THATCH: A Computer Code for Modelling Thermal Networks of High-Temperature Gas-Cooled Nuclear Reactors

Prepared by
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MASTER

ABSTRACT

This report documents the THATCH code, which can be used to model general thermal and flow networks of solids and coolant channels in two-dimensional r-z geometries.

The main application of THATCH is to model reactor thermo-hydraulic transients in High-Temperature Gas-Cooled Reactors (HTGRs). The available modules simulate pressurized or depressurized core heatup transients, heat transfer to general exterior sinks or to specific passive Reactor Cavity Cooling Systems, which can be air or water-cooled. Graphite oxidation during air or water ingress can be modelled, including the effects of added combustion products to the gas flow and the additional chemical energy release. A point kinetics model is available for analyzing reactivity excursions; for instance due to water ingress, and also for hypothetical no-scrum scenarios. For most HTGR transients, which generally range over hours, a user-selected nodalization of the core in r-z geometry is used. However, a separate model of heat transfer in the symmetry element of each fuel element is also available for very rapid transients. This model can be applied coupled to the traditional coarser r-z nodalization.

This report describes the mathematical models used in the code and the method of solution. It describes the code and its various sub-elements. Details of the input data and file usage, with file formats, is given for the code, as well as for several preprocessing and postprocessing options. The THATCH model of the currently applicable 350 MW_{th} reactor is described. Input data for four sample cases are given with output available in fiche form. Installation requirements and code limitations, as well as the most common error indications are listed.

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1. INTRODUCTION

The "Thermal Analysis for Temperatures in the Core of an HTGR" computer code (THATCH) was originally developed under NRC funding for thermal analysis of core heatup accidents in large High-Temperature Gas-Cooled Reactors (HTGRs). In its original form, THATCH solved conduction and radiation in two-dimensional cylindrical network of solids and plena. The first applications were for the 2240 MW(t) reactor in 1984.

As the modular HTGR concept developed, the code was modified and extended; several sub-modules were added for air-cooled Reactor Cavity Cooling Systems (RCCS), for point kinetics, for forced and natural circulation gas flows, and for chemical reactions of the core graphite with air or water at elevated temperatures.

In its recent version, the code has been applied extensively to model various transients in the commercial modular HTGR (MHTGR) [Kroeger, 1989], under funding by the Nuclear Regulatory Commission. A detailed description of the MHTGR can be found in a concept description report [Bechtel National, 1986]. The most essential features of the reactor are briefly given here, for those readers not familiar with the concept.

The reactor vessel and the steam generator are located in two adjacent cavities of an underground silo as shown in Figure 1-1. A schematic of the reactor with the steam generator is shown in Figure 1-2. Power is generated in a ceramic graphite moderated core using inert helium as the primary coolant for energy transfer to the steam generator. The active core fuel elements are arranged in an annular cylinder, surrounded in the center and on all sides by graphite reflector elements. Helium flow is normally provided by the main circulator. If the main circulator or any other steam generator component is not available for service, the reactor would be scrammed, and a Shutdown Cooling System (SCS), located at the bottom of the reactor vessel, would generally be used for decay heat removal.

A third heat removal system, one of the inherent safety features of the MHTGR, is a completely passive air cooling system, the Reactor Cavity Cooling System (RCCS), shown schematically in Figure 1-3. If neither of the above forced flow cooling systems is available, the reactor is scrammed, and then the heat rejection is predominantly by conduction and radiation from the active core via the side reflectors and the reactor vessel, across the reactor cavity to the RCCS cooling panels. Inside the cooling panel an airflow is created by natural circulation assisted by an outlet stack. The reactor vessel is not thermally insulated and during normal power operation, a parasitic heat loss to the RCCS of about 0.8 MW (0.25% of 350 MW_{th} design power) is allowed. Thus, the RCCS is a completely passive system, without valves, damper or other active components. It is always in operation, self-activated, whenever there is a heat flow from the reactor vessel.

This report documents the code in its current form, including a new sub-module for a water-cooled RCCS as used in the New Production Reactor (NPR-MHTGR). Section 2 presents an overview of the code and its sub-modules, outlining the types of problems it can be applied to. The physical models, equations and solution methods are described in Section 3, with some of the details relegated to the appendices.

Section 4 documents the code structure and interface between THATCH and its submodules. Detailed descriptions of input data are given in Section 5, followed by a summary of the input and output file usage in Section 6. Section 7 outlines the preprocessing requirements and the postprocessing options.

Figure 1-1. MHTGR in Underground Silo (Bechtel, 1986)

Figure 1-2. Schematic of MHTGR Primary Loop (Bechtel, 1986)

Figure 1-3. Passive Decay Heat Removal System
(Bechtel, 1986)

Section 8 describes the THATCH model used for the commercial 350-MW MHTGR, including nodalization and material property models and upper plenum natural convection models. Section 9 outlines the sample cases to be used during code installation and contains the required notes on code installation. Currently, the full code is operational on the IBM 3090 at BNL and on the CRAY at INEL.

Section 10 lists the code capabilities as well as the known, significant code limitations and error indications.

2. CODE OVERVIEW

The original THATCH code was developed to model conduction and radiation transients during core heatup transients in large MHTGRs. This main code is fairly general and can be applied to any network of solid nodes, which can be suitably described by a two-dimensional cylindrical coordinate (r-z) nodalization.

Recently, during the application of the code to MHTGR transients, several submodules were added, which apply specifically to nuclear reactors or even only to HTGRs. In this section, an overview of the function of the main code and the various sub-modules is given.

2.1 Description of the THATCH Main Code

The basic THATCH Main Code models the transient thermal conduction and radiation heat transfer in a two-dimensional nodal network presented in cylindrical (r-z) coordinates. The user selects the nodalization. The solid network is generally subdivided into "blocks" of equal materials or equal function.

The THATCH model includes internal heat generation, for instance from neutronics or decay heat, from chemical reactions (graphite oxidation), or from convective heating/cooling by a gas stream. Internal thermal resistances in gaps within the solid network or in plena with multi-dimensional radiation can be included. In some cases, internal layers of materials which are of relatively small thermal capacitance, such as an insulation blanket, can be treated optionally as quasi-steady solids, generally referred to here as "layers". The exterior boundary conditions can be selected by the user with a great amount of freedom. Material properties are generally supplied by a property library, but can also be called from any specified user - library if so desired.

Typical code applications have been for long-term core heatup accidents, initially in large HTGRs, and more recently in the MHTGR. Originally, the code was developed for depressurized scenarios, where convective heat transfer is negligible. Full convection modelling capability now exists and is discussed below with the FLOXI module.

2.2 Sub-Module Descriptions

Several sub-modules were added to the code during application to the commercial MHTGR. These modules can all be executed as free-standing codes or integrated with THATCH.

2.2.1 PASCOL Module for Air-Cooled RCCS

As a passive Reactor Cavity Cooling System (RCCS) was added to the MHTGR, the PASCOL module was developed, using air as the cooling medium.

The PASCOL module models the heat transfer across the reactor cavity to the air-cooled RCCS panels. Heat transfer is by radiation and natural convection across the reactor cavity, then by conduction and radiation in the finned RCCS panels, and ultimately by convection to the air rising inside the panels. The model includes the solution of quasi-steady energy and momentum equations for the coolant in the RCCS panels, in the ducting and in the stack. As any conceivable RCCS transients are very slow, quasi-

steady evaluations are completely satisfactory.

This module essentially provides the exterior boundary condition for the reactor vessel transient analysis of THATCH. The module has also been used to evaluate the passive air cooling systems of the advanced LMR concepts SAFR and PRISM.

2.2.2 WATCOL Module for Water-Cooled RCCS

The option for a water-heat transport loop to transfer energy from the reactor cavity to an air-water heat exchanger was incorporated into the MHTGR design. Therefore, the WATCOL Module was developed and added to the THATCH code, which models transport of energy from the reactor vessel to the water coolant, and subsequent transport of energy by convection to the air flow in the air-water heat exchanger.

The model assumes that RCCS cooling panels receive energy from the reactor vessel via radiation and natural convection from the cavity gas surroundings. The energy is transferred by conduction and convection to the water coolant located within the array of "D-tubes", which are welded to the back of the panels. The water flows by natural circulation within a closed loop, which transports the energy to an air-water heat exchanger, where the water is cooled by convective flow of air. The cooled water then flows back to the RCCS panels. The air-water heat exchanger is contained within a "natural draft" stack structure. Natural convection air flow past the heat exchanger tubes removes the energy from the water transport system.

The WATCOL module provides the boundary condition for the reactor vessel transient analysis of THATCH. The coupled, quasi-steady mass, momentum and energy equations are solved for the closed water loop and the once through air flow, driven by natural convection, in the air-water heat exchanger stack.

The present version of the water-cooled RCCS model is preliminary. The input data of the heat exchanger model should be updated as soon as a design is firmed up. The accuracy of the model should be established by comparison with either experimental data or with a set of benchmark calculations performed using an industry standard, if available.

2.2.3 FLOXI Module for Reactor Gas Flow, Heat Transfer, and Chemical Reactions

The FLOXI sub-module models gas flow, heat transfer, and chemical reactions in the reactor. This module can analyze natural or forced convection in the core. The convective heat transfer is generally only significant in the pressurized mode. However, during ingress transients, the gas to solid heat transfer in the core barrel region can be essential because it affects the overall buoyancy driving force. The flow and heat transfer computations allow for change in composition and mass addition due to chemical reactions and handle mixtures of all relevant gases. A simplified model for upper plenum heat transfer is included, but the treatment given here cannot substitute for multi-dimensional upper plenum turbulent heat transfer models, which should be used separately as free-standing models, and can ultimately provide inputs to improve the current simplified one-dimensional model.

The graphite oxidation process is a function of the temperature regime. At low temperatures, the carbon/oxygen reaction kinetics control the reaction rate. At intermediate temperatures, the in-pore diffusion is controlling, while at high temperatures the coolant to surface mass transfer by diffusion, here

in a laminar flow field, is controlling.

To consider all three regimes, a model including external mass transfer, in-pore diffusion, and chemical reaction kinetics is required, as in the Oxide-3 code [Perroomian et al., 1974]. For the current applications, we decided to use a simpler approach, combining the in-pore diffusion and chemical reaction process into a single Langmuir-Hinshelwood type semi-empirical equation as done, for instance by Moormann and Petersen [1982]. In particular, since some of the data on in-pore diffusion are not very certain, this approach is well justified at this time. As better data becomes available, a refinement of the model may become desirable.

2.2.4 PKIN Module for Point Kinetics Option

The PKIN Module, the point kinetics sub-module of THATCH, analyzes no-scrum scenarios and reactivity insertions coupled with thermohydraulic transients.

The model uses six delayed neutron groups and considers change of reactivity feedbacks due to:

- changes in fuel temperature (Doppler)
- changes in moderator temperature
- changes in reflector temperature
- changes in xenon concentration
- changes in samarium concentration
- changes in water concentration.

The PKIN module has been used to evaluate no-scrum scenarios during core heatup transients and water ingress transients. For rapid transients, the general THATCH nodalization is too coarse to model the resulting changes in temperature and in particular, the Doppler feedback. For such applications, the PKIN module can be used with the SYMELAN module, either in a free-standing mode of SYMELAN with PKIN, or also coupled with THATCH.

2.2.5 SYMELAN Module for Rapid Thermal Core Transients Using Symmetry Element Nodalization

While the THATCH reactor vessel model describes thermal and flow transients in steady state, scrammed, or other relatively slow transients, it cannot model rapid core transients where fuel and moderator temperatures may vary significantly.

For this purpose, the SYMELAN code is available as a separate code, but it can also be run integrated in THATCH. It nodalizes the symmetry element contained within the fuel elements where typically 6 fuel sticks surround each coolant hole (see Figures 3.7 and 3.8 below). This small symmetry element is generally nodalized into 6 fuel nodes and 12 moderator nodes.

The SYMELAN module has the capability to model very rapid transients, such as reactivity insertions due to severe water ingress, and also to accurately evaluate steady-state temperature distributions.

In general, the SYMELAN module is executed in the free-standing mode, with prescribed inlet flows and temperatures, and assumes no heat conduction across the active core boundaries. Both conditions are justified for many rapid scenarios; however, where desired, for example, when the effects of decreases in gas flow due to core heatup in fast transients are to be modelled, it can be run jointly as part of THATCH.

3. CODE MODEL AND METHOD OF SOLUTION

This section describes the models used in the various code modules, gives the equations, and describes the method of solution. Where appropriate, details have been relegated to Appendices.

3.1 Basic THATCH Models

3.1.1 THATCH Conduction/Radiation Heat Transfer in a Solid Network

For THATCH modelling of conduction/radiation heat transfer in a solid network, the body under consideration must be broken down into a two-dimensional r-z geometry. The user selects the number of radial or axial nodes, as well as the node spacing. Figure 3-1 shows the nodalization convention applied in the THATCH code. Index "i" applies to radial nodes, increasing with the outward pointing r-coordinate. Index "j" applies to axial nodes, increasing with the downward pointing z-coordinate. Nodes are separated by "interfaces", and the outward (or downward) interface to node (i,j) are interfaces i (or j). After selecting a suitable nodalization, the user describes the system to be modelled in terms of "blocks" of equal functions or material properties, and assigns a proper "material index" to each block. An arbitrary example of such a network is shown in Figure 3-2. Note that Block 5 is a plenum (Material Index > 100; for details see Section 5). The "gap" separating Blocks 2 and 4 from Block 6 is in terms of the nodalization, a part of Blocks 2 and 4; i.e., Blocks 2,4,5, and 7 have the same outer radius and node/interface index. Gaps are always considered to be on the outside (downside) of a block; (for details see Section 5). Outer boundaries have to be specified for the corresponding boundaries of Blocks 7,6,2, and 3. A further convention is to label sides of blocks or nodes as North, East, South, or West, or use the "side numbers" (for instance, in array indices) as shown in Figure 3-3.

Heat transfer within the solid structures of the system is described by the transient heat conduction equation which can be written as follows:

$$\rho c \frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} k r \frac{\partial \theta}{\partial r} + \frac{\partial}{\partial z} k \frac{\partial \theta}{\partial z} + q''' \quad (3.1-1)$$

where the material properties ρc and k are functions of temperature.

In finite difference form this equation can be written as follows:

$$\begin{aligned} V_{i,j} (\rho c)_{i,j} \frac{\theta_{i,j} - \theta_{i,j}^o}{\Delta t} \\ = k_{r+} A_{r+} \frac{\theta_{i+1,j} - \theta_{i,j}}{\Delta r_+} - k_{r-} A_{r-} \frac{\theta_{i,j} - \theta_{i-1,j}}{\Delta r_-} \\ + k_{z+} A_{z+} \frac{\theta_{i,j+1} - \theta_{i,j}}{\Delta z_+} - k_{z-} A_{z-} \frac{\theta_{i,j} - \theta_{i,j-1}}{\Delta z_-} \\ + V_{i,j} q'''_{i,j} \end{aligned} \quad (3.1-2)$$

Figure 3-1 Nodalization Convention of the THATCH Code

Figure 3-2 Schematic of a Solid Network Broken Down Into "Blocks" for Modelling by the THATCH Code

and / or

**Figure 3-3 Schematic of Node Interface and
Block Boundary Designations**

where θ° denotes the temperature of the preceding time step, the subscripts r_+ , r_- , z_+ , z_- denote values of the corresponding node interface, and Δr_+ etc. denote the corresponding distances between node centers.

This equation can be rearranged as follows:

$$\begin{aligned} \theta_{i,j} - \theta_{i,j}^\circ = & C_{Ni,j} (\theta_{i,j-1} - \theta_{i,j}) \\ & + C_{Ei,j} (\theta_{i+1,j} - \theta_{i,j}) \\ & + C_{Si,j} (\theta_{i,j+1} - \theta_{i,j}) \\ & + C_{Wi,j} (\theta_{i-1,j} - \theta_{i,j}) + C_{Qi,j} \end{aligned} \quad (3.1-3)$$

where,

$$C_{Y,i,j} = \frac{\Delta t}{V_{i,j} (\rho c)_{i,j}} A_Y \alpha_Y \quad (3.1-4)$$

where $\alpha_Y = k_Y/\Delta x_Y$ is the conductance between neighboring nodes, Δx represent Δr or Δz , and Y represents N,E,S or W;

$$C_Q = \frac{\Delta t}{(\rho c)_{i,j}} q'''_{i,j} \quad (3.1-5)$$

Note that the C_Y are dimensionless and C_Q has the dimension of temperature.

Equation 3.1-3 can be used to solve the temperature field in all solid structures if the C-coefficients of Equations 3.1-4 and 5 are known. This can be done, in principal, by evaluating these coefficients, using areas and node intervals from the selected nodalization, and thermal properties ρc and k from the preceding time step. The internal heating rates q''' of the original THATCH code were from decay heat only, which is available as a function of space and time, as specified with the input (see Section 5).

Modifications of the C- coefficients are required at exterior boundaries, at interior gaps or other heat transfer resistances, and at solid block to plena boundaries.

Internal thermal resistances between adjacent nodes can be modelled in the code by prescribing conductive and/or radiative resistances. To permit modelling of some solids of relatively small thermal capacitances in a quasi-steady mode, the concept of a "layer" of material is introduced. Any "gap" in the THATCH network can contain, in addition to the physical gap, an additional "layer" of a solid material. This solid layer can be located on the "+" side or the "-" side" of the gap, always progressing with increasing r or z coordinate. The total gap conductance model is outlined here for a radial gap, with a layer on the "+" side". Such a gap is shown schematically in Figure 3-4. Note that a "radial gap" is defined as a vertical gap at constant radial coordinates, while an "axial gap" is horizontal at constant axial coordinates.

Figure 3-4 Radial Gap Between Solid Structures in the THATCH Code

The total heat transfer resistance between the shown node center points can be obtained as follows:

$$\sum R = \frac{\Delta r_1}{k_1 (\theta_{1 \text{ av}})} + R_2 + \frac{\delta_1}{k_3 (\theta_{3 \text{ av}})} + \frac{\Delta r_4}{k_4 (\theta_{4 \text{ av}})} \quad (3.1-6)$$

where $\theta_{1 \text{ av}}$ is the average of θ_0 and θ_1 ,
 $\theta_{2 \text{ av}}$ is the average of θ_1 and θ_2 ,
 $\theta_{3 \text{ av}}$ is the average of θ_2 and θ_3 , and
 $\theta_{4 \text{ av}}$ is the average of θ_3 and θ_4 .

Heat transfer across the fluid gap can be either

1. zero resistance, in which case

$$R_2 = 0. \quad (3.1-7)$$

2. Conduction only, in which case

$$R_2 = \frac{\delta_{fl}}{k_2 (\theta_{2 \text{ av}})} \quad (3.1-8)$$

3. Conduction plus 1-d radiation, where

$$h_{rad} = \epsilon_{1,3} \sigma (\theta_1^2 + \theta_2^2) (\theta_1 + \theta_2) \quad (3.1-9)$$

and

$$R_2 = \frac{1}{\frac{k_2 (\theta_{2 \text{ av}})}{\delta_{fl}} + h_{rad}} \quad (3.1-10)$$

$\epsilon_{1,3}$ the effective emissivity between materials 1, and 3 is from a user input.

4. Radiation only, where

$$R_2 = \frac{1}{h_{rad}} \quad (3.1-11)$$

with h_{rad} from Equation 3.1-9.

The conductance terms of Equation (3.1-4), α_Y , are replaced at internal boundaries by the inverse of the ΣR of Equation (3.1-6), namely with

$$\alpha_Y = \frac{1}{\sum R} \quad (3.1-12)$$

Computation of the gap conductance is iterative at each time step with the nodal temperatures known, and the internal temperatures being recomputed till convergence is achieved.

A fifth option is an isolated gap, in which case α_Y is set to zero.

For external boundaries, one can similarly specify an insulated face, or a prescribed heat transfer coefficient with 1-d radiation. The conductance α_Y in the C- coefficients of Equation 3.1-4 is then modified as follows:

For the insulated case,

$$\alpha_Y = 0 \quad (3.1-13)$$

For the case of 1-d radiation and a prescribed convective heat transfer coefficient, h , one obtains

$$\frac{1}{\alpha_Y} = \frac{\Delta x_n}{2k_s (\theta_{av})} + \frac{1}{h + h_{rad}} \quad (3.1-14)$$

with

$$h_{rad} = \epsilon_{n,s} \sigma (\theta_{ns}^2 + \theta_s^2) (\theta_{ns} + \theta_s) \quad (3.1-15)$$

where Δx_n is either Δr_n or Δz_n of the last node and k_s is the conductivity of the last node material at the average temperature between the center of the node and the outside surface of the node. $\epsilon_{n,s}$ is the prescribed emissivity between node and sink material, θ_{ns} is the node surface temperature, and θ_s the sink temperature. Evaluation of the conductance is again iterative, with known node and sink temperature.

3.1.2 THATCH Plena Two-Dimensional Radiation Heat Transfer

The two-dimensional radiation model in THATCH assumes a transparent gas in an open plenum neglecting the presence of control rods and/or participating gases. Convection between the gas and the solid surfaces is neglected here, but will be included with the FLOXI sub-module in Section 3.4.

The radiation exchange between gray surfaces of a cavity is modelled following Sparrow and Cess (1966). For temperature-independent emissivities, the radiation exchange coefficient matrix Λ can be computed once for a given geometry and given nodal emissivities. Thereafter, the radiation exchange coefficient matrix can be used to compute the total heat flow from node ℓ to all plena nodes $\ell = 1, L$ as follows:

A_ℓ is the surface area of node ℓ facing the plenum, and θ_{sm} is the nodal surface temperature of node m . Details on the computation of the radiation exchange coefficient matrix are given in Appendix

$$Q_l = A_l \sum_{m=1}^L \Lambda_{lm} \sigma \theta_{sm}^4 \quad (3.1-16)$$

A. If one wanted to use temperature-dependent emissivities, one would have to modify the code, and recompute the Λ array at each time step.

The 2-dimensional plena radiation heat flow computations must be coupled with the conduction heat transfer computations of the surrounding solids.

For solid node (i,j) bounded by a plenum on the north side, as shown schematically in Figure 3-5, the condition

$$Q_{\text{cond}} = Q_{\text{rad}}$$

can be expressed as follows:

$$\begin{aligned} Q_l &= \frac{2 A_l}{\Delta z_n} k (\theta_{i,j} \text{ avg}) (\theta_{i,j} - \theta_{sl}) \\ &= A_l \sum_{m=1}^L \Lambda_{lm} \sigma \theta_{sm}^4 \end{aligned} \quad (3.1-17)$$

Note that each node adjacent to a plenum can be identified either by the general set of solid node indices (i,j) or by the "plenum node" indices (ℓ).

Equation 3.1-17 represents a set of non-linear simultaneous equations, which is solved at each time step for the set of surface temperatures θ_{sl} .

For known surface temperatures, the heat flows at the node to the surface of the plenum can then be computed from Equation (3.1-17). For nodes adjacent to plena, the solid node finite difference equations must be modified as follows: In Equation (3.1-3) the C- coefficients corresponding to the plena surfaces are set to zero, and the corresponding terms

$$C_{Y \ i,j} = \frac{\Delta t}{V_{i,j} (\rho c)_{i,j}} Q_l \quad (3.1-18)$$

are added to the corresponding $C_{Q \ i,j}$ coefficients.

3.1.3 Method of Solution for THATCH Models

Solution of the THATCH equations describing the heat conduction in solid structures with interior and/or exterior interface resistances and coupled with 2-d radiation in plena, requires the advancement of Equation (3.1-3) at each time step, after modification of the appropriate C- coefficients to account for interface resistances. Coupled with this process, Equation (3.1-17) for the plena heat flows must be solved as a system of simultaneous non-linear algebraic equations.

For the solution of the solid network finite difference equations, the Alternate Direction Implicit (ADI) method was selected (Isaacson and Keller, 1966 or Carnahan, Luther and Wilkes, 1969). This

Figure 3-5 Schematic of Heat Flows in Nodes
Adjacent to Plena

method computes the solution at $t + \Delta t$ in two steps, first processing from t to $t + 1/2 \Delta t$, solving by rows and treating all row terms as implicit, and then progressing from $t + 1/2 \Delta t$ to $t + \Delta t$, this time sweeping by columns, with in-column terms being treated as implicit. The advantage of this method is that it has the stability of fully implicit methods and requires only the solution of tridiagonal simultaneous equations, which can be done with very efficient solution algorithms.

Equations (3.1-3) can be written for the sweep by row as follows:

$$\begin{aligned} & -C_{Wi,j} \theta_{i-1,j}^m + (1 + C_{Wi,j} + C_{Ei,j}) \theta_{i,j}^m - C_{Ei,j} \theta_{i+1,j}^m \\ & = \theta_{i,j}^o + C_{Ni,j} (\theta_{i,j-1}^o - \theta_{i,j}^o) \\ & \quad + C_{Si,j} (\theta_{i,j+1}^o - \theta_{i,j}^o) + C_{Qi,j} \end{aligned} \quad \begin{matrix} (3.1-19a) \\ \\ j=2, j_L \end{matrix}$$

where superscripts o,m, and n designate old ($t=t$), mid point ($t=t + 1/2 \Delta t$), or new ($t = t + \Delta t$).

For the second sweep by columns, we use

$$\begin{aligned} & -C_{Ni,j-1} \theta_{i,j-1}^n + (1 + C_{Ni,j} + C_{Si,j}) \theta_{i,j}^n - C_{Si,j} \theta_{i,j+1}^n \\ & = \theta_{i,j}^m + C_{Wi,j} (\theta_{i-1,j}^m - \theta_{i,j}^m) \\ & \quad + C_{Ei,j} (\theta_{i+1,j}^m - \theta_{i,j}^m) + C_{Qi,j} \end{aligned} \quad \begin{matrix} (3.1-19b) \\ \\ i=1, i_L \end{matrix}$$

Note that the Δt of Equations (3.1-4,5, and 18) must be the incremental step, i.e., $1/2 \Delta t$.

The simultaneous algebraic equations for the plena are from Equation (3.1-17)

$$\sum_{m=1}^L (\delta_{lm} \alpha_l \theta_{sl} + \Lambda_{lm} \sigma \theta_{sm}^4) = \alpha_l \theta_{i,j} \quad l=1, L \quad (3.1-20)$$

where the conductance is

$$\alpha_l = \frac{2k(\theta_{i,j} \text{ avg})}{\Delta z_n} \quad (3.1-21)$$

This set of equations is solved by NEWTON, the non-linear, simultaneous equation solver, providing an analytical Jacobean matrix and residual vector computed from Equation 3.1-20.

3.2 PASCOL Models for Air-Cooled RCCS

The PASCOL module for the passive air-cooled RCCS was originally developed before some of the current RCCS design detail became available. This module includes several of the original options, but they are currently not of interest. These options have not been used recently, but are still part of the

code. This report covers the currently used options. Specifically, the following input options are affected:

1. There is thermal insulation between the downflow channels and the finned riser channels, (INSUL=true); with INSUL = false regenerative heating of the incoming air could be modelled.
2. The stack is connected to the inner RCCS channels, facing the reactor vessel (ISTACON=1). In principle, a RCCS with downflow in the inner channels and the stack connected to the outer upflow channels (ISTACON=2) has some operating advantages, but it is not self starting and, therefore, not completely passive.
3. Arithmetic average fluid temperatures are used in the solution of the fluid energy equation (EXPO = false); EXPO = true would provide the exponential formulation of a rise in gas temperature in a heated channel, corresponding to a logarithmic average temperature difference model.
4. User supplied fin effectiveness data will be used (FINK=false). With FINK=true, the simultaneous radiation and conduction in the finned RCCS panels can be internally computed. Such internal evaluations of the fin performance were used during parametric performance evaluations (Kroeger, 1989, App. B). We found that once the fin effectiveness has been determined for a specific configuration, prescribed data were much more efficient to use for general THATCH runs. Details of the internal fin evaluation are given in Appendix C.

3.2.1 Heat Transfer Across Reactor Cavity

In current MHTGR concepts, the reactor vessel is housed inside the reactor cavity, which is lined with RCCS panels. For the commercial MHTGR, these panels are cooled by a natural convection air flow inside the channels enclosed by the panels. The gap between the reactor vessel and the RCCS front panel is of the order of 1 m wide, and the cavity is about 22 m high. At the prevailing temperatures of vessel temperatures between 200°C and 500°C (during core heatup accidents) and RCCS panel temperatures of about 80°C to 160°C, the heat transfer across the reactor cavity is predominantly by radiation aided by turbulent natural convection (with Rayleigh numbers of about 10^9 to 10^{10}), which contributes about 10 to 15 % of the total heat transfer.

In principle, the radiation heat transfer across the cavity is best modelled as two-dimensional radiation through a transparent gas. The radiation exchange coefficient matrix is precomputed for prescribed constant emissivities, following the procedure in Appendix A and using the view factors in Appendix B; Section B-2. The radiation heat flow from any node ℓ is then, as already stated in Equation (3.1-16):

$$Q_l = A_l \sum_{m=1}^L \Lambda_{lm} \sigma \theta_{sm}^4 \quad \text{for } l=1,L \quad (3.2-1)$$

This procedure was used in some of the THATCH evaluations of core heatup scenarios without a functioning RCCS. However, peak vessel temperatures obtained with the above two-dimensional radiation model were only slightly lower than those obtained with the much simpler one-dimensional radiation model. The uncertainty in the vessel and panel emissivities, where textbook values of 0.8 or 0.85 are generally being applied, is sufficiently large, that use of the above two-dimensional radiation model was not justified for reactor cavity heat transfer with functioning RCCS.

In the computations for the one-dimensional reactor cavity radiation heat transfer, the radiative flow across the cavity is computed for each vertical node as follows:

$$Q_{\text{rad } j} = A_V \epsilon_{1,2} \sigma (\theta_{Vsj}^4 - \theta_{FPj}^4) \quad (3.2-2)$$

where θ_{Vsj} and θ_{FPj} are temperatures of the vessel surface, and the RCCS front panel at node j . The radiation exchange coefficient $\epsilon_{1,2}$ is for concentric cylinders

$$\epsilon_{1,2} = \frac{1}{\frac{1}{\epsilon_V} + \frac{R_V}{R_{FP}} \left(\frac{1}{\epsilon_{FP}} - 1 \right)} \quad (3.2-3)$$

where R_V and R_{FP} are reactor cavity side radii of the reactor vessel surface and the RCCS front panel, respectively. Note that with this formulation for $\epsilon_{1,2}$ the vessel surface must be used for heat flow computations.

For turbulent natural convection, the following correlation is used (Holman, 1990).

$$\begin{aligned} Nu_D &= .197 (Ra_d)^{1/4} \left[\frac{H}{D} \right]^{-1/9} & Ra < 149,200 \\ Nu_D &= .073 (Ra_d)^{1/3} \left[\frac{H}{D} \right]^{-1/9} & Ra < 149,200 \end{aligned} \quad (3.2-4)$$

Where D is the cavity width and H its height¹.

The cross-over Raleigh number is actually given by Holman as 200,000. However, we arbitrarily use the value of 149,183 to avoid a discontinuity in the Nusselt number. Since RCCS Raleigh numbers are five orders higher, this practice would only affect results if the routine were used for other applications, or if the cavity dimensions changed drastically.

Convective turbulent heat transfer in such cavities would be expected to form several circulating cells in the cavity. Computation of a heat transfer coefficient at each node level, as is currently done, is not quite correct. However, the above correlation is an overall correlation for isothermal walls, and convection is only a minor contributor to the total heat transfer. Therefore, the convective heat transfer coefficient is evaluated at each node and added to the radiative coefficient. For coupling between the

¹ Note that the PASCOL module uses as width and height of the cavity the distance from reactor vessel outside radius to RCCS panel inside radius, and the sum of all nodal heights in the RCCS panels.

THATCH nodal network and the PASCOL RCCS model, the THATCH node temperatures of the outermost reactor vessel node $\theta_{i_L j}$ are provided, and the total heat transfer resistance across the reactor cavity is evaluated, consisting of vessel conduction plus radiation augmented by convection across the cavity. The conductive resistance of the relatively thin RCCS panels is neglected. Thus, the following relationship is used for total heat transfer across the reactor cavity at each node level:

$$Q_{cav j} = AU_j (\theta_{i_L j} - \theta_{FPj}) \quad (3.2-5)$$

where,

$$\frac{1}{AU_j} = \frac{1}{A_V h_{rad} + A_{avg} h_{conv}} + \frac{\Delta r_{n,j}}{A_V 2k (\theta_{av})} \quad (3.2-6)$$

i.e., the convective heat flow is based on an averaged heat flow area, while cavity radiation and vessel conduction are based on the vessel heat transfer area. The RCCS panel temperature is θ_{FPj} . The radiation heat transfer coefficient here is derived from Equation (3.2-2).

3.2.2 Heat Transfer from the RCCS Panels to the Coolant and Coolant Energy Equation

The riser panels of the RCCS are finned internally, as shown schematically, in Figure 3-6. Heat radiated from the reactor vessel will be transferred by conduction and radiation to the fins and the back panel, and then by forced convection to the rising coolant. The code has the option to do these evaluations at each node and at each time step. Parametric evaluations showed that for the current RCCS design about 85% of the heat flow is by conduction and 15% by radiation. Details of these conduction/radiation computations are given in Appendix C.

For most code applications, a simpler and satisfactory approach is to specify a fin effectiveness coefficient. Several slightly differing definitions are in the literature. The definition to be used here is the following:

$$\Phi = \frac{\text{Total Convective Heat Flow to Coolant}}{\text{Convective Heat Flow to Coolant from Unfinned Front Panel}}$$

For the current MHTGR design (Bechtel, 1986), the value most representative for normal operation and for core heatup transients was established in parametric evaluations as $\Phi = 4.4$, which is specified as input parameter for the finned section of the RCCS.

The convective heat flow to the coolant can then be expressed for node j as follows:

$$Q_{cj} = A_{FPj} \Phi h_{coolj} (\theta_{FPj} - \theta_{fj}) \quad (3.2-7)$$

The convective heat transfer correlations used for h_{cool} are optionally (user-specified option) evaluated from the following:

$$Nu_D = 0.0243 Re^{0.8} Pr^{0.4} \quad (3.2-8a)$$

Figure 3-6 Schematic of an Internally Finned Up-Flow Channel of the RCCS

or from

$$Nu_D = 0.021 Re^{0.8} Pr^{0.6} \quad (3.2-8b)$$

At normal operating conditions of the RCCS, some Reynolds numbers are as low as 8,000. Laminar flow has not been encountered, and is currently not provided with this correlation. (The above correlations were chosen early in the development of THATCH code. To extend the subroutine HHCONVF to include lower Reynolds number domains, it might be preferable to replace these correlations with the more general correlations used by FLOXI and SYMELAM in subroutine HETCOF).

In unfinned sections of the RCCS (currently the top region), heat is transferred from the front panel to the back panel by radiation and then from both panels by convection to the coolant.

In this case, the radiation transfer from the front panel to the back panel is as follows:

$$Q_{rad \text{ int } j} = \epsilon_{1,2} \sigma (\theta_{FPj}^4 - \theta_{BPj}^4) \quad (3.2-9)$$

The convective heat flow to the coolant from the front panel is the following:

$$Q_{c1j} = A_{FPj} h_{cool j} (\theta_{FPj} - \theta_{flj}) \quad (3.2-10)$$

and from the back panel

$$Q_{c2j} = A_{BPj} h_{cool j} (\theta_{BPj} - \theta_{flj}) \quad (3.2-11)$$

For the finned section, $Q_{cav j}$ of Equation (3.2-5) must equal Q_{cj} of Equation (3.2-7), while for the unfinned section we have the following:

$$Q_{cav j} = Q_{rad \text{ int } j} + Q_{c1j} \quad (3.2-12)$$

and

$$Q_{rad \text{ int } j} = Q_{c2j} \quad (3.2-13)$$

The quasi-steady coolant energy equation can be written for any node j as follows:

$$dQ = A' dz h [\theta_w - \theta_{fl}(z)] = Wc_p d\theta_{fl} \quad (3.2-14)$$

where dz is positive in flow direction, A' is the heat transfer surface per unit length, θ_w is the wall temperature, considered constant in axial direction within one node, and θ_{fl} is the node fluid temperature. By integrating the equation within the node, we obtain the exponential formulation. This formulation was provided in PASCOL as an option, but did not provide any advantage, because the vertical nodalization was rather fine and the temperature changes were small. Therefore, this option has not been used recently. We applied the simpler option of using arithmetic average temperature differences.

Recasting Equation (3.2-14) as a difference equation we obtain:

$$Q_j = A_j h (\theta_{wj} - \theta_{fl\ avg\ j}) = Wc_p (\theta_{fl\ ex\ j} - \theta_{fl\ in\ j}) \quad (3.2-15)$$

With Equations (3.2-7), we can write for finned sections the following:

$$Q_{cj} = Wc_p (\theta_{fl\ ex\ j} - \theta_{fl\ in\ j}) \quad (3.2-16)$$

where

$$\theta_{fl\ j} = .5 (\theta_{fl\ ex\ j} - \theta_{fl\ in\ j}) \quad (3.2-17)$$

and

$$\theta_{fl\ in\ j} = \theta_{fl\ ex\ j-1} \quad (3.2-18)$$

with j increasing in flow direction.

For an unfinned region, Equation (3.2-16) must be expressed as follows:

$$(Q_{c1\ j} + Q_{c2\ j}) = Wc_p (\theta_{fl\ ex\ j} - \theta_{fl\ in\ j}) \quad (3.2-19)$$

3.2.3 Coolant Momentum Equation

The quasi-steady coolant momentum equation in heated or unheated flow passages of the RCCS can be written as a balance of friction buoyancy and momentum forces.

$$\Delta p_{frict} + \Delta p_{mom} + \int \rho g\ dz = 0 \quad (3.2-20)$$

where the z coordinate is positive pointing downward.

For quasi-steady flow we have the following:

$$\rho\ vA = W = \text{const.} \quad (3.2-21)$$

Within each node of the upflow channel, the friction term can be expressed as follows:

$$\Delta p_{fr\ j} = 4\ f\ \frac{\Delta z_j}{d_h}\ \rho\ \frac{v^2}{2} \quad (3.2-22)$$

where

$$\begin{aligned} f &= f_L = \frac{16}{Re} & Re < 2300 \\ f &= f_T = \frac{0.04}{Re^{0.16}} & Re > 8000 \end{aligned} \quad (3.2-23)$$

with linear interpolation between f_L (2300) and f_T (8000) for values of Re between 2300 and 8000.

Using Equation 3.2-21 and the gas equation of state for air at essentially atmospheric pressure:

$$\rho = \frac{p_o}{R \theta_{fl}} \quad (3.2-24)$$

Equation 3.2-22 can be expressed as the following:

$$\Delta p_{fr j} = \left[\frac{R}{2 p_o A^2} \right] (4 f_j \theta_{flj}) \left[\frac{\Delta z_j}{d_h} \right] |W| W \quad (3.2-25)$$

where the sign change in case of reverse mass flow has been incorporated into the equation.

For the total upflow channel, we obtain:

$$\Delta p_{fr up} = \left[\frac{R}{2 p_o A^2} \right] \sum_j (4 f_j \theta_{flj}) \left[\frac{\Delta z_j}{d_h} \right] |W| W \quad (3.2-26)$$

Similarly, the buoyancy term for the upflow channel is:

$$B_{up} = -\frac{g p_o}{R} \sum_j \frac{\Delta z_j}{\theta_{flj}} \quad (3.2-27)$$

The momentum pressure drop over the heated section can be written as follows:

$$\Delta p_{m up} = \left[\frac{W}{A} \right]^2 \left[\frac{1}{\rho_{ex}} - \frac{1}{\rho_{in}} \right] \quad (3.2-28)$$

or

$$\Delta p_{m up} = \frac{R}{p_o} \left[\frac{W}{A} \right]^2 (\theta_{fl in} - \theta_{fl ex}) \quad (3.2-29)$$

Friction losses in the stack, unheated ducting and in the downflow channel, as well as the stack buoyancy effects must be added to these terms.

For the stack of height h and diameter d :

$$\Delta p_{fr\ St} = \frac{R}{2 p_o A^2_{St}} 4 f \frac{h}{d} \theta_{fl\ ex} |W|W \quad (3.2-30)$$

and

$$B_{St} = -gh \frac{p_o}{R} \left[\frac{1}{\theta_{fl\ in}} - \frac{1}{\theta_{fl\ ex}} \right] \quad (3.2-31)$$

where, as in Equations (3.28) and (3.29) subscript "ex" refers to fluid leaving the heated section, while subscript "in" designates fluid entering the heated section, which is identical to ambient.

The loss coefficients for the inlet ducting, and the downflow channel and the bottom bend, preceding the heated section can be written as follows:

$$\Delta p_{fr\ in} = \frac{R}{2 p_o A^2} \left[4 f \frac{h}{d} + K_{in} + K_{bot} \right] \theta_{fl\ in} |W|W \quad (3.2-32)$$

while for the exit ducting from the heated section to the stack

$$\Delta p_{fr\ ex} + \frac{R}{2 p_o A^2} K_{ex} \theta_{fl\ ex} |W|W \quad (3.2-33)$$

The loss coefficients K_{in} , K_{bot} , and K_{ex} are user inputs.

Combining the corresponding expressions, the total momentum balance is the following:

$$\Delta p_{fr\ in} + \Delta p_{fr\ up} + \Delta p_{m\ up} + \Delta p_{fr\ ex} + \Delta p_{fr\ St} + B_{up} + B_{St} = 0 \quad (3.2-34)$$

which can be solved for the mass flow in the RCCS.

3.2.4 Method of Solution for PASCOL Module

The equations for the RCCS, as given in the previous sections, constitute a system of simultaneous non-linear algebraic equations.

In particular, at each time step the vessel temperatures are given from the THATCH evaluations, and the air inlet temperature is given. For each node in the RCCS upflow channel, the fluid temperature leaving the node must be solved for, together with temperatures for vessel surface and the RCCS front panel for finned nodes, while in un-finned nodes, the temperatures for vessel surface, the RCCS front panel plus the back panel must be obtained. Finally, the mass flow must be computed.

Solving all of these in one system of non-linear equations proved to be cumbersome. Due to the loose coupling between some of the equations (small coefficients in their Jacobean matrix), the following solution method was found to execute very rapidly.

Consider j_L RCCS nodes. The fluid energy equations (3.2-16) for finned nodes and (3.2-19) for unfinned nodes are solved together with Equation (3.2-34) for the mass flow as a system of $N=j_L+1$ equations, to be solved by a Newton-Raphson Solver.

In the Jacobean matrix only the terms

$$\begin{array}{ll} J_{j,j-1}; J_{j,j}; J_{j,N} & j=1, j_L \\ J_{N,N} & j=N \end{array}$$

were considered, which allowed for a very simple matrix inversion.

Simultaneously, at each iteration and at each node, Equations (3.2-5) and (3.2-7) must be solved for finned sections of the RCCS as two simultaneous non-linear equations in temperatures for the vessel surface and the front panel of the RCCS. For unfinned sections, Equations (3.2-5) and (3.2-9) to (3.2-13) can be considered as three equations in temperatures for the vessel surface plus front and back panels of the RCCS. The solution of these two or three additional equations is affected by a Newton-Raphson procedure internal to the above Newton-Raphson solution for fluid temperatures and mass flows, with analytical inversion of the resulting internal 2 or 3 equation systems.

3.3 WATCOL Module for Water-Cooled RCCS

3.3.1 Assumptions

Figure 3-7 is a schematic of the water-cooled RCCS. The THATCH code model will characterize the following:

- (i) the rate of heat transfer from the heat source, the reactor vessel, to the "D-tubes",
- (ii) the mass, energy and momentum processes within the water loop shown as A-B-C-D-A in Figure 3-7,
- (iii) the mass, energy and momentum transfer processes within the air-water heat exchanger.

The models for the various elements are presented in the sections which follow. The THATCH energy equation for the vessel is a transient conduction equation. For all other processes within the reactor cavity, it is assumed that quasi-steady flow and heat transfer conditions apply. One-dimensional mass, energy and momentum balance equations will be used to characterize the phenomena within the water heat removal loop.

While the cavity cooling panels are distributed irregularly around the periphery of the reactor vessel, it will be assumed here that the panels are distributed uniformly around the vessel. The total surface area exposed to thermal radiation from the vessel is conserved. This assumption simplifies the radiation treatment considerably, as discussed in more detail in Section 3.4. The assumption also permits axisymmetric treatment of the reactor vessel.

Figure 3-7 Schematic of the Flow Loop of the Water-Cooled RCCS

3.3.2 Reactor Vessel

Decay heat generated within the reactor vessel is transferred to the vessel surface, from where energy is transferred to the cavity cooling panels by thermal radiation and to the cavity gases by natural convection along the vessel surface. The temperature distribution around the vessel is assumed axisymmetric.

The length of the reactor vessel is divided into n_v nodes, one of which is shown in Figure 3-8. It is assumed that radiative heat transfer between the vessel and the cavity cooling panels is one-dimensional, i.e., radial. The heat transfer model is represented schematically, showing the transport paths from the vessel wall to the cavity gases and to the cavity cooling panels. The coupling between the THATCH model of the reactor vessel and the water-cooled RCCS module is via the outermost node of the reactor vessel. The temperature of the reactor vessel is computed within THATCH, based on WATCOL supplied overall heat transfer coefficients and temperatures of the RCCS panel. WATCOL uses the vessel temperature as input, to evaluate temperatures for vessel and panel surface as well as reactor cavity and RCCS heat transfer. The total heat transfer across the reactor cavity is the following:

$$Q_{cav,j} = AU_j (\theta_{f,j} - \theta_{sp,j}) \quad (3.3-1)$$

where $\theta_{f,j}$ is the last vessel node temperature, $\theta_{sp,j}$ is the surface temperature of the RCCS panel and U_j is the overall cavity heat transfer coefficient, based on heat transfer area A . The heat flux from the vessel internals to the outside surface of the vessel is represented by:

$$q_{vs,j} = \frac{k_{f,j}}{\Delta r_j} (\theta_{f,j} - \theta_{vs,j}) \quad (3.3-2)$$

where $k_{f,j}$ is the effective conductivity of the vessel internals at the node j and Δr_j is the half-width of the node j , and $\theta_{vs,j}$ is the outside surface temperature of the vessel wall. The overall heat transfer coefficient U_j is obtained from the following:

$$\frac{1}{AU_j} = \frac{\Delta r_j}{A_v k_{f,j}} + \frac{1}{<A>_j h_{vg,j} + A_{r,j} h_{rv,j}} \quad (3.3-3)$$

where A_v is the vessel surface area, $h_{rv,j}$ is the radiative heat transfer coefficient across the reactor cavity, as defined in Section 3.3.4, and $h_{vg,j}$ is the convective heat transfer coefficient, defined in Section 3.3.6, with $A_{r,j}$ and $<A>_j$ being the respective heat transfer surface areas.

The boundary condition at the vessel surface is discussed in further detail in Section 3.3.4.

3.3.3 Water Heat Transport Loop

As a result of natural circulation within the loop, cold water flows down the downcomer pipe along Section A-B in Figure 3-7. The pipe diameter is d_c and the flow rate is W . At the cold water header, the flow splits into n_t D-tube riser channels, each with flow rate W_t . The heated water is collected in the hot water header and is transported along path C-D, with flow rate W in a pipe of diameter d_h to the heat exchanger. It is assumed that a header within the heat exchanger splits the water flow into n_x horizontal tubes, each with flow rate W_x , and the water cools along path D-A. Sections A-B

Figure 3-8 Typical Axial Node Through Vessel and Cooling Panel

and C-D in Figure 3-7 are assumed thermally insulated. Momentum, energy and mass balance equations are derived for the four sections of the water transport path.

Single-phase water is assumed to flow through the loop. The steady-state, one-dimensional mass, momentum and energy equations for the water within any section of the loop are:

Mass Balance

$$\frac{dW}{dx} = 0, \quad \frac{dW_t}{dx} = 0, \quad \frac{dW_x}{dx} = 0 \quad (3.3-4)$$

where W represents the total water mass flow rate, W_t is the flow rate through any single D-tube, W_x is the flow rate through a heat exchanger tube, and x is the coordinate in flow direction.

Momentum Balance Around Loop

The general momentum balance equation for single phase water through a constant diameter pipe is as follows:

$$\frac{dp}{dx} = (+) \rho g - \tau_w \frac{P_w}{A} - G \frac{du}{dx} \quad (3.3-5)$$

where $G = W/A$. The negative sign in the gravity term applies to the down flow and the positive sign to the up flow, portion of the loop. The gravity term is zero in horizontal sections of the loop. The shear stress at the wall is given by the following:

$$\tau_w = \frac{1}{2} f \rho u^2 \quad (3.3-6)$$

Equation 3.3-5 is integrated around the water loop giving a zero total pressure drop, i.e.,

$$\Delta p = \sum (\Delta p)_j = 0 \quad (3.3-7)$$

where

$$(\Delta p)_j = (\Delta p_{\text{gravity}})_j + (\Delta p_{\text{friction}})_j + (\Delta p_{\text{acceleration}})_j + (\Delta p_{\text{losses}})_j \quad (3.3-8)$$

where the losses are due to pipe fittings, elbows, etc.

The acceleration pressure drop is due to heating of the water and passage of the fluid through the D-tube and heat exchanger tube banks, which act as manifolds. The acceleration pressure drop across the D-tube bank, from a point just upstream to a point just downstream is given by:

$$(\Delta p_{BC})_{\text{acc}} = -\frac{G^2}{2} \left(\frac{1}{\rho_C} - \frac{1}{\rho_H} \frac{A^2}{A_h^2} \right) - \frac{G^2}{2} \frac{A^2}{A_t^2} \left(\frac{1}{\rho_C} - \frac{1}{\rho_H} \right) \quad (3.3-9)$$

Where ρ is the water density and subscripts C and H denote cold and hot. A_h and A_c are the flow areas in the hot leg and in the cold leg, respectively. A_t and A_x are the total flow areas of the bank of D-tubes and heat exchanger tubes, respectively.

Similarly, the acceleration pressure drop across the heat exchanger is given by:

$$(\Delta p_{DA})_{acc} = \frac{G^2}{2} \left(\frac{1}{\rho_C} - \frac{1}{\rho_H} \frac{A^2}{A_h^2} \right) + \frac{G^2 A^2}{2 A_x^2} \left(\frac{1}{\rho_C} - \frac{1}{\rho_H} \right) \quad (3.3-10)$$

Therefore, the total acceleration pressure drop is the following:

$$(\Delta p)_{acc} = -G^2 \frac{1}{2} \left(\frac{A^2}{A_x^2} - \frac{A^2}{A_t^2} \right) \left(\frac{1}{\rho_H} - \frac{1}{\rho_C} \right) \quad (3.3-11)$$

The pressure drop due to losses in pipe fittings is given, for fitting k, by:

$$(\Delta p)_{loss} = -\frac{K_{fk}}{2\rho_k} G_k^2 \quad (3.3-12)$$

where K_{fk} defines the fitting loss coefficient.

Application of Equations 3.3-5 - 3.3-12 to the loop shown in Figure 3-7 yields the result

$$\begin{aligned} -G^2 \sum_i \left(2 \frac{f_i}{\rho_i} \frac{l_i}{D_i} \frac{A^2}{A_i^2} \right) - G^2 \sum_m \frac{1}{2\rho_m} K_{fm} \frac{A^2}{A_m^2} - G^2 \frac{1}{2} \left(\frac{A^2}{A_x^2} - \frac{A^2}{A_t^2} \right) \left(\frac{1}{\rho_H} - \frac{1}{\rho_C} \right) \\ + \sum_j \rho_{Cj} g l_j - \sum_k \rho_{Hk} g l_k = 0 \end{aligned} \quad (3.3-13)$$

where j represents all piping elements, and (l_j/D_j) includes allowance for fittings in the segment. The sum over j includes only vertical piping elements in the cold leg and the sum over k are over vertical elements in the hot leg. The sum over m represents all fittings in the loop. Equation 3.3-13 can be solved for G, giving the following:

$$G^2 = \frac{\sum \rho_{Cj} g l_j - \sum \rho_{Hk} g l_k}{\sum \left(2 \frac{f_j}{\rho_j} \frac{l_j}{D_j} \frac{A^2}{A_j^2} \right) + \sum \frac{1}{2\rho_m} K_{fm} \frac{A^2}{A_m^2} + \frac{1}{2} \left(\frac{A^2}{A_x^2} - \frac{A^2}{A_t^2} \right) \left(\frac{1}{\rho_H} - \frac{1}{\rho_C} \right)} \quad (3.3-14)$$

where the numerator represents the buoyancy term, which drives the flow around the loop, and the denominator the friction term and other losses.

Energy Balance for Water in D-Tubes

It is assumed that the D-tubes receive energy from the front face of the Cavity Cooling Panels and are insulated in the direction facing the cavity walls. The energy equation for the water in

one of the D-tubes is as follows:

$$W_t \frac{dh_1}{dx} = U_{pl} (\theta_{sp} - \theta_1) P_{hp} \quad (3.3-15)$$

and is based upon the nomenclature shown in Figure 3-8. P_{hp} is defined in Equation 3.3-19. Equation 3.3-15 is integrated across an axial node j shown in Figure 3-8, yielding the result for the axial variation of water temperature,

$$\theta_{1,j+1} - \theta_{1j} = < \frac{U_{pl} P_{hp} \Delta x_j}{W_t c_p} > (\theta_{sp,j+1} - \theta_{1,j+1}) \quad (3.3-16)$$

where U_{pl} is the conductance which includes conduction in the steel panel, conduction in the D-tube wall and the convective conductance of the water. θ_{sp} is the surface temperature of the panel. Equation 3.3-16 can be solved for θ_{1j} , giving

$$\theta_{1,j+1} = \frac{\theta_{1j} + C_j \theta_{sp,j+1}}{1 + C_j} \quad (3.3-17)$$

The quantity C_j represents the factor in brackets in Equation 3.3-16. The conductance U_{pl} is given by:

$$\frac{1}{U_{pl}} = \frac{\delta_p}{k_p} + \left(\frac{\delta_t}{k_t} + \frac{1}{h_1} \right) \frac{P_{hp}}{P_{ht}} \quad (3.3-18)$$

The quantity P_{hp} represents the perimeter of the panel surface which transfers energy to a single D-tube and depends on the number of D-tubes in a single loop and on the number of loops (1 or 2) assumed to be operational, and is given by:

$$P_{hp} = \frac{P_p}{n_t n_{loop}} \quad (3.3-19)$$

where n_{loop} is the number of loops operational, and n_t is the number of D-tubes in a single loop. P_p is the total panel perimeter, and P_{ht} is the perimeter of a single D-tube.

Energy Balance for Water in Heat Exchanger

It is assumed, as shown schematically in Figure 3-7, that the water line feeding the heat exchanger is manifolded and that a bank of horizontal tubes is cooled by air flowing across the tubes.

The energy equation for the water in one of the tubes is given by:

$$W_x c_{pw} \frac{d\theta_1}{dx} = U_x P_{wx} (\theta_1 - \theta_{air}) \quad (3.3-20)$$

where P_{wx} is the perimeter of a bare heat exchanger tube.

Assuming that the air temperature and conductance are constant along the horizontal tubes, the water temperature at the exit of the exchanger is as follows:

$$\theta_C = \bar{\theta}_{air} + (\theta_H - \bar{\theta}_{air}) e^{-U_x A_x / (W_x c_{pw})} \quad (3.3-21)$$

where θ_H is the hot leg temperature at the inlet to the heat exchanger, A_x is the surface area of a bare heat exchanger tube and, c_{pw} is the average specific heat of the water in the heat exchanger.

The heat exchanger tubes may be finned, and the overall heat exchanger conductance is given by:

$$\frac{1}{A_x U_x} = \frac{1}{h_{air} A_t} + \frac{1}{h_{lx} A_l} + \frac{\delta_x}{A_x k_x} \quad (3.3-22)$$

The heat transfer correlations, h_{air} for either bare or finned tubes are discussed in Section 3.6. The heat transfer coefficient on the water-side of the heat exchanger is h_{lx} , and δ_x is the tube wall thickness.

Equation 3.3-21 applies to an "average" tube within the heat exchanger and the air temperature; $\bar{\theta}_{air}$ represents the air temperature adjacent to this "average" heat exchanger tube. The

heat transfer model represented by Equation 3.3-21 is preliminary at this point. When further design information is available, a more detailed model may be incorporated.

3.3.4 Boundary Conditions at Vessel and Panel Walls

Thermal Radiation Model

It is assumed that the surface of each axial segment of the reactor vessel exchanges radiation with the surface of the opposite cooling panel node. The radiation is modeled as one-dimensional radiation transport between infinite concentric cylinders. The radiative heat flux from the vessel, $q_{rv,j}$, is given by:

$$q_{rv,j} = \frac{\sigma (\theta_{sv,j}^4 - \theta_{sp,j}^4)}{[\frac{1}{\epsilon_v} + \frac{A_{vj}}{A_{pj}} \frac{1}{\epsilon_p} - 1]} \quad (3.3-23)$$

and the heat flux to the cooling panel, $q_{rp,j}$, is as follows:

$$q_{rp,j} = \frac{A_v}{A_p} q_{rv,j} \quad (3.3-24)$$

where A_v and A_p are the vessel and panel surface areas.

Boundary Condition at the Vessel Wall

The heat balance equation at the vessel wall stipulates that the rate of conduction to the vessel wall from within the vessel is balanced by the sum of the rate of convection from the vessel wall to the cavity gas by natural convection and the radiative transfer from the vessel wall to the panel,

$$Q_{\text{conduction to vessel wall}} = Q_{\text{convection from vessel wall to panel}} + Q_{\text{radiation from vessel wall to panel}}$$

The balance equation is written as the following:

$$\frac{k_{f,j} (\theta_{f,j} - \theta_{sv,j})}{\Delta r_j} A_{v,j} = h_{vg,j} (\theta_{sv,j} - \theta_{sp,j}) <A>_j + h_{rv,j} (\theta_{sv,j} - \theta_{sp,j}) A_{v,j} \quad (3.3-25)$$

where $\theta_{sp,j}$ is the panel surface temperature, and $h_{rv,j}$, the radiation heat transfer coefficient, is defined, using Equation 3.3-23, by:

$$h_{rv,j} = \frac{\sigma (\theta_{sv,j}^2 + \theta_{sp,j}^2) (\theta_{sv,j} + \theta_{sp,j})}{\frac{1}{\epsilon_v} + \frac{A_{v,j}}{A_{p,j}} \left(\frac{1}{\epsilon_p} - 1 \right)} \quad (3.3-26)$$

$h_{vg,j}$ represents the convective heat transfer coefficient in the cavity, and $<A>$ represents an average area for cavity convective heat transfer.

Equation 3.3-25 can be solved for the vessel surface temperature, $\theta_{sv,j}$, at axial node i ,

$$\theta_{sv,j} = \frac{\frac{k_{f,j}}{\Delta r_j} \theta_{f,j} + h_{rg,j} \theta_{sp,j} + h_{rv,j} \theta_{sp,j}}{\frac{k_{f,j}}{\Delta r_j} + h_{rg,j} <A>_j / A_{v,j} + h_{rv,j}} \quad (3.3-27)$$

Boundary Condition at the Surface of the Cooling Panel

The heat balance at the cooling panel surface specifies that the rate of heat transfer from the gas to the panel wall by natural convection and the radiative transfer rate from the vessel to the panel surface, is balanced by the rate of transfer from the panel wall to the water in the D-tubes.

$$Q_{\text{convection from vessel to panel wall}} + Q_{\text{radiation from vessel to panel wall}} = Q_{\text{conductance from panel wall to water}}$$

The balance equation is written as follows:

$$h_{pg,j} (\theta_{sv,j} - \theta_{sp,j}) <A>_{p,j} + h_{rv,j} (\theta_{sv,j} - \theta_{sp,j}) A_{p,j} = U_{pl,j} (\theta_{sp,j} - \theta_{l,j}) A_{p,j} \quad (3.3-28)$$

where the panel conductance $U_{pl,j}$ is given by Equation 3.3-18.

Equation 3.3-28 can be solved for the panel surface temperature at axial node j,

$$\theta_{spj} = \frac{\langle A \rangle_j / A_{pj} h_{pgj} \theta_{gas} + h_{rpj} \theta_{spj} + U_{plj} \theta_{lj}}{\langle A \rangle_j / A_{pj} h_{pgj} + h_{rpj} + U_{plj}} \quad (3.3-29)$$

3.3.5 Air-Water Heat Exchanger

A detailed design for the heat exchanger is not available at this time. A simplified model is used which contains the essential features of a buoyancy-driven, air-water heat exchanger. Figure 3-9 schematically shows a triangular array of heat exchanger tubes, each of length l_x , stacked to a height H_x . The overall height of the stack is H_{xtot} . The heat exchanger tubes may be finned. Air enters the heat exchanger at temperature θ_{air} and exits at θ_{airx} . Heat, transferred to the air from the water flow through the heat exchanger tubes, heats the air and reduces its density relative to the air surrounding the air stack. The resultant buoyant force drives the air flow.

Momentum Balance Across the Stack

The momentum balance for the air flow in the heat exchanger stack is obtained by equating the pressure drop in the stack to the gravitational head of the air column in the atmosphere. The resulting equation is solved for the mass flux of air in the stack, in analogy to Equation 3.3-14 for the liquid flux in the water loop. The mass flux is given by:

$$G_{air}^2 = \frac{\rho_{air} g H_s - [\bar{\rho}_{air} g H_x + \rho_{air,x} g (H_s - H_x)]}{\frac{2f_t}{\rho_{air}} \left[\frac{A_x}{A_{min}} \right]^2 n_{rows} + \sum_{i=1,2} 2 \left[\frac{f}{\bar{\rho}} \frac{1}{D_h} \right]_i + \left[\frac{1}{\rho_{air,x}} - \frac{1}{\rho_{air}} \right]} \quad (3.3-30)$$

where the numerator represents the buoyancy term which drives the flow, and the denominator represents the flow resistances due to friction along the walls of the stack and the flow losses across the bank of the heat exchanger tubes. The quantity f_t is the friction factor for flow across the bank, which can be finned if desired. The summation in the denominator represents friction losses along the walls of the stack adjacent to the bank and friction losses in the bare stack above the bank.

Energy Balance Across the Heat Exchanger

A global energy balance across the heat exchanger equates the energy removed by the air flow to the energy lost by the water. The energy balance leads to the following equation for the exit temperature of the air:

$$\theta_{air,x} = \theta_{air} + \frac{W \bar{c}_{p,w}}{W_{air} \bar{c}_{p,a}} (\theta_{lH} - \theta_{lC}) \quad (3.3-31)$$

where W_{air} is the air mass flow rate through the stack, and W is the liquid loop flow rate.

Figure 3-9 Schematic of Natural Draft Water/
Air Heat Exchanger

3.3.6 Constitutive Relations

Friction Factor in D-Tubes

A smooth-tube friction factor is used for the D-tubes and is given by the following:

$$\begin{aligned} f &= 16/Re \text{ for } Re < 2300 \\ &= 0.04/Re^{0.16} \text{ for } Re > 8000 \end{aligned} \quad (3.3-32)$$

where Re is the Reynolds number based on the mass flux of liquid through a tube. A linear interpolation is used between the above Reynolds' number limits.

Friction Factor on the Air-Side of the Heat Exchanger

The flow losses within the air stack are due to flow past the bank of the tube and friction along the walls of the stack. For friction along the wall, the smooth-tube friction factor correlation, given above, is used. For the pressure drop across the bank of the tube, a friction factor for either an array of bare tubes, or an array of finned tubes is used. For either case, the pressure drop is given by:

$$\Delta P = \frac{2f_t}{\rho} \left[\frac{A_s}{A_{min}} \right]^2 n_{Rows} G_{Air}^2 \quad (3.3-33)$$

For bare tubes in a triangular array, the friction factor is given by [Zukauskas, 1983(a)]:

$$f_t = 0.355 \left[\frac{1}{\eta - 1} \right]^{0.33} Re^{-0.15} \quad (3.3-34)$$

where η is the pitch-to-diameter ratio of the tube bundle.

