.262038e-12   0.109288e-12   0.195813e-12   0.762266e-12   0.806213e-12
      0.508481e-12   0.365323e-12   0.154802e-12
5     0.740063e-13   0.157589e-12   0.190849e-12   0.262038e-12-0.371382e-11    0.226210e-12   0.608779e-12   0.111310e-11   0.470036e-12
      0.280376e-12   0.229700e-12   0.101134e-12
6     0.333564e-13   0.694281e-13   0.796388e-13   0.109288e-12   0.226210e-12  -0.248679e-11   0.120677e-11   0.323896e-12   0.153454e-12
      0.121361e-12   0.112434e-12   0.509613e-13
7     0.502533e-13   0.105691e-12   0.126316e-12   0.195813e-12   0.608779e-12   0.120677e-11-  0.320964e-11   0.335137e-12   0.201461e-12
      0.161598e-12   0.147873e-12   0.699501e-13
8     0.120314e-12   0.268806e-12   0.391306e-12   0.762266e-12   0.111310e-11   0.323896e-12   0.335137e-12-0.433825e-11    0.366721e-12
      0.287270e-12   0.251474e-12   0.117960e-12
9     0.194169e-12   0.459215e-12   0.683198e-12   0.806213e-12   0.470036e-12   0.153454e-12   0.201461e-12   0.366721e-12  -0.408669e-11
```

```
      0.320529e-12   0.291875e-12   0.139820e-12
10    0.308646e-12   0.692739e-12   0.730242e-12  0.508481e-12  0.280376e-12  0.121361e-12  0.161598e-12  0.287270e-12  0.320529e-12
     -0.389094e-11   0.321644e-12   0.158051e-12
11    0.437751e-12   0.816805e-12   0.595651e-12  0.365323e-12  0.229700e-12  0.112434e-12  0.147873e-12  0.251474e-12  0.291875e-12
      0.321644e-12  -0.373774e-11   0.167214e-12
12    0.278876e-12   0.438345e-12   0.259266e-12  0.154802e-12  0.101134e-12  0.509613e-13  0.699501e-13  0.117960e-12  0.139820e-12
      0.158051e-12   0.167214e-12  -0.193638e-11

 radp    iregs=  2   maximum current dimension for iregs is  2
 radp                  region        emittances                    cell location
                                                                ibeg iend  jbeg jend  kbeg kend
                         1         0.400   0.250                  7    8     6    6     5    8
                         2         0.400   0.250                  7    9     7    7     5    8

 radp    jregs=  2   maximum current dimension for jregs is  2
 radp                  region        emittances                    cell location
                                                                ibeg iend  jbeg jend  kbeg kend
                         1         0.250   0.400                  6    6     4    6     5    8
                         2         0.250   0.400                  7    7     5    6     5    8

 radp    kregs=  5   maximum current dimension for kregs is  5
 radp                  region        emittances                    cell location
                                                                ibeg iend  jbeg jend  kbeg kend
                         1         0.400   0.250                  2    7     6    6    22   27
                         2         0.400   0.250                  7    7     7   11    22   27
                         3         0.800   0.250                  2    6     7   11    22   27
                         4         0.250   0.400                  2    5     6    6     4    9
                         5         0.250   0.400                  7    7     8   11     4    9

 radr    RADR Input Section
 radr    Rod Emittance is 0.8

 radr    nh= 25   maximum current dimension for nh is  25
 radr    h
                nh   h2e(nh)    h2n(nh)    h2w(nh)    h2s(nh)    h3ne(nh)   h3nw(nh)   h3sw(nh)   h3se(nh)
                 1 0.1710e+00 0.0000e+00 0.0000e+00 0.1710e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.2080e+00
                 2 0.1710e+00 0.0000e+00 0.1710e+00 0.3880e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.2080e+00
                 3 0.3880e+00 0.1710e+00 0.0000e+00 0.1710e+00 0.2080e+00 0.0000e+00 0.0000e+00 0.2080e+00
                 4 0.1710e+00 0.0000e+00 0.1710e+00 0.3420e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.2080e+00
                 5 0.3420e+00 0.1710e+00 0.0000e+00 0.1710e+00 0.2080e+00 0.0000e+00 0.0000e+00 0.2080e+00
                 6 0.1710e+00 0.0000e+00 0.1710e+00 0.3420e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.2080e+00
                 7 0.3420e+00 0.1710e+00 0.0000e+00 0.1710e+00 0.2080e+00 0.0000e+00 0.0000e+00 0.2080e+00
                 8 0.0000e+00 0.0000e+00 0.1710e+00 0.3420e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.0000e+00
                 9 0.3420e+00 0.1710e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.0000e+00 0.0000e+00 0.0000e+00
                10 0.3880e+00 0.3880e+00 0.3880e+00 0.3880e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
                11 0.3880e+00 0.3420e+00 0.3880e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
```

```
 12 0.3420e+00 0.3880e+00 0.3420e+00 0.3880e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
 13 0.3880e+00 0.3420e+00 0.3880e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
 14 0.3420e+00 0.3880e+00 0.3420e+00 0.3880e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
 15 0.0000e+00 0.3420e+00 0.3880e+00 0.3420e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00
 16 0.3420e+00 0.3880e+00 0.3420e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00 0.0000e+00
 17 0.3420e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
 18 0.3420e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
 19 0.3420e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
 20 0.3420e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.2080e+00 0.2080e+00 0.2080e+00 0.2080e+00
 21 0.0000e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00
 22 0.3420e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00 0.0000e+00
 23 0.0000e+00 0.3420e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00
 24 0.3420e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.2080e+00 0.2080e+00 0.0000e+00 0.0000e+00
 25 0.0000e+00 0.3420e+00 0.3420e+00 0.0000e+00 0.0000e+00 0.2080e+00 0.0000e+00 0.0000e+00

nh   h4e(nh)     h4n(nh)     h4w(nh)     h4s(nh)
 1 0.5000e-02 0.0000e+00 0.0000e+00 0.5000e-02
 2 0.5000e-02 0.0000e+00 0.0000e+00 0.1000e-01
 3 0.1000e-01 0.0000e+00 0.0000e+00 0.5000e-02
 4 0.5000e-02 0.0000e+00 0.5000e-02 0.1000e-01
 5 0.1000e-01 0.5000e-02 0.0000e+00 0.5000e-02
 6 0.0000e+00 0.0000e+00 0.5000e-02 0.1000e-01
 7 0.1000e-01 0.5000e-02 0.0000e+00 0.0000e+00
 8 0.0000e+00 0.0000e+00 0.5000e-02 0.1000e-01
 9 0.1000e-01 0.5000e-02 0.0000e+00 0.0000e+00
10 0.1000e-01 0.0000e+00 0.0000e+00 0.1000e-01
11 0.1000e-01 0.0000e+00 0.1000e-01 0.1000e-01
12 0.1000e-01 0.1000e-01 0.0000e+00 0.1000e-01
13 0.0000e+00 0.0000e+00 0.1000e-01 0.1000e-01
14 0.1000e-01 0.1000e-01 0.0000e+00 0.0000e+00
15 0.0000e+00 0.0000e+00 0.1000e-01 0.1000e-01
16 0.1000e-01 0.1000e-01 0.0000e+00 0.0000e+00
17 0.1000e-01 0.1000e-01 0.1000e-01 0.1000e-01
18 0.0000e+00 0.1000e-01 0.1000e-01 0.1000e-01
19 0.1000e-01 0.1000e-01 0.1000e-01 0.0000e+00
20 0.0000e+00 0.1000e-01 0.1000e-01 0.0000e+00
21 0.0000e+00 0.1000e-01 0.1000e-01 0.1000e-01
22 0.1000e-01 0.1000e-01 0.1000e-01 0.0000e+00
23 0.0000e+00 0.1000e-01 0.1000e-01 0.0000e+00
24 0.0000e+00 0.1000e-01 0.1000e-01 0.0000e+00
25 0.0000e+00 0.1000e-01 0.1000e-01 0.0000e+00

nh  h5ene(nh)  h5nne(nh)  h5nnw(nh)  h5wnw(nh)  h5wsw(nh)  h5ssw(nh)  h5sse(nh)  h5ese(nh)
 1 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01
 2 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01 0.4600e-01
 3 0.4600e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.4600e-01 0.4600e-01
```

598	4	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01
599	5	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01
600	6	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00
601	7	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.4600e-01
602	8	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00
603	9	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
604	10	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01
605	11	0.4600e-01	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01
606	12	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01
607	13	0.0000e+00	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00
608	14	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.4600e-01
609	15	0.0000e+00	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00
610	16	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
611	17	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01
612	18	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00
613	19	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.4600e-01
614	20	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00
615	21	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00
616	22	0.4600e-01	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
617	23	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00
618	24	0.0000e+00	0.4600e-01	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
619	25	0.0000e+00	0.0000e+00	0.4600e-01	0.4600e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
620									

	nh	h6ne(nh)	h6nw(nh)	h6sw(nh)	h6se(nh)
621					
622	1	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
623	2	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
624	3	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
625	4	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
626	5	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
627	6	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
628	7	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
629	8	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
630	9	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
631	10	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
632	11	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
633	12	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
634	13	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
635	14	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
636	15	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
637	16	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
638	17	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
639	18	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
640	19	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
641	20	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
642	21	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
643	22	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00

```
                  23 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
                  24 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00
                  25 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00

 radr    nreg= 25   maximum current dimension for nreg is  25
 radr    lreg         region    radiation                cell location
                      number    type (nh)        lbeg lend  jbeg jend  kbeg kend
                        1          1             2    2    11   11     5   22
                        2          2             3    3    11   11     5   22
                        3          3             2    2    10   10     5   22
                        4          4             4    4    11   11     5   22
                        5          5             2    2     9    9     5   22
                        6          6             5    5    11   11     5   22
                        7          7             2    2     8    8     5   22
                        8          8             6    6    11   11     5   22
                        9          9             2    2     7    7     5   22
                       10         10             3    3    10   10     5   22
                       11         11             4    4    10   10     5   22
                       12         12             3    3     9    9     5   22
                       13         13             5    5    10   10     5   22
                       14         14             3    3     8    8     5   22
                       15         15             6    6    10   10     5   22
                       16         16             3    3     7    7     5   22
                       17         17             4    4     9    9     5   22
                       18         18             5    5     9    9     5   22
                       19         19             4    4     8    8     5   22
                       20         20             5    5     8    8     5   22
                       21         21             6    6     9    9     5   22
                       22         22             4    4     7    7     5   22
                       23         23             6    6     8    8     5   22
                       24         24             5    5     7    7     5   22
                       25         25             6    6     7    7     5   22

 radr    nt4=  1   maximum current dimension for nt4 is   1
 radr    lt4                        region                 cell location
                                    number        lbeg lend  jbeg jend  kbeg kend
                                      1            2    6     7   11     5   22

 reba    dtmax=0.200e+02   info=1

 hydro   convek=1.0   epscon=0.000e+00   mitmax= 0   thetam=0.5   wm=1.0   estpf=-.500e+00
 hydro   ndtyme=1   dtymen=0.100e-03   dtymax=0.100e+00
 hydro   newgas=0   newvel=0   extrav=0.100e+01
 hydro   pfref=0.6500000e+06   tfref=0.483e+03   dfref=0.64720e-04
 hydro   gx= 0.000000   gy= 0.000000   gz=-1.000000
 hydro   cvisa=0.700e-04   cvisb=0.400e-06
```

```
690
691     hydro   monitor mx cells= 3   maximum number currently allowed is  3
692                                                 m   i   j   k
693                                                 1   7   9   3
694                                                 2   4   4  12
695                                                 3   9   9  12
696
697     hydro   monitor my cells= 3   maximum number currently allowed is  3
698                                                 m   i   j   k
699                                                 1   4   5   3
700                                                 2   9   8  12
701                                                 3   4   3  12
702
703     hydro   monitor mz cells= 4   maximum number currently allowed is  4
704                                                 m   i   j   k
705                                                 1   7   9   3
706                                                 2   4   6   3
707                                                 3   4   4  12
708                                                 4   9   9  12
709
710     hydro   nreg=  2   maximum current dimension for nreg is   6
711     hydro   specs         region          viscosity                    cell location
712                                                                ibeg iend  jbeg jend  kbeg kend
713                             1             0.100e-19             1   1     2   11     2   23
714                             2             0.100e-19             2   11    12  12     2   23
715
716     hydro   nreg=  4   maximum current dimension for nreg is   6
717     hydro   specs         region          viscosity                    cell location
718                                           multiplier           ibeg iend  jbeg jend  kbeg kend
719                             1             0.100e+21             6   7     6   6      2   5
720                             2             0.100e+21             2   7     6   6      6   19
721                             3             0.100e+21             7   7     7   7      2   5
722                             4             0.100e+21             7   7     7   11     6   19
723
724     propm   perm0=0.100e+02
725
726     propm   info=0   region       ax                  cell location
727                                                 ibeg iend  jbeg jend  kbeg kend
728
729     propm   info=0   region       ay                  cell location
730                                                 ibeg iend  jbeg jend  kbeg kend
731
732     propm   info=0   region       az                  cell location
733                                                 ibeg iend  jbeg jend  kbeg kend
734
735     propm   info=0   region      axi                  cell location
```

```
                                                  ibeg  iend   jbeg  jend   kbeg  kend
                      1    0.100000e-05           6     7      6     11     6     19
                      2    0.100000e-05           1     6      6     6      6     19
                      3    0.100000e-05           5     7      6     6      2     5
                      4    0.100000e-05           6     7      7     7      2     5

 propm   info=0   region      ayl                        cell location
                                                  ibeg  iend   jbeg  jend   kbeg  kend
                      1    0.100000e-05           2     7      5     6      6     19
                      2    0.100000e-05           7     7      7     11     6     19
                      3    0.100000e-05           6     7      5     6      2     5
                      4    0.100000e-05           7     7      7     7      2     5

 propm   info=0   region      azi                        cell location
                                                  ibeg  iend   jbeg  jend   kbeg  kend
                      1    0.100000e-05           2     7      6     6      5     19
                      2    0.100000e-05           7     7      7     11     5     19
                      3    0.100000e-05           6     7      6     6      2     5
                      4    0.100000e-05           7     7      7     7      2     5

 propm   info=0   region      por                        cell location
                                                  ibeg  iend   jbeg  jend   kbeg  kend
                      1    0.100000e-05           2     7      6     6      6     19
                      2    0.100000e-05           7     7      7     11     6     19
                      3    0.100000e-05           6     7      6     6      2     5
                      4    0.100000e-05           7     7      7     7      2     5
                      5    0.559000e+00           2     6      7     11     2     19

 propm   info=0   region      permx                      cell location
                                                  ibeg  iend   jbeg  jend   kbeg  kend
                      1    0.466000e-02           2     6      7     11     2     19

 propm   info=0   region      permy                      cell location
                                                  ibeg  iend   jbeg  jend   kbeg  kend
                      1    0.466000e-02           2     6      7     11     2     19

 propm   info=0   region      permz                      cell location
                                                  ibeg  iend   jbeg  jend   kbeg  kend
                      1    0.980000e-02           2     6      7     11     2     19

 pdg     wp=0.80   optcon=0.500e-05

 piter   nopt= 4   nmax= 20
 piter   rebson=0.0   rebqon=1.0   afon=1.0

 piter   norda= 3   maximum current dimension for norda is  4
```

```
 782     piter   norder     3  4  1  0
 783
 784     piles   epsd=0.200e-08   omega=1.10   nmax=  4   info=0
 785
 786     rebq    nmax= 2   info=0
 787     rebq    kbound= 1   jbound= 1   ibound= 1
 788     rebq    akkmin=0.100e-20   ajjmin=0.100e-20   aiimin=0.100e-20
 789
 790     rebq    kreg=  3   maximum current dimension for kreg is   3
 791     rebq    krid            kreg      boundary                  cell location
 792                                       surfaces              ibeg iend  jbeg jend
 793                               1           1                  2   7     2   5
 794                               2           1                  2   7     6   11
 795                               3           0                  8   11    6   11
 796
 797     rebq    kbida=  6   maximum current dimension for kbida is   6
 798     rebq    kbid            kreg       sees plane   sees plane   sees plane   sees plane   sees plane
 799                                        kreg type    kreg type    kreg type    kreg type    kreg type
 800                               1          2   2
 801                               2          3   1
 802
 803     rebq    jreg=  5   maximum current dimension for jreg is   5
 804     rebq    jrid            jreg      boundary                  cell location
 805                                       surfaces              ibeg iend  kbeg kend
 806                               1           3                  2   7     2   19
 807                               2           1                  8   11    2   5
 808                               3           1                  8   11    6   19
 809                               4           1                  8   11    20  23
 810                               5           0                  2   7     20  23
 811
 812     rebq    jbida= 16   maximum current dimension for jbida is  16
 813     rebq    jbid            jreg       sees plane   sees plane   sees plane   sees plane   sees plane
 814                                        jreg type    jreg type    jreg type    jreg type    jreg type
 815                               1          2   1        3   1        5   3
 816                               2          3   3
 817                               3          4   3
 818                               4          5   -1
 819
 820     rebq    ireg=  5   maximum current dimension for ireg is   5
 821     rebq    irid            ireg      boundary                  cell location
 822                                       surfaces              jbeg jend  kbeg kend
 823                               1           3                  2   7     2   19
 824                               2           1                  8   11    2   5
 825                               3           1                  8   11    6   19
 826                               4           1                  8   11    20  23
 827                               5           0                  2   7     20  23
 828
```

```
 829     rebq    lbida= 16   maximum current dimension for lbida is  16
 830     rebq    lbid            ireg        sees plane   sees plane   sees plane   sees plane   sees plane
 831                                         ireg type    ireg type    ireg type    ireg type    ireg type
 832                              1           2    2       3    2       5    3
 833                              2           3    3
 834                              3           4    3
 835                              4           5   -2
 836
 837     af      nmax= 5   info=0
 838
 839     avg     flxedm=0.0000000e+00   flxedp=0.4960000e+06
 840
 841                                          ***hydrostatic pressure initialization***
 842
 843                     maximum
 844     plles    n      residual  i  j  k
 845              1     0.237e-11  2  9 14
 846              1     0.237e-11  2  9 14
 847 1
 848      1   thermal  time step=0.100e+00          maximum inside change( 3, 2,15)=0.138e+01
 849            t( 2, 2,10)=0.512e+02    t( 3, 4,10)=0.107e+03    t( 5, 6,10)=0.136e+03    t( 5, 7,10)=0.154e+03
 850            t(11,11,10)=0.512e+02    t( 9,10,10)=0.107e+03    t( 7, 8,10)=0.136e+03    t( 6, 8,10)=0.154e+03
 851                                          maximum  side  change( 2, 7,29)=-.925e-01
 852           ts( 2, 5,10)=0.470e+02   ts( 2,10,10)=0.470e+02   ts( 4, 5,10)=0.470e+02   ts( 4,10,10)=0.470e+02
 853      1   momentum time step=0.100e-03        tilde continuity error( 6, 7,23)=-.109e-06
 854                                        dmx( 6, 7,23)=-.122e-17   dmy( 5, 4,23)=-.983e-18   dmz( 6, 7,22)=-.533e-07
 855
 856                     maximum
 857     plles    n      residual  i  j  k
 858              1     0.794e-09  9 10 18
 859              1     0.794e-09  9 10 18
 860                                        dmx( 5, 5, 2)=-.561e-08   dmy( 8, 7, 2)=0.562e-08   dmz( 6, 7,22)=0.530e-07
 861           mx( 7, 9, 3)=-.211e-08   mx( 4, 4,12)=-.198e-11   mx( 9, 9,12)=-.521e-12   mx(
 862           my( 4, 5, 3)=0.210e-08   my( 9, 8,12)=0.150e-11   my( 4, 3,12)=0.459e-12   my(
 863           mz( 7, 9, 3)=0.128e-07   mz( 4, 6, 3)=0.128e-07   mz( 4, 4,12)=0.115e-08   mz( 9, 9,12)=0.117e-08
 864               avg. pressure=0.4895e+00            continuity error( 9,10,18)=0.414e-09
 865     201   thermal  time step=0.424e+00          maximum inside change( 2,11,26)=0.504e+00
 866            t( 2, 2,10)=0.557e+02    t( 3, 4,10)=0.985e+02    t( 5, 6,10)=0.137e+03    t( 5, 7,10)=0.167e+03
 867            t(11,11,10)=0.557e+02    t( 9,10,10)=0.985e+02    t( 7, 8,10)=0.137e+03    t( 6, 8,10)=0.167e+03
 868                                          maximum  side  change( 2, 8,15)=0.258e-01
 869           ts( 2, 5,10)=0.481e+02   ts( 2,10,10)=0.481e+02   ts( 4, 5,10)=0.479e+02   ts( 4,10,10)=0.479e+02
 870     201   momentum time step=0.100e+00        tilde continuity error( 3,10,23)=0.214e-05
 871                                        dmx( 7,11,23)=0.455e-05   dmy( 2, 5,23)=-.455e-05   dmz( 2,11,22)=0.139e-04
 872
 873                     maximum
 874     plles    n      residual  i  j  k
```

```
                1     -0.333e-08  9 10 18
                4     -0.209e-08  9  8 17

                        maximum
 piles     n           residual  i  j  k
                1     -0.772e-10  9 10 18
                1     -0.772e-10  9 10 18
                                                dmx( 3,10,23)=0.331e-06   dmy( 3, 9,23)=-.331e-06   dmz( 3,10,22)=-.470e-06
           mx( 7, 9, 3)=-.862e-04   mx( 4, 4,12)=0.194e-06   mx( 9, 9,12)=0.668e-07   mx(
           my( 4, 5, 3)=0.862e-04   my( 9, 8,12)=-.194e-06   my( 4, 3,12)=-.668e-07   my(
           mz( 7, 9, 3)=0.519e-03   mz( 4, 6, 3)=0.519e-03   mz( 4, 4,12)=-.151e-04   mz( 9, 9,12)=-.151e-04
               avg. pressure=0.4895e+00            continuity error( 9,10,18)=-.409e-10
 401   thermal  time step=0.100e+01          maximum inside change( 2, 6,22)=0.833e-01
            t( 2, 2,10)=0.602e+02    t( 3, 4,10)=0.104e+03    t( 5, 6,10)=0.144e+03    t( 5, 7,10)=0.174e+03
            t(11,11,10)=0.602e+02    t( 9,10,10)=0.104e+03    t( 7, 8,10)=0.144e+03    t( 6, 8,10)=0.174e+03
                                          maximum  side  change( 2, 7,15)=0.510e-01
           ts( 2, 5,10)=0.528e+02   ts( 2,10,10)=0.528e+02   ts( 4, 5,10)=0.525e+02   ts( 4,10,10)=0.525e+02
 401   momentum time step=0.100e+00        tilde continuity error( 3,10,23)=0.188e-06
                                                dmx( 7,11,20)=-.257e-06   dmy( 2, 5,20)=0.257e-06   dmz( 8,11,19)=0.437e-06

                        maximum
 piles     n           residual  i  j  k
                1     -0.216e-09 10 10 23
                1     -0.216e-09 10 10 23
                                                dmx( 5,10,23)=0.197e-07   dmy( 3, 7,23)=-.197e-07   dmz( 3,10,22)=-.622e-07
           mx( 7, 9, 3)=-.840e-04   mx( 4, 4,12)=0.638e-06   mx( 9, 9,12)=0.228e-06   mx(
           my( 4, 5, 3)=0.840e-04   my( 9, 8,12)=-.638e-06   my( 4, 3,12)=-.228e-06   my(
           mz( 7, 9, 3)=0.513e-03   mz( 4, 6, 3)=0.513e-03   mz( 4, 4,12)=-.102e-04   mz( 9, 9,12)=-.102e-04
               avg. pressure=0.4895e+00            continuity error( 9,10,22)=-.119e-09
 601   thermal  time step=0.100e+01          maximum inside change( 2, 6,15)=0.447e-01
            t( 2, 2,10)=0.654e+02    t( 3, 4,10)=0.109e+03    t( 5, 6,10)=0.150e+03    t( 5, 7,10)=0.180e+03
            t(11,11,10)=0.654e+02    t( 9,10,10)=0.109e+03    t( 7, 8,10)=0.150e+03    t( 6, 8,10)=0.180e+03
                                          maximum  side  change( 2, 2,15)=0.446e-01
           ts( 2, 5,10)=0.579e+02   ts( 2,10,10)=0.579e+02   ts( 4, 5,10)=0.576e+02   ts( 4,10,10)=0.576e+02
 601   momentum time step=0.100e+00        tilde continuity error( 4,10,23)=0.820e-07
                                                dmx( 7, 9,23)=0.509e-07   dmy( 4, 5,23)=-.509e-07   dmz( 6, 4,11)=0.172e-06

                        maximum
 piles     n           residual  i  j  k
                1     -0.182e-09  9 10 18
                1     -0.182e-09  9 10 18
                                                dmx( 5,10,23)=0.613e-08   dmy( 3, 7,23)=-.613e-08   dmz( 5, 4,12)=-.393e-07
           mx( 7, 9, 3)=-.810e-04   mx( 4, 4,12)=0.692e-06   mx( 9, 9,12)=0.244e-06   mx(
           my( 4, 5, 3)=0.810e-04   my( 9, 8,12)=-.692e-06   my( 4, 3,12)=-.244e-06   my(
           mz( 7, 9, 3)=0.497e-03   mz( 4, 6, 3)=0.497e-03   mz( 4, 4,12)=-.117e-04   mz( 9, 9,12)=-.117e-04
               avg. pressure=0.4895e+00            continuity error( 9,10,18)=-.989e-10
```

```
 801   thermal  time step=0.100e+01          maximum inside change( 2, 2,15)=0.387e-01
         t( 2, 2,10)=0.706e+02    t( 3, 4,10)=0.114e+03    t( 5, 6,10)=0.155e+03    t( 5, 7,10)=0.184e+03
         t(11,11,10)=0.706e+02    t( 9,10,10)=0.114e+03    t( 7, 8,10)=0.155e+03    t( 6, 8,10)=0.184e+03
                                             maximum  side  change( 2, 2,15)=0.391e-01
         ts( 2, 5,10)=0.631e+02   ts( 2,10,10)=0.631e+02   ts( 4, 5,10)=0.628e+02   ts( 4,10,10)=0.628e+02
 801   momentum time step=0.100e+00          tilde continuity error( 6,10,20)=-.538e-07
                                   dmx( 7,11, 5)=-.389e-07   dmy( 2, 5, 5)=0.389e-07   dmz( 6, 4,11)=0.147e-06

                     maximum
  piles    n         residual  i  j  k
            1      -0.303e-09  9 10 18
            1      -0.303e-09  9 10 18
                                   dmx( 7,10, 5)=-.199e-08   dmy( 3, 5, 5)=0.199e-08   dmz( 5, 4,12)=-.305e-07
         mx( 7, 9, 3)=-.779e-04   mx( 4, 4,12)=0.660e-06   mx( 9, 9,12)=0.232e-06   mx(
         my( 4, 5, 3)=0.779e-04   my( 9, 8,12)=-.660e-06   my( 4, 3,12)=-.232e-06   my(
         mz( 7, 9, 3)=0.478e-03   mz( 4, 6, 3)=0.478e-03   mz( 4, 4,12)=-.136e-04   mz( 9, 9,12)=-.136e-04
             avg. pressure=0.4895e+00            continuity error( 9,10,18)=-.164e-09
1000   thermal  time step=0.100e+01          maximum inside change( 2, 2,15)=0.339e-01
         t( 2, 2,10)=0.757e+02    t( 3, 4,10)=0.119e+03    t( 5, 6,10)=0.160e+03    t( 5, 7,10)=0.189e+03
         t(11,11,10)=0.757e+02    t( 9,10,10)=0.119e+03    t( 7, 8,10)=0.160e+03    t( 6, 8,10)=0.189e+03
                                             maximum  side  change( 2, 2,15)=0.344e-01
         ts( 2, 5,10)=0.682e+02   ts( 2,10,10)=0.682e+02   ts( 4, 5,10)=0.679e+02   ts( 4,10,10)=0.679e+02
1000   momentum time step=0.100e+00          tilde continuity error( 6, 7,20)=-.545e-07
                                   dmx( 7,11, 5)=-.391e-07   dmy( 2, 5, 5)=0.391e-07   dmz( 9, 7,11)=0.123e-06

                     maximum
  piles    n         residual  i  j  k
            1      -0.363e-09  9 10 18
            1      -0.363e-09  9 10 18
                                   dmx( 7,10, 5)=-.194e-08   dmy( 3, 5, 5)=0.194e-08   dmz( 6, 7,20)=-.283e-07
         mx( 7, 9, 3)=-.749e-04   mx( 4, 4,12)=0.613e-06   mx( 9, 9,12)=0.216e-06   mx(
         my( 4, 5, 3)=0.749e-04   my( 9, 8,12)=-.613e-06   my( 4, 3,12)=-.216e-06   my(
         mz( 7, 9, 3)=0.459e-03   mz( 4, 6, 3)=0.459e-03   mz( 4, 4,12)=-.152e-04   mz( 9, 9,12)=-.152e-04
             avg. pressure=0.4895e+00            continuity error( 9,10,18)=-.195e-09
1
                                    * * * thermal power balance summary, watts * * *

                    thermal power from inside to side at level   k
                                                                 29   -.165139e+01
                                                                 28   -.434836e+01
                                                                 27   -.716536e+01
                                                                 26   0.378800e+01
                                                                 25   0.227392e+01
                                                                 24   0.130187e+01
                                                                 23   0.205785e+01
                                                                 22   0.177996e+02
```

21		0.247999e+02
20		0.354332e+02
19		0.513323e+02
18		0.752517e+02
17		0.105157e+03
16		0.140924e+03
15		0.142044e+03
14		0.108947e+03
13		0.817615e+02
12		0.592768e+02
11		0.428461e+02
10		0.302628e+02
9		0.211010e+02
8		0.174653e+02
7		0.114181e+02
6		0.670351e+01
5		0.251733e+01
4		0.788006e+01
3		0.10340e+02
2		0.693509e+01
	thermal power from cavity to top	0.198252e+02
	thermal power from cavity to side	0.984463e+03
	thermal power from cavity to bottom	0.770241e+02
	thermal power from cavity	0.108131e+04
	thermal power from top to ambient	0.515122e+01
	thermal power from top to side	-.131651e+02
	thermal power from bottom to side	0.251631e+02
	thermal power from bottom to ambient	0.241767e-16
	thermal power from top of side to ambient	0.462020e+01
	thermal power from side to ambient	0.252627e+03
	thermal power from bottom of side to ambient	0.210228e-16
	thermal power from outside surface to ambient	0.262399e+03
	excess power leaving cavity	-.787e+02