For finned tubes with ring-shaped fins, the friction factor is [Zukauskas, 1983(b)]:

$$f_t = 1.35 \left[\frac{d^*}{d_e} \right]^{0.3} Re_d^{-0.25} \quad (3.3-35)$$

where d^* and d_e are defined as follows:

$$d^* = d \frac{A_{tube}}{A_{total}} + \frac{A_{fin}}{A_{total}} \sqrt{0.785 (D^2 - d^2)} \quad (3.3-36)$$

and

$$d_e = \frac{2 [s(s_1 - d) - 2\delta h]}{2h + s} \quad (3.3-37)$$

and where d is the bare tube diameter; D is the fin diameter; A_{tube} is the bare tube surface area per unit tube length; A_{fin} is the fin surface area per unit tube length; and A_{total} is the total surface area per unit

tube length. The quantity s is the fin spacing; s_1 is the distance between tube centers; h is the fin height; and δ is the fin thickness. The Reynolds number Re_{d^*} is based upon d^* given above, and upon the maximum fluid velocity between tubes.

Natural Convection Heat Transfer of Gas in the Reactor Cavity

Equation 3.2-4 is used for the natural convection heat transfer in the reactor cavity.

Forced Convection Heat Transfer of Water in D-Tubes

The Dittus-Boelter correlation is used to characterize the convective heat transfer conductance within the D-Tubes and on the water side of the heat exchanger.

$$Nu = 0.023 Re^{0.8} Pr^{0.04} \quad (3.3-38)$$

Forced Convection Heat Transfer for Air in the Heat Exchanger Stack

For forced convective heat transfer past an equilateral triangular array of bare tubes (no fins) in crossflow, the following correlation [McAdams, 1954] was used:

$$Nu = 0.33 Re^{0.6} Pr^{0.333} \quad (3.3-39)$$

For flow past an equilateral triangular array of finned tubes in a crossflow, the heat transfer correlation [Gnielinski, 1983] used is:

$$N = 0.2183 (s^*)^{0.18} (h^*)^{-0.14} Re^{0.65} Pr^{0.33} \quad (3.3-40)$$

where s^* is the ratio of fin spacing to tube diameter, and h^* is the ratio of fin height to tube diameter.

3.3.7 Method of Solution for the WATCOL Module

The system of simultaneous non-linear algebraic equations outlined in the preceding sections is solved, very similar to the PASCOL module equations, by a system of nested Newton Raphson methods. As in the air-cooled RCCS, the coolant temperatures and flow rates for water and air are functions of the vessel temperature profile and the ambient air temperature only.

For each node in the heated upflow channel, the fluid energy balance (Equation 3.3-17) is used to compute the coolant exit temperature as function of the coolant inlet temperature. These are coupled to the temperatures of the panel surface and the vessel surface via Equations 3.3-27 and 29. In addition, the water loop flow rate must be obtained from the momentum balance of Equation 3.3-14, while the cold leg liquid temperature is computed from the heat exchanger energy balance of Equation 3.3-21. The air-side mass flow follows from the momentum balance of Equation 3.3-30, with the air exit temperature being obtained from the energy balance of Equation 3.3-31. For a model using N nodes in the upflow channel, this results in a system of $3N+4$ simultaneous equations. However, by solving at each node, Equations 3.3-27 and 3.3-29 in an internal Newton Raphson procedure for panel and vessel surface temperatures, we can reduce the size of the set of simultaneous equations to $N+4$ equations, which are solved by an outer Newton Raphson procedure. Because the coolant exit temperature of any node n

depends only on the coolant inlet temperature, the upper left square of N entries in the total matrix is bidiagonal, with only diagonal and left-of-diagonal terms. This matrix structure permits the implementation of a special simultaneous equation solver, which reduces the system of N+4 equations to a system of only four simultaneous non-linear equations, in the last four variables, the cold leg liquid temperature, the liquid side mass flow, the air side mass flow and the air-side exit temperature. The liquid temperatures in the heated channel are then readily obtained by back substitution.

3.4 FLOXI Module for Reactor Gas Flow, Heat Transfer, and Chemical Reactions

The FLOXI module can be called at each time step in a THATCH run, to solve the quasi-steady momentum and energy equations for gas flow and heat transfer in the reactor vessel and for the graphite oxidation chemical reactions in case of air or water ingress. The solid temperatures in the reactor vessel are inputs to the FLOXI computations, which solve for gas flow rates, gas temperatures, heat transfer and mass transfer rates, changes in gas composition and mass addition due to chemical reactions.

The gas flow rates, the fluid temperatures, and the change in gas composition due to chemical reaction are coupled to each other. The FLOXI module will solve for these independently and then iterate, if so desired, among the three sets of computations, as described in Section 4.2.3.

3.4.1 Gas Flow in the Reactor Vessel

The gas flow in the reactor vessel is modelled by solving the quasi-steady momentum equation for a network of parallel channels. The number of channels is user-prescribed.

In free-standing FLOXI runs, the number is a completely free user selection. Within THATCH runs, for practical purposes, the number of parallel channels must be coordinated with the THATCH nodalization. This number is generally equal to the number of radial nodes in the active core plus one return channel, representing the up-flow channel of the core barrel and flow through the steam generator. Upper and lower plenum are the junction points for this network, and external effects such as a circulator head and the flow losses in the steam generator can be added in the return flow channel.

For each parallel channel the quasi-steady momentum equation can be expressed as follows:

$$\Delta p_o = p_{UPL} - p_{LOPL} = \Delta p_{fr i} + \Delta p_{\ell i} + \Delta p_{m i} + \Delta p_{buoy i} \quad i = 1, i_{CHP} \quad (3.4-1)$$

where i_{CH} is the number of in-core flow channels, and $i_{CHP} = i_{CH} + 1$ represents the return flow channel.

Each of the above equations can be expressed as a function of mass flow in the channel, W_i . A final mass balance for the upper or lower plenum

$$\sum W_i = 0 \quad (3.4-2)$$

results in a system of $i_{CHP} + 1$ simultaneous non-linear algebraic equations for the mass flows W_i and the plenum pressure difference Δp_o .

The friction pressure drop term of Equation (3.4-1) can be derived from the following:

$$dp_{fr} = 4f \frac{dz}{d_h} \rho \frac{v^2}{2} \quad (3.4-3)$$

In finite difference form, summed over the channel, and in terms of the mass flow

$$W = A \rho v \quad (3.4-4)$$

This can be written for any channel i

$$\Delta p_{fr i} = \sum_{j=1}^{j_{NOD}} \frac{1}{2A_i^2} 4 f_{i,j} \frac{\Delta z_j}{d_{hi,j}} \frac{1}{\rho_{i,j}} |W_{i,j}| W_{i,j} \quad (3.4-5)$$

where mass flows are defined positive for downflow, and j_{NOD} is the number of axial nodes in each channel.

While the crosssection for flow remains essentially constant in the reflector regions and in the core, the hydraulic diameter varies significantly. Therefore, the flow area was assumed to be constant, and then can be taken out of the sum.

In case of chemical reactions, gas composition and mass flow vary within the channel. Defining

$$\lambda_{i,j} = \frac{W_{i,j}}{W_{oi}} \quad (3.4-6)$$

where W_{oi} is the inlet flow into channel i, Equation (3.4-5) can be expressed as follows:

$$\Delta p_{fr i} = \frac{1}{2A_i^2} \left[\sum 4 f_{i,j} \frac{\Delta z_j}{d_{hi,j}} \frac{\lambda_{i,j}^2}{\rho_{i,j}} \right] |W_{oi}| W_{oi} \quad (3.4-7)$$

In cases with chemical reaction, the viscosity, Reynolds number, and friction factor are computed using the mixture viscosity relations of Appendix D, and evaluating Re and at each node using Equation (3.2-23).

The entrance and exit loss terms are of the following general form:

$$\Delta p_\ell = k \frac{\rho v^2}{2} = \left[\frac{k}{2A^2} \right] \frac{1}{\rho} W |W| \quad (3.4-8)$$

With one "top" and "one" bottom loss coefficient, and considering changes in mass flow due to chemical reactions, the loss pressure drop for the core channels ($i = 1, i_{CH}$) is the following:

$$\Delta p_{\ell i} = \left[\left(\frac{k_{top i}}{2 A_{top i}^2} \right) \left(\frac{\lambda_{top i}}{\rho_{top i}} \right)^2 + \left(\frac{k_{bot i}}{2 A_{bot i}^2} \right) \left(\frac{\lambda_{bot i}}{\rho_{bot i}} \right)^2 \right] |W_{oi}| W_{oi} \quad (3.4-9)$$

where top and bot designate flow channel inlet at the upper plenum and outlet at the lower plenum, respectively. The loss coefficients k_{top} , and k_{bot} are user prescribed inputs. In the return flow channel, i_{CHP} steam generator flow losses can be included by specifying a corresponding, larger bottom loss for that channel. Furthermore, a circulator head can be specified for that channel with the input in form of an absolute pressure rise, i.e., Equation (3.4-9) is for channel i_{CHP}

$$\Delta p_{\ell i_{CHP}} = \left[\left(\frac{k_{top i}}{2 A_{top i}^2} \right) \left(\frac{\lambda_{top i}}{\rho_{top i}} \right)^2 + \left(\frac{k_{bot i}}{2 A_{bot i}^2} \right) \left(\frac{\lambda_{bot i}}{\rho_{bot i}} \right)^2 \right] |W_{oi}| W_{oi} + \Delta p_{Circ Head} \quad (3.4-9a)$$

where $\Delta p_{Circ Head}$ is a user-prescribed input.

The momentum pressure drop term is derived from the following:

$$dp_m = \rho v \frac{\partial v}{\partial z} dz \quad (3.4-10)$$

which can be expressed in finite difference form, summed over the channel length as follows:

$$\Delta p_{m i} = \frac{W_{oi}}{A_i^2} \sum_{j=1}^{j_{NOD}} \lambda_{avg j} \left[\left(\frac{\lambda}{\rho} \right)_j - \left(\frac{\lambda}{\rho} \right)_{j-1} \right] \quad (3.4-11)$$

the λ and ρ values in the bracket present node inlet and exit values and the nodal average value of λ is

$$\lambda_{avg j} = \frac{1}{2} (\lambda_{j-1} + \lambda_j) \quad (3.4-12)$$

For the case of no chemical reaction, Equation (3.4-11) simplifies to

$$\Delta p_{m i} = \frac{W_{oi}}{A_i^2} \left[\frac{1}{\rho_{bot}} - \frac{1}{\rho_{top}} \right] \quad (3.4-13)$$

The hydrostatic head follows from

$$dp_{buoy} = g \rho dz \quad (3.4-14)$$

expressed in finite difference form and summed over the channel as follows:

$$\Delta p_{\text{buoy } i} = g \sum_{j=1}^{j_{\text{NOD}}} \rho_{i,j} \Delta z_j \quad (3.4-15)$$

3.4.2 Reactor Coolant to Solid Heat Transfer

In the parallel channel network of the active core and the return flow channel, convective heat transfer between coolant and solid structures can be modelled.

Within a node j in channel i , the solid-surface temperature of the node θ_s is considered to be constant at each time step.

Then

$$dQ = -Wc_p d\theta = h A' dz (\theta(z) - \theta_s) \quad (3.4-16)$$

where A' is the heat transfer surface area per unit length, and $\theta(z)$ is the fluid temperature varying in flow direction. For convenience, the node subscripts i and j will be omitted here. Integrated along the node, we obtain

$$\theta(z) - \theta_s = (\theta_{\text{in}} - \theta_s) e^{-\psi' z} \quad (3.4-17)$$

where

$$\psi' = \frac{hA'}{Wc_p} \quad (3.4-18)$$

or for the node exit

$$\theta_{\text{ex}} - \theta_s = (\theta_{\text{in}} - \theta_s) e^{-\psi} \quad (3.4-19)$$

with

$$\Psi = \frac{hA}{Wc_p} = \frac{hA' \Delta z}{Wc_p} \quad (3.4-20)$$

The integrated average fluid temperature for the node is

$$\theta_{\text{av}} = \theta_s + (\theta_{\text{in}} - \theta_s) \frac{1 - e^{-\Psi}}{\Psi} \quad (3.4-21)$$

and the heat exchanged is

$$Q = hA (\theta_{av} - \theta_s) = Wc_p (\theta_{in} - \theta_{ex}) \quad (3.4-22)$$

The changes in mass flow and gas composition, due to chemical reactions, are considered in evaluating the channel heat transfer, including the variations in c_p and Re .

The heat transfer coefficients are those for convective heat transfer in turbulent or laminar flow in circular tubes [Kaminsky, 1990].

For the laminar flow regime ($Re \leq 2300$)

$$Nu = 4 \quad (3.4-23a)$$

$$St = \frac{Nu}{Re \, Pr}$$

For the turbulent flow regime ($Re \geq 8000$)

$$St = 0.022 \, Re^{-0.2} \, Pr^{-0.6} \quad (3.4-23b)$$

and

$$h = G \, c_p \, St \quad (3.4-24)$$

where G is the mass flux.

For the transition regime, the Stanton number is computed by linear interpolation between St (2300) and St (8000).

3.4.3 Chemical Reactions During Gas Ingress Scenarios

At high temperatures, graphite will oxidize in the presence of oxygen or water, but for the high purity and high density graphite grades used in the gas-cooled reactor industry in the United States, the chemical reactivity is relatively small.

For the case of air ingress, the following chemical reactions have to be considered:

and

Equations 3.4-25 and 3.4-26 are often combined as follows:

In the temperature range of gas-cooled reactor cores, the equilibrium is strongly shifted towards CO, so that the reaction of Equation 3.4-25 dominates [Moormann et al, 1980]. While some CO₂ could be formed initially in the cooler, bottom sections of the core, such CO₂ would react in the hotter regions of the core with graphite to CO following the Boudouard reaction (Equation 3.4-27).

The energy release per kmol of oxygen from graphite oxidation to CO (Equation 3.4-25) is 242 MJ/kmol O₂, while oxidation to CO₂ (Equ. 3.4-26) results in a release of 393 MJ/kmol O₂. However, this energy release generally amounts to less than 10% of the decay heat, and because oxidation is essentially complete in cooler core regions, its contribution to raise peak fuel temperatures is negligible. The main concern is the graphite corrosion which leads to some release of fission product due to plated-out and embedded fission products, and also could reduce the structural strength of the graphite. As the reaction to CO (Equation 3.4-25) dominates and is also conservative with respect to the amount of graphite consumed per kmol of oxygen, while the slightly higher energy release of reaction to CO₂ (Equation 3.4-26) is not of much concern, the current model considers, as a conservative approach, that all oxidation is to CO, i.e., using equation 3.4-25.

The graphite oxidation is a function of the temperature regime. At low temperatures, the carbon/oxygen reaction kinetics control the reaction rate. At intermediate temperatures (about 700°C to 900°C), the in-pore diffusion is controlling, while at higher temperatures, the coolant to surface mass transfer by diffusion, here in a laminar flow field, is controlling [Rossberg and Wicke, 1956; Moormann et al 1980].

To consider all three regimes, a model including external mass transfer, in-pore diffusion, and chemical reaction kinetics is required, as for instance, in the Oxide-3 code [Perroomian et al., 1974]. For the current applications, we decided to use a simpler approach, combining the in-pore diffusion and chemical reaction process into a single Langmuir-Hinshelwood type semi-empirical equation, as done, for instance, by Moormann and Peterson [1982]. This equation is the following:

$$\Gamma_{O_2}'' = -C \frac{k_1 e^{-c_1/\theta} p_{O_2w}}{1 + k_2 e^{c_2/\theta} \sqrt{p_{O_2w}}} \cdot \sqrt{\frac{D}{D_0}} \left[\frac{\text{kmol } O_2}{\text{m}^2 \text{s}} \right] \quad (3.4-29)$$

where Γ_{O_2}'' is the oxygen reaction rate per unit surface area, p_{O_2} is the partial pressure of oxygen, and D is the binary diffusion coefficient of oxygen in the gas mixture. θ is the gas temperature and k_1 , k_2 , c_1 , c_2 are empirical constants. D_0 is the binary diffusion coefficient of oxygen in helium at a reference temperature of 800°C and a pressure of 1.5 bar. C is a conversion constant to convert from the units of k_1 (generally given in mg. carbon/cm²s) to kmol O₂/m²s. The minus sign indicates that oxygen is being consumed in the reaction.

The corresponding generation and depletion rates for CO and C, respectively, follow stoichiometrically from Equation 3.4-25:

$$\Gamma_C'' = 2 \Gamma_{O_2}'' \quad (3.4-30)$$

and

$$\Gamma_{CO}'' = - \Gamma_C'' \quad (3.4-31)$$

Equation 3.4-29 is solved simultaneously with the coolant to surface mass transfer relationship

$$\Gamma_{O_2}'' = - \frac{\beta}{\hat{R}\theta} (P_{O_2 \text{ str}} - P_{O_2 w}) \left[\frac{\text{kmol } O_2}{\text{m}^2 \text{s}} \right] \quad (3.4-32)$$

where the mass transfer coefficient β is computed from the Sherwood number correlation

$$\text{Sh} = \frac{\beta d}{D} = f(\text{Re}, \frac{\nu}{D}) \quad (3.4-33)$$

and for purely laminar flow

$$\text{Sh} = \frac{\beta d}{D} = 4.3 \quad (3.4-34)$$

$\hat{R}$ is the universal gas constant; D the coolant hole diameter; Re the Reynolds number; and ν the kinematic gas viscosity. The subscripts w and str refer to wall and bulk stream values, respectively.

There is considerable uncertainty in the available in-pore diffusion data, and during most air ingress scenarios, the mass transfer in the coolant stream is controlling. Essentially, all incoming oxygen will react. Therefore, the total amount of carbon that reacts is determined by the gas inflow rate, which, in turn, is limited by the high core friction pressure drop. Thus, this model is completely sufficient for evaluating air ingress scenarios. Its shortcoming is that for the in-pore diffusion regime it cannot predict the lateral distribution of the oxidation process, i.e., the depth of the reaction zone in radial direction. In the chemical reaction controlled regime, the burn-off is essentially uniform throughout the graphite, while for the coolant to surface mass transfer controlled regime, oxidation occurs predominantly at the surface.

The binary diffusion coefficients for various non-polar gas mixtures were computed based on the Chapman-Enskog kinetic theory [Bird et al., 1960]. For air ingress scenarios, assuming conservatively pure air to enter the reactor vessel, the diffusion coefficient for oxygen in nitrogen was approximated as follows:

$$D_{O_2 - N_2} = 1.7 \times 10^{-4} \left[\frac{\theta}{\theta_o} \right]^{1.5} \left[\frac{m^2}{s} \right] \quad (3.4-35)$$

where the reference temperature is 1000 K.

For the diffusion coefficient of oxygen in helium we used the following approximation:

$$D_{O_2 - He} = 6.5 \times 10^{-4} \left[\frac{\theta}{\theta_o} \right]^{1.5} \left[\frac{m^2}{s} \right] \quad (3.4-36)$$

For the current model, the reaction rate constants of Katcher and Moormann [1986] for A3-3 graphite, a typical core graphite, were used, because these reaction rate constants were readily available in the required format. We shall substitute corresponding data representative of H451 core graphite as they become available. The reaction rate constants currently used are given in Table 3-1.

Table 3-1
Reaction Rate Constants of THATCH/FLOXI
Model for Air and Water Ingress
(Equation 3.4-29)

Ingress	k_1^*	c_1	k_2	c_2	Reference
Air	2.34	12,850	.00399	1569	Katcher, 1986
Water	0.072	17,000	1.202×10^{-5}	7000	Moormann, 1985

* The units of k_1 are [mg carbon/cm²s]

Because there are considerable uncertainties in the reaction rate constants, as well as in the diffusion coefficients used, these have been varied parametrically. The reaction rates were raised up by one order and down by two orders. The result for several very conservative air ingress transients during core-heatup transients showed that the effect of all these variations on the amount of graphite oxidized was negligible, because essentially all oxygen entering the core will react and the amount of carbon oxidized is limited by the gas flow through the core, which remains small due to its long and narrow coolant passages [Kroeger, 1989].

Using the above rate equations, the quasi-steady mass conservation equations are solved for each gas species involved in the chemical reaction in each parallel flow channel. For species ℓ , we have the following:

$$\frac{\partial}{\partial z} c_\ell v = \Gamma_\ell''' \quad (3.4-37)$$

where c_ℓ is the molar concentration of species ℓ ; v is the local flow velocity; and Γ_ℓ''' is the volumetric generation rate of species ℓ .

In finite difference form for axial node j, this can be expressed as follows:

$$c_{j,\ell} v_j = c_{j-1,\ell} v_{j-1} + \Gamma_{j,\ell}''' \Delta z \quad (3.4-38)$$

Multiplying by the flow area and noting that the molar flow rate of species ℓ in kmol/s is

$$C_\ell = c_\ell v A_{\text{flow}} = \frac{W}{M_m} v_\ell \quad (3.4-39)$$

we obtain

$$C_{j,\ell} = C_{j-1,\ell} + A'_{\text{surf}} \Delta z \Gamma_{j,\ell}'' \quad (3.4-40)$$

where $C_{j,\ell}$ is the local molar flow rate of species ℓ leaving node j, and $\Gamma_{j,\ell}''$ is the reaction rate as given in equations 3.4-29 to 31. M_m is the mixture mole weight and v_ℓ the volume fraction of species ℓ . It has to be noted that the integration of these equations must be done in flow direction. Therefore, here the node index j counts in flow direction and does not necessarily correspond to the node index j fixed by THATCH.

For the case of water ingress, the chemical reaction to be considered is the so-called "water gas reaction":

This reaction is endothermal with the absorption of 118.8 MJ/kmol H_2O . The model for water ingress follows the same equations as the air ingress model, except that the constants of reaction rates differ.

$$\Gamma_{\text{H}_2\text{O}}'' = -C \frac{k_1 e^{-c_1/\theta} p_{\text{H}_2\text{Ow}}}{1 + k_2 e^{c_2/\theta} \sqrt{p_{\text{H}_2\text{Ow}}}} \left[\frac{\text{kmol H}_2\text{O}}{\text{m}^2\text{s}} \right] \quad (3.4-42)$$

where $\Gamma_{\text{H}_2\text{O}}''$ is the water reaction per unit surface area; $p_{\text{H}_2\text{O}}$ is the water partial pressure; and C is a conversion constant from the units of k_1 (generally mg carbon/cm²s) to kmol H_2O /m²s. The reaction constants for water ingress are given in Table 3-1.

From equation 3.4-41 it follows that

$$\Gamma_C'' = \Gamma_{H_2O}'' \quad (3.4-43)$$

$$\Gamma_{CO}'' = - \Gamma_{H_2O}'' \quad (3.4-44)$$

and

$$\Gamma_{H_2}'' = - \Gamma_{H_2O}'' \quad (3.4-45)$$

The diffusion coefficient of H_2O in He [Bird et al., 1960, pg. 505] is approximated by:

$$D_{H_2O - He} = 3.396 \times 10^{-10} [\theta \text{ (K)}]^{2.334} \quad (3.4-46)$$

3.4.4 Method of Solution for FLOXI Models

The FLOXI system of equations consists of three distinct but coupled sets of equations, as follows:

1. the flow model,
2. the heat transfer model, and
3. the chemical reaction model.

These are solved separately and, if so specified as user option, an external iteration scheme assures that all coupling has been accounted for in the final solution.

In the external iteration scheme, the heat transfer and chemical reaction computations must progress in flow direction and, therefore, are done separately for up and down flow channels. The computations include plena models, which assume complete mixing of the incoming flows and uniform temperature and composition to the outflowing channels. A schematic of this loop is shown in Figure 4-6, below.

Solution of Parallel Channel Flow Equations

Equation (3.4.-1) applied for each channel and Equation (3.4-2) form a system of $i_{CHP} + 1$ simultaneous, non-linear algebraic equations for the inflow into each channel W_{oi} , and the overall pressure difference between the plena Δp_o .

The first i_{CHP} equations are obtained from Equation 3.4-1, and of the independent variables only the flow rate of its channel and the overall pressure difference enter. In the last equation (Equation 3.4-2), all mass flows enter, but the overall pressure difference does not. With this structure of the equations, a very efficient Newton-Raphson iteration scheme can readily be implemented, using the sparse structure of the Jacobean maxtrix to solve for the residual vector. The Newton-Raphson procedure is

included in the FLOXI flow-computation routine, FLXFLOW, using sub-routine SOLSPEC for the inversion of the Jacobean matrix.

Solution of Coolant to Solid Heat Transfer Equations

Based on a known flow distribution, gas composition and solid temperature distribution, the fluid temperatures and heat flows can be readily computed by indexing through each of the parallel flow channels in flow direction. With heat transfer coefficients from Equation 3.4-23 and 24, and ψ coefficient from Equation 3.4-20, we obtain the fluid average temperature and fluid exit temperature of each node from Equations 3.4-21 and 3.4-19, respectively. The fluid-to-solid heat exchange follows from Equation 3.4-22.

Solution of Chemical Reaction and Mass Transfer Equations

Equating Equations (3.4-29) and (3.4-32), we obtain at each axial node of each parallel flow channel in the core, a non-linear equation for the stream and surface values of the reactant partial pressure (O_2 for air ingress and H_2O for water ingress).

Applying the mass balance of the reactant Equation (3.4-38) for the node exit, using Γ from Equation (3.4-32) and expressing the left-hand side as follows:

$$C_{j,\ell} = \nu_{j,\ell} \sum_{\ell=1}^L C_{j,\ell} \quad (3.4-47)$$

noting

$$p_{j,\ell} = \nu_{j,\ell} P_o \quad (3.4-48)$$

we obtain a second simultaneous equation for the reactant partial pressures. $\nu_{j,\ell}$ is the volume fraction of species ℓ at interface j .

These two equations are solved in each parallel flow channel and at each axial node, again indexing in flow direction. A Newton-Raphson procedure is used with inversion of the linear equations by Cramer's Rule. Once the reactant partial pressures are known, the source terms for the various species that change can be computed and molar flows leaving a node follow from equation (3.4-40), completing the mass balance equations.

3.5 PKIN Module for Point Kinetics Option

3.5.1 Point Kinetics Model

The point kinetics model of THATCH is based on a previous model by Cheng [1976] and also follows Knief [1981]. This model is based on one equation for the prompt neutron power plus six delayed neutron groups:

$$\frac{d\hat{P}}{dt} = \frac{\rho - \beta}{\ell^*} \hat{P} + \sum \lambda \hat{C} \quad (3.5-1)$$

$$\frac{d\hat{C}_i}{dt} = \frac{\beta_i}{\ell^*} \hat{P} - \lambda_i \hat{C}_i \quad i=1,6 \quad (3.5-2)$$

where $\hat{P} = P/P_0 = N/N_0$, with P the reactor power; P_0 the steady-state full power level; N the neutron flux; N_0 is the neutron flux at steady-state full power; and $\hat{C}_i = C_i / N_0$.

P	=	reactor power
C_i	=	delayed precursor concentrations of group i
λ_i	=	decay constant of group i (s^{-1})
β_i	=	delayed neutron fraction of group i
β	=	total delayed neutron fraction
ρ	=	total reactivity
ℓ^*	=	prompt neutron generation time (s)

At initial steady-state, $\hat{P} = 1$ and $\rho = 0$, with

$$\hat{C}_i = \frac{\beta_i}{\ell^* \lambda_i} \quad (3.5-3)$$

The Xenon-135 concentration is obtained from the two following equations for iodine and xenon [Knief, 1981]:

$$\frac{dI}{dt} = \gamma^{Te} \sum_f \Phi - \lambda^I I \quad (3.5-4)$$

$$\frac{dX}{dt} = \gamma^X \sum_f \Phi + \lambda^I I - X \sigma_a^X \Phi - \lambda^X X \quad (3.5-5)$$

where

I	I-135 concentration [m^{-3}]
X	Xe-135 concentration [m^{-3}]
γ^{Te}	fission yield of tellurium or iodine (due to short half-life of Te-135)
γ^X	fission yield of Xenon-135
$\sum_f \phi$	the fission rate [fissions/ m^3s]
λ^I, λ^X	iodine and xenon decay constants [s^{-1}]
σ_a^X	microscopic Xenon-135 absorption cross section [m^2]
Φ	the neutron flux [$m^{-2} s^{-1}$]

Scaling the above equations with the full-power, steady-state concentrations yields the following:

$$\frac{d\hat{I}}{dt} = \hat{\lambda}^I (\hat{P} - \hat{I}) \quad (3.5-6)$$

and

$$\frac{d\hat{X}}{dt} = \frac{\lambda^X + G}{\gamma^X + \gamma^{Te}} (\gamma^X \hat{P} + \gamma^{Te} \hat{I}) - (G\hat{P} + \lambda^X) \hat{X} \quad (3.5-7)$$

where

$$\begin{aligned} \hat{X} &= X/X_0, \quad \hat{I} = I/I_0 \\ \hat{P} &= P/P_0 = \Sigma_f \Phi / (\Sigma_f \Phi)_0 \end{aligned}$$

and

$$G = \left(\frac{\sigma_a^X}{\Sigma_f} \right) (\Sigma_f \Phi)_0 = \left(\frac{\sigma_a^X}{\Sigma_f} \right) \left(\frac{P_0}{E} \right) \quad (3.5-8)$$

where X_0 and I_0 are the steady-state full power xenon and iodine concentrations; Σ_f is the macroscopic fission cross-section; P_0 the steady-state, full-power power density; and E is the energy per fission.

For some of the very slow core heatup transients, Samarium-149 poisoning must be considered in the model. The corresponding ODEs for Promethium and Samarium [Knief, 1981] are:

$$\frac{dPm}{dt} = \gamma^{Nd} \Sigma_f \Phi - \lambda^{Pm} Pm \quad (3.5-9)$$

$$\frac{dS}{dt} = \lambda^{Pm} Pm - S \sigma_a^S \Phi \quad (3.5-10)$$

where

Pm	Concentration of Promethium -149 [m^{-3}]
S	Concentration of Samarium-149 [m^{-3}]
γ^{Nd}	fission yield of neodymium or promethium (due to short half-life of Nd-149)
λ^{Pm}	decay constant of promethium [s^{-1}]
σ_a^S	absorption cross-section of microscopic Samarium-149 [m^2]

Scaling these equations with the full power, steady-state concentration yields the following:

$$\frac{d\hat{P}_m}{dt} = \lambda^{P_m} (\hat{P} - \hat{P}_m) \quad (3.5-11)$$

$$\frac{d\hat{S}}{dt} = G_s (\hat{P}_m - \hat{P}_s) \quad (3.5-12)$$

with

$$G_s = \left[\frac{\sigma_a^s}{\Sigma_f} \right] \left[\frac{P_o}{E} \right] \quad (3.5-13)$$

The reactivity feedbacks included in the THATCH point kinetics model are the following:

1. Change in fuel temperature
2. Change in moderator temperature
3. Change in reflector temperature
4. Change in xenon concentration
5. Change in samarium concentration
6. Change in water concentration

These can be expressed as follows:

$$\begin{aligned} d\rho = & C_D d\theta_{\text{fuel}} + C_m d\theta_{\text{moderator}} \\ & + C_R d\theta_{\text{reflector}} \\ & + C_x d\hat{X} + C_S d\hat{S} + C_w dW \end{aligned} \quad (3.5-14)$$

where W refers to the water concentration.

The xenon feedback coefficient is

$$C_x = - \frac{\sigma_a^X}{\Sigma_t} X_o \quad (3.5-15)$$

where X_o is the steady-state, full power xenon concentration

$$X_o = \left[\frac{\gamma^X + \gamma^{Te}}{\lambda^X + G} \right] \left[\frac{P_o}{E} \right] \quad (3.5-16)$$

and Σ_t is the total macroscopic cross section.

Correspondingly, the Samarium feedback coefficient is

$$C_s = - \frac{\sigma_a^S}{\Sigma_t} S_o \quad (3.5-17)$$

with

$$S_o = \frac{\gamma^{Nd} \Sigma_f}{\sigma_a^S} \quad (3.5-18)$$

The temperature coefficients, water worth data, macroscopic cross section data and delayed neutron group fractions and decay constants are based on PSID data. Other constants used are

$$\begin{aligned} \gamma^{Te} &= 0.056 \quad ; \quad \gamma^x = 0.003 \quad ; \quad \gamma^{Nd} = .01406 \\ E &= 200 \text{ Mev/fission} = 3.2042 \times 10^{-11} \text{ J/fission} \\ P_o &= 5.96 \text{ MW/m}^3 \\ \lambda^I &= 2.9 \times 10^{-5} \text{ 1/s} \quad ; \quad \gamma^X = 2.1 \times 10^{-5} \text{ 1/s} \quad ; \quad \lambda^{Pm} = 3.63 \times 10^{-6} \text{ 1/s} \\ \sigma_a^X &= 2.65 \times 10^6 \text{ b} \quad ; \quad \sigma_a^S = 25.03 \times 10^3 \text{ b} \end{aligned}$$

3.5.2 Method of Solution for Point Kinetics Model

The Point Kinetics Model consists of eleven ODEs, one for the reactor power, six for delayed neutron concentrations, two for the iodine and xenon concentrations, and two for the promethium and samarium concentrations. For convenience, the integrated scaled power is added as a twelfth equation, i.e., for integrated power

$$\pi = \int \hat{P} \, dt \quad (3.5-19)$$

we have as ODE

$$\frac{d\pi}{dt} = \hat{P} \quad (3.5-20)$$

This set of twelve ODEs is solved by a standard stiff ODE solver. The IMSL routine DIVPAG is used for this purpose and is available in the IMSL library, Version 10.0. The ODE solver DGEAR which is available in the earlier IMSL library, Version 9.2, can also be used. As the equations are generally stiff, we found that the Gear method (MTHGEAR=2 in PKIN input) with iteration method

MITER=1 gave best results. Because this option requires a user-supplied Jacobian matrix, a subroutine computing the matrix (JACK) is provided in addition to the derivative routine (DERIV).

Much of the reactor physics data used were obtained from the PSID and are "hard-wired" in PKINLIB Block Data Routine BLDPINK. To change these data, we can optionally override these entries by using special input data records. The variables included in this option are summarized in Table 3.-2.

The point kinetics and solid node temperature computations are coupled. Fuel and graphite temperatures are functions of the heating rate or power. The power depends on the reactivity feedbacks, which, in turn, are a function of fuel and graphite temperatures. In particular, with strong reactivity incursions this coupling can be essential. The point kinetics and solid node temperature computations, therefore, can be executed iteratively, if so specified by the user (COMPMOD = 'Iterate' in Input Record 5001D). In this case, the core temperatures and the point kinetics vectors are iteratively advanced from time t_1 to time t_2 . As the point kinetics integration proceeds at its time steps, controlled by its integration routine, we assumed that the core reactivity feedbacks vary linearly between $\rho[\theta(t_1)]$ and $\rho[\theta(t_2)]$. Convergence is accepted when the core average temperatures used for core reactivity feedback evaluations vary less than some ϵ between subsequent iterations (general 10^{-3}K).

The water reactivity feedback uses PSID data on water reactivity worth versus mass of water in the core. The code computes the maximum theoretical concentration of water vapor in the core at the set point pressure of the relief valve and at the average temperature of the core coolant, assuming an ideal gas equation of state for the vapor. Depending on the input specified, beginning of ingress time and ramp time, the code then computes the current concentration of water vapor as a fraction of the maximum theoretical vapor concentration, where this fraction is specified with the input data.

3.6 SYMELAN Module for Rapid Thermal Core Transients, Using Symmetry Element Nodalization

3.6.1 Symelan Active Core Heat Transfer Model

The SYMELAN module can evaluate rapid core thermal transients where detailed modelling of heat conduction in the fuel stick and in the moderator web is essential.

The active core is again divided into a number of parallel flow channels selected by the user. Each channel represents some number of fuel element columns. Because the SYMELAN free-standing model neglects horizontal conduction between parallel flow channels, any flow channel can represent just one fuel element column, a part of a fuel element column or a group of fuel element columns, as desired. The core is also divided into a number of axial zones selected by the user, generally with two zones per fuel element, similar to the general THATCH nodalization.

In each fuel element, a coolant hole is generally surrounded by six fuel holes, as shown in Figure 3-10. The heat conduction between the center line of the fuel pin and the coolant hole can be characterized by that in the symmetry element of Figure 3-11, where the sides of the triangle, due to symmetry, can be modelled as adiabatic surfaces. Each axial node region, j , of each parallel flow channel, i , contains many symmetry elements (approximately 1200 per fuel element). The model assumes uniform heating rate and coolant inflow in node region i,j . Therefore, the temperature distribution in one symmetry element applies for all elements in node region i,j .

Figure 3-10 Standard Fuel Element of the MHTGR
(Bechtel, 1986)

Figure 3-11 Symmetry Element Contained
in MHTGR Fuel Element

Table 3.-2 Reactor Physics Data Which Can Be Varied by Use of
Input Records 5004 to 5010D of Section 5.1

Variable	Symbol	Variable Name	Positions	Units	Input Record No.
Delayed Neutron Fractions	β_i	BETA	6		5004D
Decay Constants for Delayed Neutron Groups	λ_i	DECAY	6	s^{-1}	5005D
Prompt Neutron Generation Time	ℓ^*	GENT		s	5006D
Decay Constants for Iodine	λ^I	XLAM (1)	1	s^{-1}	5007D
Decay Constants for Xenon	λ^X	XLAM (2)	1	s^{-1}	5007D
Fission Yield of Tellurium	γ^{Te}	GAM (1)	1		5008D
Fission Yield of Xenon	γ^X	GAM (2)	1		5008D
Power Density	P_o	POWD	1	W/m ³	5009D
Xenon Microscopic Absorption Cross Section	σ_a^X	SIGA	1	m ²	5009D
Macroscopic Fission Cross Section	Σ_f	SIGF	1	m ⁻¹	5009D
Total Macroscopic Cross Section	Σ_t	SIGT	1	m ⁻¹	5009D
Fission Yield of Neodymium	γ^{Nd}	GAMND	1		5010D
Decay Constant of Promethium	λ^{Pm}	XLAMPM	1	s^{-1}	5010D
Samarium Microscopic Absorption Cross-Section	σ_a^S	SIGASAM	1	m ²	5010D

The nodalization within the fuel stick of the symmetry element is regular, i.e., node boundaries are circles of constant radius and straight lines. In the graphite web, irregular boundaries were drawn, following estimated isotherms and flux lines. Three nodalizations were used, as summarized in Table 3-3.

Nodalization 1 is shown in Figure 3-10. The chosen graphite dimensions for these nodalizations are tabulated in Block Data SYMDAT in the SYMELAN library. The data file contains node volumes [mm³/mm], heat flow areas at the node boundaries [mm²/mm], and node center distances in "radial" direction [mm] (i.e., from fuel hole to coolant hole) and in transverse direction (between node rows) for the case of Nodalization 1 with two node rows. The data on radial node distance are the distances between node centers, except for the first and last entries which are from the fuel/graphite interface to the first node center, and from the last node center to the coolant hole surface. Some numerical experimentation with these nodalizations was performed, and we found that moderate variations in changes in dimensions between graphite nodes had no significant effect on the results. Further, even in the most rapid transients the conduction between rows remained very small relative to the radial conduction from fuel to coolant. Therefore, we prefer Nodalization 3 and used it in most studies. Also, we found twenty axial core nodes to be sufficient for all cases. For the number of parallel flow channels, either three or six channels were generally used. Six channels must be used in runs coupled to THATCH, to correspond with the general THATCH nodalization.

The transient heat conduction equation within the nodal network of the symmetry element can be written for any node as follows:

$$\rho c V' \frac{\partial \theta}{\partial t} = - \sum A' q''_{out} + V' q_g''' \quad (3.6-1)$$

Table 3-3

Currently Available Options for
Symmetry Element Nodalization

Nodalization No.	Number of Node Rows	Number of Fuel Node Columns*	Number of Graphite Node Columns
1	2	3	6
2	1	3	6
3	1	6	12

* Entries are values typically used; user is free to vary actual value by input data specification

With row index m and column index n, this can be written in finite difference form, for implicit solution as follows:

$$\left[(\rho c V')_{n,m} + \left[\sum_N \frac{A'}{\Delta y} k \right] \Delta t \right] \theta_{n,m} - \sum_N \frac{A'}{\Delta y} k \Delta t \theta_N$$

(3.6-2)

$$= (\rho c V')_{n,m} \theta_{n,m}^{\circ} + V'_{n,m} q_g''' \Delta t$$

where V' and A' are node volumes and heat transfer areas per unit length.

In this equation, the $\sum_N$ represents summing over all neighboring nodes, and θ° denotes the temperature at the preceding time step.

This equation applies within each node of the symmetry element and for each axial node region j, and each parallel flow channel i, i.e., all n,m arrays actually have four indices. For brevity the i,j indices will only be used where necessary.

The internal heating rate in the fuel is considered constant across the fuel stick and within the node region i,j. However, it varies based on prescribed axial and radial power profiles between axial node regions j and parallel flow channels i.

Expressing the conduction coefficients again as C_N , C_E , C_S , and C_W , we have for any node the following:

$$C_Y = \frac{A'}{\delta y} k \Delta t$$

(3.6-3)

where A' is the heat flow area at the node boundary per unit length; δy the node center to node center distance; and k is evaluated at the average temperature between nodes. Optionally, an axial conduction term between node regions of the axial can be included as an explicit term (however, we found this term to be small at all times).

Then

$$\begin{aligned}
 & \left[(\rho c V')_{n,m} + C_{N_{n,m}} + C_{E_{n,m}} + C_{S_{n,m}} + C_{W_{n,m}} \right] \theta_{n,m} \\
 & - C_{N_{n,m}} \theta_{n,m-1} + C_{E_{n,m}} \theta_{n+1,m} + C_{S_{n,m}} \theta_{n,m+1} + C_{W_{n,m}} \theta_{n-1,m} \\
 & = (\rho c V')_{n,m} \theta_{n,m}^{\circ} + V'_{n,m} q_g''' \Delta t \\
 & + \frac{1}{\Delta z} \left[\frac{A}{\Delta z_{ax}} \right] \Delta t \left[k_- (\theta_{n,m}^{\circ} - \theta_{n,m}) \right. \\
 & \quad \left. - k_+ (\theta_{n,m}^{\circ} - \theta_{n,m,j+1}) \right]
 \end{aligned} \tag{3.6-4}$$

where the additional Δz in the axial conduction term is for conversion of this term to unit length, corresponding to the other terms.

$\left[\frac{A}{\Delta z} \right]$ are the axial node to node heat transfer surfaces divided by node distance, k_- and k_+ are the conductivities evaluated at average temperatures between nodes.

For single row nodalization, the north and south terms disappear and the system of equations is tridiagonal. Even for two-row nodalization, only one off-tridiagonal would remain, and it most likely could have been treated explicitly. However, the code currently treats it implicitly and does not use the tridiagonal system in case of two-row nodalizations.

Boundary conditions must be applied at the fuel centerline, at the fuel graphite interface, and at the coolant hole surface.

At the fuel centerline

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

applies and the C_W terms of Equation (3.6-4) disappear.

At the fuel graphite interface, radiation, and conduction across a gap of user-prescribed thickness is assumed. The corresponding C_Y coefficients at the fuel graphite interface are the following:

$$C_Y = A' U \Delta t \tag{3.6-5}$$

where

$$\frac{1}{U} = \frac{\Delta r_-}{k_f(\theta_-)} + \frac{1}{h_{\text{rad}} + \frac{\delta}{k_{\text{He}}(\theta_g)}} + \frac{\Delta r_+}{k_g(\theta_+)} \quad (3.6-6)$$

where Δr_- and Δr_+ are the node center to interface distances; $k_f(\theta_-)$ and $k_g(\theta_+)$ are the fuel and graphite conductivities evaluated at the respective node temperatures; δ is the gap thickness; $k_{\text{He}}(\theta_g)$ is the thermal conductivity of helium at the gap temperature; and h_{rad} is the radiation heat transfer coefficient at a user-provided fuel to graphite effective emissivity (see Equation 3.1-15).

At the graphite and coolant interface, convection from solid to coolant is modelled as follows: within each axial node region, temperatures of the symmetry element remain constant in axial direction, and between the last node, its surface and the fluid average temperature, we have the following:

$$Q = A' \frac{k}{\Delta r} (\theta_n - \theta_s) = A' h (\theta_s - \theta_{\text{fl av}}) \quad (3.6-7)$$

or

$$Q = A' U (\theta_n - \theta_{\text{fl av}}) \quad (3.6-8)$$

where

$$\frac{1}{U} = \frac{\Delta r}{k} + \frac{1}{h} \quad (3.6-9)$$

h is the convective heat transfer coefficient, and Q is the total heat flow out of the last symmetric element node to the coolant. Note that in the SYMELAN formulation all heat transfer rates, surfaces, and volumes are expressed in terms of unit length, i.e., the dimension of the above equation is [W/m], and the surface area A' is in [m²/m].

For a node of length Δz , representing one parallel flow channel, we have as in Section 3.4-2

$$(\theta_n - \theta_{\text{fl av}}) = (\theta_n - \theta_{\text{fl in}}) \frac{1 - e^{-\Psi}}{\Psi} \quad (3.6-10)$$

where

$$\Psi = \frac{A_N U}{W c_p} \quad (3.6-11)$$

and

$$A_N = A' \Delta z n m \quad (3.6-12)$$

where Δz is axial node length; n is the number of symmetry elements per flow channel; and m is the number of node rows per symmetry element.

Substituting Equations (3.6-10) to (3.6-12) into Equation (3.6-8), we obtain:

$$Q = \frac{(1 - e^{-\Psi}) W c_p}{\Delta z n m} (\theta_n - \theta_{n \text{ in}}) \quad (3.6-13)$$

and, correspondingly, for the last node conductance coefficient

$$C_E = \frac{(1 - e^{-\Psi}) W c_p}{\Delta z n m} \Delta t \quad (3.6-14)$$

For each axial node we also have, as in Section 3.4-2, for the fluid exit temperature from each axial node region

$$\theta_{n \text{ ex}} - \theta_n = (\theta_{n \text{ in}} - \theta_n) e^{-\Psi} \quad (3.6-15)$$

3.6.2 Method of Solution

From the equations given above, for any flow channel and any axial node region with given fluid inlet temperature, the temperature field of the symmetry element can be solved, using the set of Equations 3.6-4 with conductance coefficients from Equations (3.6-3, 5, 6, and 14). Thereafter, Equation (3.6-15) is solved for the coolant inlet temperature to the next axial node.

Since axial stepping in flow direction is required, the symmetry element equations of all parallel flow channels i for one axial node region j are solved together. Then the fluid exit temperatures of the axial node region are evaluated for each flow channel, and the next axial node region is evaluated for all channels. For the generally used nodalizations of one single node row, a tridiagonal algorithm can be applied and one set of $i_{CH} \times n_N$ equations is solved, where i_{CH} is the number of flow channels, and n_N the number of symmetry element nodes. For nodalizations with two node rows, i_{CH} sets of n_N simultaneous equations are solved. (If such nodalizations were to be used extensively, one should consider to treat the C_N and C_S terms of Equation 3.6-4 explicitly and use the tridiagonal solution algorithm).

4. PROGRAM STRUCTURE

The THATCH code and its sub-modules are subdivided into two components containing specific sets of subroutines. The first component, called THATCH, contains the general THATCH routines. The second is currently assembled in a component called BIG. Because both components are maintained via Update or Historian, there are no COMMON decks shared by the two components.

BIG includes many general service routines and also the sub-module libraries. In many cases, it is convenient to subdivide BIG into several individual libraries, particularly if we only work with one or two sub-modules. Table E-1 in Appendix E lists all THATCH subroutines and entries, including their location in THATCH or BIG and to which library the routine belongs. The libraries and their general purpose are summarized in Table 4-1.

The THATCH and BIG components include several "subroutines" which actually present main programs (Table 4-2). These can be executed as free-standing programs that are called by exterior 3-line dummy programs. For example, the "subroutine" THATCH in the THATCH component must be called by a user-supplied 3-line program as follows:

```
PROGRAM THATCHM
CALL THATCH
END
```

The major functions of the THATCH and BIG subroutines are described in this section, in order by libraries.

4.1 THATCH Subroutines

In the heading of most THATCH subroutines, a significant amount of information about the routine is provided in the form of comments. These comments were mainly written during the original development of the code, and have not been updated recently. In many cases, they will be very useful to new users.

4.1.1 THATCH Main Program

Subroutine THATCH. This subroutine is actually the main program. After reading the control variables for sub-modules (records 201D and 202D), the program sets the control variable CALMODE, which is 'THATCH' for THATCH runs without SYMELAN, and 'COMBIN' for combined THATCH/SYMELAN runs. The program calls the various THATCH input routines, as well as the sub-module input routines, and then calls TIMSOL, the actual time step integration routine.

4.1.2 THATCH Input Subroutines

The names of the THATCH input routines generally begin with IN_ _ _ . Entries to these subroutines are named PRE_ _ _ for initialization before input data processing; INP_ _ _ for the main input section; and PST_ _ _ for data processing after completion of input data processing.

Table 4-1

Function of Sub-Libraries of BIG

Sub-Library	Function
FLOXLIB	FLOXI Subroutines
PKINLIB	PKIN Subroutines
SYMELLIB	SYMELAN Subroutines
PASCOLIB	PASCOL Subroutines
WATCOLIB	WATCOL Subroutines
GENLIB	General Purpose Subroutines (Interpolation, Friction and Heat Transfer Correlations, etc.)
GASPRLIB	Gas Property Routines
MATLIB	Solid Material Properties
THTCHLIB	THATCH-specific general routines, including NEWTON AE solver and MHTGR Data Bank Routines
THPROCS	THATCH Post Processing Routines (pre-plotting)
THRADLIB	Radiation Viewfactor Routines

Table 4-2

THATCH and BIG Effective
Main Programs

Subroutine	Function
THATCH	Execute THATCH
THRAD	Execute Radiation View Factor Computations
THPROCS	Execute THATCH Post-Processing
FLOXIMS	Free Standing FLOXI Execution
SYMELAN	Free Standing SYMELAN Execution

Subroutine INGEOM, with entries PREGEOM, INPGEOM, and PSTGEOM, reads, processes, and prints node geometry data. After reading radial and axial interface arrays, this subroutine computes node volumes, surface and flow areas, and other geometry coefficients for later conductance computations. The latter computations are done in entry PSTGEOM, which is called after gap data have been read in INBND, so that solid volumes, areas and node distances properly consider the gap dimensions. In entry INPGEOM, the logical variable UNIFIN from input record 301D is passed as call argument.

Subroutine INBLOCK, with entries PREBLCK and INPBLKS, reads, processes, and prints the subdivision of the structure into blocks, including the specification of boundary locations, identifying for each block face the boundary numbers of the boundaries covering it. A schematic print-out of the block breakdown is included with the output.

Subroutine INBND with entries PREBND and INPBND reads, processes, and prints the boundary descriptions, including types and dimensions of boundaries, characteristics of heat transfer and layer information. Maps of the radial and axial boundaries within the nodal network are produced with the output.

Subroutine INHTGEN, with entries PREHTGN, INPHTGN, and PSTHTGN, reads and processes data describing the in-core heat generation, including initial power, radial and axial power profile specification, and the after heat option to be applied. This subroutine produces the two-dimensional power distribution arrays for decay heat and fission power, the latter only if the point kinetics option is used. In entry INPHTGN, the logical variable UNIFIN from input record 301D is passed as a call argument.

Subroutine INPLENA, with entries PREPLNA, INPPLNA, and PSTPLNA, initializes the plena arrays. Entry INPPLNA has the following call sequence:

LP100,I1,I2,J1,J2,GEOM

where LP100 is the plenum number plus 100, as specified on input record 603D; I1,I2,J1,J2 are the range of node numbers for this plenum, and GEOM is the plenum geometry descriptor, as specified on input record 651D. In entry INPPLNA, the array IJPLENA is loaded, identifying for each plenum surface node, K=1,KMX, progressing clockwise around the plenum the I and J indices of the corresponding solid nodes. In entry PSTPLNA, heat transfer surface areas, node center to surface distances, and other parameters for later conductance coefficient computations are computed.

Subroutine INTIME, with entries PRETIME and INPT, provides for input of time step information. This subroutine also reads and processes the specifications for temperature print-out formats and for the selection of block surface temperatures to be printed.

Subroutine INTHETA, with entries PRETHETA and INPTH, reads initial temperature files and loads the corresponding internal and boundary temperature arrays from prescribed binary files and/or from the input file. To accommodate the free-field user specification of temperature by blocks or lines (see Section 5), it calls on THETA IN to process the input records.

Subroutine THETA receives the character strings specified for initial node temperatures in the input file, converts them to the proper temperature values, and loads the corresponding locations in the temperature array.

Subroutine PREINIT does initialization before input data processing by calling the various PRE _ _ _ entries and sets some of the system constants for COMMON/CONST/.

Subroutine PSTINIT does final initialization after completing the general THATCH input processing. This subroutine calls the various post-initialization entries PST_ _ _ and also reads the binary files for the two-dimensional radiation coefficient matrices. For restart runs, it locates and loads the initial temperatures and other required data from the restart file.

Subroutine FREEIN is used to unpack the boundary number specifications provided for block boundaries in input records 604D to 607D.

4.1.3 THATCH Subroutines for Internal Conductance Coefficients

Subroutine CONDUCT computes the conductances for all interfaces between internal nodes and also between nodes and boundaries during time integration at each time step. At the beginning of each call, the damage parameter array for graphite irradiation damage is updated by calling ANNELEX, before the thermal conductivities are called from PROPMAT via CONDF calls. Where boundary resistances are required, BNDCONI and BNDCONX are called.

Subroutine BNDCONI computes the effective conductance between internal node centers wherever finite boundary resistances have been specified. During the iterative solution the node surface temperatures are also obtained. The conductance computations follow Equations 3.1-6 to 15 and the geometry of Figure 3-4. The call sequence to BNDCONI is as follows:

```
COND,I,J,TINT,UB,THM,THP,THINT,THSURFM,THSURFP,MAT1,
MAT2,MAT3,MAT4,DX1,DX2,DX3,DX4,KTYPE,NCOND,LAYFL,NITMAX,
EMMI,DAM1,DAM2,DAM3,DAM4
```

where

COND	effective conductance (to be returned) [W/m ² K]
I,J	radial and axial location of interface
TINT	current time [s]
UB	boundary number
THM	node temperature on minus-side [K]
THP	node temperature on plus-side [K]
THINT	solid node/solid layer surface temperature [K]
THSURFM	solid/gas surface temperature on minus-side [K]
THSURFP	solid/gas surface temperature on plus-side [K]
MAT1 TO MAT4	material property index for use in subroutine PROPMAT. For layers not present, the corresponding entry must be set to zero by the calling routine, and its resistance is then set to zero here.
DX1 TO DX4	conductance lengths [m]
KTYPE	interior boundary type (see Table 5-1)
NCOND	conductance direction (1 = axial; 2 = radial)

LAYFL index identifying fluid layer location. LAYFL=2, fluid layer precedes solid layer (as in Figure 3-4); LAYFL=3, the sequence of the two layers is reversed.

NITMAX maximum number of iterations to be used in BNDCONI iterative computations. Convergence is achieved when at iteration n

$$\frac{\sum R - \sum R_{n-1}}{\sum R_n} < \epsilon$$

where $\epsilon = 10^{-6}$

EMMI effective emissivity between the two solid surfaces of the fluid gap

DAM1 TO DAM4 damage parameter for irradiation damage in thermal conductivity calls to PROPMAT

Subroutine BNDCONX computes the effective conductance between boundary nodes and the exterior boundary points. During the iterative solution, the node surface temperatures are also obtained. The call sequence to BNDCONX is as follows:

COND,I,J,TINT,IJB,THM,THP,THS,THSURFM,THSURFP,NCOND,KTYPE,
NITMAX,MATM,MATP,EMMI,HCONV,DXACM,DXACP,DAM

where

COND effective conductance (to be returned) [W/m²K]

I,J radial and axial location of interface

TINT current time [s]

IJB boundary number

THM node temperature on minus-side (used if boundary is on plus-side) [K]

THP node temperature on plus-side (used if boundary is on minus-side) [K]

THS sink (boundary) temperature [K]

THSURFM node surface temperature on minus-side (used if boundary is on plus-side) [K]

THSURFP node surface temperature on plus-side (used if boundary is on minus-side) [K]

NCOND conductance direction (1= axial; 2=radial)

KTYPE interior boundary type (see Table 5-1)

NITMAX maximum number of iterations to be used in BNDCONX iterative computations (convergence is achieved when at iteration n

$$\frac{\sum R_n - \sum R_{n-1}}{\sum R_n} < \epsilon$$

where $\epsilon = 10^{-3}$)

MATM to MATP material property nodes for use in subroutine PROPMAT.

EMMI effective emissivity between the two solid surfaces of the boundary.

HCONV convective heat transfer coefficient [W/m²K]

DXACM,DXACP conductance lengths [m]

DAM damage parameter for irradiation damage in thermal conductivity calls to PROPMAT

Subroutine COMCON computes the effective conductance across two layers of differing materials. During the iterative solution, the surface temperature at the interface of the two layers is also obtained. The call sequence to COMCON is as follows:

CC,THO,TH1,TH2,DX1,DX2,MAT1,MAT2,NDIR,NITMAX,DAM1,DAM2

where

CC	effective conductance (to be returned) [W/m ² K]
THO	node temperature on minus-side [K]
TH1	surface temperature between nodes [K]
TH2	node temperature on plus-side [K]
DX1,DX2	conductance lengths [m]
MAT1,MAT2	material property nodes for use in subroutine PROPMAT
NDIR	conductance direction (1=axial; 2=radial)
NITMAX	maximum number of iterations to be used in COMCON iterative computations (convergence is achieved when at iteration n

$$\frac{\sum R_n - \sum R_{n-1}}{\sum R_n} < \epsilon$$

where $\epsilon = 10^{-6}$

DAM1,DAM2 damage parameter for irradiation damage in thermal conductivity calls to PROPMAT

Subroutine CONDAPL computes the effective conductance of nodes adjacent to plena between node centers and the node/plenum interface.

Subroutine ANNEL, with entries ANNELIN and ANNELEX, computes the damage parameter array for the thermal conductivity of irradiated graphite based on initial irradiation damage data and a prescribed annealing temperature range for graphite. In entry ANNELIN, called by THATCH, the input records of Group 10 (Section 5-1) are read and loaded. In entry ANNELEX, called by CONDUC, the damage parameter array is recomputed, if annealing was specified based on the model of Section 8.3.

Subroutine FAILURE, with entries PREFAIL, INFAILP, FAILS, and ALLPLFL, permits the "failure" of certain layers and nodes. In previous HTGR designs, in particular the thermal barrier cover plates, were expected to fail as certain failure temperature levels are reached. This subroutine, with its input data from Group 9, permits the simulation of such nodes or layers to disappear or to be "redeposited", for instance from the ceiling of a plenum to the same radial position on the floor.

This code feature has not been used for the MHTGR, and currently might not be interfaced properly with other sections of the code. At this time there is no need for this feature; however, it should be tested carefully before being used again.

Subroutine HEATGEN is called to update the heat generation data at each time step. It primarily produced the QTRIP array for each node, corresponding to the volumetric heating rate q''' , which is used in computing the node solid temperatures, including the effects of afterheat, neutronic heating (PKINL=true), as well as heat from chemical reactions and convective heat transfer from the gas stream (the latter two if FLOXI=true). For further details of the model for q''' , see Section 8.4.

4.1.4 THATCH Subroutines for Time Integration of Solid Temperatures

Subroutine TIMSOL, called from THATCH, contains main time-step, loop. It calls subroutine TEMPSOL for time integration of the transient temperatures in the solid structures. Furthermore, it activates the various available modules, depending on the sub-module options of the run, to provide quasi-steady evaluations of gas flows, chemical reactions, convective heat transfer (FLOXIEX), RCCS performance (AIRCLEX), and plena heat transfer (RADTN), as well as transient point kinetics evaluations (PKINEX), and core transient temperatures from SYMELAN (TEMPSYM). The transient evaluations of core solid temperatures and point kinetics can be done iteratively if so specified (RHOINT=true, set in PKIN module if input parameter COMPMOD='Iterate').

A flow chart of the TIMSOL integration loop is presented in Figure 4-1.

Subroutine TEMPSOL evaluates the transient temperature field in the solid nodes of the THATCH network. The ADI method, used to solve the simultaneous equations, requires the solution of tridiagonal sets of equations, first progressing by rows, and then progressing by columns. For vectorized solution of these equations, it is efficient to solve one set of equations, for all rows at once, plus another set for all columns at once.

Figure 4-2 is a flow chart for the main section of TEMPSOL, solving for the solid temperature array.

During the first pass through TEMPSOL, several index arrays are set, to be used later to load the conductance and heat generation coefficients (CN,CE,CS,CW,CQ) into the tridiagonal system matrix arrays (ATR,BTR,CTR,FTR).

These arrays are as follows:

KSETT(I,J)	which is set for each node equal to its material index KMAT(I,J), except if that node is an active core node and this is a run with SYMELL=true, in which case it is set to 200. In runs using SYMELAN, these temperatures are not to be solved here, but in THYSYM, and therefore, these nodes will be bypassed in the TEMPSOL solution.
ILOC	index in tridiagonal system arrays during row-wise solution
JLOC	index in tridiagonal system arrays during column-wise solution
IINDXR (ILOC) and JINDXR (JLOC)	contain node indices I and J, corresponding to ILOC position in tridiagonal arrays
I1A (J) and I2A (J)	contain ILOC, corresponding to first and last node of row J (i.e. for nodes 1,J and IL,J)

Figure 4-1 Flow Chart of Time Step Integration Loop in TIMSOL

Transient Solution for Solid Node Temperatures in TEMPSOL

Figure 4-2 Flow Chart of TEMPSOL Solid Temperature Field Solution Procedure

IINDXC (JLOC) and JINDXC (JLOC)	contain node indices I and J, corresponding to JLOC position in tridiagonal arrays
J1A (I) and J2A (I)	contain JLOC, corresponding to first and last node of column I (i.e. for nodes I,2 and I,JL)

ISUMEQ and JSUMEQ are the total number of nodes to be solved for in TEMPSOL (The two must be equal to each other).

Function THETABC provides boundary temperatures for range J=1 (side L=1), column JLP (side L=3) and column ILP (side L=2), where the side numbers follow the convection of Figure 3.3. The call sequence is as follows:

T,I,J

where T is time [s], and I and J are the indices of a boundary node for which the temperature is to be returned. These temperatures are currently loaded from the THSINKA array, which is user-specified on input records 1502D to 1504D.

The reason not to load these input values into the main temperature array, but to reload them node by node at each time step via calls to THETABC, is to allow for time varying boundary temperatures. By modifying the extremely simple routine THETABC, the user can readily simulate time varying boundary temperatures.

Subroutine THTMPAV, with entry THTMPMX, computes average and maximum temperatures for the active core and for the reflector regions of the temperature array TH of the THATCH model. The call sequence for THTMPAV is as follows:

T THAVCOR THAVREF

where

T	time [s]
THAVCOR	average core temperature [K]
THAVREF	average reflector temperature [K]

If CALMODE='THATCH', i.e. THATCH alone, without SYMELAN, both temperatures will be returned. In CALMODE='COMBIN', i.e. THATCH with SYMELAN run, only the average reflector temperature will be computed. (Averages of active core temperature are then provided by SYMELAN subroutine SYTMPAV via call to TEMPAVG.

Subroutine TEMPLTH is called in TIMSOL within the point kinetics loop. If IKINIT=1 (first iteration), it stores the solid temperature array TH into temporary storage THO. In later iterations (IKINIT>1), it provides the original temperature again as the starting point, by loading THO into TH.

Subroutine RADTN evaluates plena surface temperatures and heat flows for two-dimensional radiation, coupled with conduction from adjacent nodes. Three calculation methods are provided for the iterative solution of plenum surface temperatures:

METHRAD='NEWTON'	uses the Newton-Raphson Solver NEWTON from THTCHLIB.
METHRAD='LINEAR'	uses iteration with under relaxation
METHRAD='ZERORAD'	assumes that the conduction from node centers to node surfaces is the predominant heat transfer resistance and that all node surface temperatures are essentially equal.