```
1013
1014                    excess power leaving top                        -.278e+02
1015
1016                    excess power leaving side                       -.739e+03
1017
1018                    excess power leaving bottom                     -.519e+02
1019 1
1020                                    * * * inside heat flux in i-direction, watts/sq. cm * * *
1021
1022                                                                    plane k= 8
1023     J    i= 1
1024    11-0.426e-18-0.116e-01 0.149e-01 0.376e-01 0.381e-01 0.749e-01 0.485e+00 0.429e+00 0.192e+00 0.770e-01 0.534e-01
1025    10-0.428e-18-0.129e-01 0.151e-01 0.509e-01 0.247e-01 0.779e-01 0.473e+00 0.411e+00 0.179e+00 0.695e-01 0.442e-01
1026     9-0.417e-18-0.126e-01 0.673e-02 0.294e-01 0.435e-01 0.802e-01 0.419e+00 0.334e+00 0.129e+00 0.566e-01 0.000e+00
1027     8-0.391e-18 0.522e-02-0.146e-01 0.238e-01 0.508e-01 0.762e-01 0.303e+00 0.194e+00 0.648e-01 0.000e+00 0.000e+00
1028     7-0.362e-18-0.125e-01 0.441e-02 0.315e-01 0.803e-01 0.149e+00 0.826e-01 0.507e-01 0.000e+00 0.000e+00
1029     6-0.293e-18 0.166e-01 0.581e-01 0.945e-01 0.350e-01 0.206e+00 0.199e+00 0.000e+00 0.000e+00
1030     5-0.256e-18 0.149e-01 0.500e-01 0.912e-01 0.904e-01 0.451e-01 0.000e+00 0.000e+00
1031     4-0.219e-18 0.121e-01 0.352e-01 0.589e-01 0.682e-01 0.000e+00 0.000e+00
1032     3-0.176e-18 0.743e-02 0.213e-01 0.293e-01 0.000e+00 0.000e+00
1033     2-0.143e-18 0.100e-02 0.132e-01 0.000e+00 0.000e+00
1034
1035 1
1036                                    * * * inside heat flux in j-direction, watts/sq. cm * * *
1037
1038                                                                    plane k= 8
1039     J    i= 2
1040    11 0.426e-18 0.428e-18 0.417e-18 0.391e-18 0.362e-18 0.293e-18 0.256e-18 0.219e-18 0.176e-18 0.143e-18
1041    10 0.116e-01 0.129e-01 0.126e-01-0.522e-02 0.125e-01-0.166e-01-0.149e-01-0.121e-01-0.743e-02-0.100e-02
1042     9-0.149e-01-0.151e-01-0.673e-02 0.146e-01-0.441e-02-0.581e-01-0.500e-01-0.352e-01-0.213e-01-0.132e-01
1043     8-0.376e-01-0.509e-01-0.294e-01-0.238e-01-0.315e-01-0.945e-01-0.912e-01-0.589e-01-0.293e-01 0.000e+00
1044     7-0.381e-01-0.247e-01-0.435e-01-0.508e-01-0.803e-01-0.350e-01-0.904e-01-0.682e-01 0.000e+00
1045     6-0.749e-01-0.779e-01-0.802e-01-0.762e-01-0.149e+00-0.206e+00-0.451e-01 0.000e+00
1046     5-0.485e+00-0.473e+00-0.419e+00-0.303e+00-0.826e-01-0.199e+00 0.000e+00
1047     4-0.429e+00-0.411e+00-0.334e+00-0.194e+00-0.507e-01 0.000e+00
1048     3-0.192e+00-0.179e+00-0.129e+00-0.648e-01 0.000e+00
1049     2-0.770e-01-0.695e-01-0.566e-01 0.000e+00
1050     1-0.534e-01-0.442e-01 0.000e+00 0.000e+00
1051
1052 1
1053                                    * * * inside heat flux in k-direction, watts/sq. cm * * *
1054
1055                                                                    plane k= 8
1056     J    i= 2
1057    11-0.129e+00-0.128e+00-0.116e+00-0.905e-01-0.263e-01-0.229e-01 0.827e+00 0.376e+00-0.365e+00-0.316e+00
1058    10-0.128e+00-0.128e+00-0.116e+00-0.873e-01-0.254e-01-0.217e-01 0.788e+00 0.309e+00-0.400e+00-0.314e+00
```

```
 9-0.116e+00-0.116e+00-0.107e+00-0.861e-01-0.235e-01-0.199e-01 0.598e+00-0.210e-01-0.569e+00-0.123e+00
 8-0.905e-01-0.873e-01-0.861e-01-0.758e-01-0.375e-01-0.235e-01 0.252e+00-0.492e+00-0.203e+00 0.000e+00
 7-0.263e-01-0.254e-01-0.235e-01-0.375e-01-0.105e+00-0.132e+01-0.175e+00-0.282e+00 0.000e+00
 6-0.229e-01-0.217e-01-0.199e-01-0.235e-01-0.132e+01-0.121e+01-0.149e+00 0.000e+00
 5 0.827e+00 0.788e+00 0.598e+00 0.252e+00-0.175e+00-0.149e+00 0.000e+00
 4 0.376e+00 0.309e+00-0.211e-01-0.492e+00-0.282e+00 0.000e+00
 3-0.365e+00-0.400e+00-0.569e+00-0.203e+00 0.000e+00
 2-0.316e+00-0.314e+00-0.123e+00 0.000e+00

1

                                        * * * inside temperature, c * * *

                                                    plane k=30
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
10 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 9 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 8 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 6 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 5 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 4 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 3 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 2 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 1 0.000e+00 0.000e+00 0.000e+00 0.000e+00

                                                    plane k=29
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.516e+02 0.516e+02 0.516e+02 0.515e+02 0.515e+02 0.515e+02 0.514e+02 0.514e+02 0.514e+02 0.515e+02 0.515e+02
10 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.515e+02 0.515e+02 0.515e+02 0.515e+02 0.515e+02 0.515e+02 0.515e+02
 9 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.515e+02 0.515e+02 0.515e+02 0.515e+02 0.515e+02 0.516e+02 0.000e+00
 8 0.515e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.000e+00
 7 0.515e+02 0.515e+02 0.515e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.517e+02 0.000e+00
 6 0.515e+02 0.515e+02 0.515e+02 0.516e+02 0.516e+02 0.516e+02 0.517e+02 0.000e+00
 5 0.514e+02 0.515e+02 0.515e+02 0.516e+02 0.516e+02 0.517e+02 0.000e+00
 4 0.514e+02 0.515e+02 0.515e+02 0.516e+02 0.517e+02 0.000e+00
 3 0.514e+02 0.515e+02 0.515e+02 0.516e+02 0.000e+00
 2 0.515e+02 0.515e+02 0.516e+02 0.000e+00
 1 0.515e+02 0.515e+02 0.000e+00 0.000e+00