'LINEAR' and 'ZERORAD' have not been used recently and 'NEWTON' is the preferred method. 'ZERORAD' is a valid method at temperatures of several thousand K, as they occur in some hypothetical accidents in large HTGRs.

After return of plenum surface temperatures, the plenum heat flows are computed and the plenum surface temperatures are stored in the appropriate node surface temperature arrays. If the upper plenum convection model is used, the appropriate calls to subroutine UPLCNV are made.

The call sequence to subroutine RADTN is as follows:

IDEBUGL MODCALL

where

IDEBUGL	is a debug print control (>0 triggers progressively more output as IDEBUGL is raised)
MODCALL	a character control variable
='ALL'	this call is for all plena in the system
='LP1'	this call is for upper plenum only
='RMP'	this call is for all but upper plenum

'LP1' and 'RMP' are used in runs with upper plenum convection, where separate calls for upper plenum only or the "remainder of plena" are required.

Subroutine RESJAC is called by NEWTON when NEWTON is called by RADTN. This subroutine computes for NEWTON the residual vector RES and the Jacobian matrix XJAC, following Equations 3.1-20 and 3.1-21. If UPLCONV=true, the model modifications of Section 8.5 are included. UPLCONV=true is transmitted by RADTN to RESJAC via logical variable CONVEC in Common PLENAS.

The call sequence for RESJAC is as follows:

Y,NEQ,XJAC,RES,BIGR,JBIGR,IDXJAC,IDEBUG

Y	variable vector (input)
NEQ	number of equations (input)
XJAC	Jacobian matrix (output)
RES	residual vector (output)

BIGR	largest absolute residual (output)
JBIGR	location of BIGR in RES (output)
IDXJAC	dimension of Jacobean array
IDDEBUG	debug control variable

Subroutine UPLCONV evaluates the upper plenum convection model of Section 8.5. Its call sequence is as follows:

NU,THS,AAR,IDPLNOD,IDPLENA,LRP,LP,IJPLMM,IWRITE

where

NU	a control variable, described below
THS	plenum surface temperature array [K]
AAR	plenum surface area array [m ²]
IDPLNOD	first dimension of the above arrays
IDPLENA	second dimension of the above arrays
LRP	number of nodes in plenum
LP	plenum number (must be 1 at this time)
IJPLMM	array of plenum node corner indices IJPLMM(1,LP)=I1 IJPLMM(2,LP)=I2 IJPLMM(3,LP)=J1 IJPLMM(4,LP)=J2
IWRITE	output print control.

On the first call to UPLCONV various surface area parameters and helium properties are set. General control of execution is through control variable NU as follows:

NU=0	Compute convective heat flow for each node, based on given temperatures and heat transfer coefficients.
NU=1	Compute Grashof and Nusselt numbers and convective heat transfer coefficient using Equation (8.5-5).
NU=2	Same as NU=1, but use Equation (8.5-6).
NU=3	The convective heat transfer coefficient is part of the simultaneous equations. Only Grashof and Nusselt numbers and some derivative coefficients for the Jacobean matrix are computed here.

4.1.5 THATCH Solid and Gap Property Routines

The material properties for solids and composite structures are computed in THATCH in subroutine PROPMAT, which must generally be user-supplied for a specific model.

The subroutine must compute effective thermal conductivities (k) and thermal capacitances (pc) for all solid material numbers that were specified in the material index designations of input record 603D. It also must compute effective thermal conductivities for all gap material indices specified in input records 901D or 902D. The calls for thermal conductivities are as follows:

CONDF(MATL,DAM,THK,N)

where

MATL	material index (1-99 for solids, 101-199 for effective gap conductivities)
DAM	irradiation damage parameters (see below)
THK	temperature [K]
N	directional index (1 = axial, 2 = radial)

The conductivities must be returned in units of W/mK. The calls for thermal capacitances are as follows:

ROCF(MATL,THK,N)

where

MATL	material index (1-99)
THK	temperature [K]
N	not used

The thermal capacitances must be returned in units of J/m³K.

Through common /THGASPR/ the following gas properties are available for property computations in PROPMAT:

RGASHEL	helium gas constant [J/kgK]
RGASAIR	air gas constant [J/kgK]
XMOLHEL	helium mole mass [kg/kmol]
XMOLAIR	air mole mass [kg/kmol]
POUPL	upper plenum pressure [N/m ²]

The routine currently embodied in the main section of THATCH models the commercial MHTGR as described in the PSID, and is described in more detail in Section 8.2.

4.1.6 THATCH Output Routines

Subroutine PRINTER, with entries BLKPRNT, PLENPRT, and SURFPRT, provides for printed output, as specified via input data records 1203D with 1301D, 1401D, and 1402D. BLKPRNT provides for printing of solid node temperatures; PLENPRT for plenum surface temperatures and summary heat flows. SURFPRT prints solid block surface temperatures.

Subroutine HTFLUX computes heat flows over block boundaries, providing these data also to the THATCH output file and prints a map of system heat flows, if the call parameter IPR is set larger than 0.

Subroutine PLOTTER, with entries BASEPLT and TIMEPLT, writes the THATCH output file (File 14) for post-processing or restarts (as File 15).

In entry BASEPLT, initial run information and header data are written, while every call to TIMEPLT produces one set of records at that time step. A summary of the records written to File 14 is available as printed output file from File 7.

The header records provided by calls to BASEPLT are given in Table 4-3. The records written at specified time steps by calls to TIMEPLT are given in Table 4-4.

Block Data THBLDAT contains a series of constants used in various sections of the code, primarily for formatting of printed output.

4.1.7 THATCH Utility Subroutines

Subroutine ERROR is used to analyze some of the earlier error messages; however, most error messages are issued directly from the routines sensing the error.

Subroutine PAGER, with entries LINEON, LINETST, and NEWPAGE provides page control during printing of output.

Subroutine NLOCF is currently not used.

4.1.8 THATCH Interface Subroutines

The interface subroutines between THATCH and its sub-modules transfer data between THATCH and the sub-modules. These subroutines are generally included in the main THATCH component and contain THATCH Commons. However, they are called by the sub-modules, with the respective sub-module variables being transferred as call arguments. A few exceptions to this design were required in the interface to SYMELAN, as described in Section 4.2.5.

Subroutines FTHIN, FTHEX, and TTTEX provide the required interfacing between THATCH and PASCOL. Their function is schematically described in Table 4-5.

Subroutines THFLXIN, THFLXEX, and FLXTHEX provide the required interfacing between THATCH and FLOXI. Their function is schematically described in Table 4-6.

Subroutine THSYMIN provides for some of the interfacing between THATCH and SYMELAN. It is called from SYMELAN routine SYMELIN during initialization and provides the initial power POW0 and the logical variable PKINL from THATCH to SYMELAN. The remaining interface routines between THATCH and SYMELAN will be described with the SYMELAN library in Section 4.2.5.

4.2 BIG Subroutine

4.2.1 PASCOL Subroutines

The PASCOL module models the heat removal by the air cooled RCCS. It computes the coolant temperatures and mass flows in the RCCs, based on input-prescribed ambient air conditions and on vessel temperatures that are provided by THATCH.

Table 4-3
Header Records on THATCH Output File

Record Number	Writing Controlled by	Variables
1		JDATE, JTIME, TITLE (Date, Time, Run Title)
2		IPL,JLP,NBLOCK,NPLENA,NFAIL IPL = Number of node columns (including boundary) JLP = Number of node rows (including boundaries) NBLOCK = Number of blocks NPLENA = Number of plena NFAIL = Number of nodes that can fail
3		(RIFA(I),I=1,IPL) Radial node interface array
4		(ZIFA(J),J=1,JLP) Axial node interface array
5		(JLO(K),JHI(K),ILO(K),IHI(K),(NS(K),K=1,NBLOCK) JLO low axial interface number JHI high axial interface number ILO low radial interface number IHI high radial interface number NS number of block node surface temperatures
6		(LR(LP),LP=1,NPLENA) LR number of surface nodes in plenum LP
7	FLOXI	FLOXI Input Data: TYPINGR,PRTCTRL,IREACT,ICHF,ICHFP,JNODF,LGAS TYPINGR ingress type, see input record 3103D PRTCTRL print control, see input record 3212D IREACT chemical reaction control, see input record 3102D ICHF number of parallel channels in core ICHFP number of parallel channels including return flow channel JNOD number of axial nodes LGAS number of gases, see input record 3104D

Table 4-4

Time Records on THATCH Output File

Record Number	Number of Records Written	Writing Controlled by	Variables
1	1		Time [hr]
2	1		((TH(I,J),I=1,ILP),J=1,JLP) Node temperatures [K]
3	NPLENA		(THETARS(L,LP),L=1,LR(LP)), Plenum surface temperatures [K]
4	1		((HEATFL(I,J),I=1,6),J=1,NBLOCK), QAFTTOT,QFLXTOT HEATFL Heat flow array [MW] I=1 North side I=2 East side I=3 South side I=4 West side I=5 Σ Heat outflow over all four sides I=6 Sum of decay heat and fission power For I=1 to 5 Heat flows out of block are positive QAFTTOT Total decay heat plus fission power [MW] QFLXTOT Total convective heat flow [MW] (positive for flow from coolant to solid)
5	NBLOCK		NSF, (THSPLOT(N),N=1,NSF) Block surface temperature [K] NSF must equal corresponding entry in NS array (Record 5 of Table 4-3)
6	1	FLOXI	Floxi output data record, see Table 4-9 for details

Table 4-4 (Cont'd)

7	1	AIRCOL	<p>WO,THFLIA,THWA</p> <p>WO Air cooler mass flow kg/s THFLIA Fluid temperature array [K] (dimensioned 0:NFL2D with NFL2D=96) THWA RCCS wall temperature array [K] (dimensioned IOPD,NFLD with IOPD=5 and NFLD=48)</p> <p>THFIA locations: N=0 fluid inlet temperature; N=1 to NFL fluid outlet temperature in downflow path for axial nodes N=1,NFL; N=NFL+1 to 2xNFL fluid outlet temperature in heated upflow path. (i.e., entry NFL is inlet into first (bottom) heated node and 2xNFL is outlet from last (top) heated node.)</p> <p>THWA (I,J) locations: I=1 RCCS panel facing reactor cavity I=2 RCCS panel on back of heated upflow channel I=3 RCCS panel on back of unheated downflow channel</p> <p>J=1,NFL from top to bottom</p>
8	1	PKIN	<p>Y Vector of PKIN-Module dimensioned IDYPKIN=26 For details, see Table 4-6</p>
9	1		<p>((DAMPAR(I,J),I=1,ILP),J=1,JLP)</p> <p>Annealing damage parameter array</p>
10	1	NFAIL > 0	<p>(LFAIL(K),K=1,NFAIL)</p> <p>Integer index indicating whether and which failure has occurred</p>

Table 4-5
THATCH-PASCOL and WATCOL Interface Routines

Subroutine	Called by	Called When	Variables Transferred		
			THATCH	PASCOL	PASCOL Index Range
FTHIN	AIRCLIN	Initialization	RIFA(IL)	---> RAA(O)	J=0,NFL
			ZIFA(JZ)	---> ZA(J)	J=1,NFL
			THSFVT(IBAIR,JZ,1)	---> THSURFA(J)	J=1,NFL
			RNOD(IL,JZ)	---> DXA(J)	J=1,NFL
			KMATRL(IL,JZ)	---> MATA(J)	J=1,NFL
FTHX	AIRCLEX (prior to RCCS solu- tion)	Execution (each time step)	TH(IL,JZ)	---> THVESS(J)	J=1,NFL
TTHEX	AIRCLEX (after RCCS solution)	Execution (each time step)	THSINKA(JZ,2)	< --- THWA(1,J)	J=1,NFL
			THSFVT(IBAIR,JZ,1)	< --- THSURFA(J)	J=1,NFL
			CONRA(IL,JZ)	< --- UAA(J)	J=1,NFL

JZ = JAIRFST+J, where JAIRFST is node offset PASCOL to THATCH.

NFL = Number of PASCOL upflow nodes [JAIRLST-(JAIRFST-1)].

JAIRFST and JAIRLST are first and second entry on input record 6103D.

Table 4-6

THATCH-FLOXI Interface Routines

Subroutine	Called by	Called When	Variables Transferred		FLOXI Index Range
			THATCH	FLOXI	
THFLXIN	FLOXIIN	Initialization	ZIFA(J)	→ZIFA(J) processed in FLOXIIN into DZA(J)	J = 1,JNODEF
THFLXEX	FLOXIEX (Load Mode 'Full' before FLOXI computations; Load Mode 'Partial' after RADTN call)	Execution (each time step)	Any Load Mode: THUPLEX* SMQUPLCV* 'Full' Load Mode only TH(I,J) QAFTOT	→THFLUPEX →QUPLCV →THRW(I,J) processed in FLOXIEX into FLOXI TH(I,J) →ENAFT	I = 1,ICHFP J = 1,JNODEF
FLXTHEX	FLOXIEX (Load Mode 'Full' after FLOXI computa- tions; Load Mode 'Partial' prior to RADTN call)	Execution (each time step)	Any Load Mode: THUPLIN* POUPL* WINUPL* or SUMWCUP2 + WCORBAR 'Full' Load Mode only QFLOX(I,J)	←THFLUPIN ←PO ←SUMWCUP2 ←QRW(I,J)	I = 1,ICHFP J = 1,JNODEF

*Variables in Common UPLCNV.

Subroutine AIR COOL, with entries AIRCLIN, AIRCLEX, AIRCLOT, AIRCLWR and AIRCLRD, constitutes the effective main program of this module. The call sequence is as follows:

MODE, TSEC, IDEBUG

MODE	character variable identifying run type (= 'THATCH' in THATCH runs)
TSEC	time [s]
IDEBUG	debug print control

Entry AIRCLIN obtains the run input data, initializes various arrays and prints the input data and options specified. It computes various design data of the system such as flow areas and heat transfer areas. If fin performance parameters are to be computed internally (FINK=true), it calls for the computation of the relevant radiation view factors.

Entry AIRCLEX is generally called once at each time step to evaluate, based on the reactor vessel temperature array and the air inlet temperature to the RCCS, all RCCS solid and coolant temperatures as well as the coolant mass flow rate, following the model of Section 3.2. The reactor vessel temperature array is obtained by a call to the THATCH/PASCOL interface routine FTHEX (see Table 4-5).

The system of simultaneous non-linear equations to be solved in AIRCLEX consists of quasi-steady fluid energy equations, one per node, plus a single quasi-steady momentum equation. This system of equations is solved by a call to NEWTON (see THATCHLIB, Section 4.2-7). The number of fluid energy equations and their arrangement in the Y-vector depends on the run options selected.

The interface points JAIRFST and JAIRLST, specified by the user, correspond to

$$NFL = JAIRLST - JAIRFST$$

nodes in vertical direction. In early versions of the RCCS, there was no thermal insulation between the down-flowing and up-flowing air paths, and regenerative heating of the incoming, downward flowing air from the upflow side was possible. The code permits this option, even though it is not used in current designs. If this option is selected, then two-fluid energy equations must be solved at each axial node, one for the downflow channel and one for the upflow channel. Thus, the number of fluid energy equations becomes

$$NFL2 = 2 NFL$$

The y-vector variable is the fluid outlet temperature of each node, in flow direction. For thermal insulation between the downflow and upflow paths, integration begins at the bottom of the upflow path and ends at the last interface, NFL, as shown schematically in Figure 4-3. Without thermal insulation, integration begins at the top of the downflow path and ends at the last interface of the upflow path, NFL2, as shown schematically in Figure 4-4. The last equation in either case is the momentum equation, with the mass flow being the last variable in the Y-vector.

The residuals and Jacobian matrix are provided to NEWTON from subroutine JACAIRO as shown in Figure 4-5. As the fluid temperatures are coupled to the solid temperatures at each node, the solid temperatures are computed at each node level in an internal Newton-Raphson procedure, which is embedded in subroutine WATSOLO.

Figure 4-3 Y-Vector Indices versus Axial Node Indices in PASCOL for Case with Thermal Insulation Between Flow Passages

Figure 4-4 Y-Vector Indices versus Axial Node Indices in PASCOL for Case without Thermal Insulation Between Flow Passages

Figure 4-5 Schematic of PASCOL Solution of Air-Cooled RCCS Performance

Entry AIRCLOT provides for printed output at the current time step.

Entries AIRCLWR and AIRCLRD will write or read one record to or from the THATCH output/restart file as per Table 4-4.

Subroutine JACAIRO is specified in the call to NEWTON from AIRCLEX as the subroutine to provide the Jacobian matrix and the residual vector. Its call sequence is specified by NEWTON (Section 4.2-7) as follows:

Y, NEQ, XJAC, RHS, BIGR, JBIGR, IDIMJAC, IDEBUG

where

Y	independent variable vector	(input)
NEQ	number of equations	(input)
XJAC	Jacobian matrix	(output)
RHS	residual vector	(output)
BIGR	absolute value of largest residual	(output)
JBIGR	location of largest residual in RHS array	(output)
IDIMJAC	leading dimension of XJAC array	(input)
IDEBUG	debug print control variable	(input)

As shown in Figure 4-5, JACAIRO calls on entries FLEN2 or FLEN3 in AIRES0 to supply the residuals and Jacobian terms for the fluid energy equation, and an entry FLOW in AIRES0 for the residual and Jacobian coefficients of the quasi-steady momentum equation.

Subroutine AIRES0 computes the residuals and the non-zero Jacobian matrix terms for Subroutine JACAIRO, via its three entries FLEN2, FLEN3 and FLOW. The call sequence for all entries is as follows:

J, JJ, Y, NEQ, RES1, RES2, IDEBUG

where

J	is the Y-vector entry for which the residual and Jacobian terms are to be evaluated. (Note that, in general, J does not correspond to axial node or interface numbers as shown in Figure 4.3 and 4.4.)
JJ	is a control index, which is generally set=0 and will cause reloading of surface temperatures and overall heat transfer coefficients. JJ≠0 will bypass the reloading and is only used in debug calls.
Y	Y-vector supplied by NEWTON
NEQ	number of equations
RES1, RES2	residuals to be returned via JACAIRO to NEWTON (two residuals in case of FLEN3 (INSUL=false), and one for FLEN2 or FLOW calls).
IDEBUG	debug print control variable.

Subroutine WALSOL0, with entries WALSOL2 and WALSOL3, provides for computation of the solid panel temperatures and cavity heat transfer, which are coupled to the fluid temperatures and flow rate. Its call sequence consists of the debug control variable IDEBUG only.

For the case of $INSUL = \text{true}$, i.e., with thermal insulation between the downflow and upflow paths, the WALSOL2 entry is used, and the set of three simultaneous equations for temperatures of front and back panels of the RCCS up-flow channel and vessel surface temperatures is solved for any vertical node J, using the current values for the coolant flow rate and coolant temperatures as well vessel node temperature, as described in Section 3.2.4. The solution is obtained from a Newton Raphson procedure, embedded in WALSOL2.

For the case $INSUL = \text{false}$, i.e., without thermal insulation between the downflow and upflow paths, entry WALSOL3 is used, and a set of four simultaneous equations for front center and back panel temperatures, plus vessel surface temperature is solved. In this case, the three panel temperatures are obtained from a Newton-Raphson procedure, embedded in the WALSOL3 section of the code and the vessel surface temperature follows from an iteration loop internal to the Newton-Raphson loop.

Subroutine STACK supplies the stack friction and buoyancy terms for the fluid momentum equation, when it is called from entry FLOW of Subroutine AIRES0. Its call sequence is as follows:

W0, TH1, TH2, STFRIC, STBUOY, IDEBUG

where

W0	air flow rate	[kg/s]
TH1	air inlet temperature of the RCCS	[K]
TH2	air outlet temperature of the RCCS	[K]
STFRIC	stack friction pressure drop term	[P/(kg/s) ²]
STBUOY	stack buoyancy pressure drop term	[P]
IDEBUG	debug print control	

Subroutine YTHETA loads the fluid temperature array THFLIA from the corresponding Y-vector entries. Its call sequence is as follows:

Y, THFLIA, NFL, NFL2, N1, N2, ISTACON, INSUL

where

Y	Y-vector
THFLIA	fluid exit temperature of node [K]. Note that array THFLIA always contains the air inlet temperature in location 0, and beyond that counts as shown for the Y-vector in Figure 4-4; i.e., for the general case of thermal insulation, it will have constant temperatures equal to the air inlet temperature in locations 0 to NFL, and the Y-vector entries 1 to NFL in locations NFL + 1 to NFL2.
NFL2	number of downflow and upflow fluid nodes (NFL2 = 2NFL)
N1	beginning of THFLIA locations to be loaded
N2	end of THFLIA locations to be loaded

ISTACON	stack connection control variable
INSUL	control variable for thermal insulation between downflow and upflow paths

Subroutine SOLVAIR solves the set of simultaneous linear equations required for the Newton-Raphson procedure called by entry AIRCLEX. It uses the specific sparse structure of this matrix as outlined in Section 3.2.4. Its call sequence is as follows:

XJAC, IDJAC, RHS, NEQ, IDEBUG

where

XJAC	Jacobian matrix
IDJAC	leading dimension of Jacobian matrix
RHS	on input, right-hand side vector; on return, the solution vector
NEQ	number of equations
IDEBUG	debug control variable

Subroutine EVALAIR is called by entry AIRCLOT to print output of the air-cooled RCCS performance at designated time intervals. Its call sequence is as follows:

TSEC,Y,NEQ,IDEBUG

where

TSEC	time [s]
Y	Y-vector
NEQ	number of equations
IDEBUG	debug print control

In addition to printing output, EVALAIR also checks whether the Reynolds numbers may have been out of the bounds of the correlations used, and ascertains the accuracy of the energy balance.

Subroutine FINNER, with entries FININ1, FININ2, and FINEXEC, is used for input and execution during optional use of internal fin performance evaluation (FINK=true).

Under entry FININ1, the required input data for fin spacing and nodalization from input records 6201D and 6202D are loaded and used to initialize internal arrays for surface areas. By calling RADCOEF, the internal radiation coefficient matrices are produced.

Under entry FININ2, an array of reactor vessel conductances is initialized.

Entry FINEXEC is called from Entry FLEN2 of Subroutine AIERESO to compute upflow channel temperatures of the RCCS as well as reactor cavity solid temperatures, following the model of Appendix C, as shown in Figure 4-5.

Subroutine NEWTON2 provides a Newton-Raphson solution to the set of simultaneous equations for the panel surface temperatures of the RCCS. Its call sequence is as follows:

Y, NEQ, EPSR, EPSY, NITMX, FRLX, IDEBUG, BIGR, ITERSNR,
IER, RHS, DY, XJAC, IDIM

where

Y	solutions vector (output) (on call, Y must contain an initial estimate of Y)
NEQ	number of equations (input)
EPSR	convergence criterion with respect to residual vector (input)
EPSY	convergence criterion with respect to change in Y-vector (input)
NITMX	maximum number of iterations allowed (input)
FRLX	underrelaxation coefficient to be applied to change in Y-vector
IDEBUG	debug print control (input)
BIGR	largest residual (computed in FCTJAC, output)
ITERSNR	number of iterations used (output)
IER	error indicator (output =0 converged, =3 not converged)
RHS	right-hand side vector (computed for NEWTON2 in FCTJAC)
DY	change in Y-vector (output)
XJAC	Jacobian matrix (computed for NEWTON2 in FCTJAC)
IDIM	leading dimension of XJAC (input)

It must be noted that NEWTON2 is called from AIRES0 via JACAIRO, which provides residuals and Jacobian coefficients to NEWTON; i.e., this Newton-Raphson procedure for the solid node temperatures in the RCCS upflow channel is called here internal to the Newton-Raphson procedure for overall RCCS coolant temperatures and flow rates. While the procedure of NEWTON2 is identical to that of NEWTON, subroutine NEWTON could not be used here because a subroutine is not allowed to call itself.

Subroutine RESJAC2 provides the equation residuals and the Jacobian coefficients for NEWTON2. Its call sequence is as follows:

Y, NEQ, PHI, XJ, IDIM, IDEBUG

where

Y	variable vector
NEQ	number of equations
PHI	residual vector
XJ	Jacobian matrix
IDIM	leading dimension of Jacobian matrix
IDEBUG	debug control variable

The residuals and Jacobian coefficients are computed from Equations C-1 to C-5.

Function UCAVF evaluates the overall heat transfer coefficient across the reactor cavity, from the last temperature of the vessel node to the temperature of the RCCS front panel, following Equations (3.2-5) and (3.2-6). Its call sequence is as follows:

THRCCS, IDEBUG

where

THRCCS	temperature of the RCCS front panel [K]
IDEBUG	debug print control

Subroutine RADCOEF is called by FINNER (Entry FININ1) to obtain the prescribed internal fin nodalization for the radiation view factors. From these, the radiation coefficient matrix is then obtained, following the procedure in Appendix A. Subroutine RADCOEF uses the functions VIEWPAR and VIEWREC to evaluate the view factors.

Function NZFCT is a utility function, called by RADCOEF to identify the side node index for a given cell node, following the nodalization schematic of Figure C-2. Its call sequence is as follows:

I, NN

where

I	cell node index
NN	total number of side nodes

The returned value of NZFCT is the side index N.

The functions VIEWPAR, and VIEWREC provide the view factors between nodes in the upflow channel of the RCCS, as required for the model of Appendix C.

Function VIEWPAR provides for view factors between parallel nodes, i.e., an opposite panels or fins of Figure C-1. Its call sequence is as follows:

X11, X12, X21, X22, DY

where

X11 and X12	coordinates of the beginning and the end of node 1 in its plane
X21, X22	corresponding coordinates for node 2
DY	normal distance between the parallel planes

The returned value of VIEWPAR is the view factor $F_{1,2}$ i.e., from node 1 to node 2.

Function VIEWREC provides for view factors between nodes on adjacent sides of the rectangular cavity of Figure C-1, i.e., for nodes at right angles to each other. Its call sequence is as follows:

X11, Y11, X12, Y12, X21, Y21, X22, Y22

These are the end-point coordinates for nodes 1 and 2 in accordance with Figure C-3. The returned value of VIEWREC is the view factor $F_{1,2}$ from node 1 to node 2.

4.2.2 WATCOL Subroutines

The WATCOL module computes the liquid and air side coolant temperatures and mass flows, based on THATCH reactor vessel temperatures and an ambient air temperature prescribed with the input data. The arrangement of the required variables is given in Table 4-7.

Table 4-7
Variable Vector of WATCOL Module

Variable Location*	Index Name	Variable Name	Variable Description	Units
1-N	1-NAXV	TL	Liquid Temperature Leaving Node n	K
N+1	NAXVP	TC	Cold Leg Temperature	K
N+2	NAXVP2	WTOT	Liquid Mass Flow	kg/s
N+3	NAXVP3	WAIR	Air Mass Flow	kg/s
N+4	NAXVP4	TAIRX	Air Exit Temperature	K

* for N axial nodes

Subroutine WATCLIN is called by THATCH to read the WATCOL input data file, and for various initialization. Its call sequence is as follows:

MODE, TSEC, IIN

where

MODE, Character Variable, = 'THATCH' for THATCH runs, and
= 'FREE' for free-standing runs
TSEC Problem time [s]
IIN Input data file identifier (currently not used)

In addition to reading and printing the input data, WATCLIN computes the required node and variable indices and various geometrical constants such as flow and surface areas. It also calls subroutine CAVIN, to estimate the initial system variables.

It obtains the vessel axial nodalization, vessel radius, and material index data from THATCH using the same interface routine as PASCOL (see Table 4-5).

Subroutines WATCLEX is called TIMSOL at each time step to provide the RCCS solution based on given vessel temperatures. Its call sequence is as follows:

MODE, TSEC

where the arguments are the same as identified above with WATCLIN.

The subroutine obtains the last radial vessel node temperatures from THATCH via interface routine FTHEX (Table 4-5).

WATCLEX calls NEWTON for a solution to its set of equations, specifying WATRESD as the routine to provide the Jacobean matrix and the residuals, and SPECWAT as the routine to solve the set of equations.

WATCLEX returns to THATCH via interface routine TTHER (Table 4-5) the temperatures of the RCCS panel surface, the temperatures of the vessel surface, and the overall heat transfer coefficient from vessel node to panel surface temperature.

Subroutine WATCLOT with entries WATCLRD and WATCLWR, prints output. Its call sequence is as follows:

MODE, TSEC

where the arguments are the same as identified above with WATCLIN.

Entry WATCLWR writes the WATCOL variable vector YWAT and the array of the panel surface temperature THWA, onto the THATCH output file (File 14). Entry WATCLRD reads the same records from the restart file (File 15) during restart runs.

Subroutine WATRESD is called by NEWTON to provide for a given variable vector Y the Jacobean matrix and the residuals. Its call sequence is as follows:

Y, NEQ, XJAC, F, BGR, JBGR, IDJAC, IDEBUG

Y	variable vector (input)
NEQ	number of equations (input)
XJAC	Jacobian matrix (input)
F	residual vector (output)
BGR	largest absolute residual (output)
JBGR	location of BGR in F (output)
IDJAC	dimension of Jacobean array
IDEBUG	debug control variable

Subroutine WATRESD calls subroutine WATRR for the actual computation of the residuals and of the Jacobean terms. The Jacobean coefficients provided by WATRR are approximations, which is generally the most efficient procedure for solving simultaneous non-linear equations (The Jacobean coefficients do not affect the accuracy of a solution, but only the speed at which convergence is attained). To check on the accuracy of these terms, subroutine WATRESD permits as a debug option the computation of a full numerical Jacobean matrix.

Subroutine WATRR does the actual computation of residuals and Jacobean matrix coefficients. Its call sequence is as follows:

Y, F, XJAC, IDJAC, NEQ, IDEBUG

where all entries are identical to the variables described above under subroutine WATRESD. Based on a given Y vector, the residuals and the most significant Jacobian terms are computed. The structure of the Y vector is given in Table 4-7.

Subroutine SPECWAT, called by Newton, solves the system of simultaneous equations, using the special form of the Jacobian matrix, as described in Section 3.3.7. Its call sequence is as follows:

XJAC, IDJAC, RHS, NEQ, IDEBUG

where

XJAC	Jacobian matrix (input)
IDJAC	dimension of XJAC array
RHS	on input, right-hand side vector; on output, solution vector
NEQ	number of equations
IDEBUG	debug control variable

Subroutine CAVIN establishes an initial estimate of the Y-vector during initialization, using several input parameters prescribed by the user. Once a satisfactory initial estimate has been established, further changes in those parameters should not be required. Its call sequence is as follows:

Y,NEQ

where

Y	Y - vector
NEQ	number of equations

Subroutine DMAT loads a two-dimensional indicator array for a specified number of axial nodes, indicating terms of the Jacobean matrix that are significant and should be used in the solution. This routine is currently not used, but it can be activated with model changes for debugging. Its call sequence is as follows:

ND, IDIMND, NEQ

where

ND	two-dimensional indicator array
IDIMND	dimension of ND
NEQ	number of equations

On return, the ND array contains 0 for insignificant terms and 1 for significant terms.

The WATCOL module includes several function type subroutines for water properties, as well as friction and heat transfer across tube banks (Table 4-8).

4.2.3 FLOXI Subroutines

Subroutine FLOXIMS is the actual main program for free-standing FLOXI runs. For these runs, a solid temperature history file must be available. This information is produced from THATCH output files by the THPRGCS post processor.

FLOXIMS is not used in THATCH runs. For free standing runs it requires input records 3105D and 3106D to be read.

Subroutine FLOXIIN is called by THATCH or by FLOXIMS and provides for FLOXI initialization, loading the input records of Groups 31 and 32 (Section 5), and calling CORINFL, the unified input option routine, if so specified. Its call sequence is as follows:

MODE, UNIFIN, TSEC, IDEBUG, IIN

where

MODE	Character variable for THATCH runs = 'THATCH' for free-standing runs = 'FREE'
UNIFIN	Logical variable specifying that the unified input option is in effect.
TSEC	problem time [s]
IDEBUG	debug print control variable
IIN	input data file identifier (currently not used)

Subroutine FLOXIEX executes the main FLOXI computations for gas flows, convective heat transfer, and chemical reactions, as specified by the input data. If user-specified, the coupling between heat flow, chemical reactions and gas-flows is considered in the FLOXIEX 350-Loop. Details of this loop are presented in Figure 4-6. Subsequent to the execution loop, several sums of heat flows and energy balance checks are computed and are included in the output file record.

Its call sequence is as follows:

MODE, TSEC, NONCONV, UPLCNV, IDEBUG

where

MODE	Character variable for THATCH runs = 'THATCH' for free standing runs = 'FREE'
TSEC	problem time [s]
NONCONV	Non-convergence indicator. Increased by one every time that non-convergence occurs in main FLOXI loop (350-Loop).

Table 4-8

WATCOL Function Type of Subroutines for Liquid Water Properties
as Well as Friction and Heat Transfer Correlations For Flow in Tubes and Across Tube Banks

Function Name	Function Description	Output Units	Call Argument Name	Call Argument Description	Input Units	Range of Applicability	Equation Number or Reference
RHOL	Density	kg/m ³	T	Temperature	K		ASTEM*
CPL	Specific heat	J/kg K	T	Temperature	K		Holman [1990]*
CONDL	Thermal conductivity	W/mK	T	Temperature	K		Holman [1990]*
VISCL	Viscosity	Ns/m ²	T	Temperature	K		Reid [1977]*
TSATL	Saturation Temperature	K	P	Pressure	N/m ²		Cole, et. al [1984]
XNUSL	Nusselt number for liquid inside tubes	-	RE PR	Reynolds number Prandtl number	- -	Re > 8000	Equ. 3.3-38

Table 4-8 (Cont'd)

XNUSTB	Nusselt number for air flow across finned or nonfinned staggered tube banks	-	RE PR PD HD NFIN	Reynolds number Prandtl number fin spacing to tube dia- meter ratio fin height to tube dia- meter ratio NFIN=0 use nonfinned tube correlation NFIN=1 use finned tube correlation	- - - - - -	NFIN=0 Eqn. 3.3.39 [McAdams, 1954] NFIN=1: Eqn. 3.3.40 [Gnielinski, 1983]
FRICT	Friction factor for air flow across finned or nonfinned staggered tube banks	-	RE PD DRAT NFIN	Reynolds number tube bundle pitch to dia- meter ratio see Eqn. 3.3-35 to 37 NFIN=0 use nonfinned tube correlation NFIN=1 use finned tube correlation	- - - -	NFIN=0 Eqn. 3.3-34 [Zukauskas, 1983(a)] NFIN=1: Eqns. 3.3-35 to 37 [Zukauskas, 1983(b)]

* BNL curve fit to the referenced data

FLOXIEX Iteration Procedure Between Flow, Heat Transfer and Chemical Reaction Computations

Figure 4-6 Flow Chart of FLOXIEX Main Loop for Coupled Flow, Heat Transfer and Chemical Reaction Computations

UPLCNV	Logical variable, if true upper plenum convective heat flow is to be computed by calling THATCH routine RADTN
IDEBUG	debug print control variable

Subroutine FLOXIOT, with entries FLOXIRD and FLOXIWR, provides for printed output as well as for writing output file records and plot file records.

The following is the call sequence for FLOXIOT (printed output) :

MODE, TSEC, IDEBUG

where

MODE	Character variable for THATCH runs = 'THATCH' for free-standing runs = 'FREE'
TSEC	problem time [s]
IDEBUG	debug print control variable

For entries FLOXIRD and FLOXIWR, the call sequence is as follows:

MODE, TSEC, IDEBUG, ITP_ _

where ITP_ _ is either ITPRD or ITPWR.

MODE	a character variable controlling the type of record to be read or written (see below)
TSEC	problem time [s]
IDEBUG	debug print control variable
ITP_ _	identifier for the file to be read from or written to.

FLOXIOT calls the major FLOXI routines with IDEBUG=1, which causes the normal printed output to be produced.

There are three different output records that can be written and read by entries FLOXIWR or FLOXIRD, depending on the MODE variable. For Mode='THATCHO', a control variable record is written or read, generally for the THATCH output file. The contents of this record are described in Table 4-3 (Record 7).

For Mode='THATCH' a large output record of time-dependent variables is written or read, generally as part of a THATCH output file. This is Record 6 of Table 4-4; Details of its contents are in Table 4-9.

For Mode='PLOT', a plot record will be written by the post processor THPROCS at each time step. In accordance with all time-dependent plot output records, this record begins with a counting integer, followed by the time [s], and the dependent variable vector. This dependent variable vector is identical to the first 59 records of the THATCH output file as described in Table 4-9.

Table 4-9

FLOXI Output Data Record
For
THATCH Output File

Location in Output Record*	Variable Name	Units	Description
1	WTOLOPL	kg/s	Mass flow to lower plenum
2	WCORBAR	kg/s	Core barrel mass flow
3	WINFLOW	kg/s	Inflow to reactor vessel
4	SUMWCUP1	kg/s	Sum of core channel upflows at bottom reflector inlet
5	SUMWCUP2	kg/s	Sum of core channel upflows at top reflector outlet
6	SUMWCDN1	kg/s	Sum of core channel downflows at top reflector inlet
7	SUMWCDN2	kg/s	Sum of core channel downflows at bottom reflector outlet
8-14	WA	kg/s	Channel mass flows (I= 1, ICHFP)
15	TSUMCAR	kg/s	Rate of graphite oxidation
16	XMAXCTH	kg/s	Maximum theoretical oxidation if all of incoming oxidizer (O ₂ or H ₂ O) reacts
17	PO	N/m ²	System pressure
18	DELPCR	N/m ²	Core pressure drop
19	DPFRAV	N/m ²	Average core friction pressure drop (absolute value)
20	ENREACTO	J/kg Carb	Specific energy release of oxidation
21	ENAFT	W	After heat plus fission power
22-28	THFLINA	K	Coolant inlet temperature for each channel
29-35	THFLEXA	K	Coolant exit temperature for each channel
36	THFLUPIN	K	Upper plenum coolant inlet temperature

Table 4-9 (Cont'd)

Location in Output Record*	Variable Name	Units	Description
37	THFLUPEX	K	Upper plenum coolant exit temperature
38	THFLLOPL	K	Lower plenum coolant exit temperature
39-45	SUMQPOS	W	Sum of positive heat flows within each channel**
46	SMSMQP	W	Sum of all positive heat flows**
47-53	SUMQNEG	W	Sum of negative heat flows within each channel**
54	SMSMQN	W	Sum of all negative heat flows**
55	SUMQCON	W	Sum of convective heat flow over all flow channels
56	SUMQRCT	W	Sum of chemical reaction heat release over all core nodes
57	QUPLCV	W	Upper plenum convective heat flow to solid
58	SMSMQCNV	W	Sum of convective heat flows over flow channels and upper plenum
59	ENCOLNT	W	Net energy removed from reactor by coolant loop
60-67	NUAUPL		Gas volume fraction array for upper plenum
68-75	NUALOPL		Gas volume fraction array for lower plenum

Table 4-9 (Cont'd)

Location in Output Record*	Variable Name	Units	Description
76-215	THFL	K	Coolant temperature array (7x20 entries)
216-355	QCONV	W	Convective heat flow array (7x20 entries)
356-495	QREACT	W	Chemical reaction heat array (7x20 entries)

*Locations in output record are for 6 in-core flow channels plus one return flow channel and 20 axial nodes. The THATCH and FLOXI write statements will work for any consistent nodalization, but the variable locations in the output record will vary for other nodalizations.

**Note that FLOXI convective heat flows are defined as positive for flow from coolant to solid.

***During post-processing (in mode 'PLOT') only variables 1 to 59 are read and written.

Subroutine FLOXISM permits a summary print out of a previously analyzed transient. It is generally called in free standing runs from FLOXIMS or in post processing runs from the THPROCS module. Its call sequence is as follows:

MODE, IDEBUG, ITPOUT

where

MODE	a character variable controlling the type of record to be read or written (see below)
IDEBUG	debug print control variable
ITPOUT	File from which transient data are to be read ('PLOT' format required)

FLOXISM will read a file written by FLOXIWR in mode 'PLOT' and print a summary output.

Subroutine FLXFLOW is the main routine solving for the gas flow distribution in the prescribed parallel channels using its own Newton-Raphson method. If call variable IDEBUG is set = 1, the normal printed output is produced after execution (see Section 3.4.1 and 3.4.4).

Subroutine AVAL provides various arrays of friction and buoyancy terms to FLXFLOW which do not change during FLXFLOW iterations.

Subroutine FLOWAPR can be called by FLXFLOW for an initial approximate flow solution if so desired. (APPROX, Input Record 3102D)

Subroutine SOLSPEC solves the simultaneous system of equation in FLXFLOW, using the sparse and special structure of the Jacobean matrix (see Section 3.4.4).

Subroutine CORINIT sets initial volume fractions, mole mass, temperature, and density arrays during its first call from FLOXIEX. At each time step it sets before the main FLOXI loop, initial values for fluid temperatures and densities.

Subroutine CORGASL solves for the mass balance during chemical oxidation computations, advancing through the active core flow channel in flow direction.

The call variable CALMDFX can be set by FLOXIEX or FLOXIOT to 'UP', 'DOWN' or 'ALL' to evaluate up-flow channels only, down-flow channels only, or all channels.

Subroutine REACT, called from CORGASL, evaluates the actual chemical reaction rate for each node based on local component partial pressures, temperatures, etc. Its call sequence is as follows:

TIME, IDEBUGL, CAVM, SUMCAVM, CAVP, SUMCAVP, GAM, GAMCARB, RGCT, RGC, NUA, II, JJ, SUMGMKG, XMCARB, PO, THFLL, THSL, PREACTSTR, PREACTW, LGAS, LDM, TYPINGR

where

TIME	time [s]
IDEBUGL	local debug print control
CAVM	molar inflow rate array for gas species (input) $\left[\frac{\text{kmol}}{\text{s}}\right]$

SUMCAVM	molar inflow rate of gas mixture (input) $[\frac{kmol}{s}]$
CAVP	molar outflow rate array for gas species (output) $[\frac{kmol}{s}]$
SUMCAVP	molar outflow rate of gas mixture (output) $[\frac{kmol}{s}]$
GAM	gas generation rate array for gas species (output) $[\frac{kmol}{s}]$
GAMCARB	molar oxidation rate for carbon $[\frac{kmol}{s}]$
RGCT	mass oxidation rate for carbon (output) $[\frac{kg}{s}]$
RGC	mass oxidation rate of carbon per unit surface area $[\frac{kg}{m^2s}]$
NUA	gas volume fraction array at node inlet (input)
II,JJ	node indices
SUMGMKG	mass increase of gas mixture (output) $[\frac{kg}{s}]$
XM CARB	mole mass of carbon $[\frac{kg}{kmol}]$
PO	system pressure [N/m ²]
THFLL	fluid temperature [K]
THSL	solid temperature [K]
PREACTSTR	reactant partial pressure in stream (output) $[\frac{N}{m^2}]$
PREACTW	reactant partial pressure at wall (output) $[\frac{N}{m^2}]$
LGAS	number of gases
LDM	dimension of arrays in call sequence
TYPINGR	type of ingress

Subroutine RUFF2OX provides the Newton-Raphson solution for the two simultaneous equations for the chemical reaction as given in Section 3.4.4. The call variable XX presents the variable vector consisting of dimensionless free stream and surface reactant partial pressure.

Subroutine HETCON solves the convective heat flows in the coolant channels, advancing within each channel in flow direction. Fluid average and fluid exit temperatures are also computed for each node, following the model of Section 3.4.2.

The call variable CALMDFX can be set by FLOXIEX or FLOXIOT to 'UP', 'DOWN' or 'ALL' to evaluate up-flow channels only, down-flow channels only, or all channels.

Subroutine PLENBAR sets up local plena inflow data and calls the plenum subroutine PLENSUM, which sums over inflows and averages outflow temperatures and gas compositions.

The call variable CALMDFX can be set by FLOXIEX or FLOXIOT to 'UPPER', 'LOWER' or 'ALL' to evaluate upper plenum only, lower plenum only, or both plena. When CALMDFX='ALL' is set, the nodal gas densities as well as gas densities of entry and exit into the plena are also evaluated.

Subroutine PLENSUM evaluates plenum inflow data to compute averages for temperatures of plenum outlet gas, gas compositions, and mole mass.

It's call sequence is as follows:

MOLAR, POSIN, BALANCED, WA, TH, CA, CAT, MOLM, NUAIN, NUAPL, THPL, THINFL, NUAINFL, ISET, ICHF, ICHFP, ICHPD, LGAS, LGASDD, LVLPR, IRLA, PLENAM, PRINTU

where

MOLAR	is a logical variable, if true, then component molar inflows are given in CA-array, or else they must be computed here.
POSIN	is a logical variable, if true, then inflows in WA-array are positive, and outflows negative, otherwise, the reverse.
BALANCED	is a logical variable, if true, then the WA-array is expected to be balanced, i.e., $\sum WA = 0$ (general mode for upper plenum). Otherwise, the core channel flows through the various core flow channels, $I=1, ICHF$, are summed and the return flow channel, ICHFP, is set to the negative of the summed core flows (general mode for lower plenum).
WA	mass flow array of gas mixture at all plenum connections to flow channels [kg/s]. (For sign convention, see variable POSIN above. Input except for WA(ICHFP), if BALANCED = false.)
TH	fluid temperature at plenum connection to flow channels [K] (input for inflows, output for ICHFP, if BALANCED = false and WA(ICHFP) > 0).
CA	molar flow array for gas species at plenum connection to flow channels $[\frac{kmol}{s}]$ (input if MOLAR = true; otherwise output)
CAT	total molar inflow rate into plenum of gas species $[\frac{kmol}{s}]$ (output)
MOLM	mole mass of plenum gas mixture $[\frac{kg}{kmol}]$ (output)
NUAIN	volume fraction array for gas species at plenum connection to flow channels (input for inflows, output for ICHFP, if BALANCED = false and WA(ICHFP) > 0).
NUAPL	volume fraction of gas species in plenum (output)
THPL	gas temperature of plenum gas mixture [K] (output)
THINFL	gas inlet temperature to reactor loop [K] (input, input data record 3103D)
NUAINFL	gas composition at inlet to reactor loop (input, input data record 3104D)
ISET	inflow/outflow control index array (output). ISET is set=1 for inflow and =0 for outflows.
ICHF and ICHFP	flow channel indices
ICHPD	dimension of all arrays in call sequence that use ICHF index
LGAS	index for number of gas species
LGASDD	dimension of all arrays in call sequence that use LGAS index
LVLPR	output print control

IRLA	array for index storage location to compute of mixture properties from spline functions (see HHMSPL and HHISPL calls)
PLENAM	character variable for plenum name, used in printed output.
PRINTU	character control for printed output. PRINTU = 'HR' flows in [kg/hr], else in [kg/s].

Subroutine RENCH checks the largest Reynolds number in the parallel channel flow network, which is generally printed in the printed output file. This check is primarily for ingress scenarios, where laminar flow in the coolant channels has always been observed, and is assumed to exist as part of the model.

Subroutine FLUINUP simulates varying coolant inlet temperatures as the gas exit temperatures vary, delayed by a time-lag prescribed by the user (input record 3103D). For most cases, this feature will not be desired, and is bypassed by setting the time-lag $> 10^6$.

Block Data FLOXDAT contains some constants which are used by more than one subroutine.

4.2.4 PKIN Subroutines

The point kinetics module is generally called from THATCH or from SYMELAN. It can also be called from a free-standing main program, PKINRUN, which requires the availability of a THATCH output file of core temperatures. This mode has not been used lately, and PKINRUN would require some updates. It is currently not part of the PKIN module, but could be updated and added within days, if desired.

Subroutine PKIN0 with entries PKININ, PKINEX, PKINOUT, PKINRD, and PKINWR is the major subroutine of this module.

In entry PKININ, the module is initialized, the input data records are processed, and the initial Y-vector is loaded by call to subroutine CALIC. The first twelve locations of the Y-vector are the integration variables, following the model of Section 3.5. For convenience, 14 more variables are added to this vector before it is written to output files, and when it is read for restart or for post processing. The total Y-vector is given in Table 4-10.

The call sequence for PKININ is as follows:

CALMODE,T1,POWKIN,RHOINT,IKINMX,IIN,THCORAV,THREFAV,THFUELAV,THFLUDAV

where

CALMODE	character variable controlling run mode
= 'THATCH'	THATCH run with point kinetics
= 'SYMELAN'	SYMELAN run with point kinetics
= 'COMBIN'	THATCH run coupled with SYMELAN and using point kinetics
T1	time [s]
POWKIN	dimensionless fission power (output)

Table 4-10

Y-Vector of the Point Kinetics Module

Location	Variable Name	Units	Description
1			Non-dimensional fission power $P/P_o = N/N_o$
2-7			Non-dimensional delayed neutron fractions C_i/N_o
8			Non-dimensional iodine concentration I/I_o
9			Non-dimensional xenon concentration X/X_o
10			Non-dimensional promethium concentration Pm/Pm_o
11			Non-dimensional samarium concentration S/S_o
12		s	Integral of scaled fission power (see Equ 3.5-19)
13	THCORAV	K	Core average temperature
14	THREFAV	K	Reflector average temperature
15	SUMRHOC		Sum of core reactivity feedbacks
16	RHOREF		Reflector reactivity feedback
17	RHOXEN		Xenon reactivity feedback
18	SUMRHO		Sum of all reactivity feedbacks
19	THCORMX	K	Maximum core temperature
20		W	Decay heat
21		W	Fission power
22	RHOSAM		Samarium reactivity feedback
23	RHOWAT		Water reactivity feedback
24	RHODOP		Doppler reactivity feedback
25			Not used
26			Not used

RHOINT	logical variable controlling execution mode, set based on input variable COMPMOD (see below)
IKINMX	maximum number of iterations in point kinetics loop (from input record 5001D) (output)
IIN	input data file identifier (currently not used)
THCORAV	average core temperature [K] (input)
THREFAV	average reflector temperature [K] (input)
THFUELAV	average fuel temperature [K] (input)
THFLUDAV	average core coolant temperature [K] (input)

The input variable COMPMOD controls the coupling between point kinetics and thermal/flow computations, as well as the internal update of reactivity feedbacks during time step integration. The modes currently provided and their effect on the computations are as follows:

COMPMOD = 'Iterate'

This is the mode generally used in most applications. Logical variable RHOINT is set to true; the point kinetics and core temperature computations are solved iteratively in the point kinetics loop of TIMSOL in THATCH, as shown in Figure 4-1 (or TIMLOP in SYMELAN for free-standing SYMELAN runs, Figure 4-8). In this case, all reactivity feedbacks are computed internally during time integration.

COMPMOD = 'CONSTCOR'

In this case, there is no coupling between point kinetics and core temperature computations. RHOINT is set = false, and the input value of IKINMX is overridden by IKINMX = 1. However, the feedbacks for xenon, samarium and water are computed internally, controlled by RHOXINT = true.

COMPMOD = 'CONSTALL'

None of the feedbacks are updated internally during time integration, and the last time step values are used for all of them (RHOXINT = false).

PKININ also calls subroutine RHOOFTH for initialization of the temperature coefficients for core reactivity feedbacks.

In entry PKINEX, the time integration from time T1 to time T2 is executed. Its call sequence is as follows:

T1,T2,POWKIN,IKINIT,KINGO,THCORAV,THREFAV,THFUELAV,THFLUDAV

where

T1 and T2	beginning and end time for current time integration step [s] (input)
POWKIN	average non-dimensional fission power between T1 and T2 (output)
IKINIT	point kinetics loop iteration counter

KINGO	logical variable controlling point kinetics loop convergence. Was set = false before the point kinetics loop, and will be set = true here, if convergence check in PKINEX shows convergence, for terminating point kinetics loop.
THCORAV	average core temperature [K] (input)
THREFAV	average reflector temperature [K] (input)
THFUELAV	average fuel temperature [K] (input)
THFLUDAV	average core coolant temperature [K] (input)

The PKINEX routine sets the required reactivity feedback data depending on the mode of execution, and calls the SOLTRAN routine, which, in turn, calls the IMSL ODE integration routines DIVPAG or DGEAR for integration from T1 to T2. A flow chart of the PKINEX section of PKINO is shown in Figure 4-7.

Entries PKINRD and PKINWR will read one record containing a Y-vector (Table 4-8) from File 15, or write one record with a Y-vector to File 14. These records are used in THATCH for reading and writing THATCH output files. (Variables Y_{19} to Y_{21} are only set in PKINOUT, and therefore, will only be available for PKINWR, if the call frequency is equal or coarser than that for PKINOUT, and if PKINOUT calls, within a time step, precede calls to PKINWR. This is true for THATCH subroutine TIMSOL.) Entry PKINOUT will write a record of time and Y-vector to output File 33 for later use in THPROCS.

Subroutine CALIC is called during initialization to compute some of the initial values in the Y-vector and other constants. It prints output of some of the initial data.

Subroutine PKSOL and Function SEXPAM are not used.

Subroutine UERTXXX is used to bypass the corresponding IMSL error subroutine called by DGEAR.

Block Data BLDPINK contains some of the input data for the point kinetics model, which can be overridden by the use of input records 5004 to 5010D. (The exception is variable $XJPF = 3.2042 \times 10^{-11}$ J/fission.)

Function RHOCORF evaluates core reactivity feedbacks, drawing on the design temperature coefficients, which are given in subroutine RHOOFTH. The following is the call sequence for RHOCORF:

MODE,CORAVG,THCORAV,THFUELAV,THREFAV

where

MODE	is the character variable RHOMODE of input data record 5001D. Currently, it must be set to "INTEGR" (see RHOOFTH below).
CORAVG	is a logical variable controlling the computation mode of the Doppler feedback. It is also user-specified on input record 5001D.

```

graph TD
    Start([Start]) --> Load[Load core reflector fuel  
and coolant temperatures  
from argument list to  
PROM comments locations]
    Load --> RHOINT{RHOINT}
    
    RHOINT -- false --> RHODTINT{RHODTINT}
    RHODTINT -- true --> SumRHOC[compute SUMRHOC  
based on last time  
step values T1) ]
    SumRHOC --> CallSoltram
    
    RHOINT -- true --> CALMODE{CALMODE}
    CALMODE -- THATCH --> Thatch[OBTAIN THFUELVAV  
from approximation  
of function THFUEL]
    CALMODE --> SumRHOC
    
    Thatch --> SumRHOC
    SumRHOC[obtain SUMRHOC from  
function RHOCORF  
depending on ANOMODE] --> IKUNIT{IKUNIT}
    
    IKUNIT -- =1 --> SumRHOC1[SUMRHOC1 = SUMRHOC  
T1TH + T1  
store Y-vector into Y0]
    SumRHOC1 --> CallSoltram
    
    IKUNIT --> SumCOP[reset Y-vector from Y0  
 $SUMCOP = \frac{SUMRHOC - SUMRHOC1}{T1 - T2}$ ]
    SumCOP --> CallSoltram
    
    CallSoltram[call SOLTRAM for  
integration of point  
kinetics ODEs from  
T1 to T2] --> PowAvg[POWAVG =  $\frac{T_{FP} - T_{FP,Last}}{T2 - T1}$   
POWKIN = POWAVG * POWCOR]
    PowAvg --> IKUNIT
    
    IKUNIT --> Convergence{Convergence check  
on change of THCDRAV}
    Convergence -- converged --> KINGO = true
    Convergence --> KINGO{KINGO}
    
    KINGO -- true --> RhointTrue{RHOINT}
    RhointTrue -- true --> Deriv[Point kinetics time  
step completed  
  
Y12 new = Y12  
call DERIV for  
all parameters to  
correspond to test  
Y-vector]
    Deriv --> PtimeStep([Produce time step  
primed output])
    PtimeStep --> Spike[Set SPIKE for reactivity  
if SUMRHOC changes sign  
at Y < PSOURCE]
    Spike --> ReturnMain((RETURN))
    
    KINGO -- false --> ReturnNotConv((RETURN))
    ReturnNotConv --- Note[Point kinetics not  
yet converged]

```

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THCORAV
THFUELAV
THREFAV

are the average temperatures for the core, fuel, and reflector [K]

This function obtains the component feedbacks from subroutine RHOOFTH and returns the sum of core feedback coefficients as follows:

CORAVG = true
RHOCORF = RHOCOR + RHOREF

CORAVG = false
RHOCORF = RHODOP + RHOMOD + RHOREF

Subroutine RHOOFTH contains the PSID temperature coefficients for the core for EOC-EQ conditions. For the integrated mode, which is generally used, the local coefficients are used to compute integrated coefficients, based on a cold reference temperature of 200°C

$$\bar{c}(\theta) = \frac{1}{\theta - \theta_{ref}} \int_{\theta_{ref}}^{\theta} c(\theta) d\theta \quad (4.2-1)$$

and in terms of these, at any temperature θ , the change in reactivity with respect to steady state is

$$\Delta\rho = \rho - \rho_{StSt} = \bar{c}(\theta)[\theta - \theta_{ref}] - \bar{c}_{StSt}[\theta_{StSt} - \theta_{ref}] \quad (4.2-2)$$

On any call to RHOOFTH, the average core temperatures must be available in Common RHO3. For initialization, these must be the initial steady-state temperatures, not restart temperatures. During initialization, called from PKININ, the integrated coefficients and the steady-state terms of Equation (4.2-2) are computed for Doppler, moderator, total core, and reflector coefficients.

During the transient, called from the function RHOCORF, the $\Delta\rho$ of Equation 4.2-2 is referred to as RHODOP, RHOMOD, RHOCOR, or RHOREF in subroutine RHOOFTH and in function RHOCORF.

The actual ODE-integration is carried out by the IMSL ODE-solvers, DIVPAG or DGEAR. These require the availability of a subroutine to compute the derivative vector and, if MITER = 1 is specified with integration control input (Input Record 5003D), also a routine for the Jacobean matrix.

Subroutines DERIV and JACK compute for a given time and Y-vector, the corresponding derivative vector and the Jacobean matrix using the equations of Section 3.5.1.

Function SUMRHOF is called during time integration by subroutines DERIV and JACK to obtain the required reactivity feedbacks.

In the case of iterative solution of point kinetics and solid core temperatures, $RHOINTL = \text{true}$, the core reactivity changes were assumed to vary linearly between times $T1$ and $T2$ (see Section 3.5.2). These are then computed, based on last iteration values, for the time interval $T1$ to $T2$. The xenon and samarium feedbacks are computed based on their concentrations (in the Y-vector), and the water reactivity feedback is obtained from Function $RHOWATF$ as a function of time. During non-iterative computations, last time step values for core reactivities are used, and the other terms are updated in $SUMRHOF$ as described above, unless $COMPMOD$ was specified as 'CONSTALL', in which case all reactivities remain constant during integration, at last time step values.

Function $RHOWATF$ computes the water reactivity based on PSID data. In the given correlation for the reactivity change, $RHOWL$, variable $XMWAT$ is the mass of water in the active core [kg]. $XMWATTH$ is the maximum mass of water that the core could contain at safety relief valve pressure and given average coolant temperature, assuming 100% water concentration and considering the superheated steam to be an ideal gas. The "hard-wired" constant $C = 1.677226E5$ represents active core gas volume times pressure divided by the gas constant for water. ($V = 10.76\text{m}^3$; $p = 72 \times 10^5\text{N/m}^2$).

The actual mass of water in the core, $XMWAT$, is obtained by the ramp data of Input Record 5002D, which include an initial time of no ingress and a "ramp time" over which the water mass rises linearly to the maximum theoretical value.

The input parameter $RHOWPAR$ (Input Record 5002D) is used for parametric variation of water reactivity effects, and multiplies the values obtained from the above reactivity correlation.

Function $THFUEL$ is used in $THATCH$ runs if separate consideration of Doppler and moderator coefficients is desired ($CORAVG = \text{false}$). Because the relatively large $THATCH$ nodes cannot provide separate values for fuel and moderator temperatures, a simple approximation for this effect is applied here, setting the average fuel temperature above the average core temperature to an input value $DTHO$ (Input Record 5001D), which represents the full-power, steady-state difference between average fuel temperature and average core temperature. During a transient, $DTHO$ is then multiplied by the dimensionless core power P/P_0 at time t to obtain the current fuel to average core temperature difference. ($SYMELAN$ computes its own average fuel temperatures and does not call this function.)

4.2.5 Symelan Subroutines

The $SYMELAN$ submodule can be executed as a free standing module from dummy subroutine $SYMELAN$, or by calling several other of its subroutines from $THATCH$.

In free standing transient runs ($SYRUNMD = \text{'Transient'}$), $SYMELAN$ will call $TIMLOP$, the main time-loop routine of this module. ($SYRUNMD = \text{'TEMPOUT'}$), another free standing mode that can be used, will only access a previous $SYMELAN$ temperature output file and print the desired sections of the temperature history.

Subroutine $SYMELAN$ serves as an effective main program to call the free-standing $SYMELAN$ code by setting $CALMODE = SYMEL$. After call to the input routine $SYMELIN$, $SYMELAN$ will branch, depending on input variable $SYRUNMD$, either to the transient routine $TIMLOP$ or to the routine $TEMPRIN$ to process a previous $SYMELAN$ temperature output file. Currently, the free-standing mode uses its own input data and bypasses the unified input option of $THATCH$. However, there should be no problem in accessing this option, and we plan to implement this feature in the near future. Following

a free-standing transient run, SYMELAN calls FILEFIN to finalize a SYMELAN plot output file with output data from SYMELAN and PKIN for immediate plotting or summary output printing. The file format will be given below.

Subroutine TIMLOP contains the time loop of SYMELAN, and it corresponds to TIMSOL of THATCH, but is much simpler. The time loop is shown schematically in Figure 4-8.

Subroutine SYMELIN is the input routine, reading input data, initializing various code sections and reading the specified initial temperature files. It also calls SYMELDT for loading the symmetry element description based on the chosen nodalization. For combined THATCH/SYMELAN runs, the interface routine is THSYMIN (see THATCH subroutines). In the SYMELAN free-standing mode, the point kinetics are initialized by determining average temperatures from subroutine TEMPAG and calling PKININ.

Subroutine SYMTPIN will read and load initial temperature files from a prescribed input file NIN searching for a time record at time TREAD.

Subroutine SYMELDT initializes the geometry of symmetry element. Node volumes, heat transfer surfaces and center distances of nodes are computed based on the selected nodalization via data specified by users for:

NOFUCOL	number of fuel column nodes
NOGRCOL	number of graphite column nodes
MOROW	number of node rows nodes
(See Input Record 4006D)	

The basic geometry data specified in Block Data SYMDAT are used. Internal units in this routine are in [mm], and all areas and volumes are expressed per unit length. For use in the remainder of SYMELAN, all data are then converted to units of [m], again expressed per unit length.

Subroutine TEMPSYM obtains the solution of the temperature field of the symmetry element for each axial node region in each parallel flow channel. Its call sequence is as follows:

T, DT, CALMODE, POWKIN, IDEBUG

where

T	new time [s]
DT	time step [s]
CALMODE	character control variable 'SYMEL' for free standing SYMELAN runs 'COMBIN' for THATCH/SYMELAN runs
POWKIN	dimensionless fission power (P/P_0)
IDEBUG	debug print control (normally=0).

The average volumetric heating rate at time T is either obtained from POWKIN, the point kinetics output, or from POWPROF, a utility routine that is user-supplied (see page 4-81).

Figure 4-8 Flow Chart of TIMLOP Time Loop in SYMELAN

After a call to subroutine PROPLD for property and local transfer data, the coefficients for the solution of the simultaneous sets of equation sets are obtained from calls to subroutines COEFFLD or COEFFL2, depending on the number of node rows in the nodalization.

The temperature field is obtained by solving the sets of simultaneous equations, solving simultaneously for all symmetry element nodes of each parallel flow channel for one axial node region. Fluid exit temperatures, convective heat flows, and node surface temperatures are then computed for the axial node region of each parallel flow channel. Thereafter, the solution is repeated for the next axial node region, stepping down through the core in flow direction.

Subroutines COEFFLD and COEFFL2 load the simultaneous equation coefficients for single-node row nodalizations or for two-node row nodalizations, respectively, using the geometry data provided by subroutine SYMELDT, and the property and heat transfer arrays from subroutine PROPLD.