                                                    plane k=28
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.517e+02 0.517e+02 0.517e+02 0.516e+02 0.516e+02 0.515e+02 0.515e+02 0.515e+02 0.515e+02 0.516e+02 0.516e+02
```

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 10 0.517e+02 0.517e+02 0.517e+02 0.517e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02
  9 0.517e+02 0.517e+02 0.517e+02 0.517e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.516e+02 0.517e+02 0.000e+00
  8 0.516e+02 0.517e+02 0.517e+02 0.517e+02 0.517e+02 0.516e+02 0.517e+02 0.517e+02 0.517e+02 0.000e+00
  7 0.516e+02 0.516e+02 0.516e+02 0.517e+02 0.517e+02 0.517e+02 0.517e+02 0.518e+02 0.000e+00
  6 0.515e+02 0.516e+02 0.516e+02 0.516e+02 0.517e+02 0.517e+02 0.518e+02 0.000e+00
  5 0.515e+02 0.515e+02 0.516e+02 0.517e+02 0.517e+02 0.518e+02 0.000e+00
  4 0.515e+02 0.516e+02 0.516e+02 0.517e+02 0.518e+02 0.000e+00
  3 0.515e+02 0.516e+02 0.516e+02 0.517e+02 0.000e+00
  2 0.516e+02 0.516e+02 0.517e+02 0.000e+00
  1 0.516e+02 0.516e+02 0.000e+00 0.000e+00

                                                    plane k=27
 j   i= 2
 12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
 11 0.520e+02 0.520e+02 0.520e+02 0.519e+02 0.518e+02 0.517e+02 0.516e+02 0.516e+02 0.517e+02 0.518e+02 0.518e+02
 10 0.520e+02 0.520e+02 0.520e+02 0.519e+02 0.518e+02 0.517e+02 0.517e+02 0.517e+02 0.517e+02 0.518e+02 0.519e+02
  9 0.520e+02 0.520e+02 0.519e+02 0.519e+02 0.518e+02 0.518e+02 0.517e+02 0.517e+02 0.518e+02 0.519e+02 0.000e+00
  8 0.519e+02 0.519e+02 0.519e+02 0.519e+02 0.518e+02 0.518e+02 0.518e+02 0.519e+02 0.520e+02 0.000e+00
  7 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.519e+02 0.520e+02 0.000e+00
  6 0.517e+02 0.517e+02 0.518e+02 0.518e+02 0.518e+02 0.519e+02 0.520e+02 0.000e+00
  5 0.516e+02 0.517e+02 0.517e+02 0.518e+02 0.519e+02 0.520e+02 0.000e+00
  4 0.516e+02 0.517e+02 0.517e+02 0.519e+02 0.520e+02 0.000e+00
  3 0.517e+02 0.517e+02 0.518e+02 0.520e+02 0.000e+00
  2 0.518e+02 0.518e+02 0.519e+02 0.000e+00
  1 0.518e+02 0.519e+02 0.000e+00 0.000e+00

                                                    plane k=26
 j   i= 2
 12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
 11 0.109e+03 0.107e+03 0.101e+03 0.938e+02 0.874e+02 0.830e+02 0.788e+02 0.724e+02 0.634e+02 0.560e+02 0.528e+02
 10 0.107e+03 0.105e+03 0.996e+02 0.929e+02 0.868e+02 0.825e+02 0.784e+02 0.719e+02 0.632e+02 0.565e+02 0.528e+02
  9 0.101e+03 0.996e+02 0.949e+02 0.896e+02 0.845e+02 0.806e+02 0.763e+02 0.691e+02 0.597e+02 0.529e+02 0.000e+00
  8 0.938e+02 0.929e+02 0.896e+02 0.856e+02 0.813e+02 0.774e+02 0.721e+02 0.631e+02 0.529e+02 0.000e+00
  7 0.874e+02 0.868e+02 0.845e+02 0.813e+02 0.772e+02 0.719e+02 0.639e+02 0.530e+02 0.000e+00
  6 0.830e+02 0.825e+02 0.806e+02 0.774e+02 0.719e+02 0.630e+02 0.530e+02 0.000e+00
  5 0.788e+02 0.784e+02 0.763e+02 0.721e+02 0.639e+02 0.530e+02 0.000e+00
  4 0.724e+02 0.719e+02 0.691e+02 0.631e+02 0.530e+02 0.000e+00
  3 0.634e+02 0.632e+02 0.597e+02 0.529e+02 0.000e+00
  2 0.560e+02 0.565e+02 0.529e+02 0.000e+00
  1 0.528e+02 0.528e+02 0.000e+00 0.000e+00

                                                    plane k=25
 j   i= 2
 12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
 11 0.123e+03 0.120e+03 0.109e+03 0.965e+02 0.866e+02 0.804e+02 0.749e+02 0.686e+02 0.613e+02 0.561e+02 0.539e+02
 10 0.120e+03 0.117e+03 0.106e+03 0.951e+02 0.859e+02 0.799e+02 0.745e+02 0.681e+02 0.612e+02 0.565e+02 0.540e+02
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 9 0.109e+03 0.106e+03 0.988e+02 0.904e+02 0.834e+02 0.778e+02 0.724e+02 0.657e+02 0.586e+02 0.540e+02 0.000e+00
 8 0.965e+02 0.951e+02 0.904e+02 0.852e+02 0.798e+02 0.741e+02 0.682e+02 0.609e+02 0.541e+02 0.000e+00
 7 0.866e+02 0.859e+02 0.834e+02 0.798e+02 0.745e+02 0.681e+02 0.615e+02 0.541e+02 0.000e+00
 6 0.804e+02 0.799e+02 0.778e+02 0.741e+02 0.681e+02 0.607e+02 0.541e+02 0.000e+00
 5 0.749e+02 0.745e+02 0.724e+02 0.682e+02 0.615e+02 0.541e+02 0.000e+00
 4 0.686e+02 0.681e+02 0.657e+02 0.609e+02 0.541e+02 0.000e+00
 3 0.613e+02 0.612e+02 0.586e+02 0.541e+02 0.000e+00
 2 0.561e+02 0.565e+02 0.540e+02 0.000e+00
 1 0.539e+02 0.540e+02 0.000e+00 0.000e+00

                                                    plane k=24
 j   I= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.128e+03 0.123e+03 0.109e+03 0.938e+02 0.811e+02 0.730e+02 0.689e+02 0.646e+02 0.598e+02 0.566e+02 0.553e+02
10 0.123e+03 0.119e+03 0.106e+03 0.916e+02 0.797e+02 0.724e+02 0.685e+02 0.643e+02 0.598e+02 0.569e+02 0.553e+02
 9 0.109e+03 0.106e+03 0.959e+02 0.849e+02 0.759e+02 0.706e+02 0.669e+02 0.626e+02 0.581e+02 0.554e+02 0.000e+00
 8 0.938e+02 0.916e+02 0.849e+02 0.779e+02 0.723e+02 0.680e+02 0.641e+02 0.595e+02 0.555e+02 0.000e+00
 7 0.811e+02 0.797e+02 0.759e+02 0.723e+02 0.686e+02 0.642e+02 0.598e+02 0.555e+02 0.000e+00
 6 0.730e+02 0.724e+02 0.706e+02 0.680e+02 0.642e+02 0.594e+02 0.556e+02 0.000e+00
 5 0.689e+02 0.685e+02 0.669e+02 0.641e+02 0.598e+02 0.556e+02 0.000e+00
 4 0.646e+02 0.643e+02 0.626e+02 0.595e+02 0.555e+02 0.000e+00
 3 0.598e+02 0.598e+02 0.581e+02 0.555e+02 0.000e+00
 2 0.566e+02 0.569e+02 0.554e+02 0.000e+00
 1 0.553e+02 0.553e+02 0.000e+00 0.000e+00

                                                    plane k=23
 j   I= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.139e+03 0.134e+03 0.122e+03 0.110e+03 0.991e+02 0.893e+02 0.831e+02 0.711e+02 0.632e+02 0.588e+02 0.570e+02
10 0.134e+03 0.130e+03 0.120e+03 0.108e+03 0.975e+02 0.878e+02 0.814e+02 0.700e+02 0.629e+02 0.591e+02 0.570e+02
 9 0.122e+03 0.120e+03 0.112e+03 0.103e+03 0.932e+02 0.832e+02 0.758e+02 0.662e+02 0.604e+02 0.571e+02 0.000e+00
 8 0.110e+03 0.108e+03 0.103e+03 0.966e+02 0.882e+02 0.788e+02 0.701e+02 0.622e+02 0.572e+02 0.000e+00
 7 0.991e+02 0.975e+02 0.932e+02 0.882e+02 0.821e+02 0.745e+02 0.646e+02 0.573e+02 0.000e+00
 6 0.893e+02 0.878e+02 0.832e+02 0.788e+02 0.745e+02 0.682e+02 0.574e+02 0.000e+00
 5 0.831e+02 0.814e+02 0.758e+02 0.701e+02 0.646e+02 0.574e+02 0.000e+00
 4 0.711e+02 0.700e+02 0.662e+02 0.622e+02 0.573e+02 0.000e+00
 3 0.632e+02 0.629e+02 0.604e+02 0.572e+02 0.000e+00
 2 0.588e+02 0.591e+02 0.571e+02 0.000e+00
 1 0.570e+02 0.570e+02 0.000e+00 0.000e+00

                                                    plane k=22
 j   I= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.190e+03 0.189e+03 0.183e+03 0.171e+03 0.154e+03 0.140e+03 0.127e+03 0.101e+03 0.788e+02 0.650e+02 0.591e+02
10 0.189e+03 0.188e+03 0.182e+03 0.170e+03 0.154e+03 0.139e+03 0.126e+03 0.995e+02 0.784e+02 0.660e+02 0.592e+02
 9 0.183e+03 0.182e+03 0.178e+03 0.168e+03 0.152e+03 0.138e+03 0.123e+03 0.935e+02 0.721e+02 0.593e+02 0.000e+00
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 8 0.171e+03 0.170e+03 0.168e+03 0.161e+03 0.147e+03 0.135e+03 0.117e+03 0.826e+02 0.595e+02 0.000e+00
 7 0.154e+03 0.154e+03 0.152e+03 0.147e+03 0.139e+03 0.132e+03 0.103e+03 0.598e+02 0.000e+00
 6 0.140e+03 0.139e+03 0.138e+03 0.135e+03 0.132e+03 0.130e+03 0.602e+02 0.000e+00
 5 0.127e+03 0.126e+03 0.123e+03 0.117e+03 0.103e+03 0.602e+02 0.000e+00
 4 0.101e+03 0.995e+02 0.935e+02 0.826e+02 0.598e+02 0.000e+00
 3 0.788e+02 0.784e+02 0.721e+02 0.595e+02 0.000e+00
 2 0.650e+02 0.660e+02 0.593e+02 0.000e+00
 1 0.591e+02 0.592e+02 0.000e+00 0.000e+00

                                                    plane k=21
 J   I= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.209e+03 0.208e+03 0.202e+03 0.187e+03 0.167e+03 0.145e+03 0.133e+03 0.107e+03 0.838e+02 0.682e+02 0.615e+02
10 0.208e+03 0.207e+03 0.200e+03 0.186e+03 0.166e+03 0.145e+03 0.132e+03 0.106e+03 0.835e+02 0.694e+02 0.616e+02
 9 0.202e+03 0.200e+03 0.196e+03 0.184e+03 0.164e+03 0.143e+03 0.129e+03 0.100e+03 0.765e+02 0.617e+02 0.000e+00
 8 0.187e+03 0.186e+03 0.184e+03 0.176e+03 0.159e+03 0.140e+03 0.123e+03 0.881e+02 0.619e+02 0.000e+00
 7 0.167e+03 0.166e+03 0.164e+03 0.159e+03 0.148e+03 0.137e+03 0.108e+03 0.623e+02 0.000e+00
 6 0.145e+03 0.145e+03 0.143e+03 0.140e+03 0.137e+03 0.135e+03 0.628e+02 0.000e+00
 5 0.133e+03 0.132e+03 0.129e+03 0.123e+03 0.108e+03 0.628e+02 0.000e+00
 4 0.107e+03 0.106e+03 0.100e+03 0.881e+02 0.623e+02 0.000e+00
 3 0.838e+02 0.835e+02 0.765e+02 0.619e+02 0.000e+00
 2 0.682e+02 0.694e+02 0.617e+02 0.000e+00
 1 0.615e+02 0.616e+02 0.000e+00 0.000e+00

                                                    plane k=20
 J   I= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.233e+03 0.233e+03 0.225e+03 0.207e+03 0.182e+03 0.154e+03 0.142e+03 0.114e+03 0.888e+02 0.719e+02 0.647e+02
10 0.233e+03 0.231e+03 0.223e+03 0.206e+03 0.181e+03 0.154e+03 0.141e+03 0.113e+03 0.885e+02 0.732e+02 0.648e+02
 9 0.225e+03 0.223e+03 0.218e+03 0.205e+03 0.180e+03 0.152e+03 0.137e+03 0.107e+03 0.809e+02 0.649e+02 0.000e+00
 8 0.207e+03 0.206e+03 0.205e+03 0.195e+03 0.173e+03 0.149e+03 0.130e+03 0.934e+02 0.652e+02 0.000e+00
 7 0.182e+03 0.181e+03 0.180e+03 0.173e+03 0.159e+03 0.146e+03 0.115e+03 0.656e+02 0.000e+00
 6 0.154e+03 0.154e+03 0.152e+03 0.149e+03 0.146e+03 0.143e+03 0.661e+02 0.000e+00
 5 0.142e+03 0.141e+03 0.137e+03 0.130e+03 0.115e+03 0.661e+02 0.000e+00
 4 0.114e+03 0.113e+03 0.107e+03 0.934e+02 0.656e+02 0.000e+00
 3 0.888e+02 0.885e+02 0.809e+02 0.652e+02 0.000e+00
 2 0.719e+02 0.732e+02 0.649e+02 0.000e+00
 1 0.647e+02 0.648e+02 0.000e+00 0.000e+00

                                                    plane k=19
 J   I= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.259e+03 0.259e+03 0.250e+03 0.230e+03 0.200e+03 0.167e+03 0.153e+03 0.122e+03 0.951e+02 0.767e+02 0.688e+02
10 0.259e+03 0.257e+03 0.248e+03 0.228e+03 0.199e+03 0.166e+03 0.152e+03 0.121e+03 0.948e+02 0.781e+02 0.689e+02
 9 0.250e+03 0.248e+03 0.242e+03 0.226e+03 0.197e+03 0.164e+03 0.148e+03 0.114e+03 0.866e+02 0.690e+02 0.000e+00
 8 0.230e+03 0.228e+03 0.226e+03 0.215e+03 0.190e+03 0.161e+03 0.141e+03 0.100e+03 0.693e+02 0.000e+00
```

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 7 0.200e+03 0.199e+03 0.197e+03 0.190e+03 0.174e+03 0.157e+03 0.124e+03 0.697e+02 0.000e+00
 6 0.167e+03 0.166e+03 0.164e+03 0.161e+03 0.157e+03 0.154e+03 0.703e+02 0.000e+00
 5 0.153e+03 0.152e+03 0.148e+03 0.141e+03 0.124e+03 0.703e+02 0.000e+00
 4 0.122e+03 0.121e+03 0.114e+03 0.100e+03 0.697e+02 0.000e+00
 3 0.951e+02 0.948e+02 0.866e+02 0.693e+02 0.000e+00
 2 0.767e+02 0.781e+02 0.690e+02 0.000e+00
 1 0.688e+02 0.689e+02 0.000e+00 0.000e+00

                                                    plane k=18
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.281e+03 0.280e+03 0.271e+03 0.249e+03 0.217e+03 0.180e+03 0.164e+03 0.131e+03 0.102e+03 0.823e+02 0.738e+02
10 0.280e+03 0.278e+03 0.269e+03 0.248e+03 0.216e+03 0.179e+03 0.163e+03 0.130e+03 0.102e+03 0.839e+02 0.738e+02
 9 0.271e+03 0.269e+03 0.262e+03 0.245e+03 0.214e+03 0.177e+03 0.159e+03 0.123e+03 0.931e+02 0.740e+02 0.000e+00
 8 0.249e+03 0.248e+03 0.245e+03 0.233e+03 0.205e+03 0.174e+03 0.151e+03 0.108e+03 0.743e+02 0.000e+00
 7 0.217e+03 0.216e+03 0.214e+03 0.205e+03 0.188e+03 0.169e+03 0.133e+03 0.748e+02 0.000e+00
 6 0.180e+03 0.179e+03 0.177e+03 0.174e+03 0.169e+03 0.166e+03 0.755e+02 0.000e+00
 5 0.164e+03 0.163e+03 0.159e+03 0.151e+03 0.133e+03 0.755e+02 0.000e+00
 4 0.131e+03 0.130e+03 0.123e+03 0.108e+03 0.748e+02 0.000e+00
 3 0.102e+03 0.102e+03 0.931e+02 0.743e+02 0.000e+00
 2 0.823e+02 0.839e+02 0.740e+02 0.000e+00
 1 0.738e+02 0.738e+02 0.000e+00 0.000e+00

                                                    plane k=17
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.293e+03 0.293e+03 0.283e+03 0.261e+03 0.228e+03 0.190e+03 0.173e+03 0.139e+03 0.109e+03 0.881e+02 0.792e+02
10 0.293e+03 0.290e+03 0.281e+03 0.259e+03 0.227e+03 0.189e+03 0.172e+03 0.138e+03 0.108e+03 0.897e+02 0.792e+02
 9 0.283e+03 0.281e+03 0.274e+03 0.257e+03 0.225e+03 0.187e+03 0.168e+03 0.130e+03 0.992e+02 0.795e+02 0.000e+00
 8 0.261e+03 0.259e+03 0.257e+03 0.244e+03 0.216e+03 0.183e+03 0.160e+03 0.115e+03 0.798e+02 0.000e+00
 7 0.228e+03 0.227e+03 0.225e+03 0.216e+03 0.198e+03 0.178e+03 0.141e+03 0.803e+02 0.000e+00
 6 0.190e+03 0.189e+03 0.187e+03 0.183e+03 0.178e+03 0.175e+03 0.809e+02 0.000e+00
 5 0.173e+03 0.172e+03 0.168e+03 0.160e+03 0.141e+03 0.809e+02 0.000e+00
 4 0.139e+03 0.138e+03 0.130e+03 0.115e+03 0.803e+02 0.000e+00
 3 0.109e+03 0.108e+03 0.992e+02 0.798e+02 0.000e+00
 2 0.881e+02 0.897e+02 0.795e+02 0.000e+00
 1 0.792e+02 0.792e+02 0.000e+00 0.000e+00

                                                    plane k=16
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.292e+03 0.291e+03 0.281e+03 0.260e+03 0.229e+03 0.192e+03 0.176e+03 0.142e+03 0.113e+03 0.925e+02 0.838e+02
10 0.291e+03 0.288e+03 0.279e+03 0.259e+03 0.227e+03 0.192e+03 0.175e+03 0.141e+03 0.112e+03 0.941e+02 0.838e+02
 9 0.281e+03 0.279e+03 0.273e+03 0.256e+03 0.225e+03 0.190e+03 0.171e+03 0.134e+03 0.104e+03 0.840e+02 0.000e+00
 8 0.260e+03 0.259e+03 0.256e+03 0.244e+03 0.217e+03 0.186e+03 0.163e+03 0.119e+03 0.843e+02 0.000e+00
 7 0.229e+03 0.227e+03 0.225e+03 0.217e+03 0.199e+03 0.181e+03 0.144e+03 0.848e+02 0.000e+00
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 6 0.192e+03 0.192e+03 0.190e+03 0.186e+03 0.181e+03 0.178e+03 0.855e+02 0.000e+00
 5 0.176e+03 0.175e+03 0.171e+03 0.163e+03 0.144e+03 0.855e+02 0.000e+00
 4 0.142e+03 0.141e+03 0.134e+03 0.119e+03 0.848e+02 0.000e+00
 3 0.113e+03 0.112e+03 0.104e+03 0.843e+02 0.000e+00
 2 0.925e+02 0.941e+02 0.840e+02 0.000e+00
 1 0.838e+02 0.838e+02 0.000e+00 0.000e+00

                                                                    plane k=15
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.293e+03 0.292e+03 0.282e+03 0.261e+03 0.230e+03 0.193e+03 0.177e+03 0.143e+03 0.114e+03 0.935e+02 0.846e+02
10 0.292e+03 0.289e+03 0.280e+03 0.260e+03 0.228e+03 0.193e+03 0.176e+03 0.142e+03 0.114e+03 0.951e+02 0.847e+02
 9 0.282e+03 0.280e+03 0.274e+03 0.257e+03 0.226e+03 0.191e+03 0.172e+03 0.135e+03 0.105e+03 0.849e+02 0.000e+00
 8 0.261e+03 0.260e+03 0.257e+03 0.245e+03 0.218e+03 0.187e+03 0.164e+03 0.120e+03 0.852e+02 0.000e+00
 7 0.230e+03 0.228e+03 0.226e+03 0.218e+03 0.200e+03 0.183e+03 0.146e+03 0.857e+02 0.000e+00
 6 0.193e+03 0.193e+03 0.191e+03 0.187e+03 0.183e+03 0.179e+03 0.864e+02 0.000e+00
 5 0.177e+03 0.176e+03 0.172e+03 0.164e+03 0.146e+03 0.864e+02 0.000e+00
 4 0.143e+03 0.142e+03 0.135e+03 0.120e+03 0.857e+02 0.000e+00
 3 0.114e+03 0.114e+03 0.105e+03 0.852e+02 0.000e+00
 2 0.935e+02 0.951e+02 0.849e+02 0.000e+00
 1 0.846e+02 0.847e+02 0.000e+00 0.000e+00