Subroutine PROPLD loads property arrays and other data on flow and heat transfer at the beginning of each time before coefficients are loaded in COEFFLD or COEFFL2.

In the computation of Reynolds numbers and heat transfer coefficients, pure helium is assumed as the coolant. The coefficient of convective heat transfer is obtained from subroutine HETCOF of GENLIB which models Equations (3.4-23 and 24). The fuel to graphite interface resistance is obtained from function HFUGRF, and the solid properties are obtained from function PROPT via calls to CONDFSM and ROCFSM (see below).

If, axial conduction is requested per user option, AXCON, in the free-standing mode, the explicit term for the right-hand side of Equation (3.6.4) will be computed here and loaded into the QUIBLCON array, for use in the coefficient load routines. In combined THATCH/SYMELAN runs, this array will be loaded from data on axial conduction computed by THATCH.

Function PROPF, with entries CONDFSM and ROCFSM, provides thermal conductivities and thermal capacitance, for fuel and graphite to SYMELAN. The call sequence for PROPF is as follows:

TH, MAT

where

TH	temperature [K]
MAT	material index
	1 = fuel
	2 = graphite

The returned values of CONDFSM and ROCFSM are in SI units [W/mK] and [J/m³K].

For fuel, the data from GA-A12985 are used, as presented in MATLIB. For graphite, the data for irradiated H-451 are used, with radial thermal conductivity.

The radial conductivity was also used to evaluate the axial conduction term in free-standing runs of SYMELAN. Strictly speaking, this evaluation is not correct. As Figure A-3 of Kroeger [1984] shows, the axial conductivity is slightly higher than the radial conductivity. This evaluation should be

corrected in future revisions of the code; however, the effect of this correction is expected to be very minor because axial conduction is very small during the rapid transients for which SYMELAN is used.

Function HFUGRF models the gap heat transfer resistance of the fuel to graphite interface including conduction and radiation, as described in Section 4.6. Its call sequence is as follows:

THNFU, THNGR, NOITS, RES1, RES3, IDEBUG

where

THNFU	temperature of last fuel node [K]
THNGR	temperature of first graphite node [K]
NOITS	maximum number of iterations
RES1	thermal resistance of 1/2 fuel node [$\text{m}^2\text{k/W}$]
RES3	thermal resistance of 1/2 graphite node [$\text{m}^2\text{k/W}$]
IDEBUG	debug print control

If NOITS is specified = 1, then the node temperatures will be used to evaluate the gap resistance. If NOITS is larger than 1, then iteration will occur and the gap resistance is computed based on the internal surface temperatures. The returned value of HFUGRF is in units [$\text{W/m}^2\text{K}$].

Subroutine TEMPLSM stores and reloads the node temperature array of SYMELAN as required in the point kinetics loop. Prior to the first iteration, the temperature array THA is stored in a THOO array. On each subsequent iteration, THA is reloaded from THOO.

The following routines are available to compute average and maximum temperatures as well as "hot fractions" of the core, where "hot fractions" are the core volume fraction exceeding a specific temperature:

Subroutines AVERAGE and AVERAG2, with entries THMAX, TEMPMX2, HOTFRAC and HOTFRC2, compute average and maximum temperatures as well as hot fractions. AVERAGE, THMAX, and HOTFRAC are called for one-node row nodalizations, while AVERAG2, TEMPMX2, and HOTFRC2 are used for two-node row nodalizations. The following arrays are computed by these routines:

Node region averages for I=1, ICHS and J=1,JNODS:

average temperature of graphite	THAVGRN (I,J)
average temperature of fuel	THAVFUN (I,J)

Average values for each parallel flow channel I=1, ICHS with overall average stored in position ICHSP:

average temperature of graphite	THAVGR(I)
average temperature of fuel	THAVFU(I)
average temperature of coolant	THAVFL(I)

Maximum values for each parallel flow channel I=1, ICHS with overall maximum stored in position ICHSP:

maximum temperature of graphite	THMXGR(I)
maximum temperature of fuel	THMXFU(I)

Volume fractions exceeding specific values of THHOT array (four input values) in each parallel flow channel:

fraction of graphite exceeding temperature	THOT(K)	FRACGR(I,K)
fraction of fuel exceeding temperature	THOT(K)	FRACFU(I,K)

Array locations ICHSP contain the overall volume fractions exceeding the specified temperatures.

Subroutine TEMPAVG, with entry TEMPMAX is used by THATCH and SYMELAN to obtain average temperatures of the core and/or reflector for the evaluations on the feedback of point kinetics reactivity, as well as maximum core temperatures. TEMPAVG does not compute these, but controls the call to the appropriate routines, depending on the type of run, as controlled by variable CALMODE. The call sequence for TEMPAVG is as follows:

T, THCORAV, THREFAF, THFUELAV, THFLUDAV, CALMODE

and for entry TEMPMAX

T, THCORM

where

T	time [s]	(input)
THCORAV	Average temperature of core [K]	(output)
THREFAV	Average temperature of reflector [K]	(output)
THFUELAV	Average temperature of fuel [K]	(output)
THFLUDAV	Average temperature of coolant [K]	(output)
THCORMX	Maximum temperature of core [K]	(output)
CALMODE	Character control variable	(input)
	= 'THATCH' THATCH run without SYMELAN	
	= 'COMBIN' combined THATCH/SYMELAN run	
	= 'SYMELAN' free standing SYMELAN run	

For free-standing SYMELAN runs, routine SYTMPAV is called for average fuel and coolant temperatures of the core, and SYTMPMX for maximum temperatures of the core. The reflector temperatures are not computed in SYMELAN, and a constant input value from Input Record 4013D is returned here.

For THATCH runs, the THATCH routine THTMPAV is called for average temperatures of the core and reflector. Average temperatures of the coolant and fuel are then set equal to the average temperature of the core. The maximum temperature of the core is obtained from entry THTMPMX in subroutine THTMPAV of THATCH.

For combined runs, the average temperatures of the core, fuel, and fluid are obtained from SYMELAN temperatures via SYTMPAV, and the maximum temperature of the core via SYTMPMX. The average temperature of the reflector is obtained from routine THTMPAV of THATCH.

Subroutine SYTMPAV, with entry SYTMPMX calls the above routine AVERAGE or AVERAG2, and loads from its output arrays, the average temperatures of the core, fuel, and coolant, or the maximum temperatures of the core. Note that the average temperature of graphite, not an average temperature of fuel and graphite is returned as the average temperature of the core.

Interfacing between SYMELAN, THATCH, and FLOXI is handled in the following subroutines:

THSYMIN (see THATCH, Section 4.1)
 THSYMEX
 SYMTHEX
 THSYME2
 SYMFLEX (Entry in SYMTHEX)

Their function is illustrated in Table 4-11.

Subroutine SYMTHEX is the first interface routine called from THATCH. It also computes the coordinate off-sets between the active core nodes of SYMELAN, THATCH, and FLOXI and stores some of these in SYMELAN/FLOXI combined common SYMFLX. The call sequence for subroutine SYMTHEX is as follows:

T, THS, IDIM, JDIM, IAFTHI, JAFTHI, IDEBUG

T	time [s]
THS	solid node temperature array of THATCH [K]
IDIM, JDIM	dimension of THS array in THATCH
IAFTLO, IAFTHI, JAFTHI	range of active core nodes in THATCH
IDEBUG	debug print control

Subroutine THSYME2 computes and transfers from THATCH to SYMELAN the core heat flow array. The call sequence to subroutine THSYME2 is as follows:

T, THS, IDIM, JDIM, IAFTHI, JAFTHI, IDEBUG

where T	time [s]
THS	solid node temperature array of THATCH [K]
IDHTH, JDHTH	dimensions of THS array in THATCH
CONAX	axial conductance array [W/K]
CONRA	radial conductance array [W/K]
IDIM, JDIM	dimension of CONAX and CONRA arrays in THATCH

Table 4-11

Interface Subroutines for SYMELAN/THATCH/FLOXI Interface

Subroutine	Calling Program	Called When/Where	Variable Transfer			SYMELAN Index Range	Variable Transfer Mode
			THATCH	SYMELAN	FLOXI		
<u>THATCH</u> : THSYMIN	SYMELIN	Initialization	POWO PKINL	----> POWO ----> PKINL			From THATCH common via argument list to SYMELIN
<u>SYMELAN</u> : THSYMEX	TIMSOL	In time step before point kinetics loop		WASYM(I) < --- THFLEXS(I,O) < ---	WA THFLXAA	I=1,ICHS I=1,ICHS	From FLOXI commons FLOWD2 and THTH to SYMELAN Common COMDAT
SYMTHEX	TIMSOL	One call for initialization before time loop; one call in time loop within point kinetics loop	TH(I,J) < -----	THAVFUN(I,J) & THAVGRN(I,J)		I=1,ICHS J=1,JNODS	Average temperatures of Fuel and Graphite node regions from SYMELAN common AVGS combined and transferred to TIMSOL via argument list

Table 4-11 (Cont'd)

THSYME2	TEMPSOL	In time loop; within point kinetics loop	CONAX CONRA } Q ---> QBLOCKA(I,J) THS		I=1,ICHS J=1,JNODS	THATCH conductances and temperatures via argument list to THSYME2; Compute inter-node conduction and load into QBLOCKA in SYMELAN common QBLOCK
SYMFLEX (Entry in SYMTHEX)	TIMSOL	In time loop; after point kinetics loop, before FLOXIEX call		SYMRUN UUA(I,J) ---> SYMRUN THSOLLA(I,J) ---> UUASM QCONV(I,J) ---> THSSMFL ---> QSMFL	I=1,ICHS J=1,JNODS	Load from SYMELAN common COMDAT to SYMELAN/FLOXI combined Common SYMFLX for use in FLOXI routine HETCON

IAFTLO, IAFTHI,	
JAFTLO, JAFTHI	range of active core nodes in THATCH
IDEBUG	debug print control

Subroutine SYMELOT provides printed output, as well as an output file in the plot file format, and an output file of complete temperature arrays. Its call sequence is as follows:

T,PRINT,PLOT,WRITMP,IDEBUG

where

T	time [s]
PRINT, PLOT, WRITMP	logical control variables to produce printed output, a plot file time record and/or a set of temperature array records.
IDEBUG	debug print control.

A list of the plot file time records for SYMELAN is given in Table 4-12, and Table 4-13 lists the temperature arrays on the temperature output file.

The total plot file for SYMELAN follows the format used in the THPROC, the post processing module of THATCH. The file contains one title record (CHARACTER * 240) and record IREC,NOREC, where NOREC is the number of time records to follow. Each time record has the following format:

JNO, Time (s), (Y(I), I=1, IREC).

(See also subroutine FILEFIN below).

Subroutine TEMPRIN is called from the main program, SYMELAN, if run mode 'TEMPOUT' was specified in a free-standing SYMELAN run. In this case, TEMPRIN reads a previous SYMELAN temperature file and produces selected printed output at time points specified with the input data from SYMELIN.

Subroutine FILEFIN finalizes a plot file at the end of a SYMELAN run and adds the number of time records to record number 2 of the file (see SYMELOT above). If the run was with point kinetics, FILEFIN adds the point kinetics vector (26 locations) of Table 4-10 in locations I=101 to 126 to the SYMELAN vector of Table 4-12.

Subroutine TIMVAR permits the user to vary mass flow and fluid inlet temperatures as a function of time in free-standing SYMELAN runs. The call sequence for TIMVAR is as follows:

T,TLAG

where

T	time [s]
TLAG	time-lag.

If TLAG is set $> 10^6$, TIMVAR is bypassed. This time-lag is currently set to 10^7 to bypass TIMVAR.

Table 4-12

SYMELAN Plot File
Variable Vector on Time Records

Variable Name	Units	Number of Entries*	Description
THAVFUC	°C	ICHSP	Average temperature of fuel
THAVGRC	°C	ICHSP	Average temperature of graphite
THAVFLC	°C	ICHSP	Average temperature of coolant
THMXFUC	°C	ICHSP	Maximum temperature of fuel
THMXGRC	°C	ICHSP	Maximum temperature of graphite
QTOFL	W	ICHSP	Heat to Coolant
FRACFU		4	Core fraction of fuel exceeding specified temperatures
FRACGR		4	Core fraction of graphite exceeding specified temperatures
THFLINC	°C	ICHS	Inlet temperature of coolant
THFLEXC	°C	ICHS	Exit temperature of coolant
THFLXAVC	°C	1	Average exit temperature of coolant
POWL		1	Dimensionless fission power P/P_o

* ICHS = Number of parallel flow channels

ICHSP = Number of parallel flow channels plus one

Table 4-13
SYMELAN Output File
of
Temperature Arrays

Heading Records

Record Number

1	Title (Character x240)	
2	ICHS	Number of parallel flow channels
	JNODS	Number of axial nodes
	NOFUCOL	Number of fuel column nodes
	NOFUCOLP	nofucol + 1
	NONODES	Number of symmetry element nodes
	DEGK	Kelvin/Centrigrade offset = 273.15K

Time Records Repeated at Each Write Step

1	Time [s]
2	((((THA(N,J,I),i = 1,ICHS),J = 1,JNODS),N = 1,NONODES) Solid Node Temperatures [K]
3	((THFLAP(I,J),I = 1,ICHS),J = 1,JNODS) Average Temperature of the Node Region between Coolant and Surface [K]
4	((THSURFA(I,J),I = 1,ICHS),J = 1,JNODS) Surface Temperatures of the Coolant Holes of the Node Regions [K]
5	((THFLA(I,J),I = 1,ICHS),J = 1,JNODS) Average Coolant Temperature of the Node Region [K]
6	((THFLEXS(I,J),I = 1,ICHS),J = 0,JNODS) Coolant Exit Temperature of the Node Region [K]

Subroutine POWPROF is called in TEMPSYM if this run is without point kinetics. The user can specify in POWPROF a time-varying, core-averaged volumetric heating rate $[W/m^3]$ as a fraction of QTRIPO, the initial, core average heating rate. Currently, as required for steady-state simulations, this subroutine keeps power constant.

Subroutine ENCHECK was used for checks of debug energy conversion. It has not been used lately, and may require updates if it were to be used again.

Functions FMAX2 and FMAX3 find the maximum entry in a two-or-three-dimensional array. The arrays are loaded into a one-dimensional array and ESVVLIB routine IDMAX is used to locate the maximum value. These routines are not used.

Block Data SYMDAT contains primarily the data on symmetry element geometry for the three internally provided nodalizations, plus a few other general constants.

4.2.6 GENLIB Subroutines

The GENLIB subroutines are general subroutines and functions for file handling, interpolation friction, and heat transfer correlations, after heat functions and other subroutines.

The following subroutines are not used within THATCH and its sub-modules and therefore, are not described here at this time:

ERFCF	PRINMAT	SOLV2
FRACT	RATDRV	SQRTF
MATVEC	RATF	SQUAPR
MODFCT	RELOD	SUMNT
ORDER	REPACK	TRIPR

The after-heat computations are done by subroutine AFTCOFS(IIN) and functions AFTANS(T), AFTER(T) and AFTPSID(T). IIN identifies the input file from which data are read (currently not used) and T is the time [s]. AFTCOFS serves for initialization and reads coefficients, as required (Input Records 1108 to 1111D). The logical variable AFTMODE controls which correlation to use.

AFTFR computes the dimensionless after-heat P/PO as a function of time by linear interpolation in the log-log table of P/PO vs time, if AFTMODE is 'NOML', 'LTR', 'PSID1', or 'READ'. For AFTMODE = 'ANS' or 'PSID2', AFTFR calls functions AFTANS or AFTPSID, respectively.

The following subroutines represent friction factor and heat transfer correlations:

Function FRIC(RE,IOPT) gives the friction pressure drop for smooth pipes as a function of Reynolds number, following Equation 3.2-23. Under IOPT=1, linear interpolation will occur between Re=2300 and Re=8000, i.e. the friction factor increases between the lower and upper limit of the transition region. With IOPT=2, the friction factor remains constant between Re=1685 and 8000 of f(8000). Option 2 is used in THATCH.

Function HETCOF (RE,PR,G,CP,NU,ST) is used for convective heat transfer coefficients of gases or gas mixtures in tubes or channels.

RE	Reynolds number (input)
PR	Prandtl number (input)
G	mass flux [$\text{k/m}^2\text{s}$] (input)
CP	specific heat [J/kgK] (input)
NU	Nusselt number (output)
ST	Stanton number (output)
HETCOF	heat transfer coefficient [$\text{W/m}^2\text{K}$] (output)

The correlation of Equation 3.4-23 is used, with linear interpolation in the transition region.

Function HHRADBL (TH1,TH2) computes the equivalent heat transfer coefficient between two black surfaces of temperatures TH1 and TH2 in units [$\text{W/m}^2\text{K}$].

Function HHCAVTY computes a heat transfer coefficient of turbulent natural convection for a closed cavity with a hot and a cold vertical surface (used for reactor cavity). Its call sequence is as follows:

TH1,TH2,XL,XD,PT,LGAS

where

TH1,TH2	hot and cold surface temperatures [K] (input)
XL,XD	cavity height and width [m] (input)
PT	gas pressure [N/m^2] (input)
LGAS	gas index (only LGAS=1 helium or LGAS=2 air are currently allowed) (input)
HHCAVTY	heat transfer coefficient [$\text{W/m}^2\text{K}$] (output)

Function HHCONVE is an earlier correlation for convective heat transfer to air. It is still used in the air cooled RCCS model of PASCOLIB, and should be replaced by function HETCOF (above).

The following subroutines or functions are used for interpolation and function evaluations:

Subroutine TBLLK (X,XA,I1,IL,INDEX,IERR) will find in an array of monotonously increasing values XA, the index of the last XA value below X, and return it as INDEX. The index range of XA is I1 to IL, and IERR is an error indicator.

IERR=0	INDEX was found; X was within range of table.
=-1	X below range; INDEX set=I1
=1	X above range; INDEX set=IL-1

This routine works by dividing the index range into half at each step which is generally faster than a sequential search from I1 to IL.

Subroutine TBLLKSEC (X,XA,IL,INDEX,IERR) has the same purpose as TBLLK for an index range of XA from 1 to IL; however, the search is sequential here, which is sometimes preferable.

Subroutine TBLLKF (X,XA,I1,IL,INDEX,NAME) is a substitute call to TBLLK; the first five arguments of the call sequence are identical. TBLLKF calls TBLLK and handles the printing of the error message IERR $\neq 0$ on return. NAME is a character variable of up to 30 characters, and is used to identify the call to TBLLKF.

Function Spline2 (X,XA,IIP,C,IDMC,IRL,IERR,IDER) evaluates a cubic spline fit as defined by the dependent coefficient array C of the spline function and independent variable vector XA. X is the value at which the function is to be evaluated. IIP is the number of entries in XA; IDMC is the leading dimension of C; IRL is on output, the range in XA where X was found (INDEX of TBLLK). On return, an initial check is made, whether or not X is still in the range of IRL, to bypass the table search if possible. IERR is the same error indicator as in TBLLK. IDER=0 results in the function evaluation, while for IDER=1, the first derivative will be computed.

Subroutine REDCOF2 (XA,C,IDIM,II,IIP,NTAPE) reads a set of spline coefficients for a cubic spline fit from input file NTAPE.

The three file records on file NTAPE are the following:

II	number of <u>intervals</u> in spline fit
(XA(I),I=1,IIP)	independent variable at node points 1 to IIP, where IIP = II + 1
((C(I,M),M=1,4), I=1,II)	spline coefficients.
IDIM	the leading dimension of the C-array

Subroutines FRITE, FCOND, and COMBINE handle plot files. The plot file format is described in Section 4.2.5 with the SYMELAN output file.

Subroutine FRITE (NSEG,NTPIN,NTPOUT,Y,IREFCMX,FILTYPE) reads a plot file from NTPIN, reading only the entry IREF from the second record. FRITE then counts the number of time records, and writes a new file onto NTPOUT, including both IREF and NOREC on record number two. IREFCMX is the dimension of Y in the calling program and must be larger than IREF. Currently, NSEG=1 and FILTYPE = 'COLWISE'.

Subroutine FCOND reduces time records on plot files and eliminates points outside of a specified range.

The call sequence is as follows:

NSEG,NTPIN1,NTPOUT1,NOTAPES,NPTS,XMIN,XMAX,Y,IREFCMX,
NTPSCR1,NTPSCR2,MINREC

NSEG	always = 1
NTPIN1	first input file to be condensed
NTPOUT1	first condensed output file
NOTAPES	number of files to be condensed (input files must have sequential numbers NTPIN1 to NTPIN1-1+NOTAPES)
NPTS	approximate number of time records desired on output file
XMIN,XMAX	independent variable range (generally time) for variables on output file (entries out of range will be eliminated)
Y	dependent variable vector
IREFCMX	maximum dimension of Y, must be $\geq$ IREC
NTPSCR1,NTPSCR2	scratch files
MINREC	minimum number of time records on output tapes (output)

Subroutine COMBINE (NTIN1,NOTAPES,NTOUT,SCR,IREFCMX,FILTYPE) will combine sequential plot file NTIN1 to NTIN1-1+NOTAPES onto output file NTOUT. SCR is a scratch vector of size IREFCMX $\geq$ IREC. FILTYPE is always 'COLWISE'.

Subroutine CONDENS,NORECF,POSITN, and RERITE are service functions for the three preceding routines and are never called by themselves. Details can be provided by the authors on request.

Subroutine RUFF (FCT,DFCT,SCALE,X,IER,EPS1,EPS2,NMX,LVLPRT) solves a single transcendental equation of the form $F(X) = 0$, as prescribed in FCT and DFCT, using the Newton-Raphson method.

FCT(X) and DFCT(X) are external functions defining the function and its derivative in terms of the independent variable X. FCT and DFCT must be provided by the user. Convergence is obtained when

$$\frac{|FCT(X)|}{SCALE} < EPS1$$

or

$$|FCT(X)| < EPS2$$

NMX is the maximum number of iterations and LVLPRT provides debug print control.

Function EXPF (X) computes EXP(X), but avoids overflow and underflow messages by limiting X to a machine-dependent range.

$$(|X| < 174. \text{ on IBM3090})$$

Subroutine TRIDG (A,B,C,F,X,N1,N2) solves a tridiagonal system of simultaneous linear equations where

A left of diagonal array
 B diagonal array
 C right of diagonal array
 F right hand side vector
 X solution vector
 N1 location of first coefficient in arrays
 N2 location of last coefficient in arrays (i.e., N2-(N1-1) equations are being solved).

Subroutine TRIDG2 (A,B,C,F,N1,N2) is identical to TRIDG, except that the original right hand side vector and the solution vector show the same storage location as the F-array.

Subroutine SOLTRAN is a generalized routine for integration of a set of ODEs. It calls either DGEAR or DIVPAG and handles its input requirements and error analysis. Its call sequence is as follows:

TIN,TOUT,Y,YDOT,NEQ,CALLTYP,RWKSP,IWK,IDEBUG

Time integration is for NEQ equations from TIN to TOUT. Y is the variable vector and YDOT is its derivative.

Control variables INTMTHD, MTHGEAR, and MITER (user-specified, Record 5003D) are transferred to SOLTRAN via Commons.

Character variable CALLTYP is set by the calling program to control the integration process based on the different requirements of DIVPAG and DGEAR (see IMSL documentation). Table 4-14 describes the implementation of the selected ODE solver in SOLTRAN.

Table 4-14

Control of Integration in SOLTRAN via DIVPAG or DGEAR
 Based on Character Control Variable CALLTYP

CALLTYP	DIVPAG	DGEAR
'FIRST'	IDO=1 Load PARAM array	INDX=1 HSTEP=HSTEPO
'RESET'	HSTEP=HSTEPO	INDX=-1 HSTEP=HSTEPO
'RESTART'	IDO=3 CALL DIVPAG() IDO=1	INDX=1 HSTEP=HSTEPO
'LAST'	IDO=3 CALL DIVPAG ()	

Block Data ODEDAT contains some of the control data and default values for the ODE integration.

Subroutine MAPRINT (A,NN,IOPD,ICOLPR0,MODE,NAME) is used for two-dimensional matrix printing. Matrix A of NNxNN entries and of dimension IOPDxIOPD is printed, ICOLPR0 columns at a time. If Mode=0 only the matrix is printed. If Mode=1, the row sum is added as the last column. The routine is primarily used by THRADLIB. Character variable NAME identifies the matrix.

Subroutine READIN (IIN,NAME) reads an input file from File 5, strips it of its comments (lines beginning with Cbb), and copies it to file IIN. Character variable NAME (up to 80 characters) identifies the file being read.

Subroutine STRACE is a system-dependent routine that indicates an error, and traces back the error location (triggered on IBM3090 by arbitrarily dividing by zero).

Function Second (T) provides elapsed execution time for code execution time control (T is a dummy variable).

Function MINATOR (DUMMY) provides execution time remaining for this run, to permit orderly run termination.

4.2.7 THTCHLIB Library Subroutines

The THTCHLIB Library contains several THATCH utility subroutines which might also be used by other codes or in free-standing FLOXI or SYMELAN runs. Furthermore, it contains the subroutines used for the unified input option, computing current commercial MHTGR geometry data, based on the design data of Block Data COREDTs. None of the subroutines in THTCHLIB contain any of the THATCH Commons.

Subroutines CORFEL, COREDTs, CORINDT, and CORINPS process the input data required under the unified input option.

Subroutine CORFEL (NREAD, LVLPR0) is called by THATCH to initialize the unified input subroutines, if this option is requested (UNIFIN=true on Input Record 301D). NREAD identifies the input file (no longer used), and LVLPR0 controls the amount of printed output.

Based on the core design data of the PSID, as stored in Block Data COREDTs, the data on fuel element geometry such as flow areas, heat transfer surfaces, fuel, moderator and coolant volumes are computed and printed. Active core-wide data of the same variables are produced and printed. The radial core nodalization is treated by considering the following five zones:

1	the central reflector zone
2 to 4	three active core power zones (corresponding to the three radial power zones of the PSID)
5	one side reflector zone, comprising replaceable and permanent side reflectors.

Based on the input data specified by the user (Records 302D to 303D), the radial nodalization of each zone is set up for either equal cross section area or equal radial width of the nodes within a zone.

If equal area were specified (SPACING='AREA'), then another option is available in the allocation of flow and heat transfer areas in the first of the three radial core power zones, provided that two radial nodes were specified for this zone. This region contains the fuel elements with Reserve Shutdown Control channels, which have less fuel and also less coolant holes. Optionally, this effect can be "smeared" over the whole inner power zone or just into the inner one of the two node rings.

Axially, the active core consists of ten fuel elements, while top and bottom reflector regions have data for four sections each. At the top, the first section represents plenum elements, and the other three represent the actual graphite top reflectors. At the bottom, the four sections have different flow and heat transfer areas for each section corresponding to the bottom reflector design. The unified input option permits the user to specify subdivisions into finer nodes. At this time, only the axial node spacing of the active core is supplied by the unified input option, with each fuel element being divided into a number of nodes of equal length specified by the user. For the reflector regions, the axial node spacing is currently not supplied by this option, but the flow and heat transfer surface areas are supplied (in FLOXI).

The unified input option includes the following radial and axial power profiles which the user can call for via Input Records 305D to 308D:

Radial 3-Zone	Fission Power Profile
Axial 3-Zone	Fission Power Profile
Axial 10-Zone	Fission Power Profile
Axial 10-Zone	Decay Heat Profile

Aside from these profiles, which were specified in the PSID, the user can ask for 1-zone models, which imply uniform power distributions.

Block Data COREDITS contains the core design data as given in the PSID. The user has the option to override any of these entries, for instance for parametric studies.

Subroutine CORINDT, with entries CORINDM, CORINFL, and CORINSY, is called from THATCH, FLOXI, and/or SYMELAN to load specified core data computed in CORFEL to the appropriate THATCH or Submodule Commons.

Entry CORINDM (LABIN, XX, ID1, ID2) will load, depending on LABIN being = 'RIFA' or = 'ZIFA', the radial node interface array for central reflector, active core and side reflectors, or the axial node interface array for the active core. The corresponding data are loaded into the XX array which is dimensioned XX(ID1:ID2).

Entry CORINFL (IC1, IC2, JC1, JC2, ICHF, JNODE, AFLOW, AFLOCOR, ASURFP, DHF, REFCORF, IDIM, JDIM) is called by FLOXI and will return to FLOXI the following:

IC1	THATCH radial node corresponding to the first parallel flow channel
IC2	THATCH radial node corresponding to the last parallel flow channel
JC1	THATCH axial node corresponding to the first axial flow channel node (upper plenum element)
JC2	THATCH axial node corresponding to the last axial flow channel node (last bottom reflector node)

ICHF	Number of parallel flow channels in the core
JNODF	Number of axial nodes in FLOXI
AFLOW	Flow cross section area [m ²], (I=1,ICHF+1)
AFLOCOR	Total active core flow area [m ²]
ASURFP	Specific heat transfer surface area [m ² /m], (I=1, ICHF + 1)
DHF	Hydraulic diameter array [m], (I=1, ICHF+1; J=1,JNOD)
REFCORF	Correction array for heat transfer surface of the active core (see input record 3207D) (J=1,JNOD)

IDIM and JDIM are the dimensions of the above arrays in FLOXI.

Entry CORINSY (ICHS, JNODS, AFLOW, AFLOCOR, ASURFP, RADFRACA, XX, IDIM, JDIM, ID1, ID2) is called by SYMELAN and will return to SYMELAN the following:

ICHF	Number of parallel flow channels
JNODF	Number of axial nodes in FLOXI
AFLOW	Flow cross section area [m ²], (I=1,ICHF+1 I=1,ICHS)
AFLOCOR	Total active core flow area [m ²]
ASURFP	Specific heat transfer surface area [m ² /m], (I=1,ICHS)
RADFRACA	Fraction of core flow area (AFLOW(I)/AFLOCOR), (I=1,ICHS)
XX	DZA array of axial node length in active core [m], (J=1,JNOD5)

The XX array is dimensional X(ID1, ID2). IDIM and JDIM are the dimensions of the other arrays in SYMELAN.

Subroutine CORINPW, with entry CORINPS, loads radial and axial power profiles to THATCH or SYMELAN, respectively.

The call sequence for CORINPW is as follows:

PHIR1, PMIR2, PHIX1, PMIX2, ID1, ID2

The call sequence to CORINP5 is the same, except that PMIR1 AND PHIX1 are omitted.

PHIR1	Radial power profile for after-heat I=1, NFLO
PHIR2	Radial power profile for fission power, I=1, NFLO
PHIX1	Axial power profile for after-heat J=1, NODZ
PHIX2	Axial power profile for fission power J=1,NODZ

where NFLO is the number of radial active core nodes, and NODZ is the number of axial active core nodes. ID1 and ID2 are the dimensions of the radial and axial power profile arrays in the calling programs.

Subroutine NEWTON provides a Newton-Raphson solution for a set of non-linear, simultaneous algebraic equations, based on a function specified by a user, which supplies the Jacobean matrix and the residual vector. Its call sequence is as follows:

Y, NEQ, EPSR, EPSY, NITMX, XJAC, IDJAC,
 RHS, DY, DYMFR, IDEBUG, BIGR, ITERSNR
 IER, FCTJAC, WRK, IDWRK, IWRK,
 IDIWRK, LINMETM, SPECSOL

where

Y	Solutions vector (output) (on call, Y must contain initial estimate of Y)
NEQ	Number of equations (input)
EPSR	Convergence criterion with respect to residual vector (input)
EPSY	Convergence criterion with respect to change in Y-vector (input)
NITMX	Maximum number of iterations allowed (input)
XJAC	Jacobian matrix (computed for NEWTON in FCTJAC)
IDJAC	Dimension of XJAC (input)
RHS	Right-hand side vector (computed for NEWTON in FCTJAC)
DY	Change in Y-vector (output)
DYMFR	Maximum fractional change permitted in Y-vector at one iteration (input)
IDEBUG	Debug print control (input)
BIGR	Largest residual (computed in FCTJAC, output)
ITERSNR	Number of iterations used (output)
IER	Error indicator (output; =0 converged; =3 not converged)
FCTJAC	Name of external subroutine supplying Jacobian matrix and residual vector (input). The call sequence of function FCTJAC is as follows: Y, NEQ, XJAC, RHS, BIGR, JBIGR, IDJAC, IDEBUG with all entries having the same meaning as in the call sequence for NEWTON.
WRK	Work array (needed with LINMETM=3 or 4 only; to be set in accordance with requirements of SLATEC or NAG library)
IDWRK	Dimension of WRK-array
IWRK	Integer work array (size must be $\geq$ NEQ)
IDIWRK	Dimension of IWRK-array
LINMETM	Control index to select method for solving of linear system of equations. Currently, = 1 ESVVLIB library routines DGEF and DGES = 2 not used = 3 NAG library routine, FO4ARF = 4 SLATEC library routine, DGEFS ≥ 5 special routine for particular structure of Jacobian, see SPECSOL below.
SPECSOL	name of subroutine for solving system of linear equations, using the of special sparse structure of Jacobian (currently used in PASCOL) The call sequence of the subroutine SPECSOL is as follows: XJAC, IDJAC, RHS, NEQ, IDEBUG, with all entries as defined in the call sequence for NEWTON.

Subroutine GASLOAD (RGASHEL, RGASAIR, XMOLHEL, XMOLAIR) initializes the gas property routines of GASPRLIB and makes the following call variables available to the calling program:

RGASHEL	Gas constant of helium [J/kgK]
RGASAIR	Gas constant of air [J/kgK]
XMOLHEL	Molar mass of helium [kg/kmol]
XMOLAIR	Molar mass of air [kg/kmol]

Subroutine TIMER, with entries TIMEIN, TIMEOUT, and TIMEPR provides the execution time in specified program sections. A call to entry TIMEIN (JSECT) begins to count the execution time for program section JSECT until terminated by calling entry TIMEOUT (JSECT). A call to entry TIMEPR (NPR1, NPR2) prints the total time accumulated for program sections, NPR1 to NPR2. Currently, the routine is set up for Sections 1 to 16 for THATCH runs and Sections 21 to 24 for SYMELAN runs.

Function POLF (A, II, X) evaluates an II-order polynomial with X as the independent variable and coefficient array A(0:II).

Subroutine TIMEX (TIME) loads character variable ITIME with time in format HH.MM.SS., and subroutine DATE (IDATE) loads character variable IDATE with the date in format MM/DD/YY.

4.2.8 GASPRLIB Subroutines

The mixture property routines for gases are contained in the GASPRLIB section of BIGLIB.

For the thermal properties, the tabulated internal energy data of Owczarek [1964] are contained in the BLOCK DATA section GASDATA together with mol weights, universal gas constant, and the energy of formation (required for combustion computations).

The gas indices used in THATCH are as follows:

$l =$	1	helium
	2	air
	3	CO
	4	CO ₂
	5	H ₂ O
	6	H ₂
	7	O ₂
	8	N ₂

The data are for all gases but helium and air. For helium the ideal gas correlations of Appendix D are used. During an initialization call to GASENER the gas properties of air are computed from those for O₂ and N₂. It should be noted that the water properties here apply for an ideal gas, i.e., for a gas of sufficient superheat and sufficiently low partial pressure.

The subroutine GASENER initializes the gas property library and returns for a specified temperature the internal energies of specified gases, obtained by linear interpolation of the data. The call sequence for GASENER is as follows:

TH	gas temperature [K]
----	---------------------

ENA	internal energy array $[\frac{J}{kmol}]$
J1,J2	indices to indicate for which gases internal energies are to be obtained (from J1 to J2, i.e. 1,8 means all, and 5,5 means H ₂ O only, etc.)

In any code run which uses the GASPRLIB thermal properties an initialization call to GASENER must be included. In this call variable J1 must be set to zero. The other variables are then not used during this call.

The mixture or single gas properties are obtained from the following subroutines:

Single gas with properties from linear interpolation:

For Function CV1 with entries CP1, ENINT1, and ENTHAL1, the call sequence is as follows:

TH, IG

where

TH	Gas Temperature [K]
IG	Gas Species

The returned properties are in $[\frac{J}{kmol}]$ or $[\frac{J}{kmolK}]$.

Gas mixtures with properties from linear interpolation:

For Function CVMIX with entries CPMIX, ENINTRL, and ENTHAL, the call sequence is as follows:

TH, NUAL, IG1, IG2

where

TH	Gas Temperature [K]
NUAL	Array of volume fractions defining gas mixture
IG1,IG2	Range (from IG1 to IG2) for which mixture properties are desired.

The returned properties are in molar units, as given above.

Single gas with properties from cubic spline:

For Function CV1SPL with entries CP1SPL, EE1SPL, and HH1SPL, the call sequence is as follows:

TH, IG, IRL

where

TH	Gas Temperature [K]
IG	Gas Species
IRL	Range index in table data at last call (spline computation routine SPLINE2 will first test whether range remains the same, thus potentially bypassing range search.

Gas mixture with properties from cubic spline:

For Function CVMIXSP with entries CPMIXSP, EEMSPL, and HHMSPL, the call sequence is as follows

TH, NUA, IG1, IG2, IPL

where

TH	Gas Temperature [K]
NUA	Array of volume fractions defining gas mixture
IG1,IG2	Range (from IG1 to IG2) for which mixture properties are desired
IPL	Range index in table data at last call (spline computation routine SPLINE2 will first test whether range remains the same, thus potentially bypassing range search.

Function THFROMH will compute the gas temperature for a given gas mixture and enthalpy. Its call sequence is as follows:

HH, XNUA, IDX, IG1, IG2, TH

where

HH	enthalpy [$\frac{J}{kmol}$]
XNUA	volume fraction array
IDX	dimension of XNUA array
IG1,IG2	range of gases in the mixture (from IG1 to IG2)
TH	initial estimate of temperature [K]

This subroutine uses the general purpose solver RUFF (see GENLIB) which calls the required functions HFCT and DHFCT.

Viscosit.: Subroutines

Function VISGSPK, provides viscosities for a single gas or a gas mixture. Its call sequence is as follows:

TH, NUAL, IGAS, TYPINGR

where

TH	Gas temperature [K]
NUAL	Gas volume fraction array
IGAS	Number of gas species in current problem (input variable)
TYPINGR	Character variable specifying type of ingress (input variable)

The returned viscosity is in $\left[\frac{Ns}{m^2}\right]$.

For IGAS=1, the helium viscosity is returned. Otherwise, for TYPINGR='air', three gases are used, or for TYPINGR='water', six gases are loaded (see Appendix D). Function VISGAS is then called to obtain the mixture viscosities.

Function VISGAS computes the component viscosities of up to six gases and then calls Function VISMIX to solve for the mixture viscosities. This function is generally called by Function VISGSPK.

Function VISMIX will compute mixture viscosities from given component viscosities, volume fractions, and mole masses, using Equation D-13. This function is generally called by VISGAS.

<u>Functions</u>	<u>VISHEL</u>
	<u>VISCO</u>
	<u>VISCO2</u>
	<u>VISAIR</u>
	<u>VISH2</u>
	<u>VISH2O</u>

Compute the component viscosities of the respective gases.

Their call sequence is as follows:

TH

where

TH	Gas temperature [K]
----	---------------------

The returned compound viscosities are in $\left[\frac{Ns}{m^2}\right]$

Thermal Conductivity Subroutines

<u>Functions</u>	<u>CONHEL</u>	compute the component thermal conductivities
	<u>CONAIR</u>	

Their call sequence is as follows:

TH

where

TH Gas temperature [K]

The returned thermal conductivities are in $[\frac{W}{mk}]$.

Function CONDGM provides a thermal conductivity for a mixture of helium and air, weighted by volume fractions. Its call sequence is as follows:

TH,NUAL,LGAS

where

TH Gas temperature [K]
NUAL Gas volume fraction array
LGAS Number of gases

The returned conductivity is in $[\frac{W}{mk}]$.

Subroutine PROPAIR

With this subroutine, we obtain within one call viscosity, thermal conductivity and Prandtl number of air.

4.2.9 MATLAB Subroutines

MATLIB subroutines contain solid material property routines for various materials used in the thermal analysis of MHTGRs.

The properties of primary interest are thermal conductivities k and thermal capacitances ρc . The main function of the library PROPTY contains all material properties as entries.

All inputs and outputs are in SI units, i.e.,
Temperatures (input) [K]
Thermal conductivities [W/mK]
Specific heat [J/kgK]
Density [kg/m³]
Thermal capacitance (ρc) [J/m³K]

All property calls, unless otherwise noted, are functions with a single-call argument, the temperature.

The following functions for graphite thermal conductivities are available:

CONRDGR	H327 radial
CONAXGR	H327 axial
CONRDG2	H451 radial (based on LTR-3 data)
CONAXG2	H451 axial (based on LTR-3 data)
CON4RU	H451 radial unirradiated*
CON4RD	H451 radial irradiated*
CON4AU	H451 axial unirradiated*
CON4AD	H451 axial irradiated*
CONFERU	effective radial conductivity of unirradiated H451 fuel element*
CONFERD	effective radial conductivity of irradiated H451 fuel element*
CONR20F	radial conductivity of stack pole 2020 graphite*
CONA20F	axial conductivity of stack pole 2020 graphite*

The following functions for graphite specific heat are available:

CPGREX	older exponential fit for graphite specific heat
CPGRAF	polynomial fit for graphite specific heat (preferred correlation)

The following function for thermal conductivity of boronated graphite pellets (upper plenum elements) is available:

CONBORG	Boronated graphite pellets*
---------	-----------------------------

The following data for steel are available:

General carbon steel:

CONCS	thermal conductivity
ROCCS	thermal capacitance

Medium carbon steel (reactor vessel):

CONMCS	thermal conductivity
ROCMCS	thermal capacitance

Alloy 800 (core barrel, upper plenum shroud):

CON800	thermal conductivity
ROC800	thermal capacitance

General Alloyed Steel (currently not used):

CONALST	thermal conductivity
ROCALST	thermal capacitance

*GA-proprietary information; not available at all installations

Hastelloy-X Alloy:

CONHA	thermal conductivity
ROCHA	thermal capacitance

The following data for insulating materials are available:

Kao wool fiber mats:

CONKA	thermal conductivity
ROCKA	thermal capacitance

Alumina (core floor):

CONALU	thermal conductivity
ROCALU	thermal capacitance

The following functions for concrete are available:

CONCC	thermal conductivity
ROCCC	thermal capacitance

The following data for fuel are available (GA-A12985):

CONFUEL	thermal conductivity
CPFUEL	specific heat

Other entries are as follows:

CONRAD	effective thermal conductivity for radiation in axial direction in coolant holes (contribution is small at all temperature levels of MHTGRs.
CONPEB	effective thermal conductivity of a pebble bed. (not used)

Subroutine COND45 is only executed on first-call to any of the H451 graphite conductivity routines to initialize the corresponding data arrays.

Function CON451A, with entries CON451R and CONFER, combines the corresponding unirradiated and irradiated conductivities by linear combination, depending on the damage parameter DAM.

The call sequence is as follows:

TH,DAM

where

TH	temperature [I]
----	-----------------

DAM

damage parameter (Section 8-3).

Subroutine TBLLKER is no longer used and will be deleted with the next revision (use TBLLKF, see Section 4.2.6).

4.2.10 THPROCS Subroutines

The THPROCS submodule post-processes THATCH output files, extracts and summarizes results in various tables, searches for peak fuel and vessel temperatures, computes gas inventories, and produces condensed output files for plotting.

Its effective main program is Subroutine THPROCS, which reads the input data (see Section 5.3) to control post-processing runs. Up to nine THATCH output files can be handled in one run. The files can be either sequential in time or parallel (i.e., for the same time period.) If PROCESS=true on the first input data record, then routine PROCRAW is called for post-processing of the output file(s), and writing of a plot file, in the format of Table 4-15.

Depending on the time points found and on the NPTS specified on the second input record, the plot file created by PROCRAW may be condensed by a call to FCOND. If COMB=true was specified on the first input record, the files are considered to be sequential, and the plot files produced by PROCRAW will be combined into a single plot file. If Plot=true was specified, plots can be produced via call to FILEPLT, which calls on DISSPLA to produce plots (This option is currently only available at BNL).

Subroutine PROCRAW is the main routine for post-processing. It is called from a loop in THPROCS, with one call for each output file to be processed. Its call sequence is as follows:

IIN,IOUT,IFLOW,IKIN,TSTART,TEND,TSTEP,ILEVOUT,NTPSCR1,NTPSCR2,NTPSCR3,
AIRCOL,PTKINS,FLOXI,WRK,IDWRK,IREFCMX,TTMPWRT

where

IIN	File number for THATCH output file to be processed
IOUT	File number for plot file to be produced
IFLOW	File number for FLOXI temperature file to be produced
IKIN	File number for output file of fine step point kinetics data to be processed
TSTART,TEND	Start and end time for processing of files to be processed [hr]
TSTEP	Desired time increment between steps [hr]
ILEVOUT	Printed output control (larger entries produce more data tables)
NTPSCR1,NTPSCR2, NTPSCR3	Identifiers for scratch files
AIRCOL	Logical variable from second input record (PASCOL was used)
PTKINS	Logical variable from second input record (PKIN was used)
FLOXI	Logical variable from second input record (FLOXI was used)
WRK	Work space
IDWRK	Dimension of work space
IREFCMX	Maximum length of Y-vector on time records of plot files

Table 4-15

Records on THPROCS Plot Files

Record No.	Content
1	Title (Character * 240)
2	IREC, NOREC
3 TO (2 + NOREC)	JNO, TIME, (Y(I),I=1,IREC)

where the contents of the Y-vector are as follows:

Location	Variable	Units	Description
1-16 17-32 33-36	THAVA THMAX QENV	°C °C MW	Block average temperatures for Blocks 1-16 Block maximum temperatures for Blocks 1-16 Conductive heat flow across four envelopes 1 = active core 2 = total core 3 = vessel 4 = to RCCS
37 38 39	QTOSOLD QQAFTTOT QFLXTOT	MW MW MW	Total heat flow to solid Decay heat plus fission power Total convection and chemical reaction heat to solid
40-51 52 53 54 55 56	GASA GASVESL GASCAV GASCOR GASUPL GASBOT	kmol kmol kmol kmol kmol kmol	Gas inventory array (see Table 4-18) Gas inventory, reactor vessel (sum of 1 to 9) Gas inventory, reactor cavity (sum of 10 to 12) Gas inventory, core (sum of 1 to 3) Gas inventory, upper head region (sum of 4 & 6) Gas inventory, bottom region (sum of 8 & 9)
57-60	FRCHT	--	Volume fraction of active core exceeding 1000, 1200, 1400 & 1600°C
61 62 63 64	WAIR THAIREX THGVEAV THGCAAV	kg/s °C °C °C	RCCS air flow RCCS air exit temperature Average gas temperature in reactor vessel Average gas temperature in reactor cavity

Table 4-15 (Cont'd)

Location	Variable	Units	Description
65	Y_1		Point kinetics vector variable P/P_o
66	Y_9		Point kinetics vector variable X/X_o
67	Y_{11}		Point kinetics vector variable Sm/Sm_o
68	Y_{15}		Point kinetics vector variable $\Sigma\rho_{core}$
69	Y_{16}		Point kinetics vector variable ρ_{refl}
70	Y_{17}		Point kinetics vector variable ρ_{xen}
71	Y_{18}		Point kinetics vector variable $\Sigma\rho$
The following five entries are only valid for THATCH runs without functioning RCCS:			
72	THAVA (KCONTOP)	°C	Average temperature of concrete top slab
73	THMAX (KCONTOP)	°C	Maximum temperature of concrete top slab
74	THAVA (KCONSID)	°C	Average temperature of concrete side wall
75	THMAX (KCONSID)	°C	Maximum temperature of concrete side wall
76	TH(IVSSUP,JVSSUP)	°C	Concrete temperature of vessel supports
77	Y_{23}		Point kinetics vector variable ρ_{wat}
78	$Y_{15} + Y_{16}$		Point kinetics vector variable $\rho_{core} + \rho_{refl}$
79	THPKFUEL	°C	Peak fuel temperature (not a SYMELAN value but approximation only)
80	WWAT	kg/s	RCCS water flow
81	THWATC	°C	RCCS water cold leg temperature
82	THWATH	°C	RCCS water hot leg temperature

TTMPWRT Time [hr] which when set > 0 will cause temperature field at TTMPWRT to be written to File 96 in initial temperature file format.

Subroutine PROCRAW calls for internal gas volume computations and reading of the files to be processed. It affects computation of average temperatures, peak temperatures and gas inventories, and writes the files shown in Table 4-16 (see also Table 4-17).

Subroutine READTOP (IIN, FLOXI, IDEBUG) reads the header records of the the THATCH output file as described in Table 4-3. If FLOXI =true, the corresponding FLOXI record of the header section is also read.

Subroutine READTIM reads the time records from the output file of THATCH, as described in Table 4-4. The call sequence is as follows:

TIME,IIN,FLOXI,AIRCOL,PTKINS,SURFPRT,IDEBUG

where

Time	time [hr]
IIN	file number of THATCH output file to be processed
AIRCOL	logical variable from second input record (PASCOL was used)
PTKINS	logical variable from second input record (PKIN was used)
FLOXI	logical variable from second input record (FLOXI was used)
SURFPRT	logical debug control of surface temperature printing
IDEBUG	debug print control

Subroutine VOLCOMP (IDEBUG) computes the gas volumes for various sections of the reactor vessel and the reactor cavity. These data are then used to compute based on system pressure and section temperature the gas inventory in the reactor vessel as a function of time.

Table 4-18 lists the sections and the computed volumes, based on PSID design data. Some of the computations use "hard-wired" design data included in Block Data CORVDAT.

Block Data CORVDAT contains core design data used in the above gas volume computations (VOLCOMP).

Subroutine GASINVT (TIME, AIRCOL, IDEBUG) computes the gas inventory in the reactor vessel and reactor cavity volumes of Table 4-18 based on system pressure and component temperatures. For most components with rather stagnant gas masses, the average temperature of gas is well-approximated by the average of the component solid surface temperatures, which is used to compute the gas inventory.

Subroutine THAVMAX (IDEBUG) computes for each solid block the volume weighted average temperature and determines the maximum temperature of the nodes in the block.

Table 4-16
Output Files Produced in Post-Processing of
THATCH Output Files

File	File No.	File Record Format	Remarks
THATCH plot file	21 ff	Table 4-15	
FLOXI plot file	21 ff	Plot file format; for Y-vector see Table 4-9	if FLOXI=true; records are added to THATCH plot file as records 101 to 159
Temperature file for free-standing FLOXI runs	41 ff	Table 4-17	
Fine-step point kinetics plot file	71 ff	Plot file format; six Y-vector entries from point kinetics vector: $Y_1, Y_9, Y_{11}, Y_{12}, Y_{20}, Y_{20} + Y_{21}$	

Table 4-17
Records on THPROCS Temperature Output File for
Free Standing FLOXI Runs

Record Number	Content
Top Only:	
1	Title (Character *240)
2	IMAXP, JMAXP
3	(RIFA(I),I=1,IMAX
4	(ZIFA(J),J=1,JMAX)
One Set of Record per Time Step:	
5	Time
6	IMAXP records: (TH(I,J)J=1,JMAXP)

Table 4-18

Gas Volumes in Reactor Vessel and Reactor Cavity

Index Reactor Vessel:	Volume	V [m ³]
1	Active Core	10.98
2	Top reflectors and plenum elements	2.20
3	Bottom reflectors	2.49
4	Upper plenum	51.70
5	Lower plenum	23.78
6	Upper plenum shroud to vessel gap	22.10
7	Core barrel to vessel gap	68.52
8	Core support structure	32.90
9	Bottom plenum & SCS	59.50
	SUM VESSEL	274.18
Reactor Cavity:		
10	Top	285.00
11	Center	313.20
12	Bottom	270.00
	SUM CAVITY	868.20

Subroutine PEAKER0 (TIME, IDEBUG), with entry PEAKER, searches for active core and reactor vessel whether the block maximum temperature, varying in time, has reached a temporal maximum, referred to here as "peak" temperature. If so, a flag is printed.

Furthermore, the conductive heat flow across four envelopes (entries 33 to 36 in Table 4-15) is compared against total heat flow to solid in the core, and when the heat flow across the envelope exceeds the heat flow to the solid, a "cross-over point" message is printed.

Subroutine OUPPUT will produce further printed output tables, as requested. Its call sequence is as follows:

ILEVOUT,ITPINT,ITPFLX,FLOXI,AIRCOL,PTKINS,WRK,IDWRK,IDEBUG

where

ILEVOUT	printed output control (larger entries produce more data tables)
ITPINT	file number of file containing data to be printed
ITPFLX	file number of FLOXI plot output file
FLOXI	logical variable from second input record (FLOXI was used)
AIRCOL	logical variable from second input record (PASCOL was used)
PTKINS	logical variable from second input record (PKIN was used)
WRK	work space
IDWRK	dimension of WRK
IDEBUG	debug print control

Subroutine PTKOUT reads the fine time step point kinetics output file produced by THATCH, prints output from it, and writes a brief plot file, as noted in Table 4-16. Its call sequence is as follows:

TSTART,TEND,IKIN,TITLE,WRK,IDWRK,NTPSCR3,IREFCMX,IDEBUG

where

TSTART,TEND	start and end time for processing of files to be processed [hr]
IKIN	file number for fine step point kinetics output file to be processed
TITLE	run title (Character * 240)
WRK	work space
IDWRK	dimension of WRK
NTPSCR3	identifiers for scratch files
IREFCMX	maximum length of Y-vector on time records of plot files
IDEBUG	debug period control

Subroutine THFLPLT (NTPTH,NTPFL,NTPOUT,WRK,IDWRK,IDEBUG) combines the THATCH plot file NTPTH and the FLOXI plot file NTPFL in File NTPOUT, adding the FLOXI records in positions 101 to 159. The routine also does several data conversions (temperatures from units K to °C, mass flows from kg/s to kg/hr, so that it is specific to the current FLOXI plot file format (see Section 4.2.3) and would require revisions if that section changes.

Block Data PLOTDAT contains values of π and DEGK = 273.15.

At this time, the THPROCS post-processor does contain some "hard-wired" entries of data, characterizing the current model of the commercial MHTGR. Such entries will be removed with the next code revision. For that purpose, and as caution to the user, they are listed here.

<u>ROUTINE</u>	<u>LOCATION</u>	<u>DATA</u>
PROCRAW	ISN26-31	PASCOL Data JAIRFST, JAIRLST NFL, NFL2
PROCRAW	ISN3	Parameter statements setting block numbers (KCORE=2, etc.)
CORVDAT	all	Block data for core volume computations
THFLPLOT		Plot variable unit conversions are hard wired and would cause problems if nodalization changed. Also, they assume mass flows <u>are</u> in kg/s, which is not necessarily true in FLOXI; see FLOXI input variable PRTCTRL on Input Record 3212D.

4.2.11 THRADLIB Subroutines

The THRADLIB subroutines constitute a separate module which is executed by calling subroutine THRAD, the effective main program of this module, which serves as pre-processor to obtain the necessary radiation coefficient matrices for two-dimensional radiation in plena and cavities.

Subroutine THRAD initializes the pre-processor and controls the calls to the various routines for view factors and radiation coefficient routines. Input to this routine is still via Namelist reading of Namelist INPUT, as described in Section 5.2 (The THATCH input data processor should replace this in the near future). Depending on input variable GEOM, either view factors and radiation coefficients for a cylindrical cavity or for an annular cylindrical cavity will be computed.

For view factor computations, either subroutine VIEWFAC or subroutine ANVIEW are called to obtain the view factors for cylindrical cavities or annular cylindrical cavities, respectively. Thereafter, the algebra of Appendix A is executed to obtain the LAMBDA-matrix of radiation coefficients to be used in THATCH. After some printouts with consistency checks, the LAMBDA-matrix is written to File 8 for later use as an input file to THATCH.

Subroutine VIEWFAC (F,X,NIS,IDIM,NRA,RA,NZA,ZA,AA,EMMIS) computes the view factors for a cylindrical cavity as described in Section B-1.

F	view factor array dimensioned IDIMxIDIM (output)
X	geometry array dimensioned IDIMx6 (output), where each surface is designated by coordinates R1,R2,H1,H2, where R is radius, and H is height (or z-coordinate).

	$X(N,1) = r_1$ coordinate
	$X(N,2) = r_2$ coordinate
	$X(N,3) = z_1$ coordinate
	$X(N,4) = z_2$ coordinate
	$X(N,5) =$ node type (= 1 flat annular or disk; = 2 side wall cylinder)
	$X(N,6) =$ surface area
NIS	is the number of surface elements in the cavity (input)
NRA	number of radial surface elements on top and bottom disks (input)
RA	radial coordinates (input)
NZA	number of surface elements (rings) on cylinder side walls (input)
ZA	axial coordinates (input)
AA	surface area array of surface elements (output)
EMMIS	thermal emissivity array of surface elements (input)

After computing the above geometric coordinates of each surface element, VIEWFAC determines an index, IQ, for the interaction between any two surfaces.

IQ	
1	Flat disks or annuli in same plane ($F_{ij}=0$)
2	Side-wall cylinders onto themselves
3	Annuli or disks to opposite side annuli or disks
4	Side-wall cylinders to annuli or disks
5	Annuli or disks to side-wall cylinders
6	Side-wall cylinders to side-wall cylinders.

For each of these, the required algebra is then executed calling on routine FDISK12, which represents Equation (B-5). Upon completion of all view factor computations they are checked against Equation (B-2) for consistency.

Subroutine ANVIEW (ZAO,JOMX,ZAI,JIMX,RA,NRA,AA,FF,IRAD,IDIMFF,IPRINT)
controls the computing of view factors for annular cylindrical cavities.

ZAO and ZAI	axial coordinates on the outer and inner cylinder
JOMX and JIMX	the number of node intervals in ZAO and ZAI (ZAO and ZAI arrays range from 0:JOMX or JIMX)
RA and NRA	the radial coordinates (same for top and bottom annuli), with NRA being the number of entries (Currently, ANVIEW requires NRA = 1, i.e. single top and bottom annuli. This restriction could be removed easily.)
AA	surface area of nodes (output)
FF	view factor array dimensioned IDIMFFxIDIMFF (output)
IRAD	number of nodes in cavity (input)
IDIMFF	leading dimension of FF array
IPRINT	output print control

Function KTYPE (ZO1,ZO2,ZI1,ZI2) facilitates the view factor computation for arbitrary cylindrical rings on the outer and inner surfaces of the cavity, where ZO1, ZO2, ZI1, and ZI2 are the coordinates of the two rings. The following are the returned types:

KTYPE=0	rings exactly opposite
=1	no overlap
=11	inner ring is larger and envelopes outer ring
=12	outer ring is larger and envelopes inner ring
=13	partial overlap

The various functions for specific view factors, required to complete the view factor array of the annular cylindrical cavity, are summarized in Table 4-19.

These routines follow the formulas of Appendix B and include the corresponding asymptotic approximations where some parameters get small or large.

Functions ASINF(X), ACOSF(X) and ATANF(X) compute the corresponding trigonometric functions, but branch for $x < 10^{-4}$ to the corresponding asymptotic approximations.

4.3 Code Maintenance via UPDATE/HISTORIAN

The THATCH code is stored in an UPDATE compatible program library format. Currently, it is installed on both the INEL CRAY and the BNL IBM 3090. The submodule codes (SYMELL, PASCOL, FLOXI and PKIN) and the auxiliary codes (MATLIB, GENLIB, GASPRLIB, THRADLIB and THPROCS) are stored in a similar manner in a second library.

The codes at all installations should be maintained by a single administrator (the only user with read/write authorization, see Section 10). All other authorized users should be granted read only access. For example, at INEL users belonging to the NPR group may read from either library, but may not alter them. This type of program management is essential maintaining the integrity of any code.

All system-dependent coding has been conditionally included in the program libraries at both sites to maintain line for line compatibility between all installed versions of the code automatically generated at each installation.

4.4 THATCH AND BIG COMMONS

The two code sections are maintained in separate component files, with no Commons being used jointly. Within each component, all Commons are in COMDECKS, following the format requirements for Update/Historian.

In many of the large THATCH Commons, additional dummy COMDECKS are available to provide nomenclature to these Common decks. These are customarily listed in the THATCH main program and are generally not repeated later in the code.

Throughout THATCH and BIG, all Commons must always have identical variable names and identical lengths, to provide traceability and reduce possibilities for inadvertent errors.

Table E-3 lists of all Commons used in THATCH and the routines using it. The same list for component BIG is given in Table E-4.

Table 4-19
View Factor Subroutines for Surface Elements
in Annular Cylindrical Cavities

Function	View Factor	Argument List	Equation
FDISK12	Two parallel concentric disks	R1,R2,Z disk radii and distance between disks	B-5
FANDISK	Two annular concentric disks, exactly opposite	R1,R2,H inner and outer radii and distance between rings	B-7
FOIF	Outer to inner cylinder rings exactly opposite	RI,RO,H inner and outer radii, ring height	B-9
FOOF	Outer cylinder ring onto itself	RI,RO,H inner and outer radii, ring height	B-10
FOAOF	Outer cylinder ring onto adjacent outer cylinder ring	RI,RO,H ₁ ,H ₂ inner and outer radii, ring heights	uses several FOOF calls
FONAOF	Outer cylinder ring onto non-adjacent outer cylinder ring	RI,RO,H ₁ ,HM,H ₂ inner and outer radii, ring height1, ring distance, ring height2	uses FOAOF calls
FOAAF	Outer cylinder ring onto adjacent annular disk	RI,RO,H inner and outer radii, ring height	uses FOIF and FOOF
FONAAF	Outer cylinder ring onto non-adjacent annular disk (vertical separation)	RI,RO,H,HM inner and outer radii, ring height, separating distance	uses FOAAF
FIAAF	Inner cylinder ring onto adjacent annular disk	RI,RO,H inner and outer radii, ring height	uses FOIF

Table 4-19 (Cont'd)

Function	View Factor	Argument List	Equation
FINAAF	Inner cylinder ring onto non-adjacent annular disk (vertical separation)	RI, RO, H, HM inner and outer radii, ring height, separating distance	uses FIAAF
FOAIF	Outer cylinder ring onto inner cylinder ring, adjacent to each other with respect to axial coordinate	RI, RO, HO, HI inner and outer radii, outer and inner ring heights	uses FOAAF FONAAF FOAOF

5. INPUT DATA DESCRIPTION FOR THATCH AND ITS SUBMODULES

5.1 Input to THATCH Runs, Including THATCH Submodules

5.1.1 THATCH Input Processor

The THATCH input data is processed by a version of the GENRD [Cox, 1972] input processor, which was originally developed at Los Alamos National Laboratory. GENRD interprets free-format alphanumeric data from 80 byte card-image records. The input is free-format in the sense that field location, field length, and type of conversion are determined solely by the user, not by an external format.

In addition to data processed by GENRD, the THATCH input processor will accept as comment, records which begin with the character string 'C' (bytes 1 through 3). These records are subsequently ignored by the input processor. As a result, they may be injected at any point within the data file. Comment may also be entered on data records processed by GENRD. One method is to use the construct

<data> \$...comment...\$ <data>

anywhere on a data record. This method, while perfectly acceptable, is somewhat less efficient than the alternate construct

<data> /...comment...

where there is no data following the comment on the record.

THATCH INPUT FILE STRUCTURE

The THATCH input file structure is based on a serial model, where all repeating records are of the same type (DATA RECORD). The overall structure of the THATCH input file is:

FILE
<BOI> --> IDENTIFICATION --> DATA <--> 'STOP'
RECORD RECORD(s)

where

FILE IDENTIFICATION RECORD: FILE VERSION NUMBER --> 'V' --> b --> 'THATCH'

and

DATA RECORD: RECORD IDENTIFIER --> 'D' --> b --> DATA-LIST

The file identification record is the first record processed. On this record, the file version number is the only entry defined by the user. It may be assigned any positive integer value; it is a simple means of identifying data sets and has no significance to the functioning of the code. A typical THATCH file identification record would be:

1V THATCH

It should be noted that GENRD is case-sensitive. All of its control information must be in its upper case. In particular, lower case 'V's and 'D's will not be processed properly.

All of the THATCH data processed by GENRD is read from data type records. For data to be properly defined, each data record is assigned a unique record identifier, which implicitly defines the sequence of data entries which constitute the record's data-list. The data-lists for each of the THATCH data records is presented later in this section.