                                                                    plane k=14
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.298e+03 0.297e+03 0.287e+03 0.265e+03 0.233e+03 0.194e+03 0.177e+03 0.142e+03 0.112e+03 0.909e+02 0.817e+02
10 0.297e+03 0.295e+03 0.285e+03 0.264e+03 0.231e+03 0.194e+03 0.176e+03 0.141e+03 0.112e+03 0.925e+02 0.818e+02
 9 0.287e+03 0.285e+03 0.279e+03 0.261e+03 0.229e+03 0.191e+03 0.172e+03 0.134e+03 0.102e+03 0.820e+02 0.000e+00
 8 0.265e+03 0.264e+03 0.261e+03 0.249e+03 0.220e+03 0.187e+03 0.164e+03 0.118e+03 0.823e+02 0.000e+00
 7 0.233e+03 0.231e+03 0.229e+03 0.220e+03 0.202e+03 0.183e+03 0.145e+03 0.828e+02 0.000e+00
 6 0.194e+03 0.194e+03 0.191e+03 0.187e+03 0.183e+03 0.180e+03 0.835e+02 0.000e+00
 5 0.177e+03 0.176e+03 0.172e+03 0.164e+03 0.145e+03 0.835e+02 0.000e+00
 4 0.142e+03 0.141e+03 0.134e+03 0.118e+03 0.828e+02 0.000e+00
 3 0.112e+03 0.112e+03 0.102e+03 0.823e+02 0.000e+00
 2 0.909e+02 0.925e+02 0.820e+02 0.000e+00
 1 0.817e+02 0.818e+02 0.000e+00 0.000e+00

                                                                    plane k=13
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.293e+03 0.293e+03 0.283e+03 0.261e+03 0.228e+03 0.190e+03 0.172e+03 0.138e+03 0.108e+03 0.868e+02 0.776e+02
10 0.293e+03 0.290e+03 0.281e+03 0.259e+03 0.227e+03 0.189e+03 0.172e+03 0.137e+03 0.107e+03 0.884e+02 0.777e+02
 9 0.283e+03 0.281e+03 0.274e+03 0.257e+03 0.225e+03 0.187e+03 0.168e+03 0.130e+03 0.983e+02 0.779e+02 0.000e+00
 8 0.261e+03 0.259e+03 0.257e+03 0.244e+03 0.216e+03 0.183e+03 0.159e+03 0.114e+03 0.783e+02 0.000e+00
 7 0.228e+03 0.227e+03 0.225e+03 0.216e+03 0.197e+03 0.178e+03 0.140e+03 0.788e+02 0.000e+00
 6 0.190e+03 0.189e+03 0.187e+03 0.183e+03 0.178e+03 0.175e+03 0.795e+02 0.000e+00
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     5 0.172e+03 0.172e+03 0.168e+03 0.159e+03 0.140e+03 0.795e+02 0.000e+00
     4 0.138e+03 0.137e+03 0.130e+03 0.114e+03 0.788e+02 0.000e+00
     3 0.108e+03 0.107e+03 0.983e+02 0.783e+02 0.000e+00
     2 0.868e+02 0.884e+02 0.779e+02 0.000e+00
     1 0.776e+02 0.777e+02 0.000e+00 0.000e+00

                                                                    plane k=12
   J    I= 2
    12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
    11 0.285e+03 0.284e+03 0.275e+03 0.253e+03 0.221e+03 0.182e+03 0.166e+03 0.132e+03 0.103e+03 0.825e+02 0.737e+02
    10 0.284e+03 0.282e+03 0.273e+03 0.251e+03 0.219e+03 0.182e+03 0.165e+03 0.131e+03 0.103e+03 0.842e+02 0.737e+02
     9 0.275e+03 0.273e+03 0.267e+03 0.249e+03 0.217e+03 0.180e+03 0.161e+03 0.124e+03 0.938e+02 0.740e+02 0.000e+00
     8 0.253e+03 0.251e+03 0.249e+03 0.237e+03 0.209e+03 0.176e+03 0.153e+03 0.109e+03 0.743e+02 0.000e+00
     7 0.221e+03 0.219e+03 0.217e+03 0.209e+03 0.190e+03 0.172e+03 0.135e+03 0.748e+02 0.000e+00
     6 0.182e+03 0.182e+03 0.180e+03 0.176e+03 0.172e+03 0.168e+03 0.754e+02 0.000e+00
     5 0.166e+03 0.165e+03 0.161e+03 0.153e+03 0.135e+03 0.754e+02 0.000e+00
     4 0.132e+03 0.131e+03 0.124e+03 0.109e+03 0.748e+02 0.000e+00
     3 0.103e+03 0.103e+03 0.938e+02 0.743e+02 0.000e+00
     2 0.825e+02 0.842e+02 0.740e+02 0.000e+00
     1 0.737e+02 0.737e+02 0.000e+00 0.000e+00

                                                                    plane k=11
   J    I= 2
    12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
    11 0.273e+03 0.272e+03 0.263e+03 0.242e+03 0.211e+03 0.174e+03 0.158e+03 0.126e+03 0.981e+02 0.788e+02 0.703e+02
    10 0.272e+03 0.270e+03 0.261e+03 0.240e+03 0.209e+03 0.174e+03 0.157e+03 0.125e+03 0.979e+02 0.803e+02 0.704e+02
     9 0.263e+03 0.261e+03 0.255e+03 0.238e+03 0.207e+03 0.172e+03 0.154e+03 0.119e+03 0.895e+02 0.706e+02 0.000e+00
     8 0.242e+03 0.240e+03 0.238e+03 0.226e+03 0.199e+03 0.168e+03 0.146e+03 0.104e+03 0.709e+02 0.000e+00
     7 0.211e+03 0.209e+03 0.207e+03 0.199e+03 0.182e+03 0.164e+03 0.128e+03 0.714e+02 0.000e+00
     6 0.174e+03 0.174e+03 0.172e+03 0.168e+03 0.164e+03 0.161e+03 0.720e+02 0.000e+00
     5 0.158e+03 0.157e+03 0.154e+03 0.146e+03 0.128e+03 0.720e+02 0.000e+00
     4 0.126e+03 0.125e+03 0.119e+03 0.104e+03 0.714e+02 0.000e+00
     3 0.981e+02 0.979e+02 0.895e+02 0.709e+02 0.000e+00
     2 0.788e+02 0.803e+02 0.706e+02 0.000e+00
     1 0.703e+02 0.704e+02 0.000e+00 0.000e+00

                                                                    plane k=10
   J    I= 2
    12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
    11 0.256e+03 0.256e+03 0.248e+03 0.228e+03 0.200e+03 0.167e+03 0.151e+03 0.120e+03 0.939e+02 0.757e+02 0.677e+02
    10 0.256e+03 0.254e+03 0.246e+03 0.227e+03 0.199e+03 0.166e+03 0.150e+03 0.119e+03 0.938e+02 0.772e+02 0.678e+02
     9 0.248e+03 0.246e+03 0.241e+03 0.226e+03 0.197e+03 0.164e+03 0.146e+03 0.113e+03 0.858e+02 0.680e+02 0.000e+00
     8 0.228e+03 0.227e+03 0.226e+03 0.215e+03 0.189e+03 0.160e+03 0.139e+03 0.994e+02 0.683e+02 0.000e+00
     7 0.200e+03 0.199e+03 0.197e+03 0.189e+03 0.172e+03 0.155e+03 0.122e+03 0.687e+02 0.000e+00
     6 0.167e+03 0.166e+03 0.164e+03 0.160e+03 0.155e+03 0.152e+03 0.692e+02 0.000e+00
     5 0.151e+03 0.150e+03 0.146e+03 0.139e+03 0.122e+03 0.692e+02 0.000e+00
```

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 4 0.120e+03 0.119e+03 0.113e+03 0.994e+02 0.687e+02 0.000e+00
 3 0.939e+02 0.938e+02 0.858e+02 0.683e+02 0.000e+00
 2 0.757e+02 0.772e+02 0.680e+02 0.000e+00
 1 0.677e+02 0.678e+02 0.000e+00 0.000e+00

                                                                  plane k= 9
 J   I= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.237e+03 0.237e+03 0.230e+03 0.213e+03 0.191e+03 0.162e+03 0.145e+03 0.115e+03 0.905e+02 0.733e+02 0.658e+02
10 0.237e+03 0.236e+03 0.229e+03 0.212e+03 0.189e+03 0.161e+03 0.144e+03 0.114e+03 0.904e+02 0.747e+02 0.659e+02
 9 0.230e+03 0.229e+03 0.225e+03 0.212e+03 0.188e+03 0.158e+03 0.140e+03 0.109e+03 0.828e+02 0.660e+02 0.000e+00
 8 0.213e+03 0.212e+03 0.212e+03 0.202e+03 0.179e+03 0.153e+03 0.132e+03 0.952e+02 0.663e+02 0.000e+00
 7 0.191e+03 0.189e+03 0.188e+03 0.179e+03 0.160e+03 0.144e+03 0.114e+03 0.666e+02 0.000e+00
 6 0.162e+03 0.161e+03 0.158e+03 0.153e+03 0.144e+03 0.141e+03 0.671e+02 0.000e+00
 5 0.145e+03 0.144e+03 0.140e+03 0.132e+03 0.114e+03 0.671e+02 0.000e+00
 4 0.115e+03 0.114e+03 0.109e+03 0.952e+02 0.666e+02 0.000e+00
 3 0.905e+02 0.904e+02 0.828e+02 0.663e+02 0.000e+00
 2 0.733e+02 0.747e+02 0.660e+02 0.000e+00
 1 0.658e+02 0.659e+02 0.000e+00 0.000e+00

                                                                  plane k= 8
 J   I= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.213e+03 0.213e+03 0.208e+03 0.195e+03 0.180e+03 0.146e+03 0.128e+03 0.109e+03 0.878e+02 0.714e+02 0.642e+02
10 0.213e+03 0.212e+03 0.207e+03 0.194e+03 0.179e+03 0.147e+03 0.128e+03 0.109e+03 0.875e+02 0.727e+02 0.643e+02
 9 0.208e+03 0.207e+03 0.204e+03 0.194e+03 0.178e+03 0.145e+03 0.124e+03 0.103e+03 0.800e+02 0.644e+02 0.000e+00
 8 0.195e+03 0.194e+03 0.194e+03 0.186e+03 0.168e+03 0.136e+03 0.115e+03 0.892e+02 0.646e+02 0.000e+00
 7 0.180e+03 0.179e+03 0.178e+03 0.168e+03 0.143e+03 0.122e+03 0.101e+03 0.649e+02 0.000e+00
 6 0.146e+03 0.147e+03 0.145e+03 0.136e+03 0.122e+03 0.121e+03 0.653e+02 0.000e+00
 5 0.128e+03 0.128e+03 0.124e+03 0.115e+03 0.101e+03 0.653e+02 0.000e+00
 4 0.109e+03 0.109e+03 0.103e+03 0.892e+02 0.649e+02 0.000e+00
 3 0.878e+02 0.875e+02 0.800e+02 0.646e+02 0.000e+00
 2 0.714e+02 0.727e+02 0.644e+02 0.000e+00
 1 0.642e+02 0.643e+02 0.000e+00 0.000e+00

                                                                  plane k= 7
 j   I= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.181e+03 0.181e+03 0.178e+03 0.167e+03 0.156e+03 0.122e+03 0.103e+03 0.903e+02 0.774e+02 0.672e+02 0.628e+02
10 0.181e+03 0.181e+03 0.177e+03 0.167e+03 0.156e+03 0.122e+03 0.103e+03 0.899e+02 0.773e+02 0.681e+02 0.628e+02
 9 0.178e+03 0.177e+03 0.175e+03 0.167e+03 0.155e+03 0.121e+03 0.101e+03 0.867e+02 0.727e+02 0.630e+02 0.000e+00
 8 0.167e+03 0.167e+03 0.167e+03 0.161e+03 0.146e+03 0.115e+03 0.959e+02 0.786e+02 0.631e+02 0.000e+00
 7 0.156e+03 0.156e+03 0.155e+03 0.146e+03 0.123e+03 0.104e+03 0.885e+02 0.634e+02 0.000e+00
 6 0.122e+03 0.122e+03 0.121e+03 0.115e+03 0.104e+03 0.103e+03 0.636e+02 0.000e+00
 5 0.103e+03 0.103e+03 0.101e+03 0.959e+02 0.885e+02 0.636e+02 0.000e+00
 4 0.903e+02 0.899e+02 0.867e+02 0.786e+02 0.634e+02 0.000e+00
```

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      3 0.774e+02 0.773e+02 0.727e+02 0.631e+02 0.000e+00
      2 0.672e+02 0.681e+02 0.630e+02 0.000e+00
      1 0.628e+02 0.628e+02 0.000e+00 0.000e+00

                                                        plane k= 6
     J   i= 2
     12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
     11 0.141e+03 0.141e+03 0.139e+03 0.131e+03 0.124e+03 0.990e+02 0.856e+02 0.774e+02 0.698e+02 0.641e+02 0.616e+02
     10 0.141e+03 0.141e+03 0.138e+03 0.131e+03 0.123e+03 0.993e+02 0.856e+02 0.772e+02 0.698e+02 0.646e+02 0.617e+02
      9 0.139e+03 0.138e+03 0.137e+03 0.132e+03 0.123e+03 0.987e+02 0.845e+02 0.754e+02 0.672e+02 0.618e+02 0.000e+00
      8 0.131e+03 0.131e+03 0.132e+03 0.128e+03 0.117e+03 0.949e+02 0.815e+02 0.708e+02 0.619e+02 0.000e+00
      7 0.124e+03 0.123e+03 0.123e+03 0.117e+03 0.101e+03 0.876e+02 0.776e+02 0.621e+02 0.000e+00
      6 0.990e+02 0.993e+02 0.987e+02 0.949e+02 0.876e+02 0.868e+02 0.623e+02 0.000e+00
      5 0.856e+02 0.856e+02 0.845e+02 0.815e+02 0.776e+02 0.623e+02 0.000e+00
      4 0.774e+02 0.772e+02 0.754e+02 0.708e+02 0.621e+02 0.000e+00
      3 0.698e+02 0.698e+02 0.672e+02 0.619e+02 0.000e+00
      2 0.641e+02 0.646e+02 0.618e+02 0.000e+00
      1 0.616e+02 0.617e+02 0.000e+00 0.000e+00