Each data record is processed completely before the next record is interpreted. A data record

is defined to have a maximum length equal to one or more card-image records (80 characters). It is terminated either by a slash (/), or by the beginning of another data record, or a STOP record (a record containing the string "STOP"). Information following a slash is not processed and may be used as a comment. From each record, GENRD parses information into discrete numeric and/or character packets. A comma and/or one or more blanks separates numeric information, which may be either a single-valued decimal constant, or a specification calling for the repetition of numeric constants. Character information is delimited by single quote marks and may contain any alphanumeric character, except the single quote mark. Character constants may not span a card-image record. If a terminal quote mark is omitted, the string is terminated at the record boundary (this method of terminating a character string may cause blank characters to be added to the end of the intended string). Logical constants, while similar to character constants, form a distinct third type of data. Logical constants may assume one of two values (TRUE and FALSE) and are delimited by periods. If an error is detected, a message describing the error is printed, processing of the current field is halted, and the next field on the record is read and processed.

GENRD provides a simple shorthand for the repetition of one or more numeric constants. The repeat (R) specification provides this function for any sequence of real and/or integer values. For example,

1.2,3R

is equivalent to

1.2, 1.2, 1.2

and

(0.1, 2.3, 456.78, 9.0),4R

is equivalent to

0.1, 2.3, 456.78, 9.0, 0.1, 2.3, 456.78, 9.0, 0.1, 2.3, 456.78, 9.0, 0.1, 2.3, 456.78, 9.0

5.1.2 Input Record Description

The input records for the THATCH code are described in the following pages, in tabular format, including variable names and variable types as well as units, where applicable. In Group 3, of the THATCH Main Module Input Data a unified input option can be specified. If this option is chosen, various inputs for THATCH and its submodules are provided from a set of data bank subroutines, with data for the commercial MHTGR as described in the PSID. This option also assures that identical data are used by THATCH and its submodules. If this option is used, some variable entries from the normal input stream will be disregarded. In the list which follows, those variables are marked with "*".

DESCRIPTION OF THATCH MAIN MODULE INPUT DATA

Record	Variable Name	Variable Type	Description	Units
<u>Group 1 - Run Title</u>				
101D	TITLE	C	THATCH run title line 1	--
102D	TITLE	C	THATCH run title line 2	--
103D	TITLE	C	THATCH run title line 3	--
<u>Group 2 - Run and Submodule Control Options</u>				
201D	FLOXI	L	Controls use of the FLOXI module for flow, convective heat transfer, and oxidation calculations.	--
	STEADY	L	Designates the run as a full-power, steady-state run to obtain an initial temperature file (Steady-state runs require the use of the FLOXI module, and if FLOXI is set to false, then STEADY will be set to false).	--
	SYMELL	L	Causes the gas and solid temperatures of the active core region (IAFTLO to IAFTHI, and JAFTLO to JAFTHI) to be evaluated by the SYMELAN code instead of by THATCH.	--
202D	PKINL	L	Controls use of point kinetics module PKIN, (if PKIN=true, point kinetics module is to be used; in that case, JOPHTG of record 1101D will be set =2).	--
	RECOMPT	L	If true, then the conductance coefficients in the iterative point kinetics and core-temperature loop in routine TEMPSOL will be recomputed within each iteration. Otherwise, they are only recomputed in the first iteration of each time step.	--

Record	Variable Name	Variable Type	Description	Units
<u>Group 3 - Unified Input Option</u>				
301D	UNIFIN	L	Controls the use of the unified input option. If specified as false, the remainder of Group 3 records need not be specified.	--
302D	IR1	I	Initial radial interface point (must be 0 for current THATCH radial interface array)	--
	SPACING	C	Node ring distribution parameter (If SPACING = 'AREA', then within each of the five sections of record 303D, all nodes will have equal cross section area. If SPACING = "DELR", then the radial node width will be equal)	--
	SMEAR		If the inner radial power zone has 2 nodes and if SPACING = 'AREA' and SMEAR = false, then the inner node ring of the inner radial power zone will have a reduced number of fuel axial coolant holes, corresponding to the Reserve Shutdown Control holes in this region. Otherwise, this effect will be "smeared out" over the nodes of the inner radial power zone.	--
303D	NONO	I	Five-position array of number of radial nodes for Central Reflector; Radial Core Power Region 1; Radial Core Power Region 2; Radial Core Power Region 3; Side Reflector.	--
304D	JZ1	I	Axial interface number at the top of the active core	--
	NOHIM	I	Number of axial nodes per fuel element	--
	NOTRM & NOBRM	I I	Axial node numbers for top and bottom reflectors, in multiples of four (i.e., entry of 1 means 4 axial nodes, etc.).	--

Record	Variable Name	Variable Type	Description	Units
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The following four records describe the axial and radial power profile options to be used. Each record contains the number of power zones and a character variable, either "D" for decay heat or "F" for fission power.

305D	LPOWR1 TYPWR1	I C	Description of base radial power profile	--
306D	LPOWR2 TYPWR2	I C	Description of point kinetics radial power profile	--
307D	LPOWZ1 TYPWZ1	I	Description of base axial power profile	--
308D	LPOWZ2 TYPWZ2	I C	Description of point kinetics axial power profile	--

The following specifications of power profiles are currently permitted:

Radial power zones	
1 'D'	(uniform power)
1 'F'	(uniform power)
3 'F'	
Axial power zones	
1 'D'	(uniform power)
1 'F'	(uniform power)
3 'F'	
10 'D'	
10 'F'	

For runs without point kinetics, only decay heat power profiles are required; records 306D and 308D can specify the integer 0, to signify that these are not used.

Record	Variable Name	Variable Type	Description	Units
<u>Group 4 - I/O Units</u>				
401D	INGUNIT	C	Input Units for reactor dimensions ('M', 'CM', 'IN', 'FT' or 1 word (max. 10 char.) users units). These units are used for all lengths to be specified in the THATCH main module. All submodules require lengths to be specified in [m].	--
402D	GEOCONV	F	If users units are specified, this record defines the conversion (multiplication) factor required to convert user units to meters. If units are M, CM, IN, or FT, then this record can be omitted.	--
403D	INTUNIT	C	'C' or 'F'. Temperature <u>input</u> units for the THATCH main module (all temperature data must be input in the same units). (All submodules required input temperatures to be in °C).	--
404D	ICONV	C	'C' or 'F'. Temperature <u>output</u> units (for printed output only; all plot file temperature will be °C).	--

Record	Variable Name	Variable Type	Description	Units
<u>Group 5 - Geometry</u>				
The node point and interface numbering convention is schematically shown in Figure 3-1.				
501D	IL	I	Number of Radial Interface points to be entered (optional) *	--
502D	RIFA	F	Radial Interface values 0*	** m
503D	RNOD (1,1)	F	Radial Node Point 1 (Centerline or sink node) *	--
504D	JL	I	Number of Axial Interface points to be entered (optional)*	--
505D	ZIFA	F	Axial Interface values. *	** m

*Record will be disregarded if UNIFIN=true was specified on Record 301D

**or as specified on Record 401D

Record	Variable Name	Variable Type	Description	Units
<u>Group 6 - Description of Node Blocks</u>				
601D	NBLOCK	I	Number of Node Blocks to be defined (optional)	--
			Records 602D to 607D are repeated for each block.	
602D	L	I	Block number	--
	BLKTIT	C	Name and description of block (up to 30 characters for the name, plus 30 more for the description)	--
603D	L	I	Block number	--
	ILO	I	Low-Radial Boundary Interface Number	--
	IHI	I	High-Radial Boundary Interface Number	--
	JLO	I	Low-Axial Boundary Interface Number	--
	JHI	I	High-Axial Boundary Interface Number	--
	MATINDX	I	Material Index Number (1 to 99 for solid blocks) or Radiation Plenum Number + 100	--

Record	Variable Name	Variable Type	Description	Units
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Description of block boundary for non-plenum blocks. See Fig. 3-3 for block surface designations. Omit records 604D to 649D for Radiation Plenum Blocks.

Face 1: Low Axial Boundary Data (top face of block):

604D	L	I	Block number	--
	INBND (1,M)	I	Boundary number	--
	INBND (2,M)	I	Low-node number for range of specified boundary	--
	INBND (3,M)	I	High-node number for range of specified boundary	--

Face 2: High-Radial Boundary Data (radially outer face of block):

605D	L	I	Block number	--
	INBND (1,M)	I	Boundary number	--
	INBND (2,M)	I	Low-node number for range of specified boundary	--
	INBND (3,M)	I	High-node number for range of specified boundary	--

Record	Variable Name	Variable Type	Description	Units
Face 3: High-Axial Boundary Data (bottom face of block):				
606D	L	I	Block number	--
	INBND (1,M)	I	Boundary number	--
	INBND (2,M)	I	Low-node number for range of specified boundary	--
	INBND (3,M)	I	High-node number for range of specified boundary	--
Face 4: Low-Radial Boundary Data (radially inner face of block)				
607D	L	I	Block number	--
	INBND (1,M)	I	Boundary number	--
	INBND (2,M)	I	Low-node number for range of specified boundary	--
	INBND (3,M)	I	High-node number for range of specified boundary	--

(Note: "Radial" boundaries are at one constant radius and extend in axial direction. "Axial" boundaries are at a constant axial coordinate and extend in radial direction.)

In records 604D to 607D, each record can have up to 12 sets of 3 integers each, specifying a boundary and its extent. If the whole face is one boundary number, then only the boundary number need be specified, i.e., one integer only. If a block boundary has already been specified as part of the input for another block, then the record may be omitted. Note that the boundary number delimiters here are the first and last node numbers and not the interface numbers, i.e., for boundary No. 1 to extend from Interface 1 to 5 and boundary 2 from Interface 5 to 10 we enter 1, 2, 5, 2, 6, 10.

Plenum Geometry Description:

For multi-dimensional plena (material index number = radiation plenum number + 100), add the following record:

Record	Variable Name	Variable Type	Description	Units
651D	L	I	Block number	--
	GEOM	C	Plena 2-d radiation geometry identifier; 'CYLIN' for cylindrical plena, or 'ANCYL' for annular cylinders.	--

Record	Variable Name	Variable Type	Description	Units
Group 7 - Plena Radiation Computation Control				
701D	METHRAD	L	Method for solution of simultaneous equations ('LINEAR', 'NEWTON', or 'ZERORAD')	--
	EPSQ	F	Convergence criterion on heat flow	--
	EPSTH	F	Convergence criterion on temperature	--
	NITMAX	I	Maximum number of iterations to be tried per pass through RADTN	--
	FRLX0 FRLXMIN	F F	Two numerical relaxation factors (in linear iteration, the first is the initial underrelaxation factor, and the second is the minimum value of underrelaxation. For the Newton method, the first is the maximum permitted fractional change for any variable per iteration. For the ZERORAD method, neither factor is used. The data specified will apply to all plena in the model.	--
702D	UPLCONV	L	To activate the option for upper-plenum convective heat transfer (in addition to 2-d radiation)	--
	XNUCOF	F	An arbitrary reduction coefficient for the upper plenum convective heat transfer coefficient (generally 1.0).	--

Group 8 - Specification of Additional Boundaries

To permit additional thermal resistances within the geometry of a block further axial and/or radial boundaries can be specified in this section. (Note: "Radial" boundaries are at one constant radius and extend in axial direction. "Axial" boundaries are at a constant axial coordinate and extend in radial direction.)

801D	NORADAD	I	Number of additional radial boundaries (optional)	--
802D	N	I	Additional boundary index	--
	NBND	I	Boundary number	--
	I	I	Radial interface number	--
	J1	I	Low-axial node number	--
	J2	I	High-axial node number	--
803D	NOAXAD	I	Number of additional axial boundaries (optional)	--
804D	N	I	Additional boundary index	--
	NBND	I	Boundary number	--
	J	I	Axial interface number	--
	I1	I	Low-radial node number	--
	I2	I	High-radial node number	--

Record	Variable Name	Variable Type	Description	Units
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Group 9 - Boundary Definition

(Note: "Radial" boundaries are at one constant radius and extend in axial direction. "Axial" boundaries are at a constant axial coordinate and extend in radial direction).

a) Radial Boundaries (Group 9a)

1 record of 6 entries per radial boundary specified in Groups 6 or 8.

901D	N	I	Boundary number	--
IBINDX	(N,1)	I	Boundary type number (see Table 5-1)	--
IBINDX	(N,2)	I	Gap material index (101 to 199 or 0 if not applicable)	--
BNDRA	(N,1)	F	Gap thickness	** m
BNDRA	(N,2)	F	Effective emissivity	--
BNDRA	(N,3)	F	Heat transfer coefficient	W/mK

**or as specified on record 401D

(Note: gap thickness must be entered in the same units as the Geometry data - see Group 5, but heat transfer coefficients must be entered in SI units). Gaps are always considered to be on the outside of a block in increasing coordinate direction, i.e., if Block 1 extended from 0.2 m to 0.6 m and were followed by Block 2 extending from 0.6 m to 0.8 m, and the separating boundary were specified to have a gap of 0.04m, then the solid material of Block 1 extends from 0.2 m to 0.56m, followed by a .04 m gap and by Block 2 extending from 0.6 m to 0.8 m.

Record	Variable Name	Variable Type	Description	Units
			b) Axial Boundaries (Group 9b).	
			1 record of 6 entries per axial boundary specified in Groups 6 or 8.	
902D	N	I	Boundary number	--
	JBINDX (N,1)	I	Boundary type number (see Table 5-1)	--
	JBINDX (N,2)	I	Gap material index (101 to 199 or 0 if not applicable)	--
	BNDAX (N,1)	F	Gap thickness	m**
	BNDAX (N,2)	F	Effective emissivity	--
	BNDAX (N,3)	F	Heat transfer coefficient	W/mk

(Note: gap thickness must be entered in the same units as the Geometry data - see Group 5, but heat transfer coefficients must be entered in SI units). Gaps are always considered to be on the outside of a block in increasing coordinate direction, i.e., if Block 1 extended from 0.2 m to 0.6 m and were followed by Block 2 extending from 0.6 m to 0.8 m, and the separating boundary were specified to have a gap of 0.04m, then the solid material of Block 1 extends from 0.2 m to 0.56m, followed by a .04 m gap and by Block 2 extending from 0.6 m to 0.8 m.

**or as specified on record 401D

TABLE 5-1

Type of Boundary Resistances:

- 1 interior; zero contact resistance
- 2 interior; finite conduction resistance
- 3 interior; conduction and 1-d radiation resistance
- 4 interior; 1-d radiation resistance
- 5 interior; insulated face
- 11 center line
- 12 exterior; insulated face on - side
- 13 exterior; insulated face on + side
- 14 exterior; prescribed heat transfer coefficient and 1-d radiation on - side
- 15 exterior; prescribed heat transfer coefficient and 1-d radiation on + side
- 21 interior; 2-d radiation
- 31 exterior air-cooled RCCS on + side
- 32 exterior water-cooled RCCS on + side

Record	Variable Name	Variable Type	Description	Units
For each boundary which includes an added layer, 2 additional input values must be specified in records 904D to 907D.				
For a layer attached to the top side of a block (i.e., low-axial position and + side of the gap):				
904D	N	I	Boundary number	--
	LAYMAT	I	Material number of added layer (1-199)	--
	DLAYER	F	Layer thickness of added layer	** m
For a layer attached to the outer radial side of a block (i.e., high radial position and - side of the gap):				
905D	N	I	Boundary number	--
	LAYMAT	I	Material number of added layer (1-199)	--
	DLAYER	F	Layer thickness of added layer	** m
For a layer attached to the bottom side of a block (i.e., high-axial position and - side of the gap):				
906D	N	I	Boundary number	--
	LAYMAT	I	Material number of added layer (1-199)	--
	DLAYER	F	Layer thickness of added layer	** m

**or as specified on record 401D

Record	Variable Name	Variable Type	Description	Units
			For a layer attached to the inner radial side of a block (i.e., low-radial position and + side of the gap):	
907D	N	I	Boundary number	--
	LAYMAT	I	Material number of added layer (1-199)	--
	DLAYER	F	Layer thickness of added layer	** m

Layer failure was used in early versions of the code which modelled cover plate failure in large HTGRs. This feature is currently not active but can be activated again. In that case, additional inputs would have to be activated in records 914D to 917D. These are currently not provided. If activated, they would have to correspond to the following format:

The Boundary Type is specified negative if failure (removal) of the layer or nodes is to be considered. For each negative boundary entry, there must be 3 or 5 extra input values. Value 1 is the failure temperature of those nodes, value 2 is the failure mode (1=node/disappear, 2=node/redeposit, 3=layer/disappear, 4=layer/redeposit), and value 3 is the node material number after failure. If the failure mode is 2 or 4 (redeposit), then there must be 2 more values; value 4 is the redeposited material number, and value 5 is the redeposited layer thickness (in the geometry input units).

**or as specified on record 401D

Record	Variable Name	Variable Type	Description	Units
<u>Group 10 - Irradiation Damage and Annealing Data</u>				
1001D	IRRADAM	L	Specifies whether core graphite irradiation damage is to be considered. For IRRADAM = false, the remainder of this section is bypassed.	--
1002D	ANNEAL	L	Specifies whether annealing during core heatup is to be considered.	--
1003D	KMATANL	I	Specifies the highest material number in subroutine PROPMAT for which annealing is to be allowed.	--
Node range for region of irradiation damage:				
1004D	IAN1	I	Low-radial node	--
	IAN2	I	High-radial node	--
	JAN1	I	Low-axial node	--
	JAN2	I	High-axial node	--
1005D	J	I	Row number:	--
	DAMPAR	F	Damage parameter array, one entry per node in radial direction	--
1006D	THDAM1	F	Beginning of temperature range over which annealing is to occur	°C
	THDAM2	F	End of temperature range over which annealing is to occur	--

Group 11 - Heat Generation and Afterheat

1101D	POW0IN	F	Initial Power	W
	TOFFHR	F	Off-set time for decay heat evaluation	hr
	PMAXAVZ	F	Axial power peaking factors	--
	PMAXAVR	F	Radial power peaking factors	--
	JOPHTG	I	Option for power profile data; if JOPHTG=1, the code will internally compute a cosine power profile using the prescribed axial and radial peaking factors of this record. (This option is currently only coded for cylindrical cores and cannot be used for annular cores.) For JOPHTG=2, power profile data must be user-supplied in records 1104D to 1107D, or they must be selected under the unified input option of Group 3.	--
1102D	IAFTLO	I	Low-radial node numbers of afterheat region	--
	IAFTHI	I	High-radial node numbers of afterheat region	--
	JAFTLO	I	Low-axial node numbers of afterheat region	--
	JAFTHI	I	High-axial node numbers of afterheat region	--

Record	Variable Name	Variable Type	Description	Units
1103D	IREFLO	I	Low-radial node numbers of reflector region	--
	IREFHI	I	High-radial node numbers of reflector region	--
	JREFLO	I	Low-axial node numbers of reflector region	--
	JREFHI	I	High-axial node numbers of reflector region.	--
Further input of radial and axial power regions for JOPHTG=2:				
1104D	PHIRA	F	Radial Base Power Profile [IAFTHI - (IAFTLO-1) entries]*	--
1105D	PHI2RA	F	Radial Point Kinetics Power Profile [IAFTHI - (IAFTLO-1) entries].* (This record only supplied if PKINL=true).	--
1106D	PHIZA	F	Axial Base Power Profile [JAFTHI - (JAFTLO-1) entries]*.	--
1107D	PHI2ZA	F	Axial Point Kinetics Power Profile [JAFTHI - (JAFTLO-1) entries].* (This record only supplied if PKINL = true).	--

*Record will be disregarded if UNIFIN=true was specified on Record 301D.

Record	Variable Name	Variable Type	Description	Units
1108D	AFTHEAT	C	After heat option, specified as character variable with the following options currently provided: 'NOML' Uses best estimate decay heat as provided in the PSID review of the MHTGR (DOE-HTGR-86-109, Rev, July 1987) 'PSID1'OR 'PSID2' Uses original decay heat data as given in Chapter 4 of the PSID (conservative). 'ANS' Uses ANS correlation as applied by KFA in Juel-1647 'LTR' Uses LTR-4 data (GA-A12499) (conservative) 'READ' User-supplied Table function (see records 1109D to 1111D) The following 3 records are only used with after heat option 'READ': 1109D IPTS I Number of points in user-supplied after-heat table (optional) 1110D PDAT1 F Times of decay heat table (first time can be very small, but must be greater than zero for log-fit). 1111D PDAT2 F After heat as a fraction of design power at times of record 1110D <u>Group 12 - Time Step, and Output Control</u> 1201D T0 F Time at start. If this value is greater than zero, then a restart input file (TAPE15) is expected. (See Section 6). 1202D NTIMES I Number of time periods to be entered (optional).	--

Record	Variable Name	Variable Type	Description	Units
1203D	IUNITS	I	Time units flag for time entries in this record (2=hours, 1=mins, 0=secs)	--
	TEND	F	End of time period	--
	DTSTEP	F	Δt (time step)	--
	DTPRNT	F	Print interval	--
	DTPLOT	F	Write interval to post-processing file.	--
<u>Group 13 - Print Formats</u>				
1301D	IBLFLD	I	Node-temperature field size (must be greater than zero and less than 21)	--
	IBLDEC	I	Number of decimal places to the right of the decimal point for node temperature output printing (> 10 then E format used) (0 will cause integer print format)	--
	IPLFLD	I	Surface-temperature field size (must be greater than zero)	--
	IPLDEC	I	Surface-temperature number of decimal places following same rule as for block temperatures. (The surface can be a plenum or a block surface).	--
<u>Group 14 - Print of Block Surface Temperatures</u>				
1401D	NBLSFPR	I	Number of block surfaces (max. 10, optional)	--
1402D	KBLSFPR(1,N) KBLSFPR(2,N)	I	Block number, and surface number for each set of block surface temperatures to be printed. (Surface: 1=N, 2=E, 3=S, 4=W, see Fig. 3-3. NBLSFPR pairs of integers must be specified)	--

Record	Variable Name	Variable Type	Description	Units
1403D	IDEBUG	I	Debug variable, controlling debug output primarily from the sub-modules =0 no debug output. Progressively higher integers trigger more output.	--
<u>Group 15 - Initial and Boundary Condition Temperatures</u>				
1501D	INPMODE	C	Control Variable for initial temperature selection	--
			= 'READRUN' Initial temperatures are read from File 27, overriding input data from this file for internal temperatures, but not for boundary temperatures.	
			= 'STEADY' Steady State Run	
			= 'OTHER'	
			Under options 'STEADY' and 'OTHER', the node temperature specified below will be used as initial temperatures.	
Boundary Temperatures:				
1502D	THSINKA	F	Top Boundary, i = 1, i _L	°C**
1503D	THSINKA	F	Side Boundary, j = 2, j _L	°C**
1504D	THSINKA	F	Bottom Boundary, i = 1, i _L	°C**
1505D	TH	F	Internal node temperatures	°C**

** or other units if so specified in Group 4 inputs

Record	Variable Name	Variable Type	Description	Units
			<p>Temperatures must be in the units specified on record 403D. The internal node temperatures can be specified in various forms. All methods to enter initial internal node temperatures use 'free' format entry. A 2-character delimiter of 'space/' is used to terminate temperature input; this can be after the last temperature value or on a separate record. The following options are currently available for record 1505D:</p> <p>a) A single value for one undefined node temperature per entry. The values are entered in node order beginning from the low-radial and low-axial node numbers and increasing in the radial direction first (e.g., 120, 150, 160 would store these 3 values into the next 3 undefined temperature locations of the model).</p> <p>b) One value repeated for a number of undefined nodes, stored in the order described in a). This data is entered as N*VALUE, e.g., 5*120 would store the next 5 undefined locations as 120°C.</p> <p>c) One value for all the undefined nodes within a block. This data is entered as BN*VALUE, where N is the block number, e.g., B3*120 would fill all nodes of block 3 with 120°C. (Note: <u>Entering temperatures for a plenum block will result in an input error</u>).</p> <p>d) One value repeated for all remaining undefined nodes. This data is entered as *VALUE, e.g., *120 would fill all nodes of the input (excluding boundary temperatures) with 120°C. (Note: This should always be the last temperature entry if it is used, since it will define all remaining undefined node temperatures).</p>	

Record	Variable Name	Variable Type	Description	Units
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e)			To combine b and c and enter a value repeated for a number of undefined nodes within one block, use a semi-colon (;) to separate block number and repeat value, (e.g., B3;4*130 would store 130 in the first 4 undefined locations of block 3).	
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NOTE

Temperature values can be entered as integer, or floating point, and using the 'E' format, if desired. However, there must be no blanks embedded in the value.

DESCRIPTION OF FLOXI INPUT DATA

Group 31 - FLOXI Main Data

Record	Variable Name	Variable Type	Description	Units
3101D	TYPINGR	C	Type of ingress indicator ('WATER', 'AIR', or 'NONE').	--
	NITRMX0	I	Maximum number of iterations in the FLOXI oxidation/flow computations loop.	--
	FRLX0	F	Under-relaxation parameter for oxidation/flow iterative computations (generally set to 1.0; primarily needed during cases of very small flow with flow reversal).	--
	FRLXOP0	L	Logical variable to activate under-relaxation option (generally set to "false").	--
3102D	APPROX	L	Controls use of approximate flow solution to precede full flow solution.	--
	VISAVI	L	Controls use of mixture viscosity computations in flow solution (VISAVI = true: mixture viscosity and flow resistance computed locally at each axial node, based on its temperature and gas composition; = false: use average channel values; Note that for IREACT = 2, VISAVI will be set = true internally).	--
	IREACT	I	Chemical reaction control parameter (=0 no chemical reaction, gas composition remains constant; =1 chemical reaction as specified by TYPINGR, but no iteration between oxidation and flow computations; =2 as above, but with iterative flow/oxidation computations).	--
	GASOMIN	F	A minimum value of reacting gas concentration (below that concentration chemical reaction is assumed to be zero).	--

Record	Variable Name	Variable Type	Description	Units
3103D	P0	F	Primary loop average gas pressure	P
	CIRCHD	F	Net pressure head of circulator and steam generator	P
	W00	F	Core mass flow (kg/s) (only used with constant flow option; for CONSTAFL=false, the specified value serves as initial estimate)	kg/s
	THFLIN0	F	Coolant inlet temperature (This is generally cross duct to core barrel annulus gas temperature; however in cases of reversed flow it will be the lower plenum gas inlet temperature)	°C
	TIMLAG	F	Time lag to be used in subroutine FLUINUP (a value > 10 ⁶ will cause bypass of FLUINUP routine)	--
	CONSTAFL	L	Constant flow option (=true, mass flow remains constant at above specified value; =false, circulator head remains constant and mass flow varies)	--

Record	Variable Name	Variable Type	Description	Units
3104D	LGAS	I	Number of gases to be considered (1 to 8).	--
	NUAO	F	Volume fraction of the respective gases at the flow inlet:	--

The following gas indices apply:

- 1 = He
- 2 = air
- 3 = CO
- 4 = CO₂
- 5 = H₂O
- 6 = H₂
- 7 = O₂
- 8 = N₂

i.e., a 30/70 vol% mixture of air and CO₂ at the inlet without chemical reaction would be specified as follows: 4, 0., 0.3, 0., 0.7. For ingress cases with chemical reaction, all 8 gases must be considered, even if the inlet flow may only include 1 or 2 components, i.e., for pure air inflow with chemical reactions, one specifies:

• 8, 0., 1.0, 0., 6R

Record	Variable Name	Variable Type	Description	Units
The following two records are only required for free-standing runs of FLOXI:				
3105D	PROCESS	L	Controls transient flow/oxidation computations, based on solid node temperature file of THATCH	--
	SUMM	L	Controls printing of an output summary file	--
3106D	T0	F	Beginning time of run	hr
	TFIN	F	End of run	hr
	TSKIP	F	Desired time interval in processing of input file	hr
	TIMEPR	F	Desired output printing time	hr
<u>Group 32 - FLOXI Geometry and Flow/Heat Transfer Data</u>				
Core Node Ranges:				
3201D	IC1 IC2	I I	THATCH radial nodes of first and last active core parallel flow channel*	--
3202D	JC1 JC2	I I	THATCH first and last axial node of core flow channels JC1, JC2 (including top and bottom reflectors, i.e., from upper plenum to lower plenum).*	--
Note: The FLOXI axial node channels count from 1 to JNOD = JC2-(JC1-1) and the parallel core flow channels from 1 to ICH=IC2-(IC1-1), with channel ICHP=ICH+1 designating the return flow channel IDN.				
3203D	AFLOW	F	Flow cross-section areas for each of the active core parallel flow channels, plus one value for the return flow channel (generally core barrel flow passages) i.e., ICHP entries.*	m ²

*Record will be disregarded if UNIFIN=true was specified on Record 301D.

Record	Variable Name	Variable Type	Description	Units
3204D	ASURCOR	F	Specific heat transfer surface area of the active core	m ² /m
	HICOR	F	Active core height	m
	ASURPBAR	F	Specific heat transfer surface area of the return flow channel. *	m ² /m
3205D	DH	F	Hydraulic diameter of active core region, one entry per axial node. These values apply for each of the parallel active core channels, from IC1 TO IC2. *	m
3206D	DH	F	Hydraulic diameter of core barrel flow passage	m
3207D	REFCORA	F	REFCORA array, an axial correction factor array, accounting for reduced exposed graphite surface area in the bottom reflector areas, and in the upper plenum element regions, one entry per axial node.	--
3208D	IDN	I	THATCH radial node of return flow channel (IDN) (generally core barrel region)	--
	JDHAVG	I	Axial node of representative hydraulic diameter to be used if average channel flow resistances are used, i.e., for VISAVI = false.	--
3209D	XKTOP	F	Loss coefficient of top region entrance/exit pressure drop for each flow channel (ICHP values).	--
3210D	XKBOT	F	Loss coefficient of bottom region entrance/exit pressure drop for each flow channel (ICHP values).	--
3211D	FLOTMP	L	Convective heat transfer computations control variable (ICHP values). (If false, the fluid temperatures will be set equal to the corresponding solid temperatures and the coolant to solid heat transfer computations for that channel will be bypassed).	--
3212D	PRTSCAL	C	• Print scale control variable ('Forced' causes printing at scale of typical forced flow values; 'Free' uses print scales applicable to natural circulation transients).	--

*Record will be disregarded if UNIFIN=true was specified on Record 301D.

INPUT DATA FOR SYMELAN MODULE

Record	Variable Name	Variable Type	Description	Units
<u>Group 40 - General SYMELAN Data</u>				
4001D	TITLE	C	First line of run title for SYMELAN.	--
4002D	TITLE	C	Second line of run title for SYMELAN.	--
4003D	TITLE	C	Third line of run title for SYMELAN.	--
4004D	SYRUNMD	C	Run control variable: in THATCH runs, this variable must always be set to 'TRANSIENT' (in free-standing run mode, SYRUNMD = 'TEMPOUT' can be used to obtain detailed outputs of temperature arrays).	--
4005D	ICHS	I	Number of active core flow channels*	--
	JNODS	I	Number of active core axial nodes*	--
	READTHP	L	Initial temperature control; if true, initial temperatures to be read from file NINTMP=28	--
	WRITMP	L	Output temperature control; if true, output temperatures to be written at specified write steps to file NEXTMP=41	--
	AXCON	L	Axial conduction control; if true, axial conduction is to be included in the transient temperature solution.	--
Symmetry element nodalization:				
4006D	NOFUCOL	I	Number of fuel columns	--
	NOGRCOL	I	Number of graphite moderator columns	--
	MPROW	I	Number of node rows (see Figure 3-11).	--

*Record will be disregarded if UNIFIN=true was specified on Record 301D.

Record	Variable Name	Variable Type	Description	Units
4007D	T0	F	Run start time	s
	NNINTV	I	Number of time-step intervals specified below	--
	TREAD	F	Time point on temperature input file, which is to be used as initial temperature	s
	DEBPRINT	L	Debug print control	--
			There must be one record 4008D for each time step interval specified in record 4007D:	
4008D	N	I	Number of time-step interval	s
	TFINA	F	End of time-step interval	s
	DTA	F	Time step	--
	NPRINTA	I	Number of print steps	--
	NPLOTA	I	Number of plot file write-steps	--

Records 4008D are used only in free-standing SYMELAN runs. In THATCH runs with SYMELAN, they are ignored and the THATCH time-step control is used (Group 12 data).

Record	Variable Name	Variable Type	Description	Units
4009D	RADFRACA	F	Distribution of radial cross-section between the ICHS parallel flow channels (ICHS entries)*	
4010D	PHIRADA	F	Radial power profile (ICHS entries)*	--
4011D	DZA	F	Axial node lengths (JNODS entries)* Note that a non-even node spacing is not permitted in SYMELAN at this time and would require some code modifications.	m
4012D	PHIAXA	F	Axial Power Profile (JNODS entries)*	--
4013D	POW0	F	Base Power	W
	WW0	F	Inlet coolant mass flow to all channels	kg/s
	THFLIN0	F	Inlet coolant temperature	°C
	HHRED	F	Coefficient reduction factor for arbitrary heat transfer (value of 0.6545 currently used here gave best match of steady-state fuel temperatures to PSID data)	--
	DELFUGR	F	Fuel/graphite interface gap	m
	EMIFUGRL	F	Fuel stick to graphite emissivity	--
	THREVA0	F	Average temperature of reflector The first three entries and the last entry on record 4013D are only used in SYMELAN free-standing runs and are ignored in THATCH runs.	K
4014D	THOT	F	Four-value temperature array for "hot fractions". These are used for output of fractions of fuel and graphite above the respective values of THOT.	°C

*Record will be disregarded if UNIFIN=true was specified on Record 301D.

Record	Variable Name	Variable Type	Description	Units
4015D	PKINLS	L	Point kinetics control, if true, point kinetics are to be used and point kinetics input data must be provided. This entry is only effective in SYMELAN free-standing runs. It is read, but ignored, in THATCH runs.	--
The following record is only used in free-standing runs of SYMELAN with SYRUNMD = 'TEMPOUT':				
4016D	LTR	I	Number of entries in TREADA - array	--
	TREADA	F	Times at which detailed temperature array data are to be printed	s

PKIN MODULE INPUT DATA FOR POINT KINETICS OPTION

Group 50 - General PKIN Data

5001D	COMPMOD	C	Computation Mode: 'ITERATE' causes iterative computations between PKIN module and THATCH, or SYMELAN module with average temperatures for fuel, core and reflector from THATCH or SYMELAN affecting the corresponding reactivities. The xenon and samarium reactivity feedbacks are also computed internally within each PKIN time-step. Otherwise, the temperature from the last THATCH/SYMELAN step are used in the reactivity computations. 'CONSTCOR' causes the Xenon reactivity to be computed internally within each PKIN time-step; 'CONSTALL' bases all reactivities on the values at the end of the last PKIN time-step.	--
	RHOMODE	C	Sets the method for using the reactivity temperature coefficients: 'INTEGR' specifies that the temperature coefficients are given as integrated average from a reference temperature. 'LOCAL' specifies that they are local values at the given temperature. Currently, only the mode 'INTEGR' is provided.	--
	CORAVG	L	Specifies whether the fuel Doppler feedback should be based on core average or fuel average temperatures. CORAVG = false causes a separate fuel temperature to be used.	--
	IKINMX	I	Maximum number of iterations in iterative temperature/reativity computations.	--
	EPS0	F	Convergence criterion for point kinetics ODE integration.	--
	PSOURC0	F	A low-value "neutron source" to allow recriticality after prolonged shutdown.	--

Record	Variable Name	Variable Type	Description	Units
5001D (Cont'd)	POWCOR	F	Fraction of the power provided by neutron flux (generally 0.94 with 0.06 being provided by decay heat; for rapid reactivity transients, use POWCOR = 1 and neglect decay heat).	--
	DTH0	F	Temperature difference between average fuel and average core temperatures at design power level (used only in THATCH runs without SYMELAN, under option CORAVG = false).	K
5002D	TWBEG	F	Beginning time for water reactivity insertion (For runs without water ingress, set TWBEG > total run time).	s
	TWRMP	F	"Ramp time" for water reactivity excursion (s). (This is the time during which the water concentration rises linearly from zero to a fraction of the maximum theoretically possible vapor concentration in the core).	s
	RHOWPAR	F	Fraction of water concentration at the end of ramp time to maximum theoretically possible concentration.	--
5003D	INTMTHD	C	ODE integration control: = DIVPAG use IMSL routine DIVPAG, = DGEAR use IMSL routine DGEAR	--
	MTHGEAR	I	MTHGEAR and MITER are integration control variables of the two above routines; see IMSL documentation; generally use MTHGEAR = 2 and MITER = 1.	--
	MITER	I		--

The following records are optional and can be used to override the best estimate data currently stored in the PKIN module Block Data BLDPINK. If any record is used all entries on that record must be specified.

Record	Variable Name	Variable Type	Description	Units
5004D	BETA	F	Delayed neutron fractions	s ⁻¹
5005D	DECAY	F	Decay constants for delayed neutron groups	--
5006D	GENT	F	Prompt neutron generation time	s
5007D	XLAM (1)	F	Decay constant for iodine	s ⁻¹
	XLAM (2)	F	Decay constant for xenon	s ⁻¹
5008D	GAM (1)	F	Fission yield of Tellurium	--
	GAM (2)	F	Fission yield of Xenon	--
5009D	POWD	F	Power density	W/m ³
	SIGA	F	Xenon microscopic absorption cross section	m ²
	SIGF	F	Macroscopic fission cross section	m ⁻¹
	SIGT	F	Total macroscopic cross section	m ⁻¹
5010D	GAMND	F	Fission yield of Neodymium	s ⁻¹
	XLAMPM	F	Decay constant of Promethium	s ⁻¹
	SIGASAM	F	Samorium microscopic absorption cross section	m ²

PASCOL MODULE INPUT DATA FOR AIR COOLED RCCS

Record	Variable Name	Variable Type	Description	Units
<u>Group 61 - PASCOL Main Data</u>				
6101D	TITLE	C	Run title for PASCOL	--
6102D	INSUL	L	Specifies that thermal insulation between downflow and upflow paths of the RCCS prevents direct heat transfer between the two paths.	--
	FINK	L	Specifies that the fin effectiveness in the upflow path is to be computed internally; otherwise, average fin effectiveness data will be read in (see below).	--
	EXPO	L	Specifies use of exponential convective heat flow computations, corresponding to log mean temperature difference; otherwise, arithmetic mean values will be used.	--
	CORR	C	Selects one of two convective heat transfer coefficient correlations, either 'BNL' or 'GA', corresponding to equations 3.2-8a and b, respectively.	--
6103D	JAIRFST JAIRLST	I	First and last axial node interface number of RCCS nodes, counting from the top	-- --
	MATRCCS	I	THATCH material number of RCCS panels in THATCH subroutine PROPMAT, see Section 4.1.5).	--

Record	Variable Name	Variable Type	Description	Units
6104D	RAA	F	Radius array of six values: Reactor vessel OD; outside and inside of the RCCS heated front-panel; and back side of the RCCS upflow/downflow separation panel; back side of RCCS downflow panel (may be concrete surface).	m
6105D	AFLO	F	Flow cross section area for upflow and downflow sides (2 entries)	m ²
	DH		Hydraulic diameter for upflow and downflow sides (2 entries)	m
			For each axial node, specify fin effectiveness for each of four panels:	--
6106D	J	F	Axial node numbers	--
	SURFEFA (1,1,1)	F	Upflow side outer panel	--
	SURFEFA (1,1,2)	F	Upflow side inner panel	--
	SURFEFA (1,2,1)	F	Downflow side outer panel	--
	SURFEFA (1,2,2)	F	Downflow sides inner panel	--
			For the current RCCS design, specify for finned the first value as an effective fin effectiveness, the second as zero (included in outside panel value), and the two downflow side values as 1.0 (no fins). For unfinned sections specify 4 times 1.0. These records only required for FINK = false.	
6107D	EMIA	F	Radiation emissivities for the six surfaces specified in the radius array of record 6104D	--

Record	Variable Name	Variable Type	Description	Units
6108D	W0	F	Air flow (initial estimate only)	kg/s
	P0	F	Air coolant pressure in the RCCS	P
	THFLIN	F	Air inlet temperature	°C
	THFLEX	F	Air outlet temperature (initial estimate only)	°C
Stack data:				
6109D	ISTACON	I	Stack connection integer (= 1 stack connected to hot side of RCCS flow path) =2 stack connected to cold side of RCCS flow path. (Note that operation with the stack connected to the outside flow path is theoretically possible and even has some advantages. However, it would not be self-starting.) Since this feature is not of much practical interest, it has not been maintained when improvements in the Jacobian computation were made. Therefore, the code will stop with a warning message if ISTACON $\neq$ 1. Before reusing this feature, the corresponding modifications in subroutine JACAIRO must be made.	--
	HIST	F	Stack height	m
	AFLOST	F	Stack flow area	m ²
	DHST	F	Stack hydraulic diameter	m
	XKAIRIN	F	Pressure drop loss coefficients for inlet ducting	--
	XKAIRBN	F	Pressure drop loss coefficients for bottom bend	--
	XKAIREX	F	Pressure drop loss coefficients for exit ducting	--
	XKAIRST	F	Pressure drop loss coefficients for exit stack	--

Record	Variable Name	Variable Type	Description	Units
Convergence criteria in internal Newton-Raphson solution of RCCS flow and heat transfer computations:				
6110D	EPSR	F	Convergence criterion for residuals	--
	EPSDY	F	Convergence criterion for change in variable	--
	DYMXFR	F	Maximum fractional change of any variable permitted from iteration to iteration	--
	NITMX	I	Maximum number of iterations.	--
<u>Group 62 - PASCOL Internal Fin Data</u>				
The following records are only required for internal fin effectiveness computations, i.e., FINK = true.				
6201D	SS0	F	Fin pitch	m
	DELFIN	F	Fin thickness	m
	OUTSEP	L	Panel connection control (OUTSEP = true: the front panel is not connected to the back panel and the fins; in MHTGR applications OUTSEP = false).	--
6202D	NN	I	Number of nodes on side fins	--
	XAFR		Length fraction for each node (i.e., NN entries)	--

WATCOL MODULE INPUT DATA FOR WATER-COOLED RCCS

Record	Variable Name	Variable Type	Description	Units
<u>Group 70 - WATCOL Main Data</u>				
7001D	NFIRST	I	Number of THATCH Vessel Axial Node Interface Position Where RCCS Begins	--
	NLAST	I	Number of THATCH Vessel Axial Node Interface Position Where RCCS Ends	--
7002D	NLOOP	I	Number of Coolant Loops Operational (1 or 2)	--
7003D	DCOLD	F	Inside Diameter of Cold Leg Piping	m
	DHOT	F	Inside Diameter of Hot Leg Piping	m
7004D	XLC	F	Total Length of Cold Leg Piping	m
	XLH	F	Total Length of Hot Leg Piping	m
	HCOLD	F	Height of Cold Leg Piping	m
	HHOT	F	Height of Hot Leg Piping	m
7005D	NDTUB	I	Total Number of D-Tubes	--
	HDTUB	F	Height of D-Tubes (Should Equal HVESL)	m
	PWDTB	F	Wetted Perimeter of D-Tubes	m
	PHDTB	F	Heated Perimeter of D-Tubes	m
	AFDTB	F	Flow Area of D-Tubes	m ²
	WTDTB	F	Wall Thickness of D-Tube Adjacent to Panel	m

Record	Variable Name	Variable Type	Description	Units
7006D	NHXTB	I	Number of Heat Exchanger Tubes	--
	NRTB	I	Number of Rows of Heat Exchanger Tubes	--
	XLHX	F	Length of Heat Exchanger Tubes	m
	DHXTB	F	Inside Diameter of Heat Exchanger Tubes	m
	WTHXT	F	Wall Thickness of Heat Exchanger Tubes	m
	SPHXT	F	Center-To-Center Spacing of Heat Exchanger Tubes (Triangular Array Assumed)	m
	AFLXH	F	Cross-Sectional Flow Area of Heat Exchanger Stack	m ²
7007D	HXTOT	F	Total Height of Heat Exchanger Stack	m
	DHHX	F	Hydraulic Diameter of Heat Exchanger Stack	--
	NFIN	I	Heat Exchanger Fin Option Indicator (0/No Fins ; 1/With Fins)	--
	DFINX	F	Fin (Ring-Shape) Outer Diameter	--
	SFINX	F	Fin Spacing	m
	WFINT	F	Fin Thickness at Fin Tip	m
	WFINR	F	Fin Thickness at Fin Root	m
	ATABR	F	Ratio of Total Tube Surface Area (Fins Plus Bare Tube) to Tube Surface Area (Bare)	--

Record	Variable Name	Variable Type	Description	Units
7007D (Cont'd)	AFAT	F	Ratio of Fin Surface Area to Total Tube Surface Area (Fins Plus Bare Tube)	--
7008D	NFTC	I	Number of Fittings in Water Loop Cold Leg Piping	--
	NFTH	I	Number of Fittings in Water Loop Hot Leg Piping	--
	RKLC	F	Loss Coefficient For Cold Leg Fittings	--
	RKLH	F	Loss Coefficient For Hot Leg Fittings	--
	DFC	F	Internal Diameter of Cold Leg Fittings	m
	DFH	F	Internal Diameter of Hot Leg Fittings	m
7009D	WPANL	F	RCCS Panel Thickness	m
	DPANL	F	Diameter of "Effective" Cylindrical Surface of Panels	m
7010D	PRESS	F	RCCS Pressure	P
	PCONT		Containment Pressure	P
7011D	TAIR	F	Ambient Atmospheric Temperature (Heat Exchanger Inlet Temperature)	K
	PAIR	F	Ambient Atmospheric Pressure	P
The following record is only required to optionally modify initial estimates of variables and should generally not be required:				
7012D	DTC	F	Additive Factor to Initial Estimate of Cold Leg Temperature	K
	DTH	F	Additive Factor to Initial Estimate of Hot Leg Temperature	K

Record	Variable Name	Variable Type	Description	Units
7012 (Cont'd)	GMLT	F	Multiplicative Factor To Initial Estimate of Water Mass Flux	--
	DTSP	F	Additive Factor to Initial Estimate of Panel Temperature	K
	DTSV	F	Additive Factor to Initial Estimate of Vessel Surface Temperature	K
7013D	HVESL	F	Height of Reactor Vessel	M
	HCAV	F	Reactor Cavity Height	M
7014D	EPSV	F	Vessel Wall Emissivity	--
	EPSP	F	Panel Wall Emissivity	--
7015D	QDHT	F	Initial Decay Heat Power	W
7016D	EPSR	F	Convergence Criterion on Residuals in Newton	--
	EPSY	F	Convergence Criterion on Change in Y- Vector in Newton	--
	NIT	I	Maximum Number of Iterations in Newton	--
	DYMXFR	F	Maximum Fractional Change in Solution per Iteration in Newton	--
	DYFRJ	F	Fractional Change in Variable Vector for Numerical Jacobian Element Derivative Evaluation (Only Used for Debug Purposes in Routine WATRES D)	--

5.2 Input to THRADLIB Pre-processor for Radiation Coefficients Matrices

The input data to the THRADLIB pre-processor includes the NAMELIST INPUT, with variables as listed in Table 5-2, followed by the following 3 records:

Record Number	Entries
1	UNITS, RADCHEC
2	NOEVAL, NOWRITA array (NOEVAL entries)
3	THA array (NN entries)

Record 2 is only read if RADCHEC = true.

Record 3 is only read if RADCHEC = false.

where

<u>Variable</u>	<u>Type</u>	<u>Description</u>
UNITS	Character *6	Unit of THA array, must be either 'CELSIUS' or 'KELVIN'
RADCHEC	Logical	If RADCHEC=true then temperature and heat flow arrays from THATCH debug output will be read from a File 37 debug checks
NOEVAL	integer ≤6	Number of debug temperature and heat flow records to be read from File 37
NOWRITA	integer array	Identifier for records on File 37 to be read
THA	floating point array	Arbitrary surface temperatures (generally in K) to be used in debug test
NN	integer	Number of plenum nodes (computed in THRAD; user must provide that many temperatures)

Table 5-2 Input Data in NAMELIST INPUT for THRADLIB

Variable Description	Symbol	Variable Name	Positions	Units	Default Value
Character Variable Defining Geometry 'CYCLIN' or 'ANCYL' only are allowed	--	GEOM	1	--	--
Number of Radial Nodes	n_r	NRA	1	--	--
Number of Axial Nodes for GEOM = 'CYLIN'; Number of Axial Nodes on Outer Cylinder for GEOM = 'ANCYL'	n_z	NZAO	1	--	--
Number of Axial Nodes on Inner Cylinder for GEOM = 'ANCYL'	n_{zi}	NZAI	1	--	--
Top Surface Emissivity	ϵ_T	EMMITOP	1	--	0.8
Bottom Surface Emissivity	ϵ_B	EMMIBOT	1	--	0.8
Outer Cylinder Surface Emissivity	ϵ_s	EMMISDO	1	--	0.8
Inner Cylinder Surface Emissivity (used for GEOM = 'ANCYL' only)	ϵ_{si}	EMMISDI	1	--	0.8
Radius Array (Interface Points)	r	RA	0:25	any	--
Axial Node Interface Points of Outer Cylinder	z	ZAO	0:50	any	--
Axial Node Interface Points of Inner Cylinder (Used for GEOM = 'ANCYL' only)	z_i	ZAI	0:50	any	--
Conversion Constant to Convert RA, ZAO and ZAI arrays to SI Unit [m]		CONVTOM	1	$\left[\frac{m}{any} \right]$	1.
Printed Output Control Higher Numbers Trigger more Intermediate Matrix Printing	--	IPRINT	1	--	1
IWRITE > 0 will cause Writing of Output Coefficient array onto File 8	--	IWRITE	1	--	0

5.3 Input to THPROCS Post Processing and Plot File Writing

The input data to the THPROCS post processor consists of the following two records:

Record Number (not part of input line)	Entries
1	NOTPSIN, PROCESS, PLOT, COMB, ILEVOUT, TTMPWRT
2	TSTART, TEND, TSTEP, AIRCOL, PTKINS, FLOXI, NPTS

where

<u>Variable</u>	<u>Type</u>	<u>Description</u>
NOTPSIN	Integer (≤ 9)	Number of THATCH output files to be processed
PROCESS	LOGICAL	= true : Post-processing to be done
PLOT	LOGICAL	= true: Plotting to be done via call to FILEPLT (currently only available at BNL via PLOTLIB and DISSPLAY)
COMB	LOGICAL	<p>= true: The output files of this post-processing run are sequential, and the plot files to be produced is a single file with plot records extracted from all NOTPSIN files of this run being added sequentially. (This option requires that the start and end times of record 2 are also sequential).</p> <p>= false: The output file of this post-processing run are all treated as individual files, each producing its own plot file.</p>
ILEVOUT	Integer	Print level index to control output printing (1 to 4)
TTMPWRT	FP	Time [hr] at which solid temperature array is to be written to output File 96 in format of a THATCH initial temperature file.
TSTART	FP	Start time for post-processing [hr]
TEND	FP	End time for post-processing [hr]
TSTEP	FP	Minimum time step between records to be processed [hr]
RCCSMOD	Character	'AIR' or 'WATER' for Air-Cooled or Water-Cooled RCCS options respectively, 'NONE' if neither is used.
PKINL	LOGICAL	= true, if Point Kinetics Option were used
FLOXI	..LOGICAL	= true, if FLOXI Module were used
NPTS	Integer	Approximate number of time records desired on plot file produced in this run.

There must be one record 2 for each of the THATCH output files to be processed, i.e., NOTPSIN records number 2.

6. FILE USAGE OF THATCH AND SUB-MODULES

Table 6-1 lists the input files required for a THATCH run; the output files created are listed in Table 6-2.

Intermediate scratch files used in THATCH runs are 13 (for the temporary storage of input data stripped of comments) and 71, 72, and 73 as intermediate binary files.

Input and output file usage for the free-standing SYMELAN runs is identical to that for THATCH runs, except that Input Files 02, 15, 21ff, and 27 are not required and Output Files 07 and 14 will not be produced. Usage of the intermediate scratch file is identical to that for THATCH.

Table 6-1
Input Files for THATCH Runs

File No.	File Description	File Type	File Record Format	Remarks
02	Spline coefficients for Gas Properties	Binary	Section 4.2.6 Subroutine REDCOF2	only required if FLOXI=true
05	Case Input Data	Character	see Section 5.1.2	
15	THATCH Output File (Output file of preceding run to serve as restart file here)	Binary	see Table 4-3 and Table 4-4 Section 4.1.6	only required for restart (TO > 0 on Input Record 1201D)
27	Initial Temperature File (generally steady state file)	Binary	1 record: ILP,JLP 1 record: ((TH(I,J), I=1,ILP),J=1,JLP)	for INPMODE = 'READRUN' on input record 1501D (common run mode)
21ff	Plenum Radiation coefficient arrays	Binary	1 record: NN 1 record: ((F(N,M) M=1,NN),N=1,NN)	one file for each plenum with 2-d radiation. In sequence of plena numbers from Input Record 603D
28	SYMELAN Initial Temperature File (generally steady state file)	Binary	see Table 4-13	for THATCH/SYMELAN runs or SYMELAN runs of READTMP=true on Input Record 4005D

Table 6-2

Output Files for THATCH Runs

File No.	File Description	File Type	File Record Format	Remarks
06	Printed THATCH output file	Character		
07	Printed catalog of THATCH output file records	Character		
09	Printed catalog of SYMELAN plot file records	Character		for THATCH/SYMELAN or free standing SYMELAN runs only.
14	THATCH output file for post processing and/or restart	Binary	see Table 4-3 and Table 4-4 in Section 4.1.6.	
33	Fine time step output of point kinetics vector	Binary	see Table 4-8 Section 4.2.4	only if PKIN = true
41	SYMELAN output temperature file	Binary	see Table 4-1 Section 4.2-5	only if SYMELAN = true
42	SYMELAN plot file	Binary	see Table 4-10 Section 4.2.5	only if SYMELL = true

7.0 PRE-PROCESSING REQUIREMENTS AND POST-PROCESSING OPTIONS

7.1 Pre-processing Requirements

For THATCH runs, the following input files must be produced before THATCH runs (see Table 6-1):

Initial Temperature File. This generally is a steady state file, created by a THATCH steady-state run (FLOXI=true and STEADY=true on Input Record 201D, and 'OTHER' for INPMODE on initial temperature input record 1501D). The output file from the run is processed then by the post-processor THPROCS, with TTMPWRT of input data record 1 set to the time records on the THATCH output file for which an initial temperature file is to be written. The format of the initial temperature file is given in Table 6-1. The file will be written by THPROCS as File 96.

Spline Coefficients for Gas Properties. This file is only required for runs with FLOXI=true. The generating program for the spline coefficients, which was used for the current spline coefficient file, is presently located at BNL, but could be made available on request.

SYMELAN Initial Temperature Files. These files are generated by free-standing SYMELAN runs, specifying no point kinetics option and constant steady state power. This file is required only for combined THATCH/SYMELAN runs.

The Plenum Radiation Coefficient Files. These files must be obtained for each plenum by executing the THRAD program of THRADLIB with input variable IWRITE=1 which then will produce a coefficient file as File 8.

7.2 Post-Processing Options

The THATCH post-processor THPROCS serves for post-processing. Its subroutines are described in Section 4.2.10. They provide printed output and permit the writing of several output files, listed in Table 4-16. Up to nine THATCH output files can be submitted to the post-processor at one time. The input data requirements of the post processor are described in Section 5.3.

The input and output file requirements for THPROCS are listed in Tables 7-1 and 7.2.; in addition, THPROCS will use internally the following scratch files:

File	File	
07	IRDIN	Temporary input data storage stripped of Comment records (Cbb in columns 1 to 3)
67	ITPFLX1	Floxi intermediate plot file
68	ITPFLX2	Floxi intermediate plot file
91	NTPSCR1	THATCH intermediate plot file

92	NTPSCR2	Intermediate storage for data to be printed later in the same run
93	NTPSCR3	THATCH intermediate plot file and point Kinetics intermediate plot file
94	NTPSCR4	Currently not used

Table 7-1

Input Files for THPROCS THATCH Post Processing Runs

File No.	File Description	File Type	File Record Format	Remarks
05	Run Input Data	Character	See Section 5.3	
11-19	THATCH Output Files	Binary	See Tables 4-3 and 4-4 in Section 4.1.6	
51-59	THATCH fine time step output file of point kinetics vectors	Binary	See Table 4-8 Section 4.2-4	

Table 7-2

Output Files for THPROCS THATCH Post Processing Runs

File No.	File Description	File Type	File Record Format	Remarks
06	Printed Output File	Character	Table 4-13	
21-29	Plot Files	Binary	Table 4-13	
31-39	Condensed Version of Plot Files	Binary	Table 4-15	
41-49	Solid Temperature History File for Free-Standing FLOXI Runs	Binary	Table 4-13	
61	Combined Sequential Plot File of Files 31 to 39	Binary	Table 4-13	
71-79	Plot File of Point Kinetics Data at Fine Time Step	Binary	Table 4-X	
96	THATCH Initial Temperature File	Binary	See File 27 of Table 6-1	

8. THATCH MODEL OF THE COMMERCIAL MHTGR

This section describes the model of the commercial MHTGR that is incorporated in THATCH. The MHTGR model includes descriptions of input data, and also models which are used in certain subroutines.

8.1 Standard Nodalization and Block Description of the Commercial MHTGR

The standard THATCH nodalization for the commercial MHTGR was developed early in 1986 for depressurized core heat-up transients. Several active core nodalizations were tried, and the current scheme of six radial active core nodes, two for each radial power zone, with 20 axial core nodes, two per fuel element was found to be economical and accurate (finer nodalizations gave essentially identical results). The remainder of the core nodalization used equivalent node sizes. Since vessel temperatures were of major concern, two radial nodes were used in the steel vessel. The complete nodalization of 21 radial and 44 axial nodes is contained in the input decks.

A scheme of the commercial MHTGR in terms of node blocks is given in Figure 8-1. (It is also available with the printed output of any THATCH run.) Table 8-1 shows the various blocks, their node interface ranges, and material indices.

The material property specifications, including effective thermal conductivity, are given in Section 8.2. The gap characteristics are specified with the boundary data of the input deck. In-core gaps between fuel elements are assumed to be 1 mm thick in radial direction and 0.5 mm in axial direction with effective emissivities $\epsilon_{1,2} = 0.82$ (corresponding to an assumed value of $\epsilon \approx 0.9$ for graphite). For steel-to-steel, the effective emissivity is generally assumed as $\epsilon_{1,2} = 0.68$ (corresponding to an assumed steel emissivity of $\epsilon \approx 0.8$).

For radiation from the core-barrel outside to the vessel inside-surface, the flow passages attached to the core-barrel effectively act like a partial radiation shield. The overall emissivity for this configuration, assuming component emissivities of 0.8 was computed to be $\epsilon_{1,2} = 0.485$, as included in the input decks (Radial Boundary 4).

Boundary maps are produced with each THATCH printed output file.

8.2 PROPMAT Subroutine for Solid and Gap Material Properties

The PROPMAT subroutine for the commercial MHTGR provides the required solid and gap material properties. In general, for the solid nodes, the thermal conductivity and thermal capacitance are required, while for gaps, effective thermal conductivities must be provided.

The materials specified for solid blocks are summarized in Table 8-2. Many of these specifications are self-explanatory, but where necessary, further details are given.

Figure 8-1 Schematic of THATCH Block Nodalization of MHTGR

TABLE 8-1

Node Block Description of the Commercial MHTGR

BLOCK NUMBER	BLOCK NAME	RADIAL INTERFACE		AXIAL INTERFACE		MATERIAL INDEX*
		LO	HI	LO	HI	
1	Central Reflector	0	6	8	36	1
2	Active Core	6	12	12	32	2
3	Inner Side Reflectors	12	15	8	36	1
4	Permanent Side Reflectors	15	18	8	36	4
5	Top Reflector	6	12	9	12	3
6	Upper Plenum Elements	6	12	8	9	15
7	Upper Bottom Reflectors	6	12	32	34	3
8	Lower Bottom Reflectors	6	12	34	36	5
9	Core Barrel	18	19	8	43	10
10	Vessel (side)	19	21	1	45	6
11	Vessel (top)	0	19	1	3	6
12	Vessel (bottom)	0	19	43	45	6
13	Shroud (side)	18	19	3	8	11
14	Shroud (top)	0	18	3	5	10
15	Upper Core Floor	0	18	38	40	4
16	Lower Core Floor	0	18	40	41	8
17	Floor Support 1	0	18	41	42	6
18	Floor Support 2	0	18	42	43	6
19	Upper Plenum	0	18	5	8	101
20	Lower Plenum	0	18	36	38	102

*Number > 100 designate plena, with plenum number = material index-100.

TABLE 8-2

Solid Node Properties of the
THATCH Commercial MHTGR Model

Material Index	Material	Application
1	H451 Graphite	Central Reflector Inner Side Reflector
2	Fuel Element Composite H451/Fuel/Coolant Holes	Active Core
3	Reflector Element Composite H451/Coolant Holes	Top and Bottom Reflectors
4	Stackpole 2020 Graphite	Permanent Side Reflectors, Lower Plenum Core Floor
5	Reflector Element Composite Stackpole 2020/Coolant Holes	Bottom Reflectors
6	Medium Carbon Steel	Reactor Vessel and Metallic Core Support Structure
7	Alloy 800 and Kaowool Composite	Upper Plenum Shroud (top)
8	Alumina Insulation	Core Floor
9	Carbon Steel	RCCS Panels
10	Alloy 800	Core Barrel and Upper Plenum Shroud
11	Alloy 800 and Kaowool Composite	Upper Plenum Shroud (side)
12	Concrete	*
13	Clay Soil	*
14	Non-Operating RCCS Structure	*
15	Composite of Alloy 800 and Boronated Graphite	Upper Plenum Elements
16	Kaowool	Core Barrel Gap (top flange area)
17	Alloy 800 and Kaowool Composite	Upper Plenum Shroud (side)

*Currently not used; have been used for analysis of core heat-up without functioning RCCS.

For the active core-fuel elements and reflectors, the volume fractions of graphite (.584), fuel (.183), and coolant holes (.233) are stated in a data statement; however, previous effective values, as given by the vendor, are still used.

The top region of the upper plenum shroud is modeled as 26 mm of Alloy 800 (Material 10) plus a quasi-steady layer of 32 mm Kaowool and 5 mm cover plates of Alloy 800 (Material 7). The side of the upper plenum shroud also is a composite of Alloy 800 and Kaowool. The radial node thickness for this node ($i=19$) is 375 mm. In the core barrel region, 295 mm of this is the core barrel gap and 80 mm the effective thickness of the core barrel. A different gap width for this shroud region could have been specified, reducing the solid node thickness to 25 mm; this would be preferable, in general. For historic reasons, a different specification is still in effect here, and will be described, to point out an additional option to the models. The node thickness was retained as 80 mm, but k and ρc of Material 11 were prorated correspondingly to account for the actual node thickness of 25 mm; this requires different proration for radial and axial thermal conductivities.

The side insulation of the upper plenum shroud is a composite layer of 19 mm Kaowool and 5 mm cover plates (Material 17). The insulation is continued downward at the outside of the core barrel to protect the vessel flange region by a 25 mm layer of Kaowool (Material 16), specified as a layer in Radial Boundary 14.

Table 8-3 summarizes the gap conductivities of the current PROPMAT subroutine, including approximations for the natural convection heat transfer correlations. Since radiation generally dominates the total gap heat transfer; the importance of these correlations is relatively small. However, these models should be improved, particularly if more detail of the upper head region is of interest.

TABLE 8-3

Gap Effective Thermal Conductivities
of the THATCH Commercial MHTGR Model

Material Index	Description
1	Zero thermal resistance
2	Stagnant helium
3	Adiabatic gap
4	Reactor cavity natural circulation (Correlation of Equ 3.2-4 using cavity dimensions $H = 20.4$ m, $\delta = 0.91$ m, and $p_o = 10^5$ P.)
5	Air-cooled RCCS thermal insulation*
6	Core barrel gap conductance (Correlation of Equ 3.2-4 using core barrel dimensions $H = 12.87$ m, $\delta = 0.295$ m, helium as gas and $p_o =$ input value of POUPL which is 10^5 P for depressurized runs and input via FLOXI for pressurized runs.)
7	Effective conductance from plenum shroud to vessel (For depressurized case use approx $\frac{1}{2}$ of h in upper plenum, i.e. $Nu \approx 100$; For pressurized case use same correlation as in upper plenum (Equ 8.5-6) with $H = .477$ m.)

*Currently not used; have been used for analysis of core heat-up without functioning RCCS.

8.3 Irradiation Damage and Annealing Model for Thermal Conductivity of Graphite

The MATLIB submodule of the code includes correlations for the thermal conductivity of H451 graphite with and without irradiation damage. In general, the correlations without irradiation damage will be used. However, the user can specify that irradiation damage is to be considered, and over which range of nodes. In that case a "damage parameter" must be supplied for each node (i,j) where

$$0 \leq D_{i,j} \leq 1.0$$

and the effective thermal conductivity is linearly prorated between damaged and undamaged graphite as

$$k_{\text{eff},i,j} = k_{\text{irrad}}(\theta_{i,j}) D_{i,j} + k_{\text{unirrad}}(\theta_{i,j}) (1-D_{i,j}) \quad (8.3-1)$$

During core heatup sequences, the graphite generally will undergo annealing and will recover the thermal conductivity of undamaged graphite. If the user wants to model this process, a temperature range over which annealing is assumed to occur must be specified. As annealing is considered to occur fast compared to the very slow core heatup scenarios, the damage parameter of any node will be reduced as the node temperature rises such that

$$D_{i,j} = \min \left[D_{i,j}, \frac{\theta_2 - \theta_{i,j}}{\theta_2 - \theta_1} \right] \quad \begin{matrix} \theta < \theta_2 \\ \theta \geq \theta_2 \end{matrix} \quad (8.3-2)$$

where θ_1 to θ_2 is the temperature range for annealing. The use of the minimum function ensures that annealing only begins when the appropriate temperature is reached, and will not reverse as cooldown begins. Strictly speaking, this model should be revised if the core becomes critical again later in any scenario, with irradiation being resumed. So far, such scenarios have not been identified or analyzed.

8.4 Modelling of Solid Heating Rate in THATCH

The THATCH model for transient solid temperatures of Section 3-1 requires prescription of the volumetric interval heat-generation rate q''' at all nodes.

This heating can be due to decay heat, fission power (if PKINL=true), or due to convective heat transfer from the coolant (if FLOXI=true and IREACT>0).

The radial and axial power distribution is either prescribed with the input data, or taken from PSID data which are given in BLOCK DATA COREDTs of THATCHLIB.

The local power fractions at any node is the product of radial and axial power fractions, i.e.,

$$\phi_{i,j} = \phi_{Ri} \phi_{Aj} \quad (8.4-1)$$

where $\phi_{i,j}$ is the local power fraction of node i,j and ϕ_{Ri} and ϕ_{Aj} are the radial and axial power fractions.

The local power fraction at any node is defined as

$$\phi_{i,j} = \frac{q_{i,j}^{///}}{\bar{q}^{///}} \quad (8.4-2)$$

and is assumed to remain constant with time. (But, note that different power profiles can be prescribed for decay heat and for fission power). Here $q^{///}$ is the local volumetric heating rate and $\bar{q}^{///}$ is the average volumetric heating rate of the core

$$\bar{q}^{///} = \frac{1}{\sum V_{i,j}} \sum q_{i,j}^{///} V_{i,j} \quad (8.4-3)$$

As total fission power and decay heat vary with time, the average volumetric heating rate can be expressed as

$$\bar{q}^{///} = \bar{q}_o^{///} \times \frac{P(t)}{P_o} \quad (8.4-4)$$

where P is total core power and the subscript o designates initial steady state values.

From (8.4-2) and (8.4-4), the local volumetric heating rate at time t is

$$q_{i,j}^{///} = \phi_{i,j} \bar{q}_o^{///} \frac{P(t)}{P_o}$$

This expression is computed for each node at each time step, separately for decay heat and fission power, and finally, the nodal convective heat flows computed in FLOXI as well as chemical reaction heats are added. Thus

$$q_{i,j}^{///} = \left\{ \phi_{D,i,j} \left[\frac{P(t)}{P_o} \right]_D + \phi_{F,i,j} \left[\frac{P(t)}{P_o} \right]_F \right\} \bar{q}_o^{///} + \frac{Q_{FLOX\ i,j}}{V_{i,j}} \quad (8.4-5)$$

where subscripts D and F denote decay heat and fission power, and V is the node volume and

$$Q_{FLOX\ i,j} = Q_{conv\ i,j} + Q_{react\ i,j} \quad (8.4-6)$$

$Q_{\text{CONV } i,j}$ is computed from equation (3.4-22) and the reaction heat is

$$Q_{\text{react } i,j} = -\Gamma_{\text{ox}}''' H_{\text{ox}} \quad (8.4-7)$$

where Γ_{ox}''' is the volumetric generation rate of the oxidant (O_2 in the case of air ingress and H_2O in the case of water ingress) as computed in Section 3.4.3 and H_{ox} is the energy release

$$H_{\text{O}_2} = 242 \frac{\text{MJ}}{\text{kmol O}_2}$$

$$H_{\text{H}_2\text{O}} = -118.8 \frac{\text{MJ}}{\text{kmol H}_2\text{O}}$$

(Note that Γ_{ox} is negative)

The FLOXI terms are computed in FLOXI and passed to THATCH routine HEATGEN where the afterheat and fission power terms are computed.

The fission power P/P_0 is computed by the point kinetics model, and the afterheat fraction is evaluated in routine AFTFR of GENLIB, using the afterheat profile specified by input data records 1108 to 1111D.

8.5 Natural Convection Model For The Upper Plenum

During core heatup scenarios, natural convection currents can be significant, since the core is essentially a cavity, heated from below. Natural convection is not of much interest in depressurized core heatup scenarios, where the gas density is low and the convective heat transfer is small compared to radiation and conduction in solids.

However, in pressurized core heatup scenarios this effect can be essential, in particular, because it increases the buoyancy-driven flow circulation through the active core. In such scenarios, gas rises in the coolant channels of the hotter regions of the core, flows through the upper plenum and returns mainly through the coolant channels of colder regions of the core, with some bypass flow through the flow channels of the core-barrel. During the flow through the upper plenum, which has its own turbulent natural circulation loop at Grashof numbers above 10^{11} , the gas will be cooled as it flows along the colder plenum shroud, resulting in a temperature drop between the gas streams entering and leaving the upper plenum. An accurate assessment of this effect would require a multi-dimensional model of turbulent convection in the upper plenum with simultaneous gas inflow and outflow at the bottom of the plenum. Such detail cannot be included here and a simplified model is given. Once the results from detailed evaluations of a separate upper-plenum multi-dimensional code are available, this simplified model can be improved by adjusting its correlations to those results.

The current model assumes convective heat transfer from each plenum node ℓ as

$$Q_{\text{conv } \ell} = A_{\ell} h_{\text{cav}} (\theta_{s\ell} - \theta_{\text{gav}}) \quad (8.5-1)$$

where

$Q_{\text{conv } \ell}$ is the heat removed from the solid surface by convection, A_{ℓ} is the node surface area, h_{cav} a cavity heat transfer coefficient, $\theta_{s\ell}$ the node surface temperature, and θ_{gav} an average gas temperature for the upper plenum.

In terms of the general plenum-heat-transfer model of Section 3.1, Equation 3.1-17 which presents a balance of conduction and radiation now would become

$$Q_{\text{cond}} = Q_{\text{rad}} + Q_{\text{conv}}$$

or

$$\begin{aligned} Q_{\ell} &= \frac{2 A_{\ell}}{\Delta Z_n} k(\theta_{i,j \text{ avg}})(\theta_{i,j} - \theta_{s\ell}) \\ &= A_{\ell} \sum_{m=1}^L \Lambda_{lm} \sigma \theta_{sm}^4 + A_{\ell} h_{\text{cav}}(\theta_{s\ell} - \theta_{\text{gav}}) \end{aligned} \quad (8.5-2)$$

A quasi-steady energy balance on the plenum gas flow yields

$$W C_p (\theta_{\text{gex}} - \theta_{\text{gin}}) = \sum_{\ell=1}^L A_{\ell} h_{\text{cav}} (\theta_{s\ell} - \theta_{\text{gav}}) \quad (8.5-3)$$

and the effective average plenum gas temperature was assumed to be

$$\theta_{\text{gav}} = 1/2 (\theta_{\text{gex}} + \theta_{\text{gin}}) \quad (8.5-4)$$

For the convective heat transfer coefficient, h , the code provides an internal option between two correlations (set in calls to UPLCONV):

Either

$$Nu = \frac{hH}{k} = 0.098 Ra^{0.33} \quad (8.5-5)$$

or

$$Nu = \frac{hH}{k} = 0.316 Ra^{0.25} - 1.3 \quad (8.5-6)$$

where H is the effective plenum height and k the gas thermal conductivity.

The first correlation is based on data presented by Catton [1978]. The second correlation was extracted by Moszynski [1982] from Catton [1978], after consulting some of the references in Catton's paper.

To solve the upper plenum heat transfer, including convection, the method of Section 3.1-3 (Equation 3.1-20) must here be amended by adding the convective term, which results in

$$\sum_{m=1}^L \left[\delta_{lm} (\alpha_\ell + h_{cav}) \theta_{s\ell} + \Lambda_{\ell m} \sigma \theta_{sm}^4 \right] - h_{cav} \theta_{gav} = \alpha_\ell \theta_{i,j} \quad \ell = 1, L \quad (8.5-7)$$

To this system of L equations, one equation for θ_{gav} must be added, which is obtained from equations (8.5-3 and 4) by eliminating θ_{gex}

$$[2Wc_p + h_{cav} \sum A_\ell] \theta_{gav} = 2Wc_p \theta_{gin} + h_{cav} \sum A_\ell \theta_{s\ell} \quad (8.5-8)$$

This system of L + 1 equations, is solved using an analytical Jacobean by the Newton Raphson method. (The code is internally hard-wired to optionally compute the system of L + 2 equations, including h_{cav} as additional variable and including equation (8.5-6) for h_{cav} in the set of equations. The option is set in RADTN via logical variable HUPLINT. From a few test cases, it is not clear which method is preferable. It is currently set to true, i.e., h_{cav} is included, and a set of L + 2 equations is solved).

To compute the effective Grashof number for the upper plenum, the temperature difference from bottom to top is computed in UPLCONV by computing area-weighted average temperatures for the top and bottom boundaries of the plenum, and disregarding the side temperatures.

The model is currently coded for helium as a gas only. Because upper plenum convection is only essential in pressurized scenarios, and potential H₂O concentrations during water ingress scenarios are small, this restriction has not proved to be serious. However, it should be kept in mind, and may have to be removed at a later date.

9. SAMPLE CASES AND INSTALLATION REQUIREMENTS

Four sample cases were selected, which exercise different options of the code. They are described in Table 9-1 and their input decks are reproduced in Appendix F. For each case, a base run, a restart run (except Case 2), and a post-processing run were executed on the IBM 3090 at BNL and on the CRAY at INEL, to assure complete correspondence of the code's versions. For holders of controlled copies of this document, the printed output files will be enclosed in fiche form with this document.

The source deck of the code is written in FORTRAN 77, including several enhancements which are available on the IBM 3090, as well as on the CRAY computer. The total source disk consists of a dummy main program with 249 subroutines (partitions).

Code installation requires loading of the source disk and code input file from the supplied magnetic tape. After compilation the code can be executed, using the above sample cases, following the rules of the installation - specific operating system.

At BNL, the IBM Engineering and scientific Subroutine Library is used to solve sets of simultaneous equations. At the INEL Cray, the IMSL library is used for that purpose. At both installations, the IMSL library is used for the ordinary differential equation integration of the point kinetics option.

Code compile times are not of any significance. Code execution times vary widely, depending on the options chosen. Table 9-1 includes the IBM 3090 execution times for the four test cases; execution times on the INEL CRAY ranged between 45% and 85% of those on the IBM 3090.

Table 9-1
THATCH Test Cases

Cases	Depressurized Core Heatup 1	Pressurized With Water Reactivity Insertion THATCH/SYMELAN 2	Core Heatup with Air Ingress 3	Water Cooled RCCS 4
<u>THATCH Base Run</u>				
Input Data File	THBASDEP	THPRTST	THBASARR	THBASWAT
Run Time	0-100 hr	0-1 min	0-200 hr	0-200 hr
PKINL	F	T	F	F
FLOXI	F	T	T	F
RCCS Option	Air	Air	Air	Water
DIVPAG of IMSL Library	No	Yes	No	No
CPU Time on IBM 3090	58s	925s	275s	93s
<u>Restart Run Test</u> Time	50-100 hr	N/A	50-100 hr	50-100 hr

10. CAPABILITIES AND LIMITATIONS OF THE THATCH CODE

10.1 Code Capabilities

The basic THATCH code can be used to model solid conduction in any network of solid nodes that can be represented in a two-dimensional cylindrical coordinate system of r-z coordinates. Gaps with conduction and radiation and cylindrical plena with two-dimensional radiation also are allowed.

Its major application has been to model thermal-hydraulic transients in the reactor vessel of gas cooled reactor. Since a user-specified nodalization is allowed, the THATCH code can be used to model local effects, employing a very fine nodalization in the areas of primary interest.

In its current model of the commercial MHTGR, described in Section 8, peak fuel and vessel temperatures during pressurized and/or depressurized core-heatup transients with loss of all forced cooling were of primary interest; therefore, the nodalization concentrated on accurate presentation of the center region of the core and center to upper beltline of the vessel.

With its modules for gas flow, convective heat transfer, chemical reactions, and point kinetics the code has been applied to such scenarios as

- pressurized and depressurized core heatup scenarios (also referred to as core cooldown events)
- natural gas circulation in the primary loop during pressurized core-heatup events
- graphite oxidation during air-or water-ingress events, including the evaluation of maximum possible entry of air into the core
- long-term no-scam transients, with recriticality after two days
- rapid reactivity insertions, for instance, due to water ingress (via SYMELAN module)
- parametric evaluations of sensitivity to changes in design data and material properties
- core-heatup scenarios with loss of RCCS performance, including a model of reactor cavity heatup

The code could readily be applied to other events like

- start up and shutdown transients, where vessel temperatures would be of major concern
- modelling of core and vessel temperature transients during load change events
- slow depressurization transients (with prescribed depressurization rate and gas flow)

10.2 Code Limitations

The THATCH code presents a model of heat transfer and fluid flow in the reactor vessel.

Generally, inputs are the coolant inlet temperature and either the coolant flow rate, or the effective positive pressure head (circulator operating), or a pressure loss head for the flow path outside the reactor (representing steam generator or SCS).

A free-standing quasi-steady model for a steam generator has sometimes been used to estimate changes in the temperatures of the return gas flow, based on changing gas and inlet temperatures, to simulate the corresponding changes in inlet gas flow via THATCH subroutine FLUINUP (Section 4.2.3). This steam generator model could be coupled with FLUINUP, but it has not been done to date.

As peak fuel and vessel temperatures were of primary interest in previous analyses, the cylindrical section of the reactor vessel has been modelled in more detail than the semi-spherical top head and bottom regions. (Some hard-wired special extensions for upper-head cooling have been used; however, they are not part of the current code). The top and bottom regions were modelled as cylindrical, with coolant volume and heat transfer surfaces being kept as closely as possible to the design data. When increased accuracy is required in the upper head and the bottom regions, the current models should be refined accordingly.

Upper-and-lower-plenum heat-transfer currently assumes radiation in free spaces. The effect of control rods and fuel support columns on heat transfer has been neglected; this should be revised as these regions gain in relative importance.

The current code does not model changes in system pressure, but uses a user prescribed upper plenum pressure, even though the routines to compute system pressure are available.

The system pressure can be shown to be a function of the sum

$$\sum \frac{V_i}{\theta_i}$$

of gas volumes divided by gas temperatures in all volumes of the primary loop. As the volume data of Table 4-14 show, the bottom plenum, core-barrel side-gap region, and upper plenum are the dominant terms for the reactor vessel. About half the primary loop gas volume is in the steam generator. Any meaningful predictions of pressure would require good models for gas temperatures, including the heat transfer from gas to sidewall, for these regions, many of which are stagnant gas volumes. The main interest of pressure transients is to determine relief-valve lift off, with relief valve pressure being approximately 10% above steady state pressure. Relatively accurate predictions of pressure would be required to assess whether and when the set point of the relief valve is reached. For this reason, system pressure computations are not made at this time, although they could be implemented. The subroutines for this computation are available.

The point kinetics equations currently are always integrated as full ODEs, with six delayed neutron groups. If computer time is a concern, then, for many transients where the reactivity changes amount to only a few cents, the jump approximation could be implemented to reduce the computer run time. To date, computer time has not been a problem, and the approximation has not been applied.

10.3 Error Indications

Most error messages produced by the code are self explanatory; those that may require experience to interpret will be listed here. Since the developers of the code may not realize what may cause difficulties for new users, we would appreciate feedback, and will expand this section, or others, as required.

At start time, the following message is often produced:

```
***** WARNING, IN PROPMAT, GR BELOW 1.E7, GR= 1.0 DELTHGR= 0.0 *****
```

This is called in Propmat for Gap Material 107 (Upper plenum shroud to reactor vessel). This is usually due to the initial temperature differences between the insulation of the upper plenum shroud and the reactor vessel's surface being zero on first call and first iteration in BNDCONI. Disregard the message if it only occurs at start time.

The general solution method for THATCH solid temperatures is implicit and, therefore, in principle numerically stable. However, since thermal properties and gap resistances are explicitly updated at each time step, instabilities can arise occasionally when coarse time steps are chosen.

The first message indicating such instability is usually due to non-convergence in the BNDCONI iteration loop for interface resistances. It reads:

```
***** NON-CONVERGENCE IN BNDCONI ROUTINE
```

```
THA (0:4) = 1.60515E+03 1.59636E+03 9.21009E+02 5.94368E+02 5.74552E+02
```

```
DELSUMR = 1.79725E-05
```

```
COF = 2.38685E+04
```

```
RADIAL BOUNDARY NO. = 16
```

```
NODE, I,J = 19, 6
```

```
TIME = 104.00 HOURS
```

Another message indicating instability is non-convergence in plena radiation and convection computations. It generally reads:

From NEWTON:

```
NON-CONVERGENCE IN NEWRAF-LOOP
```

```
JBIGR, BIGR= 18 2911884970.86540413
```

```
JBIGDY,BIGDY= 18 46281.7269896565040
```

FROM RADTN:

TIME = 104.00 HOURS ***** ERROR RETURN FROM NEWTON, PLENUM NUMBER = 1

IER = 3 NIT = 20 BGR = 2.9118853+09

Generally, only later in the onset of stability some temperatures will get out of bound in property routine calls, producing a message like:

===== ERROR IN TBLLK CALL FROM PROPAIR, THKA-ARRAY

===== INDEP VARIABLE X= 1.2645283+02

In all these cases, the remedy is a decreased time step. Often this is only required for a limited time. Run times have never posed a problem, therefore no further preventive action, like automatic time-step reductions, have ever been used or planned.

In some cases, the maximum number of function evaluations in DIVPAG have been exceeded. In general, this indicates some error in the modelling, like incorrect or inconsistent input data. The number of permissible function calls is entered in SOLTRAN (part of GENLIB) from Block Data ODEDAT. To increase these parameters may be a temporary solution, but is unlikely to be a permanent remedy. (See also, IMSL documentation of DIVPAG).

10.4 Code Service

The THATCH code and its submodules are maintained at Brookhaven National Laboratory, Department of Nuclear Energy, Reactor Analysis Division. Code modifications can be made by one person only

Robert J. Kennett (516) 282-2104
FTS 666-2104

and only with the concurrence of

Peter G. Kroeger (516) 282-2610
FTS 666-2610

These people should be the contacts for any problems, questions, or suggestions that may arise. R. J. Kennett is the prime contact for code structure and related subjects: P. G. Kroeger is the prime contact for questions regarding modelling and code capabilities.

The code is maintained, using HISTORIAN PLUS of Opcode Inc. on the IBM 3090 at Brookhaven National Laboratory. This system is similar to the UPDATE system used at other installations.

This document is openly available, as a Brookhaven National Laboratory report. However, in addition to the general copies, there will be a limited number of controlled copies. Holders of such

copies will be automatically provided with updates as changes are made.

To exercise this code, the user must have general engineering knowledge of nuclear reactor thermal fluid flow and neutronics, as well as some experience in numerical methods. Also, some familiarity with codes and computer programming is required, either in one person or in a team of engineers and programmers.

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APPENDIX A

RADIATION EXCHANGE BETWEEN GRAY SURFACES IN A CLOSED CAVITY WITH A TRANSPARENT GAS.

It is assumed that the closed cavity can be represented as a set of L isothermal nodes of a prescribed geometry for which the view factors $F_{\ell m}$ are available (see Appendix B).

For a surface which has the incident radiant energy H arriving, the net heat loss from the surface can be expressed as

$$\frac{Q_\ell}{A_\ell} = \epsilon_\ell \sigma \theta_\ell^4 - \epsilon_\ell H_\ell \quad (\text{A-1})$$

where the first term is the radiation emanating from the surface, and the second term is the fraction of the incident energy being absorbed by the surface, as shown schematically in Figure A-1.

Defining the "radiosity" B as the energy streaming away from a surface we have

$$B_\ell = \epsilon_\ell \sigma \theta_\ell^4 + (1-\epsilon_\ell)H_\ell \quad (\text{A-2})$$

Eliminating H_ℓ between Equations (A-1) and (A-2), we obtain for the heat loss from the surface ℓ

$$\frac{Q_\ell}{A_\ell} = \frac{\epsilon_\ell}{1-\epsilon_\ell} \sigma (\theta_\ell^4 - B_\ell) \quad (\text{A-3})$$

The radiation incident on surface ℓ , H_ℓ , can be summed over all nodes

$$A_\ell H_\ell = \sum_{m=1}^L A_m B_m F_{m\ell} \quad (\text{A-4})$$

where in $F_{m\ell}$ the first index denotes the surfaces from which the radiation emanates and the second subscript denotes the receiving surface.

By using the reciprocity condition

$$A_\ell F_{\ell m} = A_m F_{m\ell} \quad (\text{A-5})$$

this can be rewritten as

$$H_\ell = \sum_{m=1}^L B_m F_{\ell m} \quad (\text{A-6})$$

Substituting (A-6) into (A-2), we obtain for the radiosity as a function of surface temperatures

Figure A-1. Schematic of Incident, Absorbed, Emitted, and Reflected Energy and a Gray Surface Element.

$$B_\ell = \epsilon_\ell \sigma \theta_\ell^4 + (1 - \epsilon_\ell) \sum_{m=1}^L B_m F_{\ell m} \quad (A-7)$$

or as a set of simultaneous equations

$$X B = \Omega \quad (A-8)$$

where the X matrix has the members

$$X_{lm} = \frac{1}{\epsilon_\ell} [\delta_{lm} - (1 - \epsilon_\ell) F_{\ell m}] \quad (A-9)$$

with δ_{lm} being the Kronecker delta, B being the radiosity vector, and Ω being the black body emittance vector

$$\omega_\ell = \sigma \theta_\ell^4 \quad (A-10)$$

Inverting the X matrix and defining

$$\Psi = X^{-1} \quad (A-11)$$

we obtain

$$B_\ell = \sum_{m=1}^L \Psi_{\ell m} \sigma \theta_m^4 \quad (A-12)$$

Substituting (A-12) into (A-3) we obtain

$$\frac{Q_\ell}{A_\ell} = \sum_{m=1}^L \Lambda_{m\ell} \sigma \theta_m^4 \quad (A-13)$$

where

$$\Lambda_{\ell m} = \frac{\epsilon_\ell}{1 - \epsilon_\ell} (\delta_{ij} - \Psi_{ij}) \quad (A-14)$$

The procedure used in the THATCH 2-d radiation evaluations is to compute the X-matrix of Equation (A-9) from given view factors and emissivities, to invert the X-matrix and use the resulting Ψ matrix to compute the Λ matrix, which then is used in the code to compute heat loss from a surface using Equation (A-13).

APPENDIX B

RADIATION VIEW FACTORS FOR PRESCRIBED GEOMETRIES

In developing radiation view factors between parts of cavities, the following relationships, which are derived from energy conservation principles, are extensively applied [Sparrow and Cess, 1967].

For two surfaces A_i and A_j the following reciprocity relationship applies

$$A_i F_{A_i - A_j} = A_j F_{A_j - A_i} \quad (B-1)$$

In an enclosure with N surfaces, since the view factor $F_{A_i - A_j}$ is the fraction of the energy leaving A_i that arrives at A_j

$$\sum_{j=1}^N F_{A_i - A_j} = 1 \quad (B-2)$$

where $F_{A_i - A_j}$ is the view factor from area A_i to area A_j .

If one subdivides A_j into A_j' and A_j'' , then

$$A_i F_{A_i - A_j} = A_i (F_{A_i - A_j'} + F_{A_i - A_j''}) \quad (B-3)$$

or with Equation (B-1)

$$(A_j' + A_j'') F_{A_j - A_i} = A_j' F_{A_j' - A_i} + A_j'' F_{A_j'' - A_i} \quad (B-4)$$

In the THATCH code we have to consider cylindrical cavities, described in r - z geometry, symmetric with respect to the z -axis. These cavities can be regular cylindrical ones with flat top and bottom sections and an outer side wall or annular cavities which have an inner and an outer side wall.

In this report, surfaces on the top and bottom will be referred to either as "disks" or as "annular disks", depending on whether they include the center of the top or bottom section. Surfaces on the cylinder walls will be referred to as "outer cylinder rings" or "inner cylinder rings", depending on whether they are parts of the outer or inner wall.

Outer cylinder rings have a view factor onto themselves. All other surfaces to be considered here do not.

B-1 Radiation View Factors in a Cylindrical Cavity

Following Figure B-1, for two disks of radius r_1 and r_2 , one from the top surface of the cavity and one from the bottom surface, with cavity height h , we have

Figure B-1. Schematic of Geometry for
Disk and Annular Disk
View Factors

$$F_{A_1 - A_2} = \phi(r_1, r_2, h) = 1/2 (Z - \sqrt{Z^2 - 4X^2 Y^2}) \quad (B-5)$$

where

$$X = \frac{r_2}{h}; Y = \frac{h}{r_1}; Z = 1 + (1 + X^2)Y^2$$

From this disk-to-disk formula, we can apply Equations (B-1) to (B-4) to obtain view factors between any disks or annuli on the opposing top and bottom surfaces. Following the schematic of Figure B.1, D_i denotes a disk of radius r_i , and A_i an annular disk extending from r_{i-1} to r_i .

Then, for the view factor from annular disk A_{12} to disk D_{21} :

$$\begin{aligned} (r_{12}^2 - r_{11}^2) F_{A_{12} - D_{21}} &= r_{12}^2 \phi(r_{12}, r_{21}, h) \\ &- r_{11}^2 \phi(r_{11}, r_{21}, h) \end{aligned} \quad (B-6)$$

and for the view factor from annular disk A_{12} to annular disk A_{22}

$$\begin{aligned} (r_{12}^2 - r_{11}^2) F_{A_{12} - A_{22}} &= r_{12}^2 [\phi(r_{12}, r_{22}, h) - \phi(r_{12}, r_{21}, h)] \\ &- r_{11}^2 [\phi(r_{11}, r_{22}, h) - \phi(r_{11}, r_{21}, h)] \end{aligned} \quad (B-7)$$

For a cylindrical cavity of radius r and height h , the view factor from the top disk (1) or bottom disk (2) to the side wall (3) is

$$F_{1,3} = 1 - F_{1,2} = 1 - \phi(r, r, h). \quad (B-8)$$

With

$$F_{3,1} = \frac{A_1}{A_3} F_{1,3}$$

and

$$2F_{3,1} + F_{3,3} = 1$$

we obtain for the view factor of the side wall or any outer cylinder ring onto itself

$$F_{i,i} = 1 - \frac{r_i}{h_i} [1 - \phi(r_i, r_i, h_i)] \quad (B-9)$$

By further applying Equations (B-1) to (B-4), the corresponding relationships for view factors between outer cylinder rings of different elevation and between outer cylinder rings and disks or annular disks on the top and bottom surface follow from simple algebra.

The view factors, as currently implemented in THATCH, require the same radial division into annular disks for the top and bottom surfaces of the cavity. However, the above equations are general and this restriction can readily be removed.

B-2 Radiation View Factors in an Annular Cylindrical Cavity

The radiation view factors between the surfaces of an annular cylindrical cavity, following the surface designations of Figure B-2, are as follows [Sparrow and Cess, 1967].

Outer cylinder to inner cylinder:

$$F_{A_1-A_2} = \frac{1}{X} - \frac{1}{\pi X} \left\{ \cos^{-1} \frac{B}{A} - \frac{1}{2Y} \left[\sqrt{(A+2)^2 - (2X)^2} \cos^{-1} \frac{B}{XA} + B \sin^{-1} \frac{1}{X} \frac{\pi A}{2} \right] \right\} \quad (B-9)$$

Outer cylinder onto itself

$$F_{A_1-A_1} = 1 - \frac{1}{X} + \frac{2}{\pi X} \tan^{-1} \left[2 \frac{\sqrt{X^2 - 1}}{Y} \right] - \frac{Y}{2} \pi X \left\{ \frac{\sqrt{4X^2 + Y^2}}{Y} \sin^{-1} \left[\frac{4(X^2 - 1) + \frac{Y^2}{X^2}(X^2 - 2)}{Y^2 + 4(X^2 - 1)} \right] - \sin^{-1} \left[\frac{X^2 - 2}{X^2} \right] + \frac{\pi}{2} \left[\frac{\sqrt{4X^2 + Y^2}}{Y} - 1 \right] \right\} \quad (B-10)$$

where

$$X = \frac{r_2}{r_1}; Y = \frac{h}{r_1}$$

$$A = Y^2 + X^2 - 1 \text{ and } B = Y^2 - X^2 + 1$$

From the above equations with Equation (B-2) follows

$$F_{A_1 - A_3} = 1/2 (1 - F_{A_1 - A_1} - F_{A_1 - A_2})$$

With these relationships, one can employ Equations (B-1) to (B-4) to develop, in straightforward algebra, all view factors between elements of these surfaces. The annular cylinder subroutines permit any nodalization of either side surface and do not require equal node spacing on the inside and outside surfaces. The routines also include limiting expressions for the trigonometric functions at small values or values close to multiples of π .

Figure B-2. Schematic of Annular Cylindrical Cavity

APPENDIX C

INTERNAL EVALUATION OF HEAT TRANSFER IN FINNED RCCS UPFLOW PANELS

In the internally finned upflow channels of the air-cooled RCCS heat transferred from the reactor cavity flows from the front panel of the RCCS by conduction and radiation to the fins and to the rear panel of the RCCS. All sides then transfer heat by convection to the upflowing coolant.

The PASCOL module permits the user to model the effect of the fins at each axial node either by prescribing a fin effectiveness, as outlined in Section 3.2, or by solving internally for simultaneous conduction and radiation in a nodalized fin structure, as shown schematically in Figure C-1.

To evaluate conduction and radiation at each axial node, the geometry of the coolant passage is considered to be rectangular, and radiation among the panel and fin nodes at each axial elevation is assumed to be in the radial and azimuthal direction only, i.e., neglecting any axial radiation. For fin spacing of about 10 cm and 15 cm fin lengths, at an RCCS panel radius of about 3.4 m, the curvature effects are indeed small. The effect of axial radiation was found to be very small in the reactor cavity (Kroeger, 1989) and would be even less at the temperature levels within the RCCS channels.

Figure C-2 is a scheme of a nodalized cell of the upflow channel. It consists of one half of each of two opposite fins and the corresponding sections of the front and back panels. Since the THATCH code assumes no variations of temperature in azimuthal direction, the two opposite fin halves have identical temperature distributions, and the solution can be restricted to computing the heat flows between nodes 1 to i_{op} . However, to compute the radiative heat flow it proved to be logically simpler to sum over all cell nodes.

A quasi-steady energy balance for node i can be expressed as

$$Q_{cond \ in} - Q_{rad} + Q_{conv} + Q_{cond \ ex} , \quad (C-1)$$

i.e., the conductive heat inflow equals the radiative plus convective plus conductive heat outflow. For node 1 the equation is essentially the same, except that $Q_{cond \ in}$ is replaced by the heat flow from the reactor vessel

$$Q_{ves} = A_{HT \ ex} U_{cav} (\theta_{ves} - \theta_1) \quad (C-2)$$

where $A_{HT \ ex}$ is the exterior heat transfer surface of the RCCS panel, U_{cav} the overall reactor cavity heat transfer coefficient, θ_{ves} the outer vessel node temperature, and θ_1 the RCCS front panel temperature (i.e., the temperature of node 1).

The various terms of equation C-1 can be expressed as follows:

For the conductive heat flow between nodes i and $i + 1$

Figure C-1: Schematic of Nodalized Internal
Fin Structure of Air-Cooled RCCS

i = cell node index
 n = side node index

C-2: Schematic of Node Indices for
 RCCS Upflow Channel

$$Q_{\text{cond } i} = \frac{A_{\text{cond } i}}{\Delta x_i} k(\theta_{\text{av}}) (\theta_i - \theta_{i+1}) \quad (\text{C-3})$$

where $A_{\text{cond } i}$ is the conductive heat flow cross section area, Δx_i is the distance between the centers of nodes i and $i + 1$, $k(\theta_{\text{av}})$ is the thermal conductivity at the average temperature between the two nodes, and θ is the node temperatures. Note that $A_{\text{cond } i}$ is generally based on one half of the fin thickness, corresponding to the heat flows between side nodes. However, the $Q_{\text{cond ex}}$ term for node 1 and the $Q_{\text{cond in}}$ term for node i_{op} must be multiplied by two, since two side nodes of one half the fin thickness are connected to each of these two nodes.

The radiative heat flow leaving node i is

$$Q_{\text{rad } i} = A_{\text{HT}} \sigma \sum_{j=1}^{i_L} \lambda_{i,j} \theta_j^4 \quad (\text{C-4})$$

where the radiation coefficients $\lambda_{i,j}$ are computed as described in Appendix A, based on the view factors given below. A_{HT} is the node convection and radiation heat transfer area and σ the Stefan - Boltzmann constant.

For the convective heat flow leaving node i we have

$$Q_{\text{conv } i} = A_{\text{HT}} h (\theta_i - \theta_{\text{fl}}) \quad (\text{C-5})$$

where h is the convective heat transfer coefficient (evaluated from Equation 3.2-8), and θ_{fl} is the coolant temperature.

With Equations (C-2) to (C-5) substituted into (C-1), equation (C-1) represents a set of i_{op} equations in the i_{op} unknown solid-node temperatures. The PASCOL module solves this set of equations using a Newton-Raphson procedure. For convenience, the equations were scaled by the node heat transfer area A_{HT} . Since the radiation heat exchange couples all node temperatures in each equation, the Jacobian matrix is dense, and the full system of equations must be solved at each iteration.

The radiation view factors between the nodes of a flow channel at a given axial elevation can readily be obtained from Hottel's String Method (Sparrow and Cess, 1966) which actually applies only to long channels, but can be used here since axial radiation is neglected.

Following Figure C-3, the view factors between any two surfaces elongated in the z -direction can be obtained as

$$F_{1,2} = \frac{1}{2s_1} [\ell_{11-22} + \ell_{12-21} - \ell_{11-21} - \ell_{12-22}] \quad (\text{C-6})$$

where s_1 is the length of A_1 in the x - y plane, and $\ell_{i,j}$ is the length of a straight line between points i and j .

Figure C-3: Schematic for View Factors
Between Surfaces Parallel in the
Z-Direction

In a rectangular geometry none of the nodes has a view factor with respect to itself, and the view factors between all nodes are readily computed from specified node end-point coordinates in the x-y plane substituting into equation C-6 the expressions

$$s_i = \sqrt{(x_{i1} - x_{i2})^2 + (y_{i1} - y_{i2})^2} \quad (C-7)$$

and

$$\ell_{m-n} = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2} \quad (C-8)$$

APPENDIX D

PROPERTIES OF GASES AND GAS MIXTURES

The THATCH code can handle mixtures of eight component gases.

The gases and their indices in all gas property arrays are

<u>Index</u>	<u>Gas</u>
1	helium
2	air
3	CO
4	CO ₂
5	H ₂ O
6	H ₂
7	O ₂
8	N ₂

The properties computed are the four thermal properties, specific heat at constant volume and pressure, internal energy and enthalpy as well as the thermodynamic properties of dynamic viscosity, and for some gases, thermal conductivity and the Prandtl number.

Densities for all gases are computed from the ideal gas state equation

$$pV = N\Re\theta \quad (D-1)$$

or

$$pv = R\theta \quad (D-2)$$

where p is the pressure, V the absolute volume, N the number of kilomoles, $\Re$ the universal gas constant, θ the gas temperature, v the specific volume, and $R = \Re/M$ the gas specific gas constant, with M being the mole weight of the gas species or of a gas mixture.

The gas data to be used are coded in the GASPRLIB section of BIG.

It should be noted that the data presented here for H₂O are those of an ideal gas, i.e., they apply for states sufficiently far from the saturation line, which means at sufficiently low pressure and high temperature.

D.1 Thermal Gas Properties

The evaluation of thermal gas properties is based on data for molar internal energy and energy of formation given in tabular form by Owczarek [1964] for all gases of interest, except helium. For helium, ideal gas values can readily be used at all pressures and temperatures of interest, and the corresponding expressions are given below. The given data extends from 300K to 4250K. For

convenience (to avoid "out of range" error messages), a data point at 273K was added, by a linear extrapolation; it was not a measured data point.

From the internal energies, E, the enthalpies, H, and specific heats, C_v and C_p , are readily computed as

$$H = E + \Re \theta \quad \left[\frac{\text{J}}{\text{kmol}} \right] \quad (\text{D-3})$$

$$C_v = \frac{\Delta E}{\Delta \theta} \quad \left[\frac{\text{J}}{\text{kmol K}} \right] \quad (\text{D-4})$$

$$C_p = C_v + \Re \quad \left[\frac{\text{J}}{\text{kmol K}} \right] \quad (\text{D-5})$$

where $\Re$ is the universal gas constant and ΔE and $\Delta \theta$ are the differences in internal energy and temperature. For helium we used

$$C_v = \frac{3}{2} \Re \quad \left[\frac{\text{J}}{\text{kmol K}} \right] \quad (\text{D-6})$$

$$C_p = \frac{5}{2} \Re \quad \left[\frac{\text{J}}{\text{kmol K}} \right] \quad (\text{D-7})$$

and

$$E = C_v \theta \quad \left[\frac{\text{J}}{\text{kmol}} \right] \quad (\text{D-8})$$

$$H = C_p \theta \quad \left[\frac{\text{J}}{\text{kmol}} \right] \quad (\text{D-9})$$

As all properties are in molar units, the properties for gas mixtures are obtained from the table data as

$$y_m = \sum \nu_\ell y_\ell \quad (\text{D-10})$$

where y stands for either of the four above properties (E, H, C_p , or C_v). ν_ℓ is the volume fraction of gas species ℓ , and subscripts m and ℓ signify "mixture" or "gas species ℓ ", respectively.

The actual computations and data tabulations are carried out in the GASPRLIB portion of BIG. The individual routines are described in Section 4 of this report. We note that the gas properties for gas

mixtures or for a single gas can be either obtained by linear interpolation in the internal energy tables, or by using a spline fit which was computed from the table data assuming a zero second derivative at both end points of the table. The spline fit is generally preferable since linear interpolation of the specific heats from Equation (D-4) leads to discontinuities at the mesh points of the table data, which could cause convergence problems in some instances.

D.2 Gas Viscosities

The code uses gas viscosity data for the first six gases. For the helium viscosity, the following correlation is employed

$$\mu = C \left[\frac{\theta}{\theta_o} \right]^n \left[\frac{\text{Ns}}{\text{m}^2} \right] \quad (\text{D-11})$$

where θ is the gas temperature in K, and θ_o a reference temperature. Currently

$$n = 0.674$$

and

$$\theta_o = 589\text{K}$$

$$C = 3.1137 \times 10^{-5} \left[\frac{\text{Ns}}{\text{m}^2} \right]$$

and for coding convenience

$$\frac{C}{\theta_o^n} = .4229 \times 10^{-6}$$

The viscosities for the other gases are mainly given in Table form and are generally computed by linear interpolation. The data are summarized in Tables D-1 to D-4. The actual code data may have more digits than the table entries, but these digits were essentially "generated" by conversion of original data in the literature to SI units using automated procedures to produce these data arrays.

The data source for gas viscosities [Vargaftik, 1975] indicated that CO viscosities are essentially equal to those of CO₂; therefore, the latter data were used.

For water vapor at temperatures up to 1200K the following ASME steam table correlation is used, with table data from table D-3 being used above 1200K.

$$\mu = (80.4 + 0.407 \times \theta [\text{C}]) \times 10^{-7} \left[\frac{\text{Ns}}{\text{m}^2} \right]$$

Table D-1
Thermodynamic Properties of Air

Temperature K	Viscosity $\frac{Ns}{m^2}$	Thermal Conductivity $\frac{W}{mK}$	Prandtl Number
250	1.598×10^{-5}	0.02226	0.722
300	1.847	0.02622	0.708
350	2.075	0.03001	0.697
400	2.286	0.03362	0.689
450	2.484	0.03705	0.683
500	2.671	0.04035	0.680
550	2.848	0.04357	0.680
600	3.018	0.04656	0.680
650	3.177	0.04950	0.682
700	3.332	0.05227	0.684
750	3.481	0.05505	0.686
800	3.625	0.05775	0.689
850	3.765	0.06024	0.692
1200	4.627	0.07627	0.714
1700	5.643	0.09599	0.749
2566.5	7.069	0.12262	0.972

Table D-2
Dynamic Viscosities of CO₂

Temperature K	Viscosity $\frac{\text{Ns}}{\text{m}^2}$
300 500 700	15.1 x 10 ⁻⁶ 23.7 30.7
900 1100 1300	36.8 42.1 47.0
1500 1700 1900	51.5 55.6 59.5
2100 2300 2500	63.2 66.6 70.04

Table D-3
Dynamic Viscosities of H₂O*

Temperature K	Viscosity $\frac{\text{Ns}}{\text{m}^2}$
1200	45.76 x 10 ⁻⁶
1400	51.2
1600	56.3
1800	61.2
2000	65.9
2200	70.3
2400	74.2
2600	77.5
2800	79.8
3000	81.0
3200	81.4
3400	81.6
3600	82.5

* below 1200K use equation D-12

Table D-4
Dynamic Viscosity of H₂*

Temperature K	Viscosity $\frac{Ns}{m^2}$
250	8.0×10^{-6}
500	12.64
750	16.6
1000	20.1

* beyond 1000K, linear extrapolation is used

The gas mixture viscosities are computed from the generally accepted formula of Wilke [1950]

$$\mu_m = \sum_{i=1}^L \frac{\mu_i}{1 + \sum_{j=1}^L \frac{\nu_j}{\nu_i} \phi_{ij} (1 - \delta_{ij})} \quad (D-13)$$

with

$$\phi_{i,j} = \frac{\left[1 + \left[\frac{\mu_i}{\mu_j} \right]^{0.5} \left[\frac{M_j}{M_i} \right]^{0.25} \right]^2}{\sqrt{8 \left(1 + \frac{M_i}{M_j} \right)}}$$

where μ is the viscosity, ν is the volume fraction, M is the molar mass, $\delta_{i,j}$ is the Kronecker delta, and the subscript m denotes mixture. L is the number of gases.

In current practice, for viscosities of gas mixtures, THATCH uses three gases in the case of air ingress, namely helium, air, and CO with the N_2 content being added to air. For water ingress, six gases are used, adding CO_2 , H_2O , and H_2 to the above three gases and, again, considering the N_2 concentration with the air.

D.3 Gas Thermal Conductivities

The present code provides thermal conductivities only for helium and air. For air-ingress scenarios, where CO and N_2 occupy most of the core, the resulting error is not expected to be severe since the thermal conductivity of N_2 and CO is close to that of air. In the water-ingress scenarios investigated so far, the concentrations of H_2O and H_2 remained very small and the use of He conductivities alone was again justified. However, values for H_2O , H_2 and CO should be added as soon as possible. Also, a better equation for conductivities of gas mixtures should be provided.

The thermal conductivity of helium is computed here from the helium viscosity. Noting that the Prandtl number remains virtually constant, over the temperature range of interest $Pr = 0.72$, and because the specific heat of helium is constant, we have

$$k = \left[\frac{C_p}{M Pr} \right] \mu \left[\frac{W}{mK} \right]$$

where k is thermal conductivity, C_p the molar specific heat, M the mole mass, and μ the viscosity.

The thermal conductivity of air is prescribed in tabular form, and was included in table D-1.

For helium-air mixtures, a very crude mixture correlation is currently used, namely:

$$k_m = \sum_{i=1}^2 \nu_i k_i$$

where ν_i represents the volume fractions.

This relationship should be replaced for more detailed future applications. As stated above, for the air ingress cases handled so far (pure air entering the system), the ensuing error should have been small.

APPENDIX E

TABULAR SUMMARY OF THATCH SUBROUTINES AND COMMON DECKS

Table E-1
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
AFTANS	BIG (GENLIB)	FUNCTION(R*8)	AFTANS AFTPSID TBLLKF
AFTCOFS	BIG (GENLIB)	SUBROUTINE	
AFTFR	BIG (GENLIB)	FUNCTION(R*8)	
AFTPSID	BIG (GENLIB)	FUNCTION(R*8)	
AIR	BIG (PASCOLIB)	BLOCK DATA	
AIRCLEX	BIG (PASCOLIB)	ENTRY (AIRCOOL)	
AIRCLIN	BIG (PASCOLIB)	ENTRY (AIRCOOL)	
AIRCLOT	BIG (PASCOLIB)	ENTRY (AIRCOOL)	
AIRCLRD	BIG (PASCOLIB)	ENTRY (AIRCOOL)	
AIRCLWR	BIG (PASCOLIB)	ENTRY (AIRCOOL)	
AIRCOOL	BIG (PASCOLIB)	SUBROUTINE	CP1 EVALAIR FININ1 FININ2 FLEN2(2) FLEN3(2) FLOW(2) FTHIN FTHIN GASENER NEWTON TIMEIN TIMEOUT TTHEX YTHETA YTHETA(4)
AIRESD	BIG (PASCOLIB)	SUBROUTINE	
ALLPLFL	THATCH	ENTRY (FAILURE)	
ANNEL	THATCH	SUBROUTINE	
ANNELEX	THATCH	ENTRY (ANNEL)	
ANNELIN	THATCH	ENTRY (ANNEL)	
AVAL	BIG (FLOXLIB)	SUBROUTINE	
AVERAGE	BIG (SYMELLIB)	SUBROUTINE	
AVERAG2	BIG (SYMELLIB)	SUBROUTINE	
BASEPLT	THATCH	ENTRY (PLOTTER)	
BLDPINK	BIG (PKINLIB)	BLOCK DATA	IDMAX(2)
BLKPRNT	THATCH	ENTRY (PRINTER)	IDMAX(2)

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
BNDCONI	THATCH	SUBROUTINE	CONDF (2)
BNDCONX	THATCH	SUBROUTINE	CONDF
CALIC	BIG (PKINLIB)	SUBROUTINE	
CAVIN	BIG (WATCOLIB)	SUBROUTINE	CPL CPISPL RHOL (2)
CLOCKK	BIG (THATCHLIB)	SUBROUTINE	DATIM
COEFFLD	BIG (SYMELLIB)	SUBROUTINE	
COEFFL2	BIG (SYMELLIB)	SUBROUTINE	
COMBINE	BIG (GENLIB)	SUBROUTINE	
COMCON	THATCH	SUBROUTINE	CONDF (2)
CONAIR	BIG (GASPLIB)	FUNCTION (R*8)	TBLKF
CONALST	BIG (MATLIB)	ENTRY (PROPTY)	
CONALU	BIG (MATLIB)	ENTRY (PROPTY)	
CONAXGR	BIG (MATLIB)	ENTRY (PROPTY)	
CONAXG2	BIG (MATLIB)	ENTRY (PROPTY)	
CONA20F	BIG (MATLIB)	ENTRY (PROPTY)	
CONBORG	BIG (MATLIB)	ENTRY (PROPTY)	
CONCC	BIG (MATLIB)	ENTRY (PROPTY)	
CONCS	BIG (MATLIB)	ENTRY (PROPTY)	
CONDAPL	THATCH	SUBROUTINE	COMCON CONDF
CONDENS	BIG (GENLIB)	SUBROUTINE	NORECF RERITE
CONDF	THATCH	ENTRY (PROPMAT)	
CONDFSM	BIG (SYMELLIB)	ENTRY (PROPT)	
CONDGM	BIG (GASPLIB)	FUNCTION (R*8)	CONAIR CONHEL (2)
CONDL	BIG (WATCOLIB)	FUNCTION (R*8)	

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
CONDOC	THATCH	SUBROUTINE	ANNELEX BNDCONI(2) BNDCONX(2) CONDF(6) THETABC(2) TIMEIN TIMEOUT
COND451	BIG (MATLIB)	SUBROUTINE	
CONFER	BIG (MATLIB)	ENTRY (CON451A)	
CONFERD	BIG (MATLIB)	ENTRY (PROPTY)	
CONFERU	BIG (MATLIB)	ENTRY (PROPTY)	
CONFUEL	BIG (MATLIB)	ENTRY (PROPTY)	
CONHA	BIG (MATLIB)	ENTRY (PROPTY)	
CONHEL	BIG (GASPRLIB)	FUNCTION(R*8)	VISHL
CONKA	BIG (MATLIB)	ENTRY (PROPTY)	
CONMCS	BIG (MATLIB)	ENTRY (PROPTY)	
CONPEB	BIG (MATLIB)	ENTRY (PROPTY)	
CONRAD	BIG (MATLIB)	ENTRY (PROPTY)	
CONRDGR	BIG (MATLIB)	ENTRY (PROPTY)	
CONRDG2	BIG (MATLIB)	ENTRY (PROPTY)	
CONR20F	BIG (MATLIB)	ENTRY (PROPTY)	
CON4AD	BIG (MATLIB)	ENTRY (PROPTY)	
CON4AU	BIG (MATLIB)	ENTRY (PROPTY)	
CON4RD	BIG (MATLIB)	ENTRY (PROPTY)	
CON4RU	BIG (MATLIB)	ENTRY (PROPTY)	
CON451A	BIG (MATLIB)	FUNCTION(R*8)	CONFERD CONFERU CON4AD CON4AU CON4RD CON4RU
CON451R	BIG (MATLIB)	ENTRY (CON451A)	
CON800	BIG (MATLIB)	ENTRY (PROPTY)	
COREDTS	BIG (THTCHLIB)	BLOCK DATA	
CORFEL	BIG (THTCHLIB)	SUBROUTINE	

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
CORGASL	BIG (FLOXLIB)	SUBROUTINE	REACT
CORINDM	BIG (THTCHLIB)	ENTRY (CORINDT)	
CORINDT	BIG (THTCHLIB)	SUBROUTINE	
CORINFEL	BIG (THTCHLIB)	ENTRY (CORINDT)	
CORINIT	BIG (FLOXLIB)	SUBROUTINE	
CORINPS	BIG (THTCHLIB)	ENTRY (CORINPW)	
CORINPW	BIG (THTCHLIB)	SUBROUTINE	
CORINSY	BIG (THTCHLIB)	ENTRY (CORINDT)	
CPFUEL	BIG (MATLIB)	ENTRY (PROPTY)	
CPGRAF	BIG (MATLIB)	ENTRY (PROPTY)	
CPGREX	BIG (MATLIB)	ENTRY (PROPTY)	
CPL	BIG (WATCOLIB)	FUNCTION (R*8)	
CPMIX	BIG (GASPRLIB)	ENTRY (CVMIX)	
CPMIXSP	BIG (GASPRLIB)	ENTRY (CVMIXSP)	
CP1	BIG (GASPRLIB)	ENTRY (CV1)	
CP1SPL	BIG (GASPRLIB)	ENTRY (CV1SPL)	
CVMIX	BIG (GASPRLIB)	FUNCTION (R*8)	GASENER TBLLKF
CVMIXSP	BIG (GASPRLIB)	FUNCTION (R*8)	TBLLKF
CV1	BIG (GASPRLIB)	FUNCTION (R*8)	GASENER(2) TBLLKF
CV1SPL	BIG (GASPRLIB)	FUNCTION (R*8)	GASENER SPLINE2(2)
DATE	BIG (THTCHLIB)	SUBROUTINE	DATIM
DERIV	BIG (PKINLIB)	SUBROUTINE	SUMRHOF
DHFCT	BIG (GASPRLIB)	FUNCTION (R*8)	CPMIXSP CP1SPL
DMAT	BIG (WATCOLIB)	SUBROUTINE	

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
DRHODTH	BIG (WATCOLIB)	ENTRY (RHOL)	
EEMSPL	BIG (GASPRLIB)	ENTRY (CVMIXSP)	
EEISPL	BIG (GASPRLIB)	ENTRY (CV1SPL)	
ENCHECK	BIG (SYMELLIB)	SUBROUTINE	CONDFSM(4) HFUGRF ROCFSM
ENINTRL	BIG (GASPRLIB)	ENTRY (CVMIX)	
ENINT1	BIG (GASPRLIB)	ENTRY (CV1)	
ENTHAL	BIG (GASPRLIB)	ENTRY (CVMIX)	
ENTHAL1	BIG (GASPRLIB)	ENTRY (CV1)	
ERROR	THATCH	SUBROUTINE	
EVALAIR	BIG (PASCOLIB)	SUBROUTINE	CONDF(2) FLOW HHCAVITY(2) HHCONVF(3) HHRADBL(4) YTHETA
EXPF	BIG (GENLIB)	FUNCTION(R=8)	
FAILS	THATCH	ENTRY (FAILURE)	
FAILURE	THATCH	SUBROUTINE	LINEON(3) LINETST
FCOND	BIG (GENLIB)	SUBROUTINE	CONDENS POSITN
FILEFIN	BIG (SYMELLIB)	SUBROUTINE	FRITE(2)
FINEXEC	BIG (PASCOLIB)	ENTRY (FINNER)	
FININ1	BIG (PASCOLIB)	ENTRY (FINNER)	
FININ2	BIG (PASCOLIB)	ENTRY (FINNER)	
FINNER	BIG (PASCOLIB)	SUBROUTINE	CONDF(2) HHCONVF NEWTON2 RADCOEF UCAVF
FLEN2	BIG (PASCOLIB)	ENTRY (AIRES0)	
FLEN3	BIG (PASCOLIB)	ENTRY (AIRES0)	
FLOW	BIG (PASCOLIB)	ENTRY (AIRES0)	
FLOWAPR	BIG (FLOXLIB)	SUBROUTINE	FRIC(2) VISGSPK(2)
FLOXDAT	BIG (FLOXLIB)	BLOCK DATA	

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
FLOXIEX	BIG (FLOXLIB)	SUBROUTINE	AFTER CORGASL(2) CORINIT FLUINUP FLXFLOW FLXTHEX(2) HETCON(2) HHMSPL(4) HH1SPL(4) PLENBAR(4) RADTN THFLXEX(2) TIMEIN TIMEOUT
FLOXIIN	BIG (FLOXLIB)	SUBROUTINE	CORINFL GASENER REDCOF2 THFLXIN
FLOXIMS	BIG (FLOXLIB)	SUBROUTINE	AFTCOFS FLOXIEX FLOXIIN FLOXIOT FLOXISM FLOXIWR FRITE READIN
FLOXIOT	BIG (FLOXLIB)	SUBROUTINE	CORGASL FLXFLOW HETCON PLENBAR RENCH STRACE
FLOXIRD	BIG (FLOXLIB)	ENTRY (FLOXIOT)	
FLOXISM	BIG (FLOXLIB)	SUBROUTINE	FLOXIRD
FLOXIWR	BIG (FLOXLIB)	ENTRY (FLOXIOT)	
FLUINUP	BIG (FLOXLIB)	SUBROUTINE	TBLKSEC
FLXFLOW	BIG (FLOXLIB)	SUBROUTINE	AVAL FLOWAPR FRIC(2) SOLSPEC VISGSPK(3)
FLXTHEX	THATCH	SUBROUTINE	
FMAX2	BIG (SYMELLIB)	FUNCTION(R*8)	IDMAX
FMAX3	BIG (SYMELLIB)	FUNCTION(R*8)	IDMAX
FREEIN	THATCH	SUBROUTINE	
FRIC	BIG (GENLIB)	FUNCTION(R*8)	
FRICT	BIG (WATCOLIB)	FUNCTION(R*8)	
FRITE	BIG (GENLIB)	SUBROUTINE	NORECF POSITN(2) RERITE
FTHEX	THATCH	SUBROUTINE	
FTHIN	THATCH	SUBROUTINE	
GASDATA	BIG (GASPRLIB)	BLOCK DATA	
GASENER	BIG (GASPRLIB)	SUBROUTINE	TBLKCF
GASLOAD	BIG (THATCHLIB)	SUBROUTINE	GASENER
HEATGEN	THATCH	SUBROUTINE	AFTER TIMEIN TIMEOUT
HETCOF	BIG (GENLIB)	FUNCTION(R*8)	
HETCON	BIG (FLOXLIB)	SUBROUTINE	CPMIXSP CP1 EXPF HETCOF

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

HFUGRF Subroutine or Entry	BIG (SYMELLIB) Location	FUNCTION(R*8) Type	CONHEL Subroutines Referenced by this Unit
HFCT	BIG (GASPRLIB)	FUNCTION(R*8)	HMSPL HH1SPL
HHCAVY	BIG (GENLIB)	FUNCTION(R*8)	CONHEL PROPAIR VISHEL
HHCONVF	BIG (GENLIB)	FUNCTION(R*8)	CONAIR VISAIR
HMSPL	BIG (GASPRLIB)	ENTRY(CVMIXSP)	
HHRADBL	BIG (GENLIB)	FUNCTION(R*8)	
HH1SPL	BIG (GASPRLIB)	ENTRY(CV1SPL)	
HOTFRAC	BIG (SYMELLIB)	ENTRY(AVERAGE)	
HOTFRC2	BIG (SYMELLIB)	ENTRY(AVERAGE2)	
HTFLUX	THATCH	SUBROUTINE	LINEON(2) LINETST
INBLOCK	THATCH	SUBROUTINE	ERROR(4) FREEIN INPPLNA LINEON(8) LINETST(2) NEWPAGE
INBND	THATCH	SUBROUTINE	INFALP LINEON(8) LINETST(3) NEWPAGE
INDEXF	BIG (PASCOLIB)	SUBROUTINE	
INFALP	THATCH	ENTRY(FAILURE)	
INGEOM	THATCH	SUBROUTINE	CORINDM(2) ERROR LINEON(12) LINETST(3) NEWPAGE(3)
INHGTEN	THATCH	SUBROUTINE	AFTCOFS CORINPW HEATGEN LINEON NEWPAGE
INPBLKS	THATCH	ENTRY(INBLOCK)	
INPBND	THATCH	ENTRY(INBND)	
INPGEOM	THATCH	ENTRY(INGEOM)	
INPHTGN	THATCH	ENTRY(INHTGEN)	
INPLENA	THATCH	SUBROUTINE	ERROR(3)
INPPLNA	THATCH	ENTRY(INPLENA)	
INPT	THATCH	ENTRY(INTIME)	
INPTH	THATCH	ENTRY(INTHETA)	

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
INTHETA	THATCH	SUBROUTINE	BLKPRNT NEWPAGE PLENPRT THETABC(3) THETA IN
INTIME	THATCH	SUBROUTINE	ERROR LINEON NEWPAGE
JACAIR0	BIG (PASCOLIB)	SUBROUTINE	FLEN2 FLEN3 FLOW
JACK	BIG (PKINLIB)	SUBROUTINE	SUMRHOF
LINEON	THATCH	ENTRY (PAGER)	
LINETST	THATCH	ENTRY (PAGER)	
MAPRINT	BIG (GENLIB)	SUBROUTINE	
MINATOR	BIG (GENLIB)	FUNCTION(I=4)	LEFT1A
NEWPAGE	THATCH	ENTRY (PAGER)	
NEWTON	BIG (THATCHLIB)	SUBROUTINE	DGEF DGEFS DGES F04ARF IDAMAX
NEWTON2	BIG (PASCOLIB)	SUBROUTINE	DGEFS RESJAC2
NLOCF	THATCH	FUNCTION(I=4)	
NORECF	BIG (GENLIB)	FUNCTION(I=4)	
NZFCT	BIG (PASCOLIB)	FUNCTION(I=4)	
ODEDAT	BIG (GENLIB)	BLOCK DATA	
PAGER	THATCH	SUBROUTINE	
PKINEX	BIG (PKINLIB)	ENTRY (PKIN0)	
PKININ	BIG (PKINLIB)	ENTRY (PKIN0)	
PKINOUT	BIG (PKINLIB)	ENTRY (PKIN0)	
PKINRD	BIG (PKINLIB)	ENTRY (PKIN0)	
PKINWR	BIG (PKINLIB)	ENTRY (PKIN0)	
PKIN0	BIG (PKINLIB)	SUBROUTINE	CALIC DERIV ERRSET IWKIN RHOCORF(2) RHOOFTH RHOWATF(2) SECOND(2) SOLTRAN TEMPMAX THFUEL(2) TIMEIN TIMEOUT(2) UERTXXX
PLENBAR	BIG (FLOXLIB)	SUBROUTINE	PLENSUM(2)

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
PLENPT	THATCH	ENTRY (PRINTER)	
PLENSUM	BIG (FLOXLIB)	SUBROUTINE	HMSPL HHISPL THFROMH
PLOTTER	THATCH	SUBROUTINE	AIRCLR FLOXIWR (2) PKINWR
POLF	BIG (THCHLIB)	FUNCTION (R*8)	
POSITN	BIG (GENLIB)	SUBROUTINE	
POWPROF	BIG (SYMELLIB)	FUNCTION (R*8)	
PREBLCK	THATCH	ENTRY (INBLOCK)	
PREBND	THATCH	ENTRY (INBND)	
PREFAIL	THATCH	ENTRY (FAILURE)	
PREGEOM	THATCH	ENTRY (INGEOM)	
PREHTGN	THATCH	ENTRY (INHGTEN)	
PREINIT	THATCH	SUBROUTINE	DATE PREBLCK PREBND PREFAIL PREGEOM PREHTGN PREPLNA PREHTA PRETIME TIMEX
PREPLNA	THATCH	ENTRY (INPLENA)	
PREHTA	THATCH	ENTRY (INHETA)	
PRETIME	THATCH	ENTRY (INTIME)	
PRINTER	THATCH	SUBROUTINE	LINEON (10) LINETST (2) TIMEIN (3) TIMEOUT
PROPAIR	BIG (GASPRLIB)	SUBROUTINE	TBLKF
PROPLD	BIG (SYMELLIB)	SUBROUTINE	CONDFSM HETCOF HFUGRF (2) ROCFSM VISHEL
PROPMAT	THATCH	FUNCTION (R*8)	CONALU CONA20F (2) CONBORG CONCC CONCS (2) CONFER CONHEL (4) CONKA (3) CONMCS CONRAD (3) CONR20F (2) CON451A (4) CON451R CON800 (6) CPGRAF (6) HHCAVY (2) ROCALU ROCCC ROCCS (2) ROCKA (3) ROCMCS ROC800 (5) VISHEL
PROPT	BIG (SYMELLIB)	FUNCTION (R*8)	CONFUEL CON4RD CPFUEL CPGRAF STRACE (2)
PROPTY	BIG (MATLIB)	FUNCTION (R*8)	COND451 (4) TBLKF (10)
PSTGEOM	THATCH	ENTRY (INGEOM)	