                                                        plane k= 5
     J   i= 2
     12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
     11 0.923e+02 0.927e+02 0.917e+02 0.885e+02 0.855e+02 0.756e+02 0.697e+02 0.665e+02 0.637e+02 0.617e+02 0.608e+02
     10 0.927e+02 0.924e+02 0.913e+02 0.885e+02 0.851e+02 0.758e+02 0.697e+02 0.665e+02 0.638e+02 0.619e+02 0.609e+02
      9 0.917e+02 0.913e+02 0.913e+02 0.889e+02 0.853e+02 0.757e+02 0.694e+02 0.659e+02 0.629e+02 0.610e+02 0.000e+00
      8 0.885e+02 0.885e+02 0.889e+02 0.873e+02 0.831e+02 0.743e+02 0.685e+02 0.643e+02 0.611e+02 0.000e+00
      7 0.855e+02 0.851e+02 0.853e+02 0.831e+02 0.764e+02 0.717e+02 0.675e+02 0.613e+02 0.000e+00
      6 0.756e+02 0.758e+02 0.757e+02 0.743e+02 0.717e+02 0.714e+02 0.614e+02 0.000e+00
      5 0.697e+02 0.697e+02 0.694e+02 0.685e+02 0.675e+02 0.614e+02 0.000e+00
      4 0.665e+02 0.665e+02 0.659e+02 0.643e+02 0.613e+02 0.000e+00
      3 0.637e+02 0.638e+02 0.629e+02 0.611e+02 0.000e+00
      2 0.617e+02 0.619e+02 0.610e+02 0.000e+00
      1 0.608e+02 0.609e+02 0.000e+00 0.000e+00

                                                        plane k= 4
     J   i= 2
     12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
     11 0.653e+02 0.653e+02 0.650e+02 0.644e+02 0.635e+02 0.624e+02 0.618e+02 0.613e+02 0.610e+02 0.609e+02 0.608e+02
     10 0.653e+02 0.652e+02 0.650e+02 0.644e+02 0.636e+02 0.625e+02 0.618e+02 0.614e+02 0.611e+02 0.609e+02 0.609e+02
      9 0.650e+02 0.650e+02 0.647e+02 0.643e+02 0.635e+02 0.625e+02 0.618e+02 0.614e+02 0.611e+02 0.610e+02 0.000e+00
      8 0.644e+02 0.644e+02 0.643e+02 0.639e+02 0.633e+02 0.625e+02 0.619e+02 0.615e+02 0.612e+02 0.000e+00
      7 0.635e+02 0.636e+02 0.635e+02 0.633e+02 0.631e+02 0.630e+02 0.620e+02 0.615e+02 0.000e+00
      6 0.624e+02 0.625e+02 0.625e+02 0.625e+02 0.630e+02 0.627e+02 0.619e+02 0.000e+00
      5 0.618e+02 0.618e+02 0.618e+02 0.619e+02 0.620e+02 0.619e+02 0.000e+00
      4 0.613e+02 0.614e+02 0.614e+02 0.615e+02 0.615e+02 0.000e+00
      3 0.610e+02 0.611e+02 0.611e+02 0.612e+02 0.000e+00
```

```
 2 0.609e+02 0.609e+02 0.610e+02 0.000e+00
 1 0.608e+02 0.609e+02 0.000e+00 0.000e+00

                                                    plane k= 3
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.642e+02 0.642e+02 0.639e+02 0.634e+02 0.628e+02 0.621e+02 0.616e+02 0.612e+02 0.610e+02 0.608e+02 0.608e+02
10 0.642e+02 0.641e+02 0.639e+02 0.634e+02 0.628e+02 0.621e+02 0.617e+02 0.613e+02 0.610e+02 0.609e+02 0.608e+02
 9 0.639e+02 0.639e+02 0.637e+02 0.633e+02 0.627e+02 0.621e+02 0.617e+02 0.613e+02 0.611e+02 0.610e+02 0.000e+00
 8 0.634e+02 0.634e+02 0.633e+02 0.630e+02 0.626e+02 0.621e+02 0.617e+02 0.613e+02 0.612e+02 0.000e+00
 7 0.628e+02 0.628e+02 0.627e+02 0.626e+02 0.623e+02 0.620e+02 0.616e+02 0.614e+02 0.000e+00
 6 0.621e+02 0.621e+02 0.621e+02 0.621e+02 0.620e+02 0.617e+02 0.615e+02 0.000e+00
 5 0.616e+02 0.617e+02 0.617e+02 0.617e+02 0.616e+02 0.615e+02 0.000e+00
 4 0.612e+02 0.613e+02 0.613e+02 0.613e+02 0.614e+02 0.000e+00
 3 0.610e+02 0.610e+02 0.611e+02 0.612e+02 0.000e+00
 2 0.608e+02 0.609e+02 0.610e+02 0.000e+00
 1 0.608e+02 0.608e+02 0.000e+00 0.000e+00

                                                    plane k= 2
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.638e+02 0.638e+02 0.635e+02 0.631e+02 0.625e+02 0.620e+02 0.615e+02 0.611e+02 0.609e+02 0.607e+02 0.606e+02
10 0.638e+02 0.637e+02 0.635e+02 0.631e+02 0.625e+02 0.620e+02 0.616e+02 0.612e+02 0.609e+02 0.607e+02 0.607e+02
 9 0.635e+02 0.635e+02 0.633e+02 0.630e+02 0.625e+02 0.619e+02 0.616e+02 0.612e+02 0.610e+02 0.608e+02 0.000e+00
 8 0.631e+02 0.631e+02 0.630e+02 0.627e+02 0.623e+02 0.619e+02 0.615e+02 0.612e+02 0.610e+02 0.000e+00
 7 0.625e+02 0.625e+02 0.625e+02 0.623e+02 0.620e+02 0.617e+02 0.614e+02 0.612e+02 0.000e+00
 6 0.620e+02 0.620e+02 0.619e+02 0.619e+02 0.617e+02 0.614e+02 0.612e+02 0.000e+00
 5 0.615e+02 0.616e+02 0.616e+02 0.615e+02 0.614e+02 0.612e+02 0.000e+00
 4 0.611e+02 0.612e+02 0.612e+02 0.612e+02 0.612e+02 0.000e+00
 3 0.609e+02 0.609e+02 0.610e+02 0.610e+02 0.000e+00
 2 0.607e+02 0.607e+02 0.608e+02 0.000e+00
 1 0.606e+02 0.607e+02 0.000e+00 0.000e+00

                                                    plane k= 1
 j   i= 2
12 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
11 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
10 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 9 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 8 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 6 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 5 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 4 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 3 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.000e+00
 2 0.270e+02 0.270e+02 0.270e+02 0.000e+00
```

```
 1 0.000e+00 0.000e+00 0.000e+00 0.000e+00

1

                                        * * * side temperature, c * * *

                                                    plane k=30
 i   j= 2
 2 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 3 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 4 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 5 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 6 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 7 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00

                                                    plane k=29
 i   j= 2
 2 0.515e+02 0.515e+02 0.516e+02 0.516e+02 0.517e+02 0.517e+02 0.517e+02 0.517e+02 0.516e+02 0.516e+02 0.515e+02 0.515e+02
 3 0.516e+02 0.516e+02 0.516e+02 0.517e+02 0.517e+02 0.517e+02 0.517e+02 0.517e+02 0.517e+02 0.516e+02 0.516e+02 0.516e+02
 4 0.516e+02 0.517e+02 0.517e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.517e+02 0.517e+02 0.516e+02
 5 0.516e+02 0.517e+02 0.517e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.517e+02 0.517e+02 0.516e+02
 6 0.516e+02 0.517e+02 0.517e+02 0.517e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.517e+02 0.517e+02 0.517e+02 0.516e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=28
 i   j= 2
 2 0.516e+02 0.517e+02 0.517e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.517e+02 0.517e+02 0.516e+02
 3 0.517e+02 0.517e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.518e+02 0.517e+02 0.517e+02
 4 0.519e+02 0.519e+02 0.519e+02 0.520e+02 0.520e+02 0.520e+02 0.520e+02 0.520e+02 0.520e+02 0.519e+02 0.519e+02 0.519e+02
 5 0.518e+02 0.519e+02 0.519e+02 0.520e+02 0.520e+02 0.520e+02 0.520e+02 0.520e+02 0.520e+02 0.519e+02 0.519e+02 0.518e+02
 6 0.518e+02 0.518e+02 0.519e+02 0.519e+02 0.520e+02 0.520e+02 0.520e+02 0.520e+02 0.519e+02 0.519e+02 0.518e+02 0.518e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=27
 i   j= 2
 2 0.519e+02 0.520e+02 0.520e+02 0.521e+02 0.521e+02 0.521e+02 0.521e+02 0.521e+02 0.521e+02 0.520e+02 0.520e+02 0.519e+02
 3 0.520e+02 0.521e+02 0.521e+02 0.522e+02 0.522e+02 0.522e+02 0.522e+02 0.522e+02 0.522e+02 0.521e+02 0.521e+02 0.520e+02
 4 0.522e+02 0.523e+02 0.523e+02 0.523e+02 0.524e+02 0.524e+02 0.524e+02 0.524e+02 0.523e+02 0.523e+02 0.523e+02 0.522e+02
 5 0.522e+02 0.522e+02 0.523e+02 0.523e+02 0.524e+02 0.524e+02 0.524e+02 0.524e+02 0.523e+02 0.523e+02 0.522e+02 0.522e+02
 6 0.522e+02 0.522e+02 0.522e+02 0.523e+02 0.523e+02 0.523e+02 0.523e+02 0.523e+02 0.523e+02 0.522e+02 0.522e+02 0.522e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=26
 i   j= 2
 2 0.528e+02 0.528e+02 0.529e+02 0.529e+02 0.529e+02 0.530e+02 0.530e+02 0.529e+02 0.529e+02 0.529e+02 0.528e+02 0.528e+02
 3 0.528e+02 0.528e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.528e+02 0.528e+02
 4 0.528e+02 0.528e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.528e+02 0.528e+02
```

```
 5 0.528e+02 0.528e+02 0.528e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.528e+02 0.528e+02 0.528e+02
 6 0.527e+02 0.528e+02 0.528e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.529e+02 0.528e+02 0.528e+02 0.527e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=25
 i   j= 2
 2 0.539e+02 0.540e+02 0.540e+02 0.541e+02 0.541e+02 0.541e+02 0.541e+02 0.541e+02 0.541e+02 0.540e+02 0.540e+02 0.539e+02
 3 0.539e+02 0.540e+02 0.540e+02 0.541e+02 0.541e+02 0.541e+02 0.541e+02 0.541e+02 0.541e+02 0.540e+02 0.540e+02 0.539e+02
 4 0.539e+02 0.539e+02 0.540e+02 0.540e+02 0.541e+02 0.541e+02 0.541e+02 0.541e+02 0.540e+02 0.540e+02 0.539e+02 0.539e+02
 5 0.539e+02 0.539e+02 0.540e+02 0.540e+02 0.540e+02 0.541e+02 0.541e+02 0.540e+02 0.540e+02 0.540e+02 0.539e+02 0.539e+02
 6 0.538e+02 0.539e+02 0.539e+02 0.540e+02 0.540e+02 0.540e+02 0.540e+02 0.540e+02 0.540e+02 0.539e+02 0.539e+02 0.538e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=24
 i   j= 2
 2 0.553e+02 0.553e+02 0.554e+02 0.555e+02 0.555e+02 0.555e+02 0.555e+02 0.555e+02 0.555e+02 0.554e+02 0.553e+02 0.553e+02
 3 0.553e+02 0.553e+02 0.554e+02 0.555e+02 0.555e+02 0.555e+02 0.555e+02 0.555e+02 0.555e+02 0.554e+02 0.553e+02 0.553e+02
 4 0.553e+02 0.553e+02 0.554e+02 0.554e+02 0.555e+02 0.555e+02 0.555e+02 0.555e+02 0.554e+02 0.554e+02 0.553e+02 0.553e+02
 5 0.552e+02 0.553e+02 0.553e+02 0.554e+02 0.555e+02 0.555e+02 0.555e+02 0.555e+02 0.554e+02 0.553e+02 0.553e+02 0.552e+02
 6 0.552e+02 0.552e+02 0.553e+02 0.554e+02 0.554e+02 0.554e+02 0.554e+02 0.554e+02 0.554e+02 0.553e+02 0.552e+02 0.552e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=23
 i   j= 2
 2 0.570e+02 0.570e+02 0.571e+02 0.572e+02 0.573e+02 0.574e+02 0.574e+02 0.573e+02 0.572e+02 0.571e+02 0.570e+02 0.570e+02
 3 0.570e+02 0.570e+02 0.571e+02 0.572e+02 0.573e+02 0.574e+02 0.574e+02 0.573e+02 0.572e+02 0.571e+02 0.570e+02 0.570e+02
 4 0.569e+02 0.570e+02 0.571e+02 0.572e+02 0.573e+02 0.573e+02 0.573e+02 0.573e+02 0.572e+02 0.571e+02 0.570e+02 0.569e+02
 5 0.569e+02 0.569e+02 0.570e+02 0.571e+02 0.572e+02 0.573e+02 0.573e+02 0.572e+02 0.571e+02 0.570e+02 0.569e+02 0.569e+02
 6 0.568e+02 0.569e+02 0.570e+02 0.571e+02 0.572e+02 0.572e+02 0.572e+02 0.572e+02 0.571e+02 0.570e+02 0.569e+02 0.568e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=22
 i   j= 2
 2 0.591e+02 0.591e+02 0.592e+02 0.594e+02 0.597e+02 0.600e+02 0.600e+02 0.597e+02 0.594e+02 0.592e+02 0.591e+02 0.591e+02
 3 0.590e+02 0.590e+02 0.591e+02 0.593e+02 0.595e+02 0.597e+02 0.597e+02 0.595e+02 0.593e+02 0.591e+02 0.590e+02 0.590e+02
 4 0.589e+02 0.589e+02 0.590e+02 0.592e+02 0.594e+02 0.595e+02 0.595e+02 0.594e+02 0.592e+02 0.590e+02 0.589e+02 0.589e+02
 5 0.588e+02 0.589e+02 0.590e+02 0.591e+02 0.593e+02 0.593e+02 0.593e+02 0.593e+02 0.591e+02 0.590e+02 0.589e+02 0.588e+02
 6 0.587e+02 0.588e+02 0.589e+02 0.590e+02 0.592e+02 0.593e+02 0.593e+02 0.592e+02 0.590e+02 0.589e+02 0.588e+02 0.587e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=21
 i   j= 2
 2 0.615e+02 0.615e+02 0.617e+02 0.619e+02 0.622e+02 0.626e+02 0.626e+02 0.622e+02 0.619e+02 0.617e+02 0.615e+02 0.615e+02
 3 0.614e+02 0.614e+02 0.616e+02 0.618e+02 0.620e+02 0.623e+02 0.623e+02 0.620e+02 0.618e+02 0.616e+02 0.614e+02 0.614e+02
 4 0.612e+02 0.613e+02 0.614e+02 0.616e+02 0.618e+02 0.620e+02 0.620e+02 0.618e+02 0.616e+02 0.614e+02 0.613e+02 0.612e+02
 5 0.611e+02 0.612e+02 0.613e+02 0.615e+02 0.617e+02 0.618e+02 0.618e+02 0.617e+02 0.615e+02 0.613e+02 0.612e+02 0.611e+02
```