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
PSTHTGN	THATCH	ENTRY (INHGTEN)	
PSTINIT	THATCH	SUBROUTINE	AIRCLRD ALLPLFL ERROR(2) FLOXIRD NEWPAGE PKINRD PSTGEOM PSTHTGN PSTPLNA SYMTPIN
PSTINRS	THATCH	ENTRY (PSTINIT)	
PSTPLNA	THATCH	ENTRY (INPLENA)	
RADCOEF	BIG (PASCOLIB)	SUBROUTINE	LINV3F MAPRINT(3) NZFCT(3) VIEWPAR(2) VIEWREC(2)
RADTN	THATCH	SUBROUTINE	CONDAPL(2) NEWTON TIMEIN TIMEOUT UPLCONV(2)
REACT	BIG (FLOXLIB)	SUBROUTINE	EXPF(2) RUFF20X
READIN	BIG (GENLIB)	SUBROUTINE	
REDCOF2	BIG (GENLIB)	SUBROUTINE	
RENCH	BIG (FLOXLIB)	SUBROUTINE	
RERITE	BIG (GENLIB)	SUBROUTINE	
RESJAC	THATCH	SUBROUTINE	CONDAPL IDAMAX UPLCONV
RESJAC2	BIG (PASCOLIB)	SUBROUTINE	CONDH HHCONVF UCAVF
RHOCORF	BIG (PKINLIB)	FUNCTION(R*8)	RHOOFTH(2)
RHOL	BIG (WATCOLIB)	FUNCTION(R*8)	
RHOOFTH	BIG (PKINLIB)	SUBROUTINE	TBLCLKF(8)
RHOWATF	BIG (PKINLIB)	FUNCTION(R*8)	
ROCALST	BIG (MATLIB)	ENTRY (PROPTY)	
ROCALU	BIG (MATLIB)	ENTRY (PROPTY)	
ROCCC	BIG (MATLIB)	ENTRY (PROPTY)	
ROCCS	BIG (MATLIB)	ENTRY (PROPTY)	
ROCF	THATCH	ENTRY (PROPMAT)	
ROCFSM	BIG (SYMELLIB)	ENTRY (PROPT)	
ROCHA	BIG (MATLIB)	ENTRY (PROPTY)	

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
ROCKA	BIG (MATLIB)	ENTRY (PROPTY)	
ROCMCS	BIG (MATLIB)	ENTRY (PROPTY)	
ROC800	BIG (MATLIB)	ENTRY (PROPTY)	
RUFF	BIG (GENLIB)	SUBROUTINE	
RUFF20X	BIG (FLOXLIB)	SUBROUTINE	
SECOND	BIG (GENLIB)	FUNCTION(R*8)	CPUTIME
SOLSPEC	BIG (FLOXLIB)	SUBROUTINE	
SOLTRAN	BIG (GENLIB)	SUBROUTINE	DGEAR DIVPAG(3) EULER NIRC2 N1RTY
SOLVAIR	BIG (PASCOLIB)	SUBROUTINE	
SPECWAT	BIG (WATCOLIB)	SUBROUTINE	
SPLINE2	BIG (GENLIB)	FUNCTION(R*8)	TBLK
STACK	BIG (PASCOLIB)	SUBROUTINE	FRIC VISAIR
STRACE	BIG (GENLIB)	SUBROUTINE	
SUMRHOF	BIG (PKINLIB)	FUNCTION(R*8)	RHOWATF(2)
SURFPRT	THATCH	ENTRY (PRINTER)	
SYMDAT	BIG (SYMELLIB)	BLOCK DATA	
SYMELAN	BIG (SYMELLIB)	SUBROUTINE	FILEFIN SYMELIN TEMPRIN TIMEPR TIMLOP
SYMELDT	BIG (SYMELLIB)	SUBROUTINE	
SYMELIN	BIG (SYMELLIB)	SUBROUTINE	CORINPS CORINST CP1 GASENER PKININ READIN SYMELDT SYMTPIN TEMPAVG THSYMIN
SYMELOT	BIG (SYMELLIB)	SUBROUTINE	AVERAGE AVERAG2 HOTFRAC HOTFRC2 PKINOUT TEMPMX2 THMAX
SYMFLEX	BIG (SYMELLIB)	ENTRY (SYMTEX)	
SYMTEX	BIG (SYMELLIB)	SUBROUTINE	
SYMTPIN	BIG (SYMELLIB)	SUBROUTINE	
SYTMPAV	BIG (SYMELLIB)	SUBROUTINE	AVERAGE AVERAG2 THMAX

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
SYTMPMX	BIG (SYMELLIB)	ENTRY (SYTMPAV)	
TBLKSEC	BIG (GENLIB)	SUBROUTINE	
TBLLK	BIG (GENLIB)	SUBROUTINE	
TBLKLF	BIG (GENLIB)	SUBROUTINE	TBLK
TEMPAVG	BIG (SYMELLIB)	SUBROUTINE	SYTMPAV(2) SYTMPMX THTMPAV(2) THTMPMX
TEMPLSM	BIG (SYMELLIB)	SUBROUTINE	
TEMPLTH	THATCH	SUBROUTINE	
TEMPMAX	BIG (SYMELLIB)	ENTRY (TEMPAVG)	
TEMPMX2	BIG (SYMELLIB)	ENTRY (AVERAG2)	
TEMPRIN	BIG (SYMELLIB)	SUBROUTINE	
TEMPSOL	THATCH	SUBROUTINE	CONDUCT DGTF(2) DGTS(2) ROCF THETABC(3) THSYME2 TIMEIN TIMEOUT
TEMPSYM	BIG (SYMELLIB)	SUBROUTINE	COEFFLD COEFFL2 DGEF DGES DGTF DGTS ENCHECK POWPROF PROPLOD TIMEIN(2) TIMEOUT(2)
THATCH	THATCH	SUBROUTINE	AIRCLIN ANNELIN CORFEL ERROR(2) FLOXIN GASLOAD INPBLKS INPBD INPGEOM INPHTGN INPT INPTH KMAND NEWPAGE PKININ PKINOUT PREINIT PSTINIT PSTINRS SYMELIN TEMPVAVG TIMEIN(3) TIMEOUT(3) TIMEPR(3) TIMSOL XUFLOW
THBLDAT	THATCH	BLOCK DATA	
THETABC	THATCH	FUNCTION(R*8)	
THETA IN	THATCH	SUBROUTINE	
THFLXEX	THATCH	SUBROUTINE	
THFLXIN	THATCH	SUBROUTINE	
THFROMH	BIG (GASPRLIB)	FUNCTION(R*8)	
THFUEL	BIG (PKINLIB)	FUNCTION(R*8)	RUFF
THMAX	BIG (SYMELLIB)	ENTRY (AVERAGE)	

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
THSYMEX	BIG (SYMELLIB)	SUBROUTINE	
THSYME2	BIG (SYMELLIB)	SUBROUTINE	
THSYMIN	THATCH	SUBROUTINE	
THTMPAV	THATCH	SUBROUTINE	
THTMPMX	THATCH	ENTRY (THTMPAV)	
TIMEIN	BIG (THTCHLIB)	ENTRY (TIMER)	
TIMEOUT	BIG (THTCHLIB)	ENTRY (TIMER)	
TIMEPLT	THATCH	ENTRY (PLOTTER)	
TIMEPR	BIG (THTCHLIB)	ENTRY (TIMER)	
TIMER	BIG (THTCHLIB)	SUBROUTINE	NEWPAGE SECOND(2) STRACE
TIMEX	BIG (THTCHLIB)	SUBROUTINE	CLOCKK
TIMLOP	BIG (SYMELLIB)	SUBROUTINE	JOBSTP MINATOR PKINEX SYMELOT TEMPVAV TEMPLSM TEMPSYM TIMEIN TIMEOUT TIMVAR
TIMSOL	THATCH	SUBROUTINE	AIRCLEX(2) AIRCLOT BASEPLT BLKPRNT CONDOC FAILS FILEFIN FLOXIE(2) FLOXIOT HEATGEN HTFLUX(2) JOBSTP KWAND LINEON MINATOR(2) NEWPAGE(2) PKINEX PKINOUT PLENPRT RADTN(2) SECOND(2) SURFPRT SYMELOT(2) SYMFLEX SYMTHEX(2) TEMPVAV(2) TEMPLSM TEMPLTH TEMPSOL TEMPSYM THETABC THSYMEX TIMEPLT
TIMVAR	BIG (SYMELLIB)	SUBROUTINE	
TRIDG	BIG (GENLIB)	SUBROUTINE	
TSATL	BIG (WATCOLIB)	FUNCTION(R*8)	
TTHEX	THATCH	SUBROUTINE	
UCAVF	BIG (PASCOLIB)	FUNCTION(R*8)	CONDF HHCADTY HHRADBL
UERTXXX	BIG (PKINLIB)	SUBROUTINE	
UPLCONV	THATCH	SUBROUTINE	CONHEL(2) CP1 VISHEL
VIEWPAR	BIG (PASCOLIB)	FUNCTION(R*8)	
VIEWPRØ	BIG (PASCOLIB)	FUNCTION(R*8)	

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
VIEWRC0	BIG (PASCOLIB)	FUNCTION(R*8)	
VIEWREC	BIG (PASCOLIB)	FUNCTION(R*8)	
VISAIR	BIG (GASPRLIB)	FUNCTION(R*8)	TBLKF
VISCL	BIG (WATCOLIB)	FUNCTION(R*8)	
VISCO	BIG (GASPRLIB)	FUNCTION(R*8)	VISCO2
VISCO2	BIG (GASPRLIB)	FUNCTION(R*8)	
VISGAS	BIG (GASPRLIB)	FUNCTION(R*8)	VISAIR VISCO VISCO2 VISH2 VISH20 VISMIX
VISGSPK	BIG (GASPRLIB)	FUNCTION(R*8)	VISGAS VISH2
VISH2	BIG (GASPRLIB)	FUNCTION(R*8)	
VISH20	BIG (GASPRLIB)	FUNCTION(R*8)	
VISMIX	BIG (GASPRLIB)	FUNCTION(R*8)	
WALSOL0	BIG (PASCOLIB)	SUBROUTINE	CONDF(2) HHCAVITY(2) HHCONVF(3) HHRADBL(3)
WALSOL2	BIG (PASCOLIB)	ENTRY(WALSOL0)	
WALSOL3	BIG (PASCOLIB)	ENTRY(WALSOL0)	
WATCLEX	BIG (WATCOLIB)	SUBROUTINE	CONDF FTHEX NEWTON TIMEIN TIMEOUT TTTEX
WATCLIN	BIG (WATCOLIB)	SUBROUTINE	CAVIN FTHIN SETDCK SETGRV SETPI SETSTF
WATCLOT	BIG (WATCOLIB)	SUBROUTINE	CPL CPISPL TSATL
WATCLRD	BIG (WATCOLIB)	ENTRY(WATCLOT)	
WATCLWR	BIG (WATCOLIB)	ENTRY(WATCLOT)	
WATCONS	BIG (WATCOLIB)	BLOCK DATA	
WATRES0	BIG (WATCOLIB)	SUBROUTINE	IDAMAX WATRR
WATRR	BIG (WATCOLIB)	SUBROUTINE	CONCS(2) CONDL(2) CPL(2) CPISPL DRHODTH(3) FRIC(6) FRICT(2) HHCAVITY HHRADBL PROPAIR(2) RHOL(5) VISCL(6) XNUSL(2) XNUSTB

Table E-1 (continued)
List of THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Location	Type	Subroutines Referenced by this Unit
XNUSL	BIG (WATCOLIB)	FUNCTION(R*8)	
XNUSTB	BIG (WATCOLIB)	FUNCTION(R*8)	
YTHETA	BIG (PASCOLIB)	SUBROUTINE	

Table E-2
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
AFTANS	FUNCTION (R*8)	AFTER
AFTCOFS	SUBROUTINE	FLOXIMS INHTGEN
AFTER	FUNCTION (R*8)	HEATGEN FLOXIEX
AFTPSID	FUNCTION (R*8)	AFTER
AIRCLEX	ENTRY (AIRC00L)	TIMSOL (2)
AIRCLIN	ENTRY (AIRC00L)	THATCH
AIRCLOT	ENTRY (AIRC00L)	TIMSOL
AIRCLRD	ENTRY (AIRC00L)	PSTINIT
AIRCLWR	ENTRY (AIRC00L)	PLOTTER
ALLPLFL	ENTRY (FAILURE)	PSTINIT
ANNELEX	ENTRY (ANNEI)	CONDOC
ANNELIN	ENTRY (ANNEI)	THATCH
AVAL	SUBROUTINE	FLXFLOW
AVERAGE	SUBROUTINE	SYTMPAV SYMELOT
AVERAG2	SUBROUTINE	SYMELOT SYTMPAV
BASEPLT	ENTRY (PLOTTER)	TIMSOL
BLKPRNT	ENTRY (PRINTER)	TIMSOL INTHETA
BNDCONI	SUBROUTINE	CONDOC (2)
BNDCONX	SUBROUTINE	CONDOC (2)
CALIC	SUBROUTINE	PKINØ
CAVIN	SUBROUTINE	WATCLIN
CLOCKK	SUBROUTINE	TIMEX
COEFFLD	SUBROUTINE	TEMPSYM

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
C0EFFL2	SUBROUTINE	TEMPSYM
COMCON	SUBROUTINE	CONDAPL
CONAIR	FUNCTION(R*8)	CONDGM HHCONVF
CONALU	ENTRY (PROPTY)	PROPMAT
CONA20F	ENTRY (PROPTY)	PROPMAT (2)
CONBORG	ENTRY (PROPTY)	PROPMAT
CONCC	ENTRY (PROPTY)	PROPMAT
CONCS	ENTRY (PROPTY)	PROPMAT (2)
CONDAPL	SUBROUTINE	RESJAC RADTN (2)
CONDENS	SUBROUTINE	FCOND
CONDF	ENTRY (PROPMAT)	CONDC (6) COMCON (2) BNDCONX BNDCONI (2) EVALAIR (2) CONDAPL WALSOL0 (2) FINNER (2) RESJAC2 UCARE
CONDFSM	ENTRY (PROPT)	ENCHECK (4) PROPLOD
CONDL	FUNCTION(R*8)	WATRR (2)
CONDC	SUBROUTINE	TIMSOL TEMPSOL
COND451	SUBROUTINE	PROPTY (4)
CONFER	ENTRY (CON451A)	PROPMAT
CONFERD	ENTRY (PROPTY)	CON451A
CONFERU	ENTRY (PROPTY)	CON451A
CONFUEL	ENTRY (PROPTY)	PROPT
CONHEL	FUNCTION(R*8)	CONDGM (2) PROPMAT (4) UPLCONV (2) HFUGRF HHCAVITY
CONKA	ENTRY (PROPTY)	PROPMAT (3)
CONMCS	ENTRY (PROPTY)	PROPMAT

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
CONRAD	ENTRY (PROPTY)	PROPMAT (3)
CONR20F	ENTRY (PROPTY)	PROPMAT (2)
CON4AC	ENTRY (PROPTY)	CON451A
CON4AU	ENTRY (PROPTY)	CON451A
CON4RD	ENTRY (PROPTY)	CON451A PROPT
CON4RU	ENTRY (PROPTY)	CON451A
CON451A	FUNCTION (R*8)	PROPMAT (4)
CON451R	ENTRY (CON451A)	PROPMAT
CON800	ENTRY (PROPTY)	PROPMAT (6)
CORFEL	SUBROUTINE	THATCH
CORGASL	SUBROUTINE	FLOXIEX (2) FLOXIOT
CORINDM	ENTRY (CORINDT)	INGEOM (2)
CORINFL	ENTRY (CORINDT)	FLOXIIN
CORINIT	SUBROUTINE	FLOXIEX
CORINPS	ENTRY (CORINPW)	SYMELIN
CORINPW	SUBROUTINE	INHTGEN
CORINSY	ENTRY (CORINDT)	SYMELIN
CPFUEL	ENTRY (PROPTY)	PROPT
CPGRAF	ENTRY (PROPTY)	PROPMAT (6) PROPT
CPL	FUNCTION (R*8)	WATRR (2) WATCLOT CAVIN
CPMIXSP	ENTRY (CVMIXSP)	HETCON DHFCT
CPUTIME	SUBROUTINE	SECOND

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
CP1	ENTRY(CV1)	UPLCONV HETCON SYMELIN AIRCOOL
CP1SPL	ENTRY(CV1SPL)	DHCT
DATE	SUBROUTINE	PREINIT
DATIM	SUBROUTINE	DATE CLOCKK
DERIV	SUBROUTINE	PKINØ
DGEAR	SUBROUTINE	SOLTRAN
DGEF	SUBROUTINE	NEWTON TEMPSYM
DGEFS	SUBROUTINE	NEWTON2 NEWTON
DGES	SUBROUTINE	NEWTON TEMPSYM
DGTF	SUBROUTINE	TEMPSOL (2) TEMPSYM
DGTS	SUBROUTINE	TEMPSOL (2) TEMPSYM
DIVPAG	SUBROUTINE	SOLTRAN (3)
ENCHECK	SUBROUTINE	TEMPSYM
ERROR	SUBROUTINE	INGEOM INBLOCK (4) THATCH (2) PSTINIT (2) INPLENA (3) INTIME
ERSET	SUBROUTINE	PKINØ
EULER	SUBROUTINE	SOLTRAN
EVALAIR	SUBROUTINE	AIRCOOL
EXPF	FUNCTION(R*8)	REACT (2) AIRESØ (3) HETCON
FAILS	ENTRY (FAILURE)	TIMSOL
FILEFIN	SUBROUTINE	TIMSOL SYMELAN
FINEXEC	ENTRY (FINNER)	AIRESØ
FININI	ENTRY (FINNER)	AIRCOOL

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
FININ2	ENTRY (FINNER)	AIRC00L
FLEN2	ENTRY (AIRES0)	AIRC00L (2) JACAIR0
FLEN3	ENTRY (AIRES0)	AIRC00L (2) JACAIR0
FLOW	ENTRY (AIRES0)	JACAIR0 EVALAIR AIRC00L (2)
FLOWAFR	SUBROUTINE	FLXFLOW
FLOXIEX	SUBROUTINE	TIMSOL (2) FLOXIMS
FLOXIIN	SUBROUTINE	FLOXIMS THATCH
FLOXIOT	SUBROUTINE	TIMSOL FLOXIMS
FLOXIRD	ENTRY (FLOXIOT)	FLOXISM PSTINIT
FLOXISM	SUBROUTINE	FLOXIMS
FLOXIWR	ENTRY (FLOXIOT)	FLOXIMS PLOTTER (2)
FLUINUP	SUBROUTINE	FLOXIEX
FLXFLOW	SUBROUTINE	FLOXIOT FLOXIEX
FLXTHEX	SUBROUTINE	FLOXIEX (2)
FREEIN	SUBROUTINE	INBLOCK
FRIC	FUNCTION (R*8)	FLXFLOW (2) STACK FLOWAPR (2) AIRES0 (2)
FRIC1	FUNCTION (R*8)	WATRR (2)
FRITE	SUBROUTINE	FLOXIMS FILEFIN (2)
FTHEX	SUBROUTINE	AIRC00L
FTHIN	SUBROUTINE	AIRC00L
F04ARF	SUBROUTINE	NEWTON
GASENER	SUBROUTINE	SYMELIN CVMIX CV1 (2) AIRC00L FLOXIIN GASLOAD CVISPL
GASLOAD	SUBROUTINE	THATCH

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
HEATGEN	SUBROUTINE	TIMSOL INHTGEN
HETCOF	FUNCTION(R*8)	HETCON PROPLOD
HETCON	SUBROUTINE	FLOXIEX(2) FLOXIOT
HFUGRF	FUNCTION(R*8)	ENCHECK PROPLOD(2)
HHCADTY	FUNCTION(R*8)	PROPMAT(2) WALSOL0(2) EVALAIR(2) UCAVF
HHCONVF	FUNCTION(R*8)	RESJAC2 EVALAIR(3) WALSOL0(3) FINNER
HHMSPL	ENTRY(CVMIXSP)	HFCT FLOXIEX(4) PLENSUM
HHRADBL	FUNCTION(R*8)	WALSOL0(3) EVALAIR(4) UCAVF
HH1SPL	ENTRY(CV1SPL)	FLOXIEX(4) PLENSUM HFCT
H0TFRAC	ENTRY(AVERAGE)	SYMELOT
H0TFRC2	ENTRY(AVERAG2)	SYMELOT
HTFLUX	SUBROUTINE	TIMSOL(2)
IDAMAX	FUNCTION(I*4)	RESJAC NEWTON
IDMAX	FUNCTION(I*4)	AVERAGE(2) AVERAG2(2) FMAX3 FMAX2
INFALIP	ENTRY(FAILURE)	INBND
INFBLKS	ENTRY(INBLOCK)	THATCH
INPBND	ENTRY(INBND)	THATCH
INPGEOM	ENTRY(INGEOM)	THATCH
INPHTGN	ENTRY(INHTGEN)	THATCH
INPLPLNA	ENTRY(INPLENA)	INBLOCK
INPT	ENTRY(INTIME)	THATCH
INPTH	ENTRY(INTHETA)	THATCH

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
IWKIN	SUBROUTINE	PKINØ
JOBSTP	FUNCTION(I*4)	TIMSOL TIMLOP
KMAND	FUNCTION(I*4)	THATCH TIMSOL
LEFT1A	SUBROUTINE	MINATOR
LINEON	ENTRY (PAGER)	INBND(8) INGEOM(12) INHTGEN INTIME PRINTER(10) TIMSOL INBLOCK(8) HTFLUX(2) FAILURE(3)
LINE1ST	ENTRY (PAGER)	INBND(3) INGEOM(3) FAILURE INBLOCK(2) PRINTER(2) HTFLUX
LINV3F	SUBROUTINE	RADCOEF
MAPRINT	SUBROUTINE	RADCOEF(3)
MINATOR	FUNCTION(I*4)	TIMSOL(2) TIMLOP
NEWPAGE	ENTRY (PAGER)	INHTGEN TIMER INGEOM(3) INBLOCK INTHETA TIMSOL(2) PSTINIT INTIME THATCH INBND
NEWTON	SUBROUTINE	RADTN AIRCOOL
NEWTON2	SUBROUTINE	FINNER
NORECF	FUNCTION(I*4)	FRITE CONDENS
NZECT	FUNCTION(I*4)	RADCOEF(3)
N1RCD	FUNCTION(I*4)	SOLTRAN
N1RTY	FUNCTION(I*4)	SOLTRAN
PKINEX	ENTRY (PKINØ)	TIMSOL TIMLOP
PKININ	ENTRY (PKINØ)	THATCH SYMELIN
PKINOUT	ENTRY (PKINØ)	SYMELOT THATCH TIMSOL
PKINRD	ENTRY (PKINØ)	PSTINIT
PKINWR	ENTRY (PKINØ)	PLOTTER

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
PLENBAR	SUBROUTINE	FLOXIEX(4) FLOXIOT
PLENPRT	ENTRY (PRINTER)	INTHETA TIMSOL
PLENSUM	SUBROUTINE	PLENBAR(2)
POSITN	SUBROUTINE	FCOND FRITE(2)
POWPROF	FUNCTION(R=8)	TEMPSYM
PREBLACK	ENTRY (INBLOCK)	PREINIT
PREBND	ENTRY (INBND)	PREINIT
PREFAIL	ENTRY (FAILURE)	PREINIT
PREGEOM	ENTRY (INGEOM)	PREINIT
PREHTGN	ENTRY (INHTGEN)	PREINIT
PREINIT	SUBROUTINE	THATCH
PREPLNA	ENTRY (INPLENA)	PREINIT
PRETHTA	ENTRY (INTHETA)	PREINIT
PRETIME	ENTRY (INTIME)	PREINIT
PROPAIR	SUBROUTINE	HHCAVITY
PROPLOD	SUBROUTINE	TEMPSYM
PSTGEOM	ENTRY (INGEOM)	PSTINIT
PSTHTGN	ENTRY (INHTGEN)	PSTINIT
PSTINIT	SUBROUTINE	THATCH
PSTINRS	ENTRY (PSTINIT)	THATCH
PSTPLNA	ENTRY (INPLENA)	PSTINIT
RADCOEF	SUBROUTINE	FINNER

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
RADTN	SUBROUTINE	TIMSOL(2) FLOXIEX
REACT	SUBROUTINE	CORGASL
READIN	SUBROUTINE	SYMELIN FLOXIMS
REDCOF2	SUBROUTINE	FLOXIIN
RENCH	SUBROUTINE	FLOXIOT
RERITE	SUBROUTINE	CONDENS FRITE
RESJAC2	SUBROUTINE	NEWTON2
RHOCORF	FUNCTION(R*8)	PKINØ(2)
RHOL	FUNCTION(R*8)	WATRR(5) CAVIN(2)
RHOOFTH	SUBROUTINE	RHOCORF(2) PKINØ
RHOWATF	FUNCTION(R*8)	SUMRHOF(2) PKINØ(2)
ROCALU	ENTRY(PROPTY)	PROPMAT
ROCCC	ENTRY(PROPTY)	PROPMAT
ROCCS	ENTRY(PROPTY)	PROPMAT(2)
ROCF	ENTRY(PROPMAT)	TEMPSOL
ROCFSM	ENTRY(PROPT)	ENCHECK PROPLD
ROCKA	ENTRY(PROPTY)	PROPMAT(3)
ROCMCS	ENTRY(PROPTY)	PROPMAT
ROC8ØØ	ENTRY(PROPTY)	PROPMAT(5)
RUFF	SUBROUTINE	THFROMH
RUFF20X	SUBROUTINE	REACT
SECOND	FUNCTION(R*8)	TIMSOL(2) TIMER(2) PKINØ(2)
SEXPAM	FUNCTION(R*8)	PKSOL(2)

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
SOLSPEC	SUBROUTINE	FLXFLOW
SOLTRAN	SUBROUTINE	PKINØ
SPECWAT	SUBROUTINE	NEWTON (On Call from WATCLEX)
SPLINE2	FUNCTION(R*8)	CVISPL(2)
STACK	SUBROUTINE	AIRESØ
STRACE	SUBROUTINE	PROPT(2) FLOXIOT TBLKTKR TIMER
SUMRHOF	FUNCTION(R*8)	DERIV JACK
SURFPRT	ENTRY (PRINTER)	TIMSOL
SYMELOT	SUBROUTINE	SYMELIN
SYMELIN	SUBROUTINE	SYMELAN THATCH
SYMELOT	SUBROUTINE	TIMLOP TIMSOL(2)
SYMFLEX	ENTRY (SYMTHEX)	TIMSOL
SYMTHEX	SUBROUTINE	TIMSOL(2)
SYMTPIN	SUBROUTINE	SYMELIN PSTINIT
SYTMPAV	SUBROUTINE	TEMPAVG(2)
SYTMPMX	ENTRY (SYTMPAV)	TEMPAVG
TBLKSEC	SUBROUTINE	FLUINUP
TBLK	SUBROUTINE	TBLKLF SPLINE2
TBLKLF	SUBROUTINE	RHOOFTH(8) PROPTY(10) AFTER PROPAIR CVMIX CASENER VISAIR CONAIR CV1 CVMIXSP
TEMPAVG	SUBROUTINE	TIMLOP THATCH SYMELIN TIMSOL(2)
TEMPLSM	SUBROUTINE	TIMSOL TIMLOP
TEMPLTH	SUBROUTINE	TIMSOL
TEMPMAX	ENTRY (TEMPAVG)	PKINØ

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
TEMPMX2	ENTRY (AVERAGE2)	SYMELOT
TEMPRIN	SUBROUTINE	SYMELAN
TEMPSOL	SUBROUTINE	TIMSOL
TEMPSYM	SUBROUTINE	TIMSOL TIMLOP
THETABC	FUNCTION (R=8)	TIMSOL INTHETA(3) TEMPSOL(3) CONDUCT(2)
THETA IN	SUBROUTINE	INTHETA
THFLXEX	SUBROUTINE	FLOXIEX(2)
THFLXIN	SUBROUTINE	FLOXIIN
THFROMH	FUNCTION (R=8)	PLENSUM
THFUEL	FUNCTION (R=8)	PKINØ(2)
THMAX	ENTRY (AVERAGE)	SYTMPAV SYMELOT
THSYMEX	SUBROUTINE	TIMSOL
THSYME2	SUBROUTINE	TEMPSOL
THSYMIN	SUBROUTINE	SYMELIN
THTMPAV	SUBROUTINE	TEMPAVG(2)
THTMPMX	ENTRY (THTMPAV)	TEMPAVG
TIMEIN	ENTRY (TIMER)	FLOXIEX TIMLOP TEMPSYM(2) THATCH(3) PRINTER(3) RADTN TEMPSOL CONDUCT PKINØ HEATGEN AIRCOOL
TIMEOUT	ENTRY (TIMER)	CONDUCT PKINØ(2) PRINTER RADTN THATCH(3) HEATGEN TEMPSYM(2) TIMLOP FLOXIEX AIRCOOL TEMPSOL
TIMEPLT	ENTRY (PLOTTER)	TIMSOL
TIMEPR	ENTRY (TIMER)	THATCH(2) SYMELAN
TIMEX	SUBROUTINE	PREINIT

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
TIMLOP	SUBROUTINE	SYMELAN
TIMSOL	SUBROUTINE	THATCH
TIMVAR	SUBROUTINE	TIMLOP
TSATL	FUNCTION(R*8)	WATCLOT
TTHEX	SUBROUTINE	AIRCOOL
UCAVF	FUNCTION(R*8)	RESJAC2 FINNER
UERTXXX	SUBROUTINE	PKINØ
UPLCONV	SUBROUTINE	RESJAC RADTN(2)
VIEWPAR	FUNCTION(R*8)	RADCOEF(2)
VIEWREC	FUNCTION(R*8)	RADCOEF(2)
VISAIR	FUNCTION(R*8)	STACK AIRESØ(2) VISGAS HHCONVF
VISCL	FUNCTION(R*8)	WATRR(6)
VISCO	FUNCTION(R*8)	VISGAS
VISCO2	FUNCTION(R*8)	VISGAS VISCO
VISGAS	FUNCTION(R*8)	VISGSPK
VISGSPK	FUNCTION(R*8)	FLOWAPR(2) FLXFLOW(3)
VISHL	FUNCTION(R*8)	VISGAS VISGSPK PROPMAT CONHEL UPLCONV PROPLOD HHCAVTY
VISH2	FUNCTION(R*8)	VISGAS
VISH20	FUNCTION(R*8)	VISGAS
VISMIX	FUNCTION(R*8)	VISGAS
WALSOL2	ENTRY (WALSOLØ)	AIRESØ
WALSOL3	ENTRY (WALSOLØ)	AIRESØ

Table E-2 (continued)
Call Locations for THATCH and BIGLIB Subroutines and Entries

Subroutine or Entry	Type	Locations of Calls for this Unit
WATCLEX	SUBROUTINE	TIMSOL(2)
WATCLIN	SUBROUTINE	THATCH
WATCLOT	SUBROUTINE	TIMSOL
WATCLRD	ENTRY(WATCLOT)	PSTINIT
WATCLWR	ENTRY(WATCLOT)	PLOTTER
WATRR	SUBROUTINE	WATRESD
XNUSL	FUNCTION(R#8)	WATRR(2)
XNUSTB	FUNCTION(R#8)	WATRR
XUFLOW	SUBROUTINE	THATCH
YTHETA	SUBROUTINE	AIRESØ(4) EVALAIR AIRCOOL

Table E-3
List of THATCH COMMONS

COMMON Name	Subroutines Referencing this Unit
AFT	INHTGEN(b) HEATGEN(b) HTFLUX(b) THTMPAV(f) PSTINIT(f) TIMSOL(b) FLXTHEX(s) TEMPSOL(b) THSYMIN(f) THATCH(b) PLOTTER(b)
ANML	CONDUCT(b) PLOTTER(b) THBLDAT(s) CONDAPL(f) ANNEL(b) PSTINIT(b)
ANML2	ANML(s) PROPMAT(b)
BLOCK	INBLOCK(b) TIMSOL(n) PREINIT(n) THETA(n) TEMPSOL(b) INBND(s) PRINTER(f) CONDUCT(b) FTHIN(f) THTMPAV(n) INTIME(n) RADTN(n) PLOTTER(b) HTFLUX(f) FAILURE(b) PSTINIT(b) THATCH(n)
BLOCKCH	FTHIN(n) PSTINIT(s) THATCH(n) FAILURE(s) INTIME(n) TEMPSOL(n) PRINTER(b) TIMSOL(n) HTFLUX(b) PLOTTER(n) INBLOCK(b) RADTN(n) PREINIT(n) INBND(s) THETA(n) THTMPAV(n) CONDUCT(n)
BOUND	PSTINIT(b) PREINIT(n) TTHEX(f) PLOTTER(f) PRINTER(f) CONDUCT(b) FAILURE(s) INTHETA(b) TIMSOL(f) FTHIN(f) HTFLUX(f) RADTN(f) INBLOCK(b) INBND(s) INGEOM(f) THATCH(f)
CALCHAR	INHTGEN(n) TIMSOL(b) PSTINIT(b) FLXTHEX(n) THATCH(b) PLOTTER(b) TEMPSOL(n) THSYMIN(n) HEATGEN(n) HTFLUX(n) THTMPAV(b)
CAVDAT	BNDCONI(s) PROPMAT(b) THBLDAT(s)
COND	TEMPSOL(b) THATCH(n) INBLOCK(s) HTFLUX(b) CONDUCT(s) PLOTTER(b) TTHEX(s)
CONST	CONDUCT(f) THATCH(n) PLOTTER(f) THETA(n) PREINIT(b) HEATGEN(n) PRINTER(f) RADTN(f) TIMSOL(f) INHTGEN(f) PAGER(f) BNDCONI(f) RESJAC(f) PSTINIT(f) INGEOM(f) INBLOCK(f) THBLDAT(n) FAILURE(f) CONDAPL(n) UPLCONV(f) INPLENA(f) INTIME(n) BNDCONX(f)
CONSTCH	RESJAC(n) PRINTER(n) PREINIT(b) PLOTTER(n) THATCH(n) RADTN(n) PAGER(n) HEATGEN(n) BNDCONI(n) BNDCONX(n) INTIME(b) THETA(n) CONDAPL(n) CONDUCT(n) INPLENA(n) THBLDAT(s) INHTGEN(n) FAILURE(n) TIMSOL(n) INGEOM(n) UPLCONV(n) PSTINIT(n) INBLOCK(f)
FAIL	CONDUCT(n) PSTINIT(b) PLOTTER(b) INBLOCK(b) FAILURE(b) TIMSOL(f) INBND(s) THATCH(n)
GEOMCH	HEATGEN(n) INHTGEN(n) THFLXIN(n) FTHEX(n) THETA(n) PRINTER(n) INPLENA(n) FTHIN(n) PLOTTER(n) TTHEX(n) THETABC(n) FAILURE(n) INTHETA(n) PSTINIT(n) PREINIT(n) THFLXEX(n) FLXTHEX(n) HTFLUX(n) INGEOM(f) INBLOCK(n) TEMPSOL(n) THATCH(b) INBND(s) RADTN(n) INTIME(n) CONDUCT(n) TIMSOL(n) TEMPLTH(n)
GEOMTRY	TTHEX(f) TEMPLTH(f) INBND(s) INBLOCK(f) TEMPSOL(b) PREINIT(n) INGEOM(b) PLOTTER(b) HTFLUX(n) PRINTER(f) FLXTHEX(f) THFLXEX(f) HEATGEN(f) CONDUCT(b) INHTGEN(f) TIMSOL(b) FTHIN(f) THETA(n) FTHEX(f) THFLXIN(f) PSTINIT(f) INPLENA(f) FAILURE(n) INTHETA(b) RADTN(n) INTIME(n) THATCH(b) THETABC(b)
OUT	PREINIT(s) PSTINIT(b) FREEIN(b) THATCH(b) THBLDAT(n) INGEOM(b) TIMSOL(b) PRINTER(f) HTFLUX(n) PAGER(b) FAILURE(f) INTIME(b) INHTGEN(n) INPLENA(s) CONDUCT(n) RADTN(n) INTHETA(n) ERROR(b) PLOTTER(b) HEATGEN(n) INBLOCK(s)

Table E-3 (continued)
List of THATCH COMMONS

COMMON Name	Subroutines Referencing this Unit
OUTCH	HEATGEN(n) INBLOCK(n) ERROR(n) PLOTTER(b) FAILURE(b) INTIME(b) CONDUCT(n) INTHETA(b) PREINIT(b) PRINTER(b) INGEOM(n) INPLENA(n) THATCH(b) PAGER(b) HTFLUX(n) RADTN(n) TIMSOL(b) PSTINIT(n) FREEIN(n) THBLDAT(s) INHTGEN(n)
PKINCTR	TIMSOL(b) THATCH(b)
PLENA	INTHETA(f) TEMPSOL(f) INTIME(f) INBLOCK(b) RESJAC(b) TIMER(b) THETA(n) PLOTTER(b) HTFLUX(f) THATCH(n) PRINTER(f) CONDAPL(f) RADTN(b) FAILURE(b) PSTINIT(b) INPLENA(b) PREINIT(n) TIMSOL(f)
PLENACH	FAILURE(b) PSTINIT(n) PLOTTER(n) INBLOCK(b) INPLENA(b) TIMSOL(n) RADTN(f) INTIME(n) PREINIT(n) PRINTER(f) RESJAC(n) TEMPSOL(n) TIMER(n) THATCH(n) THETA(n) HTFLUX(n) CONDAPL(n) INTHETA(n)
PLENAS	RADTN(b) HTFLUX(b) INTHETA(b) THATCH(s) TIMER(n) TEMPSOL(b) RESJAC(b) PSTINIT(b) PLOTTER(b) PRINTER(f) INTIME(b) FAILURE(s) CONDAPL(b) INBLOCK(b) TIMSOL(b) INPLENA(b) THETA(n) PREINIT(n)
SINKTH	TTHEX(s) INTHETA(b) THETABC(f)
TEMPS	FTHEX(f) RADTN(b) THATCH(n) TTHEX(s) FAILURE(f) CONDAPL(b) TIMSOL(b) THFLXEX(f) TEMPSOL(b) INBLOCK(n) PREINIT(n) PSTINIT(s) PRINTER(f) TEMPLTH(b) FTHIN(f) PLOTTER(b) HTFLUX(f) THETA(n) CONDUCT(b) INTHETA(b) THETABC(f) ANNEL(f) THTMPAV(f)
TEMPSCH	PLOTTER(n) PRINTER(n) INBLOCK(f) TEMPSOL(n) INTHETA(f) THETABC(n) CONDUCT(n) HTFLUX(n) THETA(n) TTHEX(n) PREINIT(n) THATCH(b) FTHIN(n) PSTINIT(n) FTHEX(n) CONDAPL(n) RADTN(n) ANNEL(n) THTMPAV(n) TEMPLTH(n) TIMSOL(n) THFLXEX(n) FAILURE(n)
THGASPR	FLXTHEX(s) PROPMAT(b) THATCH(b) UPLCONV(f)
TIME	PAGER(f) INHTGEN(b) FAILURE(f) INTIME(b) THATCH(b) PSTINIT(b) PREINIT(n) RADTN(f) PLOTTER(b) HEATGEN(n) TIMSOL(b)
TRIDIAG	THATCH(n) TEMPSOL(b)
UPLCNV1	RADTN(b) FLXTHEX(s) INBLOCK(b) PRINTER(b) THFLXEX(f) UPLCONV(b) RESJAC(b)
UPLCNV2	UPLCONV(b) RESJAC(f) RADTN(b)
WORK	RESJAC(b) THATCH(n)

(f) = fetched
(s) = set
(b) = both
(n) = not referenced

Table E-4
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
AFBOUND	THSYME2(f) SYMTEX(b)
AFTCHAR	AFTER(f) AFTCOFS(b)
AFTHEAT	AFTER(b) AFTCOFS(b)
AIRCTR	EVALAIR(b) WALSOL0(b) FINNER(b) AIRES0(b) JACAIRO(b) AIRCOOL(b) STACK(f)
AIRPROP	GASDATA(s) PROPAIR(b) VISAIR(b) CONAIR(b)
AIR0	AIRCOOL(b)
AIR1	FINNER(f) AIRES0(b) WALSOL0(f) AIRCOOL(b) EVALAIR(b)
AIR2	EVALAIR(b) FINNER(b) AIRCOOL(b) AIRES0(b) WALSOL0(f)
AVGS	SYMELIN(s) SYMTEX(f) AVERAG2(b) SYMELOT(b) AVERAGE(b) SYTMPAV(f)
BASIN	THSYMEX(f) TEMPSYM(b) TEMPLSM(f) SYMELDT(f) SYMTPIN(f) TIMLOP(f) THSYME2(f) SYMTEX(b) COEFFL2(f) SYMELOT(b) SYMELAN(b) AVERAGE(f) SYMELIN(b) PROPLOD(b) SYMDAT(s) ENCHECK(f) COEFFLD(f) AVERAG2(f) SYTMPAV(f) TEMPVAV(f) TIMVAR(b) TEMPRIN(b)
CHARAC	FINNER(b) WALSOL0(b) RESJAC2(b) AIRCOOL(b) EVALAIR(b)
CHARCTR	CORGASL(b) HETCON(f) FLOXIEX(n) FLOXIIN(b) PLENBAR(f) FLXFLOW(b) FLOXIOT(b) FLOWAPR(b) FLOXISM(f)
CHARDAT	ODEDAT(s) SOLTRAN(b) PKIN0(b)
CHARTIT	EVALAIR(b) AIRCOOL(b)
CNTRL	RENCH(f) FLOXIOT(b) FLXFLOW(b) CORGASL(f) FLOXIEX(b) FLOWAPR(f) FLOXIIN(b) HETCON(f) FLOXDAT(s) FLOXISM(f) PLENBAR(f)
COEFS	SYMELDT(b) COEFFL2(f) SYMELOT(f) SYMELIN(f) ENCHECK(f) AVERAG2(n) AVERAGE(n) PROPLOD(f) COEFFLD(f)
COMDAT	SYMELOT(b) THSYMEX(s) TEMPLSM(b) TIMVAR(s) SYMTEX(f) TEMPRIN(b) PROPLOD(b) ENCHECK(f) COEFFLD(b) SYMTPIN(s) TEMPSYM(b) AVERAGE(f) SYMELIN(b) AVERAG2(f) COEFFL2(b)
COMTIT	FILEFIN(b) SYMELOT(b) SYMELIN(b)
CONSTAR	WALSOL0(f) AIRCOOL(f) FINNER(f) AIR(s) RADCOEF(f) EVALAIR(f) RESJAC2(n)
CON451	COND451(b) PROPTY(b)

Table E-4 (continued)
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
CORBDAT	COREDTS(s) CORINDT(f)
CORDATC	CORINDT(f) CORINPW(f) CORFEL(b) COREDTs(s)
CORDATF	FLOXIIN(b)
CORDEX	CORFEL(b) CORINDT(f) CORINPW(f)
CORNODF	FLOXIEX(f) SYMTEX(f) FLOXIIN(b)
CORPWEX	CORFEL(s) CORINPW(f)
DATAPT	FLOXIMS(b)
DELTHFL	PKIN0(b) THFUEL(f)
DUMMY	NEWTON2(b)
FILCTRL	TIMLOP(b) FILEFIN(h) SYMDAT(s) TEMPRIN(b) SYMELIN(n) SYMELIN(b) SYMELOT(b)
FLOWD1	FLOXIEX(n) FLXFLOW(b) FLOXISM(b) AVAL(b) FLOXIOT(b) FLOWAPR(b) FLOXIIN(b)
FLOWD2	FLOWAPR(b) FLXFLOW(b) FLOXIOT(b) RENCH(b) FLOXIIN(b) CORINIT(b) HETCON(f) FLOXIEX(b) CORGASL(b) AVAL(f) SYMTEX(n) THSYMEX(f) FLOXISM(b) PLENBAR(b)
FLOWD3	FLOXIOT(n) REACT(f) FLOXIIN(b) AVAL(f) FLOXIEX(n) FLXFLOW(f) FLOXDAT(n) HETCON(b) FLOWAPR(f) FLOXISM(n)
FLUPROP	HETCON(b) FLOXIIN(b) FLOXISM(n) CORGASL(b) FLOXIEX(b) FLOXIOT(b) FLOWAPR(b) AVAL(f) PLENBAR(b) FLXFLOW(b) CORINIT(b)
FRACLS	COEFFLD(f) ENCHECK(f) SYMELIN(b) AVERAG2(f) SYMELOT(f) COEFFL2(f) AVERAGE(f) TIMVAR(f)
FUGR	SYMELIN(b) SYMDAT(n) HFUGRF(f)
GASENR	GASENER(b) CV1(b) GASDATA(s) CVMIX(b)
GASINDX	GASENER(f) GASDATA(s) VIGAS(n) GASLOAD(f)
GASLAB	GASENER(b) CORGASL(b) PLENSUM(b) FLOXISM(n) GASDATA(s) FLOXIIN(b) FLOXIEX(n) FLOXIOT(n)
GASPROP	GASLOAD(f) CORGASL(f) FLOXIOT(n) SYMELIN(f) FLOXISM(n) HHCAVITY(f) GASDATA(s) REACT(f) HETCON(f) PLENBAR(n) CVMIXSP(f) CV1(f) CVMIX(f) VIGAS(b) GASENER(b) CV1SPL(f) AIRCOOL(f) FLOXIIN(b) CORINIT(n) PLENSUM(f) FLOXIEX(f) THFROMH(f)

Table E-4 (continued)
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
GASSCOF	FLOXIEX(n) FLOXISM(n) CVMIXSP(b) FLOXIIN(b) FLOXIOT(n) CV1SPL(b)
GEAR	SOLTRAN(f)
GEAREX	SOLTRAN(b)
GEARWRK	SOLTRAN(b)
GENDAT	FLOXIEX(f) FLOXIOT(f) FLOXIIN(f) HETCON(f) PLENBAR(f) FLOWAPR(n) FLXFLOW(n) FLOXISM(n) FLOXDAT(s) AVAL(f)
GRAPHDT	SYMELDT(f) SYMDAT(s)
INCTRL	SOLTRAN(b) PKINØ(b) ODEDAT(s)
JACTR	JACAIRØ(f) AIRESØ(s)
MATCOF	SYMELOT(b) TEMPSYM(b) COEFFLD(b) ENCHECK(f) PROPLOD(b) COEFFL2(b) SYMELIN(b)
MATCOF2	COEFFL2(b) TEMPSYM(b)
NODL	FLOXIOT(b) FLOWAPR(b) FLOXIIN(b) CORINIT(f) HETCON(b) FLOXISM(f) FLOXIEX(b) PLENBAR(b) AVAL(f) CORGASL(b) FLXFLOW(b) RENCH(f)
PICKAIR	AIRCOOL(n) AIR(s) JACAIRØ(n)
PKIN	SUMRHOF(f) CALIC(b) JACK(f) PKINØ(b) BLDPINK(s) PKSOL(f) DERIV(f)
PKINC	SUMRHOF(n)
PKINTMP	PKINØ(b)
PKNCTRS	SYMELIN(b) TIMLOP(b)
POWDAT	COREDTS(s) CORFEL(f) CORINPW(n)
PROPAS	PROPLOD(b) COEFFL2(f) COEFFLD(f)
QARRAYS	FLOXIEX(b) CORGASL(b) FLOXIIN(s) FLOXISM(b) HETCON(b) FLOXIOT(b) CORINIT(s)
QBLOCK	SYMELOT(f) PROPLOD(f) THSYME2(b)
RADDAT	RESJAC2(f) EVALAIR(f) RADCOEF(b) FINNER(b)
RAWDAT	FLOXIEX(b) FLOXIIN(b) FLOXIMS(b)

Table E-4 (continued)
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
REFLDAT	CORFEL(b) COREDT(s) CORINDT(f)
RELO	HHCONVF(b) AIR(s) AIRCOOL(b)
REPEAT	AIRCOOL(n)
RHOCHAR	JACK(b) DERIV(b) PKINØ(b)
RH01	PKINØ(b) SUMRHOF(b)
RH02	SUMRHOF(f) PKINØ(s)
RH03	RH00FTH(b) PKINØ(b) RHOCORF(b)
RUFFOXD	REACT(b) FLOXDAT(s) RUFF20X(b)
SAMAR	SUMRHOF(f) PKINØ(b) JACK(f) DERIV(f) BLDPINK(s) CALIC(b)
SCRATCH	FILEFIN(b) SYMELAN(n) SYMELIN(n)
SINGDAT	UCAVF(b) WALSOLO(b) FINNER(b) AIRCOOL(b) EVALAIR(b) RESJAC2(b) AIRESØ(b)
SMFLLOG	THSYMEX(n) FLOXDAT(s) SYNTHEX(s) HETCON(f)
STACKD	AIRCOOL(b) STACK(f)
STATE	PKINØ(b)
SYMCHAR	SYMELIN(b) SYMELAN(b)
SYMFLX	THSYMEX(f) HETCON(f) SYNTHEX(b)
SYMLDTS	AVERAG2(f) AVERAGE(f) SYMELOT(n) SYMELDT(b) SYMDAT(s) SYNTHEX(f)
SYMLDT2	AVERAG2(f) SYMELDT(b) COEFFL2(f)
TI:FRMHC	DHFCT(b) THFROMH(s) HFCT(b)
THTH	CORGASL(f) CORINIT(b) FLOXIIN(b) FLXFLOW(f) AVAL(f) FLOXIEX(b) THSYMEX(f) PLENBAR(b) HETCON(b)
	FLOXISM(n) FLOXIOT(b)
TIMCTRL	SYMELIN(b) TIMLOP(b) FILEFIN(n)
TMPREAD	SYMELIN(s) TEMPRIN(f)

Table E-4 (continued)
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
TODERIV	JACK(f) DERIV(b) PKINØ(b)
WALL	WALSOLØ(b) FINNER(b) AIRESØ(b)
WATREAC	PKINØ(b) RHOWATF(f)
WORKSP	PKINØ(b)
XENON	BLDPINK(s) PKINØ(b) DERIV(f) SUMRHOF(f) JACK(f) CALIC(b)

(f) = fetched

(s) = set

(b) = both

(n) = not referenced

Table E-4
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
AFBOUND	THSYME2(f) SYMTEX(b)
AFTCHAR	AFTFR(f) AFTCOFS(b)
AFTHEAT	AFTFR(b) AFTCOFS(b)
AIRCTR	EVALAIR(b) WALSOLØ(b) FINNER(b) AIRESØ(b) JACAIRO(b) AIRCOOL(b) STACK(f)
AIRPROP	GASDATA(s) PROPAIR(b) VISAIR(b) CONAIR(b)
AIRØ	AIRCOOL(b)
AIR1	FINNER(f) AIRESØ(b) WALSOLØ(f) AIRCOOL(b) EVALAIR(b)
AIR2	EVALAIR(b) FINNER(b) AIRCOOL(b) AIRESØ(b) WALSOLØ(f)
AVGS	SYMELIN(s) SYMTEX(f) AVERAG2(b) SYMELOT(b) AVERAGE(b) SYTMPAV(f)
BASIN	THSYMEX(f) TEMPSYM(b) TEMPLSM(f) SYMELDT(f) SYMTPIN(f) TIMLOP(f) THSYME2(f) SYMTEX(b) COEFFFL2(f) SYMELOT(b) SYMELAN(b) AVERAGE(f) SYMELIN(b) PROPLOD(b) SYMDAT(s) ENCHECK(f) COEFFFLD(f) AVERAG2(f) SYTMPAV(f) TEMPAVG(f) TIMVAR(b) TEMPRIN(b)
CHARAC	FINNER(b) WALSOLØ(b) RESJAC2(b) AIRCOOL(b) EVALAIR(b)
CHARCTR	CORGASL(b) HETCON(f) FLOXIEX(n) FLOXIIN(b) PLENBAR(f) FLXFLOW(b) FLOXIOT(b) FLOWAPR(b) FLOXISM(f)
CHARDAT	ODEDAT(s) SOLTRAN(b) PKINØ(b)
CHARTIT	EVALAIR(b) AIRCOOL(b)
CNTRL	RENCH(f) FLOXIOT(b) FLXFLOW(b) CORGASL(f) FLOXIEX(b) FLOWAPR(f) FLOXIIN(b) HETCON(f) FLOXDAT(s) FLOXISM(f) PLENBAR(f)
COEFS	SYMELDT(b) COEFFFL2(f) SYMELOT(f) SYMELIN(f) ENCHECK(f) AVERAG2(n) AVERAGE(n) PROPLOD(f) COEFFFLD(f)
COMDAT	SYMELOT(b) THSYMEX(s) TEMPLSM(b) TIMVAR(s) SYMTEX(f) TEMPRIN(b) PROPLOD(b) ENCHECK(f) COEFFFLD(b) SYMTPIN(s) TEMPSYM(b) AVERAGE(f) SYMELIN(b) AVERAG2(f) COEFFFL2(b)
COMTIT	FILEFIN(b) SYMELOT(b) SYMELIN(b)
CONSTAR	WALSOLØ(f) AIRCOOL(f) FINNER(f) AIR(s) RADCOEF(f) EVALAIR(f) RESJAC2(n)
CON451	COND451(b) PROPTY(b)

Table E-4 (continued)
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
CORBDAT	COREDTS(s) CORINDT(f)
CORDATC	CORINDT(f) CORINPW(f) CORFEL(b) COREDTs(s)
CORDATF	FLOXIIN(b)
CORDDEX	CORFEL(b) CORINDT(f) CORINPW(f)
CORNODF	FLOXIEX(f) SYMTEX(f) FLOXIIN(b)
CORPWEX	CORFEL(s) CORINPW(f)
DATAPT	FLOXINS(b)
DELTHFL	PKINØ(b) THFUEL(f)
DUMMY	NEWTON2(b)
FILCTRL	TIMLOP(b) FILEFIN(b) SYMDAT(s) TEMPRIN(b) SYMELAN(n) SYMELIN(b) SYMELOT(b)
FLOWD1	FLOXIEX(n) FLXFLOW(b) FLOXISM(b) AVAL(b) FLOXIOT(b) FLOWAPR(b) FLOXIIN(b)
FLOWD2	FLOWAPR(b) FLXFLOW(b) FLOXIOT(b) RENCH(b) FLOXIIN(b) CORINIT(b) HETCON(f) FLOXIEX(b) CORGASL(b) AVAL(f) SYMTEX(n) THSYMEX(f) FLOXISM(b) PLENBAR(b)
FLOWD3	FLOXIOT(n) REACT(f) FLOXIIN(b) AVAL(f) FLOXIEX(n) FLXFLOW(f) FLOXDAT(n) HETCON(b) FLOWAPR(f) FLOXISM(n)
FLUPROP	HETCON(b) FLOXIIN(b) FLOXISM(n) CORGASL(b) FLOXIEX(b) FLOXIOT(b) FLOWAPR(b) AVAL(f) PLENBAR(b) FLXFLOW(b) CORINIT(b)
FRACLS	COEFFLD(f) ENCHECK(f) SYMELIN(b) AVERAG2(f) SYMELOT(f) COEFFL2(f) AVERAGE(f) TIMVAR(f)
FUGR	SYMELIN(b) SYMDAT(n) HFUGRF(f)
GASENR	GASENER(b) CV1(b) GASDATA(s) CVMIX(b)
GASINDX	GASENER(f) GASDATA(s) VISGAS(n) GASLOAD(f)
GASLAB	GASENER(b) CORGASL(b) PLENSUM(b) FLOXISM(n) GASDATA(s) FLOXIIN(b) FLOXIEX(n) FLOXIOT(n)
GASPROP	GASLOAD(f) CORGASL(f) FLOXIOT(n) SYMELIN(f) FLOXISM(n) HHCAVITY(f) GASDATA(s) REACT(f) HETCON(f) PLENBAR(n) CVMIXSP(f) CV1(f) CVMIX(f) VISGAS(b) GASENER(b) CV1SPL(f) AIRCOOL(f) FLOXIIN(b) CORINIT(n) PLENSUM(f) FLOXIEX(f) THFROMH(f)

Table E-4 (continued)
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
GASSCOF	FLOXIEX(n) FLOXISM(n) CVMIXSP(b) FLOXIIN(b) FLOXIOT(n) CV1SPL(b)
GEAR	SOLTRAN(f)
GEAREX	SOLTRAN(b)
GEARWRK	SOLTRAN(b)
GENDAT	FLOXIEX(f) FLOXIOT(f) FLOXIIN(f) HETCON(f) PLENBAR(f) FLOWAPR(n) FLXFLOW(n) FLOXISM(n) FLOXDAT(s) AVAL(f)
GRAPHDT	SYMELDT(f) SYMDAT(s)
GSSPLCF	GASLOAD(b) CVMIXSP(b) CV1SPL(b) FLOXIEX(n) FLOXIIN(n) FLOXIOT(n) FLOXISM(n)
HTEXP	WATCONS(s) WATRR(f) XNUSL(f) XNUSTB(f)
INCTRL	SOLTRAN(b) PKINØ(b) ODEDAT(s)
JACOB	WATCLEX(b)
JACTR	JACAIRØ(f) AIRESØ(s)
MATCOF	SYMELOT(b) TEMPSYM(b) COEFFLD(b) ENCHECK(f) PROPLOD(b) COEFFL2(b) SYMELIN(b)
MATCOF2	COEFFL2(b) TEMPSYM(b)
NODL	FLOXIOT(b) FLOWAPR(b) FLOXIIN(b) CORINIT(f) HETCON(b) FLOXISM(f) FLOXIEX(b) PLENBAR(b) AVAL(f) CORGASL(b) FLXFLOW(b) RENCH(f)
PICKAIR	AIRCOOL(n) AIR(s) JACAIRØ(n)
PKIN	SUMRHOF(f) CALIC(b) JACK(f) PKINØ(b) BLDPPINK(s) PKSOL(f) DERIV(f)
PKINC	SUMRHOF(n)
PKINTMP	PKINØ(b)
PKNCTRS	SYMELIN(b) TIMLOP(b)
POWDAT	COREDTS(s) CORFEL(f) CORINPW(n)
PROP	WATCLIN(b) WATCLOT(f) CAVIN(f) WATRR(f)
PROPAS	PROPLOD(b) COEFFL2(f) COEFFLD(f)

Table E-4 (continued)
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
QARRAYS	FLOXIEX(b) CORGASL(b) FLOXIIN(s) FLOXISM(b) HETCON(b) FLOXIOT(b) CORINIT(s)
QBLOCK	SYMELOT(f) PROPLD(f) THSYME2(b)
RADDAT	RESJAC2(f) EVALAIR(f) RADCOEF(b) FINNER(b)
RAWDAT	FLOXIEX(b) FLOXIIN(b) FLOXIMS(b)
RCCS1	WATCLOT(f) CAVIN(f) WATCLIN(b) WATRR(b)
RCCS2	WATCLOT(b) WATRR(b) WATCLIN(b) CAVIN(f)
RCCS3	WATRR(b) WATCLIN(b) CAVIN(b) WATCLOT(b)
RCCS4	WATCLOT(f) CAVIN(f) WATCLIN(b) WATRR(f)
RCCS5	WATCLIN(b)
RCCS6	WATRR(b) WATCLIN(b) WATCLOT(b) CAVIN(b) GASINVT(f) READTIM(s) WATCLEX(b)
REFLDAT	CORFEL(b) COREDT(s) CORINDT(f)
RELO	HHCONVF(b) AIR(s) AIRCOOL(b)
REPEAT	AIRC00L(n)
RHOCHAR	JACK(b) DERIV(b) PKINØ(b)
RH01	PKINØ(b) SUMRHOF(b)
RH02	SUMRHOF(f) PKINØ(s)
RH03	RH00FTH(b) PKINØ(b) RH0CORF(b)
RUFFOXD	REACT(b) FLOXDAT(s) RUFF2DX(b)
SAMAR	SUMRHOF(f) PKINØ(b) JACK(f) DERIV(f) BLDPPINK(s) CALIC(b)
SCRATCH	FILEFIN(b) SYMELAN(n) SYMELIN(n)
SINGDAT	UCAVF(b) WALSOLO(b) FINNER(b) AIRCOOL(b) EVALAIR(b) RESJAC2(b) AIRESØ(b)
SMFLLOG	THSYMEX(n) FLOXDAT(s) SYMTEX(s) HETCON(f)
STACKD	AIRC00L(b) STACK(f)

Table E-4 (continued)
List of BIG COMMONS

COMMON Name	Subroutines Referencing this Unit
STATE	PKINØ(b)
SYMPCHAR	SYMELIN(b) SYMELAN(b)
SYMPFLX	THSYMEX(f) HETCON(f) SYMTHEX(b)
SYMLDTS	AVERAG2(f) AVERAGE(f) SYMELOT(n) SYMELDT(b) SYMDAT(s) SYMTHEX(f)
SYMLDT2	AVERAG2(f) SYMELDT(b) COEFFL2(f)
THFRMHC	DHFCT(b) THFROMH(s) HFCT(b)
THTH	CORGASL(f) CORINIT(b) FLOXIN(b) FLXFLOW(f) AVAL(f) FLOXIEX(b) THSYMEX(f) PLENBAR(b) HETCON(b) FLOXISM(n) FLOXIOT(b)
TIMCTRL	SYMELIN(b) TIMLOP(b) FILEFIN(n)
TMPREAD	SYMELIN(s) TEMPRIN(f)
TODERIV	JACK(f) DERIV(b) PKINØ(b)
WALL	WALSOLØ(b) FINNER(b) AIRESØ(b)
WATARRS	WATCLEX(b) WATCLOT(b) WATCLIN(b)
WATINDX	SPECWAT(f) WATRR(f) CAVIN(f) WATCLOT(b) WATCLEX(b) WATCLIN(b) DMAT(f)
WATLDAT	WATCLIN(b) WATRR(b)
WATREAC	PKINØ(b) RHOWATF(f) PROCRAW(n)
WATVEC	READTIM(b) WATCLEX(b) PROCRAW(f) WATCLOT(b) WATCLIN(b)
WORKSP	PKINØ(b)
XENON	BLDPINK(s) PKINØ(b) DERIV(f) SUMRHOF(f) JACK(f) CALIC(b)

(f) = fetched
(s) = set
(b) = both
(n) = not referenced

APPENDIX F

INPUT DECKS FOR SAMPLE CASES OF SECTION 9

Input Deck for THATCH Sample Case No 1

THBASDEP

OV THATCH

C

C This input data file is for Base Depressurized Core Heatup
 C Status of Sept 90. Includes all shroud and core
 C barrel modifications. After SYMELAN integration into code.
 C Revised Input Processor and Unified Input Option

C

C

C Option of 10 Axial Power Zones Available.

C

C TITLE (SECTION 1) ** ** ** **

101D ' ANNULAR CORE 350MW MODULAR HTGR\$'

102D ' DEPRESSURIZED CORE HEATUP ACCIDENT, RCCS OPERATINGS'

103D ' Base Depressurized Core Heatup\$\$'

C

C FLOXI OPTION, STEADY, SYMELL OPTION

C STEADY CAN ONLY BE TRUE IF FLOXI IS TRUE

201D .F., .F., .F.

C

C POINT KINETICS OPTION, RECOMPT OPTION

C RECOMPT ONLY USED IF PKINL = TRUE

202D .F., .F.

C

C UNIFIED INPUT OPTION CONTROL

C UNIFIN

301D .T.

C INITIAL RADIAL INTERACE POINT (MUST BE ZERO FOR CURRENT THATCH

C RIFA-ARRAY, NODE DISTRIBUTION BY 'AREA' OR 'DELR', SMEARING OF

C RSC-CHANNEL LOSS OF AREA EFFECT IN INNER RADIAL CORE POWER ZONE

302D 0, 'AREA', .T.