```
 6 0.611e+02 0.611e+02 0.613e+02 0.614e+02 0.616e+02 0.617e+02 0.617e+02 0.616e+02 0.614e+02 0.613e+02 0.611e+02 0.611e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=20
 i    j= 2
 2 0.646e+02 0.647e+02 0.649e+02 0.651e+02 0.655e+02 0.659e+02 0.659e+02 0.655e+02 0.651e+02 0.649e+02 0.647e+02 0.646e+02
 3 0.645e+02 0.646e+02 0.648e+02 0.650e+02 0.653e+02 0.656e+02 0.656e+02 0.653e+02 0.650e+02 0.648e+02 0.646e+02 0.645e+02
 4 0.644e+02 0.645e+02 0.646e+02 0.648e+02 0.651e+02 0.652e+02 0.652e+02 0.651e+02 0.648e+02 0.646e+02 0.645e+02 0.644e+02
 5 0.643e+02 0.644e+02 0.645e+02 0.647e+02 0.649e+02 0.650e+02 0.650e+02 0.649e+02 0.647e+02 0.645e+02 0.644e+02 0.643e+02
 6 0.642e+02 0.643e+02 0.644e+02 0.646e+02 0.648e+02 0.650e+02 0.650e+02 0.648e+02 0.646e+02 0.644e+02 0.643e+02 0.642e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=19
 i    j= 2
 2 0.687e+02 0.688e+02 0.690e+02 0.693e+02 0.697e+02 0.702e+02 0.702e+02 0.697e+02 0.693e+02 0.690e+02 0.688e+02 0.687e+02
 3 0.686e+02 0.687e+02 0.688e+02 0.691e+02 0.694e+02 0.697e+02 0.697e+02 0.694e+02 0.691e+02 0.688e+02 0.687e+02 0.686e+02
 4 0.684e+02 0.685e+02 0.687e+02 0.689e+02 0.692e+02 0.694e+02 0.694e+02 0.692e+02 0.689e+02 0.687e+02 0.685e+02 0.684e+02
 5 0.683e+02 0.684e+02 0.686e+02 0.688e+02 0.690e+02 0.692e+02 0.692e+02 0.690e+02 0.688e+02 0.686e+02 0.684e+02 0.683e+02
 6 0.682e+02 0.683e+02 0.685e+02 0.687e+02 0.689e+02 0.691e+02 0.691e+02 0.689e+02 0.687e+02 0.685e+02 0.683e+02 0.682e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=18
 i    j= 2
 2 0.737e+02 0.738e+02 0.740e+02 0.743e+02 0.747e+02 0.753e+02 0.753e+02 0.747e+02 0.743e+02 0.740e+02 0.738e+02 0.737e+02
 3 0.735e+02 0.736e+02 0.738e+02 0.741e+02 0.745e+02 0.748e+02 0.748e+02 0.745e+02 0.741e+02 0.738e+02 0.736e+02 0.735e+02
 4 0.734e+02 0.734e+02 0.736e+02 0.739e+02 0.742e+02 0.744e+02 0.744e+02 0.742e+02 0.739e+02 0.736e+02 0.734e+02 0.734e+02
 5 0.732e+02 0.733e+02 0.735e+02 0.737e+02 0.740e+02 0.741e+02 0.741e+02 0.740e+02 0.737e+02 0.735e+02 0.733e+02 0.732e+02
 6 0.731e+02 0.732e+02 0.734e+02 0.736e+02 0.739e+02 0.741e+02 0.741e+02 0.739e+02 0.736e+02 0.734e+02 0.732e+02 0.731e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=17
 i    j= 2
 2 0.791e+02 0.792e+02 0.794e+02 0.797e+02 0.802e+02 0.807e+02 0.807e+02 0.802e+02 0.797e+02 0.794e+02 0.792e+02 0.791e+02
 3 0.789e+02 0.790e+02 0.792e+02 0.795e+02 0.799e+02 0.802e+02 0.802e+02 0.799e+02 0.795e+02 0.792e+02 0.790e+02 0.789e+02
 4 0.787e+02 0.788e+02 0.790e+02 0.793e+02 0.796e+02 0.798e+02 0.798e+02 0.796e+02 0.793e+02 0.790e+02 0.788e+02 0.787e+02
 5 0.786e+02 0.787e+02 0.788e+02 0.791e+02 0.794e+02 0.795e+02 0.795e+02 0.794e+02 0.791e+02 0.788e+02 0.787e+02 0.786e+02
 6 0.785e+02 0.786e+02 0.788e+02 0.790e+02 0.793e+02 0.794e+02 0.794e+02 0.793e+02 0.790e+02 0.788e+02 0.786e+02 0.785e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=16
 i    j= 2
 2 0.837e+02 0.838e+02 0.840e+02 0.843e+02 0.847e+02 0.853e+02 0.853e+02 0.847e+02 0.843e+02 0.840e+02 0.838e+02 0.837e+02
 3 0.835e+02 0.836e+02 0.838e+02 0.841e+02 0.844e+02 0.848e+02 0.848e+02 0.844e+02 0.841e+02 0.838e+02 0.836e+02 0.835e+02
 4 0.833e+02 0.834e+02 0.836e+02 0.838e+02 0.842e+02 0.844e+02 0.844e+02 0.842e+02 0.838e+02 0.836e+02 0.834e+02 0.833e+02
 5 0.831e+02 0.832e+02 0.834e+02 0.837e+02 0.839e+02 0.841e+02 0.841e+02 0.839e+02 0.837e+02 0.834e+02 0.832e+02 0.831e+02
 6 0.831e+02 0.832e+02 0.833e+02 0.836e+02 0.838e+02 0.840e+02 0.840e+02 0.838e+02 0.836e+02 0.833e+02 0.832e+02 0.831e+02
```

```
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=15
 i   j= 2
 2 0.846e+02 0.846e+02 0.849e+02 0.852e+02 0.856e+02 0.862e+02 0.862e+02 0.856e+02 0.852e+02 0.849e+02 0.846e+02 0.846e+02
 3 0.844e+02 0.845e+02 0.847e+02 0.850e+02 0.853e+02 0.857e+02 0.857e+02 0.853e+02 0.850e+02 0.847e+02 0.845e+02 0.844e+02
 4 0.842e+02 0.843e+02 0.845e+02 0.847e+02 0.850e+02 0.853e+02 0.853e+02 0.850e+02 0.847e+02 0.845e+02 0.843e+02 0.842e+02
 5 0.840e+02 0.841e+02 0.843e+02 0.846e+02 0.848e+02 0.850e+02 0.850e+02 0.848e+02 0.846e+02 0.843e+02 0.841e+02 0.840e+02
 6 0.839e+02 0.840e+02 0.842e+02 0.845e+02 0.847e+02 0.849e+02 0.849e+02 0.847e+02 0.845e+02 0.842e+02 0.840e+02 0.839e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=14
 i   j= 2
 2 0.816e+02 0.817e+02 0.819e+02 0.823e+02 0.827e+02 0.833e+02 0.833e+02 0.827e+02 0.823e+02 0.819e+02 0.817e+02 0.816e+02
 3 0.815e+02 0.815e+02 0.817e+02 0.820e+02 0.824e+02 0.828e+02 0.828e+02 0.824e+02 0.820e+02 0.817e+02 0.815e+02 0.815e+02
 4 0.813e+02 0.813e+02 0.815e+02 0.818e+02 0.821e+02 0.824e+02 0.824e+02 0.821e+02 0.818e+02 0.815e+02 0.813e+02 0.813e+02
 5 0.811e+02 0.812e+02 0.814e+02 0.816e+02 0.819e+02 0.821e+02 0.821e+02 0.819e+02 0.816e+02 0.814e+02 0.812e+02 0.811e+02
 6 0.810e+02 0.811e+02 0.813e+02 0.815e+02 0.818e+02 0.820e+02 0.820e+02 0.818e+02 0.815e+02 0.813e+02 0.811e+02 0.810e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=13
 i   j= 2
 2 0.776e+02 0.776e+02 0.779e+02 0.782e+02 0.787e+02 0.792e+02 0.792e+02 0.787e+02 0.782e+02 0.779e+02 0.776e+02 0.776e+02
 3 0.774e+02 0.775e+02 0.777e+02 0.780e+02 0.784e+02 0.787e+02 0.787e+02 0.784e+02 0.780e+02 0.777e+02 0.775e+02 0.774e+02
 4 0.772e+02 0.773e+02 0.775e+02 0.778e+02 0.781e+02 0.783e+02 0.783e+02 0.781e+02 0.778e+02 0.775e+02 0.773e+02 0.772e+02
 5 0.770e+02 0.771e+02 0.773e+02 0.776e+02 0.779e+02 0.780e+02 0.780e+02 0.779e+02 0.776e+02 0.773e+02 0.771e+02 0.770e+02
 6 0.770e+02 0.771e+02 0.772e+02 0.775e+02 0.778e+02 0.779e+02 0.779e+02 0.778e+02 0.775e+02 0.772e+02 0.771e+02 0.770e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=12
 i   j= 2
 2 0.736e+02 0.737e+02 0.739e+02 0.742e+02 0.747e+02 0.752e+02 0.752e+02 0.747e+02 0.742e+02 0.739e+02 0.737e+02 0.736e+02
 3 0.734e+02 0.735e+02 0.737e+02 0.740e+02 0.744e+02 0.747e+02 0.747e+02 0.744e+02 0.740e+02 0.737e+02 0.735e+02 0.734e+02
 4 0.733e+02 0.733e+02 0.735e+02 0.738e+02 0.741e+02 0.743e+02 0.743e+02 0.741e+02 0.738e+02 0.735e+02 0.733e+02 0.733e+02
 5 0.731e+02 0.732e+02 0.734e+02 0.736e+02 0.739e+02 0.741e+02 0.741e+02 0.739e+02 0.736e+02 0.734e+02 0.732e+02 0.731e+02
 6 0.730e+02 0.731e+02 0.733e+02 0.736e+02 0.738e+02 0.740e+02 0.740e+02 0.738e+02 0.736e+02 0.733e+02 0.731e+02 0.730e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                    plane k=11
 i   j= 2
 2 0.703e+02 0.703e+02 0.705e+02 0.708e+02 0.713e+02 0.718e+02 0.718e+02 0.713e+02 0.708e+02 0.705e+02 0.703e+02 0.703e+02
 3 0.701e+02 0.702e+02 0.704e+02 0.707e+02 0.710e+02 0.713e+02 0.713e+02 0.710e+02 0.707e+02 0.704e+02 0.702e+02 0.701e+02
 4 0.700e+02 0.700e+02 0.702e+02 0.705e+02 0.708e+02 0.710e+02 0.710e+02 0.708e+02 0.705e+02 0.702e+02 0.700e+02 0.700e+02
 5 0.698e+02 0.699e+02 0.701e+02 0.703e+02 0.706e+02 0.707e+02 0.707e+02 0.706e+02 0.703e+02 0.701e+02 0.699e+02 0.698e+02
 6 0.697e+02 0.698e+02 0.700e+02 0.702e+02 0.705e+02 0.706e+02 0.706e+02 0.705e+02 0.702e+02 0.700e+02 0.698e+02 0.697e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
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                                                plane k=10
 i   j= 2
 2 0.677e+02 0.677e+02 0.679e+02 0.682e+02 0.686e+02 0.690e+02 0.690e+02 0.686e+02 0.682e+02 0.679e+02 0.677e+02 0.677e+02
 3 0.675e+02 0.676e+02 0.678e+02 0.680e+02 0.684e+02 0.686e+02 0.686e+02 0.684e+02 0.680e+02 0.678e+02 0.676e+02 0.675e+02
 4 0.674e+02 0.675e+02 0.676e+02 0.679e+02 0.681e+02 0.683e+02 0.683e+02 0.681e+02 0.679e+02 0.676e+02 0.675e+02 0.674e+02
 5 0.673e+02 0.673e+02 0.675e+02 0.677e+02 0.679e+02 0.681e+02 0.681e+02 0.679e+02 0.677e+02 0.675e+02 0.673e+02 0.673e+02
 6 0.672e+02 0.673e+02 0.674e+02 0.676e+02 0.679e+02 0.680e+02 0.680e+02 0.679e+02 0.676e+02 0.674e+02 0.673e+02 0.672e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                plane k= 9
 i   j= 2
 2 0.657e+02 0.658e+02 0.660e+02 0.662e+02 0.665e+02 0.669e+02 0.669e+02 0.665e+02 0.662e+02 0.660e+02 0.658e+02 0.657e+02
 3 0.656e+02 0.657e+02 0.659e+02 0.661e+02 0.663e+02 0.666e+02 0.666e+02 0.663e+02 0.661e+02 0.659e+02 0.657e+02 0.656e+02
 4 0.655e+02 0.656e+02 0.657e+02 0.659e+02 0.661e+02 0.663e+02 0.663e+02 0.661e+02 0.659e+02 0.657e+02 0.656e+02 0.655e+02
 5 0.654e+02 0.654e+02 0.656e+02 0.658e+02 0.660e+02 0.661e+02 0.661e+02 0.660e+02 0.658e+02 0.656e+02 0.654e+02 0.654e+02
 6 0.653e+02 0.654e+02 0.655e+02 0.657e+02 0.659e+02 0.660e+02 0.660e+02 0.659e+02 0.657e+02 0.655e+02 0.654e+02 0.653e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                plane k= 8
 i   j= 2
 2 0.642e+02 0.642e+02 0.644e+02 0.646e+02 0.649e+02 0.652e+02 0.652e+02 0.649e+02 0.646e+02 0.644e+02 0.642e+02 0.642e+02
 3 0.641e+02 0.642e+02 0.643e+02 0.645e+02 0.647e+02 0.649e+02 0.649e+02 0.647e+02 0.645e+02 0.643e+02 0.642e+02 0.641e+02
 4 0.640e+02 0.640e+02 0.642e+02 0.643e+02 0.645e+02 0.647e+02 0.647e+02 0.645e+02 0.643e+02 0.642e+02 0.640e+02 0.640e+02
 5 0.639e+02 0.639e+02 0.641e+02 0.642e+02 0.644e+02 0.645e+02 0.645e+02 0.644e+02 0.642e+02 0.641e+02 0.639e+02 0.639e+02
 6 0.638e+02 0.639e+02 0.640e+02 0.642e+02 0.643e+02 0.644e+02 0.644e+02 0.643e+02 0.642e+02 0.640e+02 0.639e+02 0.638e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                plane k= 7
 i   j= 2
 2 0.628e+02 0.628e+02 0.629e+02 0.631e+02 0.633e+02 0.635e+02 0.635e+02 0.633e+02 0.631e+02 0.629e+02 0.628e+02 0.628e+02
 3 0.627e+02 0.628e+02 0.629e+02 0.630e+02 0.632e+02 0.634e+02 0.634e+02 0.632e+02 0.630e+02 0.629e+02 0.628e+02 0.627e+02
 4 0.626e+02 0.627e+02 0.628e+02 0.629e+02 0.631e+02 0.632e+02 0.632e+02 0.631e+02 0.629e+02 0.628e+02 0.627e+02 0.626e+02
 5 0.625e+02 0.626e+02 0.627e+02 0.629e+02 0.630e+02 0.631e+02 0.631e+02 0.630e+02 0.629e+02 0.627e+02 0.626e+02 0.625e+02
 6 0.625e+02 0.625e+02 0.627e+02 0.628e+02 0.629e+02 0.630e+02 0.630e+02 0.629e+02 0.628e+02 0.627e+02 0.625e+02 0.625e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                plane k= 6
 i   j= 2
 2 0.616e+02 0.617e+02 0.618e+02 0.619e+02 0.621e+02 0.622e+02 0.622e+02 0.621e+02 0.619e+02 0.618e+02 0.617e+02 0.616e+02
 3 0.616e+02 0.616e+02 0.617e+02 0.619e+02 0.620e+02 0.621e+02 0.621e+02 0.620e+02 0.619e+02 0.617e+02 0.616e+02 0.616e+02
 4 0.615e+02 0.616e+02 0.617e+02 0.618e+02 0.619e+02 0.620e+02 0.620e+02 0.619e+02 0.618e+02 0.617e+02 0.616e+02 0.615e+02
 5 0.614e+02 0.615e+02 0.616e+02 0.617e+02 0.619e+02 0.619e+02 0.619e+02 0.619e+02 0.617e+02 0.616e+02 0.615e+02 0.614e+02
 6 0.614e+02 0.615e+02 0.616e+02 0.617e+02 0.618e+02 0.618e+02 0.618e+02 0.618e+02 0.617e+02 0.616e+02 0.615e+02 0.614e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
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```
                                                                plane k= 5
   i   j= 2
 2 0.608e+02 0.609e+02 0.610e+02 0.611e+02 0.613e+02 0.614e+02 0.614e+02 0.613e+02 0.611e+02 0.610e+02 0.609e+02 0.608e+02
 3 0.608e+02 0.609e+02 0.610e+02 0.611e+02 0.612e+02 0.613e+02 0.613e+02 0.612e+02 0.611e+02 0.610e+02 0.609e+02 0.608e+02
 4 0.607e+02 0.608e+02 0.609e+02 0.610e+02 0.611e+02 0.612e+02 0.612e+02 0.611e+02 0.610e+02 0.609e+02 0.608e+02 0.607e+02
 5 0.606e+02 0.607e+02 0.608e+02 0.609e+02 0.610e+02 0.610e+02 0.610e+02 0.610e+02 0.609e+02 0.608e+02 0.607e+02 0.606e+02
 6 0.606e+02 0.606e+02 0.607e+02 0.608e+02 0.609e+02 0.610e+02 0.610e+02 0.609e+02 0.608e+02 0.607e+02 0.606e+02 0.606e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                                plane k= 4
   i   j= 2
 2 0.608e+02 0.609e+02 0.610e+02 0.612e+02 0.614e+02 0.617e+02 0.617e+02 0.614e+02 0.612e+02 0.610e+02 0.609e+02 0.608e+02
 3 0.607e+02 0.608e+02 0.609e+02 0.611e+02 0.613e+02 0.614e+02 0.614e+02 0.613e+02 0.611e+02 0.609e+02 0.608e+02 0.607e+02
 4 0.603e+02 0.603e+02 0.604e+02 0.605e+02 0.606e+02 0.607e+02 0.607e+02 0.606e+02 0.605e+02 0.604e+02 0.603e+02 0.603e+02
 5 0.602e+02 0.603e+02 0.604e+02 0.605e+02 0.606e+02 0.606e+02 0.606e+02 0.606e+02 0.605e+02 0.604e+02 0.603e+02 0.602e+02
 6 0.602e+02 0.602e+02 0.603e+02 0.604e+02 0.605e+02 0.605e+02 0.605e+02 0.605e+02 0.604e+02 0.603e+02 0.602e+02 0.602e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                                plane k= 3
   i   j= 2
 2 0.608e+02 0.608e+02 0.609e+02 0.611e+02 0.613e+02 0.614e+02 0.614e+02 0.613e+02 0.611e+02 0.609e+02 0.608e+02 0.608e+02
 3 0.607e+02 0.607e+02 0.608e+02 0.610e+02 0.612e+02 0.613e+02 0.613e+02 0.612e+02 0.610e+02 0.608e+02 0.607e+02 0.607e+02
 4 0.601e+02 0.601e+02 0.602e+02 0.603e+02 0.604e+02 0.604e+02 0.604e+02 0.604e+02 0.603e+02 0.602e+02 0.601e+02 0.601e+02
 5 0.600e+02 0.601e+02 0.602e+02 0.603e+02 0.604e+02 0.604e+02 0.604e+02 0.604e+02 0.603e+02 0.602e+02 0.601e+02 0.600e+02
 6 0.600e+02 0.600e+02 0.601e+02 0.602e+02 0.603e+02 0.603e+02 0.603e+02 0.603e+02 0.602e+02 0.601e+02 0.600e+02 0.600e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                                plane k= 2
   i   j= 2
 2 0.606e+02 0.606e+02 0.608e+02 0.609e+02 0.611e+02 0.612e+02 0.612e+02 0.611e+02 0.609e+02 0.608e+02 0.606e+02 0.606e+02
 3 0.604e+02 0.605e+02 0.606e+02 0.607e+02 0.609e+02 0.609e+02 0.609e+02 0.609e+02 0.607e+02 0.606e+02 0.605e+02 0.604e+02
 4 0.601e+02 0.602e+02 0.603e+02 0.604e+02 0.605e+02 0.606e+02 0.606e+02 0.605e+02 0.604e+02 0.603e+02 0.602e+02 0.601e+02
 5 0.600e+02 0.600e+02 0.601e+02 0.602e+02 0.603e+02 0.604e+02 0.604e+02 0.603e+02 0.602e+02 0.601e+02 0.600e+02 0.600e+02
 6 0.599e+02 0.600e+02 0.601e+02 0.602e+02 0.602e+02 0.603e+02 0.603e+02 0.602e+02 0.602e+02 0.601e+02 0.600e+02 0.599e+02
 7 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02

                                                                plane k= 1
   i   j= 2
 2 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 3 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 4 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 5 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 6 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02 0.270e+02
 7 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00

 1
```

```
                                        * * * mass flux in i-direction, g/sq. cm sec * * *

                                                                  plane k= 2
    j    i= 2
 11-0.132e-05-0.422e-05-0.774e-05-0.120e-04-0.188e-04-0.134e-03-0.153e-03-0.828e-04-0.187e-04
 10-0.129e-05-0.405e-05-0.746e-05-0.117e-04-0.185e-04-0.133e-03-0.150e-03-0.792e-04-0.174e-04
  9-0.106e-05-0.328e-05-0.624e-05-0.103e-04-0.173e-04-0.130e-03-0.136e-03-0.596e-04-0.895e-05
  8-0.683e-06-0.210e-05-0.411e-05-0.712e-05-0.156e-04-0.113e-03-0.969e-04-0.197e-04 0.000e+00
  7-0.295e-06-0.802e-06-0.104e-05 0.125e-05 0.101e-20-0.105e-20-0.140e-04 0.000e+00 0.000e+00
  6-0.121e-04-0.344e-04-0.385e-04-0.311e-20-0.144e-21-0.155e-21 0.000e+00 0.000e+00
  5-0.169e-04-0.487e-04-0.702e-04-0.821e-04-0.232e-04 0.000e+00 0.000e+00
  4-0.151e-04-0.416e-04-0.527e-04-0.491e-04 0.000e+00 0.000e+00
  3-0.849e-05-0.203e-04-0.146e-04 0.000e+00 0.000e+00
  2-0.288e-05-0.569e-05 0.000e+00 0.000e+00

                                                                  plane k=10
    j    i= 2
 11 0.840e-08 0.251e-07 0.381e-07 0.363e-07 0.302e-21-0.298e-21 0.988e-06 0.107e-05 0.330e-06
 10 0.839e-08 0.247e-07 0.375e-07 0.362e-07 0.115e-21-0.107e-21 0.963e-06 0.101e-05 0.298e-06
  9 0.780e-08 0.225e-07 0.347e-07 0.347e-07-0.390e-22 0.467e-22 0.854e-06 0.746e-06 0.143e-06
  8 0.729e-08 0.206e-07 0.322e-07 0.326e-07-0.702e-23 0.148e-22 0.617e-06 0.258e-06 0.000e+00
  7 0.765e-08 0.210e-07 0.321e-07 0.308e-07 0.119e-21-0.111e-21 0.332e-06 0.000e+00 0.000e+00
  6 0.420e-21 0.733e-21 0.606e-21 0.569e-21 0.893e-21 0.889e-21 0.000e+00 0.000e+00
  5 0.190e-06 0.568e-06 0.875e-06 0.102e-05 0.604e-06 0.000e+00 0.000e+00
  4 0.357e-06 0.104e-05 0.139e-05 0.106e-05 0.000e+00 0.000e+00
  3 0.271e-06 0.725e-06 0.584e-06 0.000e+00 0.000e+00
  2 0.100e-06 0.224e-06 0.000e+00 0.000e+00

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                                        * * * mass flux in k-direction, g/sq. cm sec * * *

                                                                  plane k= 2
    j    i= 2
 11 0.926e-05 0.959e-05 0.985e-05 0.984e-05 0.130e-04 0.331e-03 0.113e-03-0.136e-03-0.220e-03-0.105e-03
 10 0.959e-05 0.964e-05 0.985e-05 0.989e-05 0.128e-04 0.326e-03 0.104e-03-0.145e-03-0.220e-03-0.103e-03
  9 0.985e-05 0.985e-05 0.104e-04 0.105e-04 0.128e-04 0.289e-03 0.555e-04-0.187e-03-0.208e-03-0.651e-04
  8 0.984e-05 0.989e-05 0.105e-04 0.105e-04 0.109e-04 0.176e-03-0.248e-04-0.213e-03-0.102e-03 0.000e+00
  7 0.130e-04 0.128e-04 0.128e-04 0.109e-04 0.437e-05-0.814e-22-0.630e-04-0.123e-03 0.000e+00
  6 0.331e-03 0.326e-03 0.289e-03 0.176e-03-0.814e-22-0.119e-22-0.581e-04 0.000e+00
  5 0.113e-03 0.104e-03 0.555e-04-0.248e-04-0.630e-04-0.581e-04 0.000e+00
  4-0.136e-03-0.145e-03-0.187e-03-0.213e-03-0.123e-03 0.000e+00
  3-0.220e-03-0.220e-03-0.208e-03-0.102e-03 0.000e+00
  2-0.105e-03-0.103e-03-0.651e-04 0.000e+00

                                                                  plane k=10
    j    i= 2
```

```
 11 0.237e-04 0.236e-04 0.233e-04 0.224e-04 0.200e-04 0.241e-22 0.353e-03 0.174e-03-0.210e-03-0.185e-03
 10 0.236e-04 0.236e-04 0.233e-04 0.223e-04 0.199e-04 0.456e-22 0.338e-03 0.142e-03-0.226e-03-0.182e-03
  9 0.233e-04 0.233e-04 0.230e-04 0.222e-04 0.197e-04 0.438e-22 0.273e-03-0.100e-04-0.315e-03-0.146e-03
  8 0.224e-04 0.223e-04 0.222e-04 0.214e-04 0.188e-04 0.406e-22 0.163e-03-0.227e-03-0.234e-03 0.000e+00
  7 0.200e-04 0.199e-04 0.197e-04 0.188e-04 0.164e-04 0.359e-22-0.130e-04-0.310e-03 0.000e+00
  6 0.241e-22 0.456e-22 0.438e-22 0.406e-22 0.359e-22 0.955e-23-0.167e-03 0.000e+00
  5 0.353e-03 0.338e-03 0.273e-03 0.163e-03-0.130e-04-0.167e-03 0.000e+00
  4 0.174e-03 0.142e-03-0.100e-04-0.227e-03-0.310e-03 0.000e+00
  3-0.210e-03-0.226e-03-0.315e-03-0.234e-03 0.000e+00
  2-0.185e-03-0.182e-03-0.146e-03 0.000e+00

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                                        * * * pressure change, dynes/sq. cm * * *

                                                                plane k= 8
  j   i= 2
 11-0.247e-03-0.247e-03-0.247e-03-0.247e-03-0.247e-03 0.136e+03-0.251e-03  0.251e-03-0.251e-03-0.251e-03
 10-0.247e-03-0.247e-03-0.247e-03-0.247e-03-0.247e-03 0.414e+02-0.251e-03 -0.251e-03-0.251e-03-0.251e-03
  9-0.247e-03-0.247e-03-0.247e-03-0.247e-03-0.247e-03 0.342e+02-0.251e-03 -0.251e-03-0.251e-03-0.251e-03
  8-0.247e-03-0.247e-03-0.247e-03-0.247e-03-0.247e-03 0.339e+02-0.251e-03 -0.251e-03-0.251e-03 0.000e+00
  7-0.247e-03-0.247e-03-0.247e-03-0.247e-03-0.247e-03 0.371e+02-0.251e-03 -0.251e-03 0.000e+00
  6 0.136e+03 0.414e+02 0.342e+02 0.339e+02 0.371e+02 0.677e+02-0.251e-03  0.000e+00
  5-0.251e-03-0.251e-03-0.251e-03-0.251e-03-0.251e-03-0.251e-03 0.000e+00
  4-0.251e-03-0.251e-03-0.251e-03-0.251e-03-0.251e-03 0.000e+00
  3-0.251e-03-0.251e-03-0.251e-03-0.251e-03 0.000e+00
  2-0.251e-03-0.251e-03-0.251e-03 0.000e+00

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