C NO OF NODES/CHANNELS IN

C CENTRAL REFL, ACT CORE REGN 1, REGN2, REGN3, SIDE REFLECTORS

303D 6, 2, 2, 2, 6

C INITIAL AXIAL INTERFACE POINT (TOP OF ACTIVE CORE), NO OF

C AXIAL NODES PER FUEL ELEMENT, TOP & BOT REFL NODE MULTIPLIER

C (MULTIPLES OF 4 NODES EACH)

304D 12, 2, 1, 1

C BASE RADIAL POWER PROFILE

305D 1, 'D'

C POINT KINETICS RADIAL POWER PROFILE

306D 0, 'F'

C BASE AXIAL POWER PROFILE

307D 10, 'D'

C POINT KINETICS AXIAL POWER PROFILE

308D 0, 'F'


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C
C   UNITS ( SECTION 2 ) ** ** ** **
C   GEOMETRY (LENGTHS) ** **
401D 'M'
C   INPUT TEMPERATURES ** **
403D 'C'
C   OUTPUT TEMPERATURES ** **
404D 'C'
C   GEOMETRY ( SECTION 3 ) ** ** **
C   RADIAL INTERFACE ** **
501D 21
502D 0.336352, 0.475674, 0.582579, 0.672704, 0.752106, 0.823891
      1.000166, 1.149724, 1.323095, 1.476243, 1.614932, 1.742619
      1.982994, 2.197229, 2.413, 2.572724, 2.741251, 2.900000
      3.275, 3.342, 3.408
C   RADIAL POINT 0 ** **
503D 0.
C   AXIAL INTERFACE ** **
504D 45
505D -5.29, -5.21, -4.653, -4.603, -4.59, -3.59, -2.59, -1.59
      -1.2, -.8, -.4, 0.
      0.396500, 0.793000, 1.189500, 1.586000, 1.982500, 2.379000
      2.775500, 3.172000, 3.568500, 3.965000, 4.361500, 4.758000
      5.154500, 5.551000, 5.947500, 6.344000, 6.740500, 7.137001
      7.533500, 7.930000
      8.38, 8.83, 9.28, 9.73, 10.33
      10.93, 11.10, 11.28, 11.43, 12.28, 15.13, 15.19, 15.26
C   BLOCKS ( SECTION 4 ) ** ** **
601D 20
C   BLOCK 1 ** **
602D 1 'CENTRAL REFLECTOR'
603D 1 0, 6, 8, 36, 1
604D 1 4
605D 1 1
606D 1 7

C   BLOCK 2 ** **
602D 2 'ACTIVE CORE'
603D 2 6, 12, 12, 32, 2
604D 2 5
605D 2 2
606D 2 6
607D 2 1
C   BLOCK 3 ** **
602D 3 'INNER SIDE REFLECTORS'
603D 3 12, 15, 8, 36, 1
604D 3 4
605D 3 13
606D 3 7
607D 3 2

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C BLOCK 4 ** **
 602D 4 'PERMANENT SIDE REFLECTORS'
 603D 4 15, 18, 8, 36, 4
 604D 4 4
 605D 4 3
 606D 4 7
 607D 4 13

C BLOCK 5 ** **
 602D 5 'TOP REFLECTOR'
 603D 5 6, 12, 9, 12, 3
 604D 5 13
 605D 5 2
 606D 5 5
 607D 5 1

C BLOCK 6 ** **
 602D 6 'UPPER PLENUM ELEMENTS'
 603D 6 6, 12, 8, 9, 15
 604D 6 4
 605D 6 2
 606D 6 13
 607D 6 1

C BLOCK 7 ** **
 602D 7 'UPPER BOTTOM REFLECTORS'
 603D 7 6, 12, 32, 34, 3
 604D 7 6
 605D 7 2
 606D 7 16
 607D 7 1

C BLOCK 8 ** **
 602D 8 'LOWER BOTTOM REFLECTORS'
 603D 8 6, 12, 34, 36, 5
 604D 8 16
 605D 8 2
 606D 8 7
 607D 8 1

C BLOCK 9 ** **
 602D 9 'CORE BARREL'
 603D 9 18, 19, 8, 43, 10
 604D 9 14
 /605D 9 114, 9, 10, 4, 11, 43
 605D 9, 14, 9, 10, 4, 11, 43
 905D 14, 16, .025
 606D 9 15
 607D 9 3, 9, 36, 11, 37, 38, 12, 39, 43

C ** ** BLOCK 10 ** ** ** **
 602D 10 'VESSEL (SIDE)'
 603D 10 19, 21, 1, 45, 6
 604D 10 1
 605D 10 7, 2, 43, 8, 44, 45
 606D 10 12
 607D 10 5, 2, 3, 6, 44, 45

```

C  ** ** BLOCK 11 ** ** ** ** ** ** ** ** 
602D 11 'VESSEL (TOP)'
603D 11 0, 19, 1, 3, 6
604D 11 1
605D 11 5
C  ** ** BLOCK 12 ** ** ** 
602D 12 'VESSEL (BOTTOM)'
603D 12 0, 19, 43, 45, 6
604D 12 11,1,18, 15,19,19
605D 12 6
606D 12 12
C  ** ** BLOCK 13 ** ** ** 
602D 13 'SHROUD (SIDE)'
603D 13 18, 19, 3, 8, 11
604D 13 18
/605D 13 116,4,7, 115, 8,8
605D 13 16,4,7, 15, 8,8
905D 16 17, .024
905D 15 17, .024
606D 13 14
607D 13 10,4,5, 9,6,8
C  ** ** BLOCK 14 ** ** ** 
602D 14 'SHROUD (TOP)'
603D 14 0, 18, 3, 5, 10
/604D 14 102,1,18
604D 14 2,1,18
904D 2 7, .037
605D 14 10
606D 14 3
C  ** ** BLOCK 15 ** ** ** 
602D 15 'UPPER CORE FLOOR'
603D 15 0, 18, 38, 40, 4
604D 15 8
605D 15 12
606D 15 17
C  ** ** BLOCK 16 ** ** ** 
602D 16 'LOWER CORE FLOOR'
603D 16 0, 18, 40, 41, 8
604D 16 17
605D 16 12
606D 16 9
C  ** ** BLOCK17 ** ** ** 
602D 17 'FLOOR SUPPORT 1'
603D 17 0, 18, 41, 42, 6
604D 17 9
605D 17 12
606D 17 10

```

```

C ** ** BLOCK 18 ** ** ** ** ** ** ** ** ** ** ** ** ** ** 
602D 18 'FLOOR SUPPORT 2'
603D 18 0, 18, 42, 13, 6
604D 18 10
605D 18 12
606D 18 11
C ** ** BLOCK 19 ** ** ** 
602D 19 'UPPER PLENUM'
603D 19 0, 18, 5, 8, 101
651D 19 'CYLIN'
C ** ** BLOCK 20 ** ** ** 
602D 20 'LOWER PLENUM'
603D 20 0, 18, 36, 38, 102
651D 20 'CYLIN'
C
C RADIATION PLENA ( SECTION 5 ) ** ** ** 
701D 'NEWTON', 1.0E-04, 0.01, 20, 0.4, 0.0
C
C UPPER PLENUM CONVECTION HT CONTROL
C ( IF FLOXI IS SPECIFIED FALSE BELOW, THEN A VALUE OF TRUE GIVEN
C HERE IS OVERRIDDEN, I.E. UPLCNV = .T. REQUIRES FLOXI = .T.)
702D .F., 1.
C
C ADDITIONAL RADIAL GAPS
801D 5
802D 1 17, 2, 9,36
802D 2 18, 4, 9,36
802D 3 19, 8, 9,36
802D 4 20, 10, 9,36
802D 5 21, 14, 9,36
C
C ADDITIONAL AXIAL GAPS
803D 8
804D 1 19, 12, 1,6
804D 2 20, 12, 13,15
804D 3 21, 32, 1,6
804D 4 22, 32, 13,15
804D 5 23, 16, 1,15
804D 6 24, 20, 1,15
804D 7 25, 24, 1,15
804D 8 26, 28, 1,15
C
C BOUNDARIES/GAPS ( SECTION 6 ) ** ** ** 
C ** ** RADIAL ** ** ** 
901D 1,3,102,.001,.82,0.
901D 2,3,102,.001,.82,0.
901D 3,3,102,.001,.82,0.
901D 4,3,106,.295,.485,0.
901D 5,1,0,0.,0.,0.
901D 6,1,0,0.,0.,0.
901D 7,31,0,0.,0.,0.
901D 8,13,0,0.,0.,0.
901D 9,21,0,0.,0.,0.

```

```

901D 10,1,0,0.,0.,0.
901D 11,21,0,0.,0.,0.
901D 12,1,0,0.,0.,0.
901D 13,3,102,.001,.82,0.
901D 14,3,106,.270,.68,0.
901D 15,3,106,.271,.68,0.
901D 16,3,106,.271,.68,0.
901D 17,3,102,.001,.82,0.
901D 18,3,102,.001,.82,0.
901D 19,3,102,.001,.82,0.
901D 20,3,102,.001,.82,0.
901D 21,3,102,.001,.82,0.
C    ** ** AXIAL ** ** **
902D 1,12,0,0.,0.,0.
902D 2,3,107,.477,.68,0.
902D 3,21,0,0.,0.,0.
902D 4,21,0,0.,0.,0.
902D 5,3,102,.0005,.82,0.
902D 6,3,102,.0005,.82,0.
902D 7,21,0,0.,0.,0.
902D 8,21,0,0.,0.,0.
902D 9,1,0,0.,0.,0.
902D 10,3,102,.7,.68,0.
902D 11,3,102,2.,.68,0.
902D 12,13,0,0.,0.,0.
902D 13,3,102,.0005,.82,0.
902D 14,1,0,0.,0.,0.
902D 15,3,102,2.,.68,0.
902D 16,3,102,.0005,.82,0.
902D 17,1,0,0.,0.,0.
902D 18,5,0,0.,0.,0.
902D 19,3,102,.0005,.82,0.
902D 20,3,102,.0005,.82,0.
902D 21,3,102,.0005,.82,0.
902D 22,3,102,.0005,.82,0.
902D 23,3,102,.0005,.82,0.
902D 24,3,102,.0005,.82,0.
902D 25,3,102,.0005,.82,0.
902D 26,3,102,.0005,.82,0.
C    IRRADIATION AND ANNEALING DATA
C    IF FIRST PARAMETER ( IRRADN IS FALSE, THEN THIS SECTION IS BYPASSED )
1001D .T.
1002D .T.
1003D 3

```

C ASSUMED BASE CASE IRRADIATION DAMAGE

1004D 3,15, 12,33

1005D 12 0.0,4R, 1.0,6R, 0.0,3R/

1005D 13 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 14 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 15 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 16 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 17 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 18 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 19 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 20 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 21 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 22 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 23 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 24 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 25 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 26 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 27 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 28 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 29 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 30 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 31 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 32 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

1005D 33 0.0,4R, 0.82,6R, 0.0,3R/

1006D 1000., 1300.

C

C ** ** AFTERHEAT DATA (SECTION 7) ** ** ** **

C INITIAL POWER ** ** **

1101D 350.E6, 0., 1.4, 1., 2

C AFTERHEAT REGION ** ** **

1102D 7,12, 13,32

C REFLECTOR REGION ** ** **

1103D 1, 15, 10, 34

C ** ** ** **

C

C BASE RADIAL POWER PROFILE (IHI - (ILO-1) ENTRIES)

1104D 1.0,6R/

C BASE AXIAL POWER PROFILE (JHI - (JLO-1) ENTRIES)

1106D 1.36,10R, 0.77,6R, 0.445,4R/

C ** AFTER HEAT OPTIONS

1108D 'NOML'

C ** ** TIME CONTROL (SECTION 8A) ** ** **

C START TIME (HR) ** ** **

1201D 0.

C TIME PERIODS ** ** **

1202D 7

C NORMAL TIME STEPS FOR DEPRESSURIZED TRANSIENTS

```

1203D 0,240.,15.,240.,240.
      1,10.,1.,10.,6.
      1,60.,5.,50.,25.
      2, 5.,.25,4.,1.
      2, 20.,.5,15.,1.
      2,100., 1.,20.,1.
      2,200.,.5,20.,1.

```

C OUTPUT FORMATS (SECTION 8B) ** ** ** **

```
1301D 4,0, 8,1
```

C BLOCK SURFACES OUTPUT (SECTION 8C) ** ** **

```
1401D 2
```

```
1402D 10,2, 10,4
```

C DEBUG (SECTION 8D) ** ** **

C DEBUG CONTROL VARIABLE

```
1403D 0
```

C DEBUG SET DATA (BYPASS AT THIS TIME, SETTING NO OF SETS = 0

```
/ 0
```

C ** ** INITIAL TEMPERATURES (SECTION 9) ** ** **

```
1501D 'READRUN '
```

```
C 'OTHER'
```

```
1502D 100.0,21R
```

```
1503D 100.0,35R, 80.0,9R
```

```
1504D 100.0,21R
```

C BLOCK TEMPERATURES ** ** **

```

1505D B1;24*258.
      B1;6*269.
      B1;6*290.
      B1;6*312.
      B1;6*333.
      B1;6*355.
      B1;6*376.
      B1;6*397.
      B1;6*419.
      B1;6*440.
      B1;6*462.
      B1;6*483.
      B1;6*505.
      B1;6*526.
      B1;6*548.
      B1;6*569.
      B1;6*590.
      B1;6*612.
      B1;6*633.
      B1;6*655.
      B1;6*676.
      B1;24*687.
      B2;6*269.
      B2;6*290.
      B2;6*312.

```

B2;6*333.
 B2;6*355.
 B2;6*376.
 B2;6*397.
 B2;6*419.
 B2;6*440.
 B2;6*462.
 B2;6*483.
 B2;6*505.
 B2;6*526.
 B2;6*548.
 B2;6*569.
 B2;6*590.
 B2;6*612.
 B2;6*633.
 B2;6*655.
 B2;6*676.
 B3;24*258., 120*400., 24*470.
 B4*258.
 B5*687.
 B6*258.
 B7*219.
 B8*219.
 B9*219.
 B10*258.
 B11*258.
 B12*500.
 B13*400.
 B14*258.

1000*777. /

C

C AIR COOLER INPUT DATA

6101D 'FIN PERFORMANCE COEFFICIENTS ARE INPUT'

6102D .T., .F., .F., 'BNL'

6103D 1, 43, 9

6104D 3.408, 4.316, 4.326, 4.4784, 4.4884, 4.85

6105D 3.95, 7.8, .0762, .54

C SURFACE EFFECTIVENESS DATA

6106D 1 1.0, 4R

6106D 2 1.0, 4R

6106D 3 1.0, 4R

6106D 4 1.0, 4R

6106D 5 1.0, 4R

6106D 6 1.0, 4R

6106D 7 1.0, 4R

6106D 8 4.4, 0., 1., 1.

6106D 9 4.4, 0., 1., 1.

6106D 10 4.4, 0., 1., 1.

6106D 11 4.4, 0., 1., 1.

6106D 12 4.4, 0., 1., 1.

6106D 13 4.4, 0., 1., 1.

6106D 14 4.4, 0., 1., 1.

6106D 15 4.4, 0., 1., 1.
6106D 16 4.4, 0., 1., 1.
6106D 17 4.4, 0., 1., 1.
6106D 18 4.4, 0., 1., 1.
6106D 19 4.4, 0., 1., 1.
6106D 20 4.4, 0., 1., 1.
6106D 21 4.4, 0., 1., 1.
6106D 22 4.4, 0., 1., 1.
6106D 23 4.4, 0., 1., 1.
6106D 24 4.4, 0., 1., 1.
6106D 25 4.4, 0., 1., 1.
6106D 26 4.4, 0., 1., 1.
6106D 27 4.4, 0., 1., 1.
6106D 28 4.4, 0., 1., 1.
6106D 29 4.4, 0., 1., 1.
6106D 30 4.4, 0., 1., 1.
6106D 31 4.4, 0., 1., 1.
6106D 32 4.4, 0., 1., 1.
6106D 33 4.4, 0., 1., 1.
6106D 34 4.4, 0., 1., 1.
6106D 35 4.4, 0., 1., 1.
6106D 36 4.4, 0., 1., 1.
6106D 37 4.4, 0., 1., 1.
6106D 38 4.4, 0., 1., 1.
6106D 39 4.4, 0., 1., 1.
6106D 40 4.4, 0., 1., 1.
6106D 41 4.4, 0., 1., 1.
6106D 42 4.4, 0., 1., 1.
C END OF SURF EFF DATA
6107D 0.8, 6R
6108D 13., 1.E5, 20., 91.
6109D 1, 22.5, 7.4, 1.93, 16., 3.6, 0., 12.
6110D .1, .001, .40, 30
C FIN DATA
C .0508, .00635, .F.
C 3, .166666666667, .333333333333, .5
C END OF MODULAR TEST CASE DATA
STOP

Input Deck for THATCH Sample Case No 2

THPRTST

OV THATCH

C

C This input data file is for THATCH/SYMELAN run
C with water reactivity insertion.

C

C Status of Sept 90. Includes all shroud and core
C barrel modifications. After SYMELAN integration into code.
C Revised Input Processor and Unified Input Option

C

C

C Option of 10 Axial Power Zones Available.

C

C TITLE (SECTION 1) ** ** ** ** **
101D ' ANNULAR CORE 350MW MODULAR HTGR\$'
102D ' PRESSURIZED CORE HEATUP ACCIDENT, RCCS OPERATING\$'
103D ' WATER REACTIVITY INSERTION, 10 s Ramp\$\$'

C

C FLOXI OPTION, STEADY, SYMELL OPTION
C STEADY CAN ONLY BE TRUE IF FLOXI IS TRUE
201D .T., .F., .T.

C

C POINT KINETICS OPTION, RECOMPT OPTION
C RECOMPT ONLY USED IF PKINL = TRUE
202D .T., .F.

C

C UNIFIED INPUT OPTION CONTROL
C UNIFIN

301D .T.
C INITIAL RADIAL INTERACE POINT (MUST BE ZERO FOR CURRENT THATCH
C RIFA-ARRAY, NODE DISTRIBUTION BY 'AREA' OR 'DELR', SMEARING OF
C RSC-CHANNEL LOSS OF AREA EFFECT IN INNER RADIAL CORE POWER ZONE
302D 0, 'AREA', .F.

C NO OF NODES/CHANNELS IN
C CENTRAL REFL, ACT CORE REGN 1, REGN2, REGN3, SIDE REFLECTORS
303D 6, 2, 2, 2, 6

C INITIAL AXIAL INTERFACE POINT (TOP OF ACTIVE CORE), NO OF
C AXIAL NODES PER FUEL ELEMENT, TOP & BOT REFL NODE MULTIPLIER
C (MULTIPLES OF 4 NODES EACH)

304D 12, 2, 1, 1
C BASE RADIAL POWER PROFILE

305D 0, 'D'
C POINT KINETICS RADIAL POWER PROFILE

306D 3, 'F'
C BASE AXIAL POWER PROFILE

307D 0, 'F'
C POINT KINETICS AXIAL POWER PROFILE

308D 10, 'F'
/ STOP

```

C
C   UNITS ( SECTION 2 ) ** ** ** **
C   GEOMETRY (LENGTHS) ** **
401D 'M'
C   INPUT TEMPERATURES ** **
403D 'C'
C   OUTPUT TEMPERATURES ** **
404D 'C'
C   GEOMETRY ( SECTION 3 ) ** ** **
C   RADIAL INTERFACE ** **
501D 21
502D 0.336352, 0.475674, 0.582579, 0.672704, 0.752106, 0.823891
      1.000166, 1.149724, 1.323095, 1.476243, 1.614932, 1.742619
      1.982994, 2.197229, 2.413, 2.572724, 2.741251, 2.900000
      3.275, 3.342, 3.408
C   RADIAL POINT 0 ** **
503D 0.
C   AXIAL INTERFACE ** **
504D 45
505D -5.29, -5.21, -4.653, -4.603, -4.59, -3.59, -2.59, -1.59
      -1.2, -.8, -.4, 0.
      0.396500, 0.793000, 1.189500, 1.586000, 1.982500, 2.379000
      2.775500, 3.172000, 3.568500, 3.965000, 4.361500, 4.758000
      5.154500, 5.551000, 5.947500, 6.344000, 6.740500, 7.137001
      7.533500, 7.930000
      8.38, 8.83, 9.28, 9.73, 10.33
      10.93, 11.10, 11.28, 11.43, 12.28, 15.13, 15.19, 15.26
C   BLOCKS ( SECTION 4 ) ** ** **
601D 20
C   BLOCK 1 ** **
602D 1 'CENTRAL REFLECTOR'
603D 1 0, 6, 8, 36, 1
604D 1 4
605D 1 1
606D 1 7

C   BLOCK 2 ** **
602D 2 'ACTIVE CORE'
603D 2 6, 12, 12, 32, 2
604D 2 5
605D 2 2
606D 2 6
607D 2 1

C   BLOCK 3 ** **
602D 3 'INNER SIDE REFLECTORS'
603D 3 12, 15, 8, 36, 1
604D 3 4
605D 3 13
606D 3 7
607D 3 2

```

```

C      BLOCK 4 ** **
602D 4 'PERMANENT SIDE REFLECTORS'
603D 4 15, 18, 8, 36, 4
604D 4 4
605D 4 3
606D 4 7
607D 4 13
C      BLOCK 5 ** **
602D 5 'TOP REFLECTOR'
603D 5 6, 12, 9, 12, 3
604D 5 13
605D 5 2
606D 5 5
607D 5 1
C      BLOCK 6 ** **
602D 6 'UPPER PLENUM ELEMENTS'
603D 6 6, 12, 8, 9, 15
604D 6 4
605D 6 2
606D 6 13
607D 6 1
C      BLOCK 7 ** **
602D 7 'UPPER BOTTOM REFLECTORS'
603D 7 6, 12, 32, 34, 3
604D 7 6
605D 7 2
606D 7 16
607D 7 1
C      BLOCK 8 ** **
602D 8 'LOWER BOTTOM REFLECTORS'
603D 8 6, 12, 34, 36, 5
604D 8 16
605D 8 2
606D 8 7
607D 8 1
C      BLOCK 9 ** **
602D 9 'CORE BARREL'
603D 9 18, 19, 8, 43, 10
604D 9 14
/605D 9 114,9,10, 4,11,43
  605D 9, 14,9,10, 4,11,43
905D 14, 16, .025
606D 9 15
607D 9 3,9,36, 11,37,38, 12,39,43
C      ** ** BLOCK 10 ** ** ** ** ** ** ** ** ** 
602D 10 'VESSEL (SIDE)'
603D 10 19, 21, 1, 45, 6
604D 10 1
605D 10 7,2,43, 8,44,45
606D 10 12
607D 10 5,2,3, 6,44,45

```

```

C  ** ** BLOCK 11 ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** *
602D 11 'VESSEL (TOP)'
603D 11 0, 19, 1, 3, 6
604D 11 1
605D 11 5

```

```

C  ** ** BLOCK 12 ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** *
602D 12 'VESSEL (BOTTOM)'
603D 12 0, 19, 43, 45, 6
604D 12 11,1,18, 15,19,19
605D 12 6
606D 12 12

```

```

C  ** ** BLOCK 13 ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** *
602D 13 'SHROUD (SIDE)'
603D 13 18, 19, 3, 8, 11
604D 13 18
/605D 13 116,4,7, 115, 8,8
605D 13 16,4,7, 15, 8,8
905D 16 17, .024
905D 15 17, .024
606D 13 14
607D 13 10,4,5, 9,6,8

```

```

C  ** ** BLOCK 14 ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** *
602D 14 'SHROUD (TOP)'
603D 14 0, 18, 3, 5, 10
/604D 14 102,1,18
604D 14 2,1,18
904D 2 7, .037
605D 14 10
606D 14 3

```

```

C  ** ** BLOCK 15 ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** *
602D 15 'UPPER CORE FLOOR'
603D 15 0, 18, 38, 40, 4
604D 15 8
605D 15 12
606D 15 17

```

```

C  ** ** BLOCK 16 ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** *
602D 16 'LOWER CORE FLOOR'
603D 16 0, 18, 40, 41, 8
604D 16 17
605D 16 12
606D 16 9

```

```

C  ** ** BLOCK17 ** ** ** ** ** ** ** ** ** ** ** 
602D 17 'FLOOR SUPPORT 1'
603D 17 0, 18, 41, 42, 6
604D 17 9
605D 17 12
606D 17 10

```

```

C  ** ** BLOCK18 ** ** ** 
602D 18 'FLOOR SUPPORT 2'
603D 18 0, 18, 42, 43, 6
604D 18 10
605D 18 12
606D 18 11

```

```

C  ** ** BLOCK 19 ** ** ** 
602D 19 'UPPER PLENUM'
603D 19 0, 18, 5, 8, 101
651D 19 'CYLIN'

```

```

C  ** ** BLOCK 20 ** ** ** 
602D 20 'LOWER PLENUM'
603D 20 0, 18, 36, 38, 102
651D 20 'CYLIN'

```

```

C  RADIATION PLENA ( SECTION 5 ) ** ** ** 
701D 'NEWTON', 1.0E-04, 0.01, 20, 0.4, 0.0

```

```

C  UPPER PLENUM CONVECTION HT. CONTROL

```

```

C  ( IF FLOXI IS SPECIFIED FALSE BELOW, THEN A VALUE OF TRUE GIVEN
C    HERE IS OVERRIDDEN, I.E. UPLCNV = .T. REQUIRES FLOXI = .T.)

```

```

702D .T., 1.

```

```

C  ADDITIONAL RADIAL GAPS

```

```

801D 5
802D 1 17, 2, 9,36
802D 2 18, 4, 9,36
802D 3 19, 8, 9,36
802D 4 20, 10, 9,36
802D 5 21, 14, 9,36

```

```

C  ADDITIONAL AXIAL GAPS

```

```

803D 8
804D 1 19, 12, 1,6
804D 2 20, 12, 13,15
804D 3 21, 32, 1,6
804D 4 22, 32, 13,15
804D 5 23, 16, 1,15
804D 6 24, 20, 1,15
804D 7 25, 24, 1,15
804D 8 26, 28, 1,15

```

```

C  BOUNDARIES/GAPS ( SECTION 6 ) ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
C  ** ** RADIAL ** ** **
901D 1,3,102,.001,.82,0.
901D 2,3,102,.001,.82,0.
901D 3,3,102,.001,.82,0.
901D 4,3,106,.295,.485,0.
901D 5,1,0,0.,0.,0.
901D 6,1,0,0.,0.,0.
901D 7,31,0,0.,0.,0.
901D 8,13,0,0.,0.,0.
901D 9,21,0,0.,0.,0.
901D 10,1,0,0.,0.,0.
901D 11,21,0,0.,0.,0.
901D 12,1,0,0.,0.,0.
901D 13,3,102,.001,.82,0.
901D 14,3,106,.270,.68,0.
901D 15,3,106,.271,.68,0.
901D 16,3,106,.271,.68,0.
901D 17,3,102,.001,.82,0.
901D 18,3,102,.001,.82,0.
901D 19,3,102,.001,.82,0.
901D 20,3,102,.001,.82,0.
901D 21,3,102,.001,.82,0.
C  ** ** AXIAL ** ** **
902D 1,12,0,0.,0.,0.
902D 2,3,107,.477,.68,0.
902D 3,21,0,0.,0.,0.
902D 4,21,0,0.,0.,0.
902D 5,3,102,.0005,.82,0.
902D 6,3,102,.0005,.82,0.
902D 7,21,0,0.,0.,0.
902D 8,21,0,0.,0.,0.
902D 9,1,0,0.,0.,0.
902D 10,3,102,.7,.68,0.
902D 11,3,102,2.,.68,0.
902D 12,13,0,0.,0.,0.
902D 13,3,102,.0005,.82,0.
902D 14,1,0,0.,0.,0.
902D 15,3,102,2.,.68,0.
902D 16,3,102,.0005,.82,0.
902D 17,1,0,0.,0.,0.
902D 18,5,0,0.,0.,0.
902D 19,3,102,.0005,.82,0.
902D 20,3,102,.0005,.82,0.
902D 21,3,102,.0005,.82,0.
902D 22,3,102,.0005,.82,0.
902D 23,3,102,.0005,.82,0.
902D 24,3,102,.0005,.82,0.
902D 25,3,102,.0005,.82,0.
902D 26,3,102,.0005,.82,0.

```

```

C IRRADIATION AND ANNEALING DATA
C IF FIRST PARAMETER ( IRRADN IS FALSE, THEN THIS SECTION IS BYPASSED )
1001D .T.
1002D .T.
1003D 3
C ASSUMED BASE CASE IRRADIATION DAMAGE
1004D 3,15, 12,33
1005D 12 0.0,4R, 1.0,6R, 0.0,3R/
1005D 13 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 14 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 15 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 16 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 17 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 18 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 19 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 20 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 21 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 22 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 23 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 24 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 25 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 26 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 27 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 28 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 29 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 30 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 31 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 32 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 33 0.0,4R, 0.82,6R, 0.0,3R/
1006D 1000., 1300.
C
C ** ** AFTERHEAT DATA (SECTION 7 ) ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** 
C INITIAL POWER ** ** ** 
1101D 350.E6, 0., 1.4, 1., 2
C AFTERHEAT REGION ** ** ** 
1102D 7,12, 13,32
C REFLECTOR REGION ** ** ** 
1103D 1, 15, 10, 34
C ** ** ** ** ** ** ** ** ** ** ** ** *AFTER HEAT PROFILE DATA** ** ** 
C BASE RADIAL POWER PROFILE ( IHI - (ILO-1) ENTRIES )
1104D 1.0,6R/
C POINT KINETICS RADIAL POWER PROFILE ( IHI - (ILO-1) ENTRIES )
1105D 0.7121,2R, 1.053,2R, 1.163,2R/
C BASE AXIAL POWER PROFILE ( JHI - (JLO-1) ENTRIES )
1106D 1.36,10R, 0.77,6R, 0.445,4R/
C POINT KINETICS AXIAL POWER PROFILE ( IHI - (ILO-1) ENTRIES )
1107D 1.36,10R, 0.77,6R, 0.445,4R/

```



```

C ** AFTER HEAT OPTIONS
1108D 'NOML'
C ** ** TIME CONTROL ( SECTION 8A ) ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** 
C START TIME (HR) ** ** ** ** ** 
1201D 0.
C TIME PERIODS ** ** ** 
1202D 3
C TIME STEPS FOR RAPID REACTIVITY EXCURSION
1203D 0, 2., .01, .5, 0.2
      0, 12., .01, 2., 0.2
      0, 36., .05, 6., 0.5
C      0, 42., .1, 2., 0.5
C 0, 96., .2, 6., 1.0
C 0, 100., .2, 4., 1.0
C NORMAL TIME STEPS FOR PRESSURIZED TRANSIENTS
C 0, 60., .2, 30., 2.
C 0, 120., .5, 30., 5.
C 0, 240., 1., 60., 10.
C 0, 600., 2., 120., 20.
C 0,240., 1., 40., 4.
C 0,600., 2., 60., 10.
C 0,600., .2, 30., 1.
C 1, 60., .2, 5., 1.
C 0,240., 15.,240.,60.
C 1, 10., 1., 8.,6.
C 1, 60., 5., 50.,10.
C 2, 5., .25, 4.,.25
C 2, 20., .25, 15.,.50
C 2, 40., .50, 20.,1.
C 2, 60., .25, 20.,1.
C 2,120., .50, 20.,1.
C 2,200., .25, 20.,1.
C NORMAL TIME STEPS FOR DEPRESSURIZED TRANSIENTS
C 0,240.,15.,240.,240.
C 1,10.,1.,10.,6.
C 1,60.,5.,50.,25.
C 2,5.,.25,4.,1.
C 2,20.,.5,15.,1.
C 2,50.,1.,10.,1.
C 2,100.,1., 5.,1.
C 2,200.,1.,20.,1.
C OUTPUT FORMATS ( SECTION 8B ) ** ** ** 
1301D 4,0, 8,1
C BLOCK SURFACES OUTPUT ( SECTION 8C ) ** ** ** 
1401D 2
1402D 10,2, 10,4
C DEBUG ( SECTION 8D ) ** ** ** 

```

```

C  DEBUG CONTROL VARIABLE
1403D 0
C  DEBUG SET DATA ( BYPASS AT THIS TIME, SETTING NO OF SETS = 0
/ 0
C  ** **  INITIAL TEMPERATURES ( SECTION 9 ) ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
1501D 'READRUN '
C  'OTHER'
1502D 100.0,21R
1503D 100.0,35R, 80.0,9R
1504D 100.0,21R
C  BLOCK TEMPERATURES ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
1505D B1;24*258.
      B1;6*269.
      B1;6*290.
      B1;6*312.
      B1;6*333.
      B1;6*355.
      B1;6*376.
      B1;6*397.
      B1;6*419.
      B1;6*440.
      B1;6*462.
      B1;6*483.
      B1;6*505.
      B1;6*526.
      B1;6*548.
      B1;6*569.
      B1;6*590.
      B1;6*612.
      B1;6*633.
      B1;6*655.
      B1;6*676.
      B1;24*687.
      B2;6*269.
      B2;6*290.
      B2;6*312.
      B2;6*333.
      B2;6*355.
      B2;6*376.
      B2;6*397.
      B2;6*419.
      B2;6*440.
      B2;6*462.
      B2;6*483.
      B2;6*505.
      B2;6*526.
      B2;6*548.
      B2;6*569.
      B2;6*590.

```

B2;6*612.
 B2;6*633.
 B2;6*655.
 B2;6*676.
 B3;24*258.,120*400.,24*470.
 B4*258.
 B5*687.
 B6*258.
 B7*219.
 B8*219.
 B9*219.
 B10*258.
 B11*258.
 B12*500.
 B13*400.
 B14*258.

1000*777. /

C
 C FLOXI INPUT DATA
 C TYPE OF INGRESS, MAX NO OF ITERATIONS IN FLOW/RECT LOOP,
 C UNDER RELAX FACTOR, UNDER RELAX CONTROL
 3101D 'NONE', 40, 1., .F.
 C APPROX FLOW SOLN CTRL, VISC COMP CTRL, CHEM REACT (IREACT), GASOMIN
 3102D .F., .F., 0, 1.E-6
 C PO, STG LOOP HEAD, MASS FLOW (USED IN CONST FLOW CASE ONLY)
 C TH FL IN, FLUINUP TIME LAG, CONST FLOW OPT
 C TIMLAG GE 1.E6 KEEPS THFLIN CONSTANT
 3103D 72.E5, .433E5, 140., 259., 1.E7, .F.
 C INLET GAS COMPOSITION
 3104D 1, 1.
 C CORE NODE RANGES
 3201D 7, 12
 3202D 9, 36
 C FLOW CROSS SECTION AREAS
 3203D 0.185002,2R, 0.246669,4R, 1.1700
 C CORE HT SURFACE, HEIGHT, CORE BARRELL HT AREA (M2 / M)
 C ASURCOR, HICOR, ASURPBAR
 3204D 2733., 7.93, 19.2
 C HYDRAULIC DIAMS, ETC
 3205D 0.060, 0.015875,25R, 0.068, 0.120
 3206D 0.244,28R
 3207D 0.4, 1.0,24R, 0.667, 0.240, 0.142
 C RETURN FLOW CHANNEL NODE IN THATCH, J-INDEX FOR AVG DH
 3208D 19, 2
 C PRESSURE DROP LOSS HEADS (IN, 1 TO ICHP, EX, 1 TO ICHP)
 3209D 1.,6R, 1.
 3210D 1.,6R 10.
 C CONVECTIVE HT COMPS CONTROL (PER CHANNEL)
 3211D .T., .T., .T., .T., .T., .T., .T.
 C PRINT SCALE FOR FOCED OR FREE FLOW
 3212D 'FORCED'

```

C
C
C SYMELAN INPUT DATA
C
C
C RUN TITLE ( 3 LINES )
4001D '10s Water Ramp, Internally Computed Fuel/Graph HT Coeff
4002D '10 Zone Axial Power Profile, BE Fuel Properties, w/o Ax-Con
4003D '6 Fuel Nodes, 12 Graph Nodes, 6 Parallel Channels, 20 Axial Nodes
C RUNMODE
4004D 'TRANSIENT'
C NO OF CHANNELS, NO AXIAL NODES, READ INPUT TEMPS, WRITE OUTPUT TEMPS
C                                     , AXIAL COND OPTION
4005D 6, 20, .T., .T., .F.
/4005D 3, 10, .T., .T., .F.
C NO FUEL COLS TO BE USED, NO GRAPH NODE COLS ( 6 OR 12 )
C                                     ,NO OF NODE ROWS
4006D 6, 12, 1
C 3, 6, 2
C TO, NO OF TIME STEP INTERVALS, READ TIME FOR TEMP INPUT FILE
C                                     ,DEBUG PRINT
4007D 0., 5, 180000., .F.
C TFINA, DTA, NO PRINT&PLOT STEPS, ( 1 LINE PER INTERVAL )
4008D 1 12., .01, 12, 120
4008D 2 36., .1, 12, 60
4008D 3 42., .1, 6, 15
4008D 4 96., .2, 9, 54
4008D 5 100., .2, 1, 4
C 40., .2, 6, 75
C 200., 1., 16, 80
C 3600., 10., 30, 100
C RADIAL AREA FRACTIONS
C .2727266, .3636367, .3636367
4009D 0.1363633,2R, 0.18181835,4R
/ 4009D 0.0,3R
C RADIAL POWER PROFILE
4010D 0.7121,2R, 1.053,2R, 1.163,2R
/ 4010D 0.0,3R
C AXIAL NODE LENGTHS
C NOTE, NON-EVEN SPACING WOULD REQUIRE CODE MODIFICATIONS
4011D 0.3965,20R
/ 4011D 0.0,10R
C AXIAL POWER PROFILE 10-ZONE DATA
C DECAY HEAT
C 2*1.08, 2*1.11, 2*1.15, 2*1.16, 2*1.14, 2*1.04
C 2*.99, 2*.91, 2*.81, 2*.61
C FISSION POWER
/ 4012D 0.0,10R
4012D 1.13,2R, 1.26,2R, 1.37,2R, 1.4,2R, 1.37,2R,
0.88,2R, 0.82,2R, 0.77,2R, 0.54,2R, 0.46,2R

```

```

C  AXIAL POWER PROFILE  3-ZONE DATA
C  10*1.36, 6*.77, 4*.445
C  BASE POWER, INLET MASS FLOW, INLET FLUID TEMP, HT COEFF REDUCTION,
C  FUEL /GRAPHITE GAP(mm), GAP EMISS, AVG REFLECTOR TEMP (K) ( FOR USE
C  IN FREE STANDING SYMEL RUNS ONLY)
4013D  350.E6, 140., 259., .6545, .127E-3, .81, 745.4
C  TEMPERATURE ARRAY FOR HOT FRACTIONS
4014D  1200., 1400., 1600., 1800.
C  POINT KINETICS OPTION ( FOR USE WITHIN SYMEL )
4015D  .T.
C
C
C
C  POINT KINETICS INPUT DATA
C
C  COMPMOD, RHOMODE, CORAVG, IKINMX, EPSO,PSOURCO,POWCOR,DTHO,VARYIN
C  FOR SLOW REACTIVITY TRANSIENTS W/O SYMELAN USE POWCOR = .94 AND
C  INCLUDE DECAY HEAT.
C  FOR RAPID REACTIVITY EXCURSIONS, USE POWCOR = 1.0, AND NELECT
C  DECAY HEAT
5001D  'ITERATE', 'INTEGR', .F., 20, 1.E-7, 1.E-9, 1.0, 0.
C  ODE INTEFRATION CONTROL'
C  INTMTHD, MTHGEAR, MITER
5003D  'DIVPAG', 2, 1
C  WATER REACTIVITY INSERTION, BEGIN TIME, RAMP TIME, PARAM COEFFICNT
C  NOTE THAT END OF RAMP REACTIVITY IS NOW COMPUTED AND
C  INPUT VALUE IS NO LONGER USED
5002D  0., 10., 1.
C  OPTIONAL OVERRIDE OF POINT KINETICS DATA IF VARYIN = TRUE
C  $VARYINP
C      SIGASAM=12.32E-25
C  $END
C
C
C  AIR COOLER INPUT DATA
6101D  'FIN PERFORMANCE COEFFICIENTS ARE INPUT'
6102D  .T., .F., .F., 'BNL'
6103D  1, 43, 9
6104D  3.408, 4.316, 4.326, 4.4784, 4.4884, 4.85
6105D  3.95, 7.8, .0762, .54
C  SURFACE EFFECTIVENESS DATA
6106D  1 1.0,4R
6106D  2 1.0,4R
6106D  3 1.0,4R
6106D  4 1.0,4R
6106D  5 1.0,4R
6106D  6 1.0,4R
6106D  7 1.0,4R
6106D  8 4.4, 0., 1., 1.

```

```

6106D  9  4.4, 0., 1., 1.
6106D 10  4.4, 0., 1., 1.
6106D 11  4.4, 0., 1., 1.
6106D 12  4.4, 0., 1., 1.
6106D 13  4.4, 0., 1., 1.
6106D 14  4.4, 0., 1., 1.
6106D 15  4.4, 0., 1., 1.
6106D 16  4.4, 0., 1., 1.
6106D 17  4.4, 0., 1., 1.
6106D 18  4.4, 0., 1., 1.
6106D 19  4.4, 0., 1., 1.
6106D 20  4.4, 0., 1., 1.
6106D 21  4.4, 0., 1., 1.
6106D 22  4.4, 0., 1., 1.
6106D 23  4.4, 0., 1., 1.
6106D 24  4.4, 0., 1., 1.
6106D 25  4.4, 0., 1., 1.
6106D 26  4.4, 0., 1., 1.
6106D 27  4.4, 0., 1., 1.
6106D 28  4.4, 0., 1., 1.
6106D 29  4.4, 0., 1., 1.
6106D 30  4.4, 0., 1., 1.
6106D 31  4.4, 0., 1., 1.
6106D 32  4.4, 0., 1., 1.
6106D 33  4.4, 0., 1., 1.
6106D 34  4.4, 0., 1., 1.
6106D 35  4.4, 0., 1., 1.
6106D 36  4.4, 0., 1., 1.
6106D 37  4.4, 0., 1., 1.
6106D 38  4.4, 0., 1., 1.
6106D 39  4.4, 0., 1., 1.
6106D 40  4.4, 0., 1., 1.
6106D 41  4.4, 0., 1., 1.
6106D 42  4.4, 0., 1., 1.
C  END OF SURF EFF DATA
6107D 0.8,6R
6108D 13., 1.E5, 20., 91.
C  CP AIR, NOW SET INTERNALLY
C  1020.9
6109D 1, 22.5, 7.4, 1.93, 16., 3.6, 0., 12.
6110D .1, .001, .40, 30
C  FIN DATA
C  .0508, .00635, .F.
C  3, .1666666666667, .3333333333333, .5
C  END OF MODULAR TEST CASE DATA
STOP

```

Input Deck for THATCH Sample Case No 3

THBASARR

OV THATCH

```

C
C This input data file is for AIR INGRESS SIMULATION
C Status of Sept 90. Includes all shroud and core
C barrel modifications. After SYMELAN integration into code.
C
C Revised Input Processor and Unified Input Option
C
C Option of 10 Axial Power Zones Available.
C
C TITLE ( SECTION 1 ) ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
101D '          ANNULAR CORE 350MW MODULAR HTGRS'
102D '          DEPRESSURIZED CORE HEATUP ACCIDENT, RCCS OPERATING$'
103D '          CORE HEATUP WITH AIR INGRESS$$'
C
C FLOXI OPTION, STEADY, SYMELL OPTION
C STEADY CAN ONLY BE TRUE IF FLOXI IS TRUE
201D .T., .F., .F.
C
C POINT KINETICS OPTION, RECOMPT OPTION
C RECOMPT ONLY USED IF PKINL = TRUE
202D .F., .F.
C
C UNIFIED INPUT OPTION CONTROL
C UNIFIN
301D .T.
C INITIAL RADIAL INTERACE POINT ( MUST BE ZERO FOR CURRENT THATCH
C RIFA-ARRAY, NODE DISTRIBUTION BY 'AREA' OR 'DELR', SMEARING OF
C RSC-CHANNEL LOSS OF AREA EFFECT IN INNER RADIAL CORE POWER ZONE
302D 0, 'AREA', .F.
C NO OF NODES/CHANNELS IN
C CENTRAL REFL, ACT CORE REGN 1, REGN2, REGN3, SIDE REFLECTORS
303D 6, 2, 2, 2, 6
C INITIAL AXIAL INTERFACE POINT ( TOP OF ACTIVE CORE ), NO OF
C AXIAL NODES PER FUEL ELEMENT, TOP & BOT REFL NODE MULTIPLIER
C          ( MULTIPLES OF 4 NODES EACH )
304D 12, 2, 1, 1
C BASE RADIAL POWER PROFILE
305D 1, 'D'
C POINT KINETICS RADIAL POWER PROFILE
306D 0, 'F'
C BASE AXIAL POWER PROFILE
307D 3, 'D'
C POINT KINETICS AXIAL POWER PROFILE
308D 0, 'F'

```

```

C
C   UNITS ( SECTION 2 ) ** ** ** **
C   GEOMETRY (LENGTHS) ** **
401D 'M'
C   INPUT TEMPERATURES ** **
403D 'C'
C   OUTPUT TEMPERATURES ** **
404D 'C'
C   GEOMETRY ( SECTION 3 ) ** ** **
C   RADIAL INTERFACE ** **
501D 21
502D 0.336352, 0.475674, 0.582579, 0.672704, 0.752106, 0.823891
      1.000166, 1.149724, 1.323095, 1.476243, 1.614932, 1.742619
      1.982994, 2.197229, 2.413, 2.572724, 2.741251, 2.900000
      3.275, 3.342, 3.408
C   RADIAL POINT 0 ** **
503D 0.
C   AXIAL INTERFACE ** **
504D 45
505D -5.29, -5.21, -4.653, -4.603, -4.59, -3.59, -2.59, -1.59
      -1.2, -.8, -.4, 0.
      0.396500, 0.793000, 1.189500, 1.586000, 1.982500, 2.379000
      2.775500, 3.172000, 3.568500, 3.965000, 4.361500, 4.758000
      5.154500, 5.551000, 5.947500, 6.344000, 6.740500, 7.137001
      7.533500, 7.930000
      8.38, 8.83, 9.28, 9.73, 10.33
      10.93, 11.10, 11.28, 11.43, 12.28, 15.13, 15.19, 15.26
C   BLOCKS ( SECTION 4 ) ** ** **
601D 20
C   BLOCK 1 ** **
602D 1 'CENTRAL REFLECTOR'
603D 1 0, 6, 8, 36, 1
604D 1 4
605D 1 1
606D 1 7

C   BLOCK 2 ** **
602D 2 'ACTIVE CORE'
603D 2 6, 12, 12, 32, 2
604D 2 5
605D 2 2
606D 2 6
607D 2 1
C   BLOCK 3 ** **
602D 3 'INNER SIDE REFLECTORS'
603D 3 12, 15, 8, 36, 1
604D 3 4
605D 3 13
606D 3 7
607D 3 2

```



```

C      BLOCK 4 ** **
602D 4 'PERMANENT SIDE REFLECTORS'
603D 4 15, 18, 8, 36, 4
604D 4 4
605D 4 3
606D 4 7
607D 4 13
C      BLOCK 5 ** **
602D 5 'TOP REFLECTOR'
603D 5 6, 12, 9, 12, 3
604D 5 13
605D 5 2
606D 5 5
607D 5 1
C      BLOCK 6 ** **
602D 6 'UPPER PLENUM ELEMENTS'
603D 6 6, 12, 8, 9, 15
604D 6 4
605D 6 2
606D 6 13
607D 6 1
C      BLOCK 7 ** **
602D 7 'UPPER BOTTOM REFLECTORS'
603D 7 6, 12, 32, 34, 3
604D 7 6
605D 7 2
606D 7 16
607D 7 1
C      BLOCK 8 ** **
602D 8 'LOWER BOTTOM REFLECTORS'
603D 8 6, 12, 34, 36, 5
604D 8 16
605D 8 2
606D 8 7
607D 8 1
C      BLOCK 9 ** **
602D 9 'CORE BARREL'
603D 9 18, 19, 8, 43, 10
604D 9 14
/605D 9 114,9,10, 4,11,43
605D 9, 14,9,10, 4,11,43
905D 14, 16, .025
606D 9 15
607D 9 3,9,36, 11,37,38, 12,39,43
C      ** ** BLOCK 10 ** ** ** ** ** ** ** ** 
602D 10 'VESSEL (SIDE)'
603D 10 19, 21, 1, 45, 6
604D 10 1
605D 10 7,2,43, 8,44,45
606D 10 12
607D 10 5,2,3, 6,44,45

```

```

C  ** ** BLOCK 11 ** ** ** ** ** ** ** ** ** ** 
602D 11 'VESSEL (TOP)'
603D 11 0, 19, 1, 3, 6
604D 11 1
605D 11 5

```

```

C  ** ** BLOCK 12 ** ** ** 
602D 12 'VESSEL (BOTTOM)'
603D 12 0, 19, 43, 45, 6
604D 12 11,1,18, 15,19,19
605D 12 6
606D 12 12

```

```

C  ** ** BLOCK 13 ** ** ** 
602D 13 'SHROUD (SIDE)'
603D 13 18, 19, 3, 8, 11
604D 13 18
/605D 13 116,4,7, 115, 8,8
605D 13 16,4,7, 15, 8,8
905D 16 17, .024
905D 15 17, .024
606D 13 14
607D 13 10,4,5, 9,6,8

```

```

C  ** ** BLOCK 14 ** ** ** 
602D 14 'SHROUD (TOP)'
603D 14 0, 18, 3, 5, 10
/604D 14 102,1,18
604D 14 2,1,18
904D 2 7, .037
605D 14 10
606D 14 3

```

```

C  ** ** BLOCK 15 ** ** ** 
602D 15 'UPPER CORE FLOOR'
603D 15 0, 18, 38, 40, 4
604D 15 8
605D 15 12
606D 15 17

```

```

C  ** ** BLOCK 16 ** ** ** 
602D 16 'LOWER CORE FLOOR'
603D 16 0, 18, 40, 41, 8
604D 16 17
605D 16 12
606D 16 9

```

```

C  ** ** BLOCK17 ** ** ** ** ** ** ** ** ** ** 
602D 17 'FLOOR SUPPORT 1'
603D 17 0, 18, 41, 42, 6
604D 17 9
605D 17 12
606D 17 10

C  ** ** BLOCK18 ** ** ** 
602D 18 'FLOOR SUPPORT 2'
603D 18 0, 18, 42, 43, 6
604D 18 10
605D 18 12
606D 18 11

C  ** ** BLOCK 19 ** ** ** 
602D 19 'UPPER PLENUM'
603D 19 0, 18, 5, 8, 101
651D 19 'CYLIN'
C  ** ** BLOCK 20 ** ** ** 
602D 20 'LOWER PLENUM'
603D 20 0, 18, 36, 38, 102
651D 20 'CYLIN'
C  RADIATION PLENA ( SECTION 5 ) ** ** ** 
701D 'NEWTON', 1.OE-04, 0.01, 20, 0.4, 0.0
C  UPPER PLENUM CONVECTION HT CONTROL
C  ( IF FLOXI IS SPECIFIED FALSE BELOW, THEN A VALUE OF TRUE GIVEN
C    HERE IS OVERRIDDEN, I.E. UPLCNV = .T. REQUIRES FLOXI = .T.)
702D .F., 1.
C  ADDITIONAL RADIAL GAPS
801D 5
802D 1 17, 2, 9,36
802D 2 18, 4, 9,36
802D 3 19, 8, 9,36
802D 4 20, 10, 9,36
802D 5 21, 14, 9,36
C  ADDITIONAL AXIAL GAPS
803D 8
804D 1 19, 12, 1,6
804D 2 20, 12, 13,15
804D 3 21, 32, 1,6
804D 4 22, 32, 13,15
804D 5 23, 16, 1,15
804D 6 24, 20, 1,15
804D 7 25, 24, 1,15
804D 8 26, 28, 1,15

```

```

C  BOUNDARIES/GAPS ( SECTION 6 ) ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
C      ** ** RADIAL ** ** **
901D 1,3,102,.001,.82,0.
901D 2,3,102,.001,.82,0.
901D 3,3,102,.001,.82,0.
901D 4,3,106,.295,.485,0.
901D 5,1,0,0.,0.,0.
901D 6,1,0,0.,0.,0.
901D 7,31,0,0.,0.,0.
901D 8,13,0,0.,0.,0.
901D 9,21,0,0.,0.,0.
901D 10,1,0,0.,0.,0.
901D 11,21,0,0.,0.,0.
901D 12,1,0,0.,0.,0.
901D 13,3,102,.001,.82,0.
901D 14,3,106,.270,.68,0.
901D 15,3,106,.271,.68,0.
901D 16,3,106,.271,.68,0.
901D 17,3,102,.001,.82,0.
901D 18,3,102,.001,.82,0.
901D 19,3,102,.001,.82,0.
901D 20,3,102,.001,.82,0.
901D 21,3,102,.001,.82,0.
C      ** ** AXIAL ** ** **
902D 1,12,0,0.,0.,0.
902D 2,3,107,.477,.68,0.
902D 3,21,0,0.,0.,0.
902D 4,21,0,0.,0.,0.
902D 5,3,102,.0005,.82,0.
902D 6,3,102,.0005,.82,0.
902D 7,21,0,0.,0.,0.
902D 8,21,0,0.,0.,0.
902D 9,1,0,0.,0.,0.
902D 10,3,102,.7,.68,0.
902D 11,3,102,2.,.68,0.
902D 12,13,0,0.,0.,0.
902D 13,3,102,.0005,.82,0.
902D 14,1,0,0.,0.,0.
902D 15,3,102,2.,.68,0.
902D 16,3,102,.0005,.82,0.
902D 17,1,0,0.,0.,0.
902D 18,5,0,0.,0.,0.
902D 19,3,102,.0005,.82,0.
902D 20,3,102,.0005,.82,0.
902D 21,3,102,.0005,.82,0.
902D 22,3,102,.0005,.82,0.
902D 23,3,102,.0005,.82,0.
902D 24,3,102,.0005,.82,0.
902D 25,3,102,.0005,.82,0.
902D 26,3,102,.0005,.82,0.

```

```

C  IRRADIATION AND ANNEALING DATA
C  IF FIRST PARAMETER ( IRRADN IS FALSE, THEN THIS SECTION IS BYPASSED )
1001D .T.
1002D .T.
1003D 3
C  ASSUMED BASE CASE IRRADIATION DAMAGE
1004D 3,15, 12,33
1005D 12 0.0,4R, 1.0,6R, 0.0,3R/
1005D 13 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 14 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 15 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 16 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 17 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 18 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 19 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 20 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 21 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 22 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 23 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 24 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 25 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 26 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 27 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 28 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 29 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 30 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 31 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 32 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 33 0.0,4R, 0.82,6R, 0.0,3R/
1006D 1000., 1300.
C
C  ** ** AFTERHEAT DATA (SECTION 7 ) ** ** ** ** ** ** ** ** 
C  INITIAL POWER ** ** ** 
1101D 350.E6, 0., 1.4, 1., 2
C  AFTERHEAT REGION ** ** ** 
1102D 7,12, 13,32
C  REFLECTOR REGION ** ** ** 
1103D 1, 15, 10, 34
C  ** ** ** ** ** ** ** ** AFTER HEAT PROFILE DATA** ** ** 
C  BASE RADIAL POWER PROFILE ( IHI - (ILO-1) ENTRIES )
1104D 1.0,6R/
C  POINT KINETICS RADIAL POWER PROFILE ( IHI - (ILO-1) ENTRIES )
1105D 0.7121,2R, 1.053,2R, 1.163,2R/
C  BASE AXIAL POWER PROFILE ( JHI - (JLO-1) ENTRIES )
1106D 1.36,10R, 0.77,6R, 0.445,4R/
C  POINT KINETICS AXIAL POWER PROFILE ( IHI - (ILO-1) ENTRIES )
1107D 1.36,10R, 0.77,6R, 0.445,4R/

```

```

C  ** AFTER HEAT OPTIONS
1108D 'NOML'
C  ** ** TIME CONTROL ( SECTION 8A ) ** ** ** **
C  START TIME (HR) ** ** ** **
1201D 0.
C  TIME PERIODS ** ** ** *
1202D 7
C  TIME STEPS FOR RAPID REACTIVITY EXCURSION
1203D 0,240.,15.,120.,240.
      1,10.,1.,6.,6.
      1,60.,5.,50.,25.
      2,5.,.25,4.,1.
      2,20.,.5,15.,1.
      2,100.,1.,20.,1.
      2,200.,1.,50.,1.
C  2,400.,2.,50.,2.
C  2,700.,2.,20.,4.
C  2,2000.,2.,100.,4.
C  OUTPUT FORMATS ( SECTION 8B ) ** ** ** *
1301D 4,0, 8,1
C  BLOCK SURFACES OUTPUT ( SECTION 8C ) ** ** ** *
1401D 2
1402D 10,2, 10,4
C  DEBUG ( SECTION 8D ) ** ** ** *
C  DEBUG CONTROL VARIABLE
1403D 0
C  DEBUG SET DATA ( BYPASS AT THIS TIME, SETTING NO OF SETS = 0
/ 0
C  ** ** INITIAL TEMPERATURES ( SECTION 9 ) ** ** ** *
1501D 'READRUN '
C  'OTHER'
1502D 100.0,21R
1503D 100.0,35R, 80.0,9R
1504D 100.0,21R
C  BLOCK TEMPERATURES ** ** ** *
1505D B1;24*258.
      B1;6*269.
      B1;6*290.
      B1;6*312.
      B1;6*333.
      B1;6*355.
      B1;6*376.
      B1;6*397.
      B1;6*419.
      B1;6*440.
      B1;6*462.
      B1;6*483.
      B1;6*505.
      B1;6*526.

```

B1;6*548.
 B1;6*569.
 B1;6*590.
 B1;6*612.
 B1;6*633.
 B1;6*655.
 B1;6*676.
 B1;24*687.
 B2;6*269.
 B2;6*290.
 B2;6*312.
 B2;6*333.
 B2;6*355.
 B2;6*376.
 B2;6*397.
 B2;6*419.
 B2;6*440.
 B2;6*462.
 B2;6*483.
 B2;6*505.
 B2;6*526.
 B2;6*548.
 B2;6*569.
 B2;6*590.
 B2;6*612.
 B2;6*633.
 B2;6*655.
 B2;6*676.
 B3;24*258., 120*400., 24*470.
 B4*258.
 B5*687.
 B6*258.
 B7*219.
 B8*219.
 B9*219.
 B10*258.
 B11*258.
 B12*500.
 B13*400.
 B14*258.

1000*777. /

C

C FLOXI INPUT DATA

C TYPE OF INGRESS, MAX NO OF ITERATIONS IN FLOW/RECT LOOP,
 C UNDER RELAX FACTOR, UNDER RELAX CONTROL

3101D 'AIR', 20, 1., .F.

C APPROX FLOW SOLN CTRL, VISC COMP CTRL, CHEM REACT (IREACT), GASOMIN
 3102D .F., .T., 2, 1.E-6

```

C PO, STG LOOP HEAD, MASS FLOW (USED IN CONST FLOW CASE ONLY)
C TH FL IN, FLUINUP TIME LAG, CONST FLOW OPT
C TIMLAG GE 1.E6 KEEPS THFLIN CONSTANT
3103D 1.E5, 0.0, 1., 259., 1.E7, .F.
C INLET GAS COMPOSITION
3104D 8, 0.0, 1.0, 0.0, 6R
C CORE NODE RANGES
3201D 7, 12
3202D 9, 36
C FLOW CROSS SECTION AREAS
3203D 0.185002, 2R, 0.246669, 4R, 1.1700
C CORE HT SURFACE, HEIGHT, CORE BARRELL HT AREA ( M2 / M )
C ASURCOR, HICOR, ASURPBAR
3204D 2733., 7.93, 19.2
C HYDRAULIC DIAMS, ETC
3205D 0.060, 0.015875, 25R, 0.068, 0.120
3206D 0.244, 28R
3207D 0.4, 1.0, 24R, 0.667, 0.240, 0.142
C RETURN FLOW CHANNEL NODE IN THATCH, J-INDEX FOR AVG DH
3208D 19, 2
C PRESSURE DROP LOSS HEADS ( IN, 1 TO ICHP, EX, 1 TO ICHP )
3209D 1., 6R, 1.
3210D 1., 6R, 5.
C CONVECTIVE HT COMPS CONTROL ( PER CHANNEL )
3211D .T., .T., .T., .T., .T., .T., .T.
C PRINT SCALE FOR FOCED OR FREE FLOW
3212D 'FREE'
C
C AIR COOLER INPUT DATA
6101D 'FIN PERFORMANCE COEFFICIENTS ARE INPUT'
6102D .T., .F., .F., 'BNL'
6103D 1, 43, 9
6104D 3.408, 4.316, 4.326, 4.4784, 4.4884, 4.85
6105D 3.95, 7.8, .0762, .54
C SURFACE EFFECTIVENESS DATA
6106D 1 1.0, 4R
6106D 2 1.0, 4R
6106D 3 1.0, 4R
6106D 4 1.0, 4R
6106D 5 1.0, 4R
6106D 6 1.0, 4R
6106D 7 1.0, 4R
6106D 8 4.4, 0., 1., 1.
6106D 9 4.4, 0., 1., 1.
6106D 10 4.4, 0., 1., 1.
C 10
6106D 11 4.4, 0., 1., 1.
6106D 12 4.4, 0., 1., 1.
6106D 13 4.4, 0., 1., 1.
6106D 14 4.4, 0., 1., 1.

```



```

6106D 15 4.4, 0., 1., 1.
6106D 16 4.4, 0., 1., 1.
6106D 17 4.4, 0., 1., 1.
6106D 18 4.4, 0., 1., 1.
6106D 19 4.4, 0., 1., 1.
6106D 20 4.4, 0., 1., 1.
C 20
6106D 21 4.4, 0., 1., 1.
6106D 22 4.4, 0., 1., 1.
6106D 23 4.4, 0., 1., 1.
6106D 24 4.4, 0., 1., 1.
6106D 25 4.4, 0., 1., 1.
6106D 26 4.4, 0., 1., 1.
6106D 27 4.4, 0., 1., 1.
6106D 28 4.4, 0., 1., 1.
6106D 29 4.4, 0., 1., 1.
6106D 30 4.4, 0., 1., 1.
C 30
6106D 31 4.4, 0., 1., 1.
6106D 32 4.4, 0., 1., 1.
6106D 33 4.4, 0., 1., 1.
6106D 34 4.4, 0., 1., 1.
6106D 35 4.4, 0., 1., 1.
6106D 36 4.4, 0., 1., 1.
6106D 37 4.4, 0., 1., 1.
6106D 38 4.4, 0., 1., 1.
6106D 39 4.4, 0., 1., 1.
6106D 40 4.4, 0., 1., 1.
C 40
6106D 41 4.4, 0., 1., 1.
6106D 42 4.4, 0., 1., 1.
C END OF SURF EFF DATA
6107D 0.8,6R
6108D 13., 1.E5, 20., 91.
C CP AIR, NOW SET INTERNALLY
C 1020.9
6109D 1, 22.5, 7.4, 1.93, 16., 3.6, 0., 12.
6110D .1, .001, .40, 30
C FIN DATA
C .0508, .00635, .F.
C 3, .1666666666667, .3333333333333, .5
C END OF MODULAR TEST CASE DATA
STOP

```

Input Deck for THATCH Sample Case No. 4

BASWAT

```

C
C This input data file is for Base Depressurized Core Heatup
C Status of Sept 90. Includes all shroud and core
C barrel modifications. After SYMELAN integration into code.
C Revised Input Processor and Unified Input Option
C
C
C Option of 10 Axial Power Zones Available.
C
C TITLE ( SECTION 1 ) ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
C
OV THATCH
101D '                ANNULAR CORE 350MW MODULAR HTGR'
102D '                DEPRESSURIZED CORE HEATUP ACCIDENT, RCCS OPERATING
103D '                WATER COOLED RCCS'
C
C FLOXI OPTION, STEADY, SYMELL OPTION
C STEADY CAN ONLY BE TRUE IF FLOXI IS TRUE
201D .F., .F., .F.
C
C POINT KINETICS OPTION, RECOMPT OPTION
C RECOMPT ONLY USED IF PKINL = TRUE
202D .F., .F.
C
C UNIFIED INPUT OPTION CONTROL
C UNIFIN
301D .T.
C INITIAL RADIAL INTERACE POINT ( MUST BE ZERO FOR CURRENT THATCH
C RIFA-ARRAY, NODE DISTRIBUTION BY 'AREA' OR 'DELR', SMEARING OF
C RSC-CHANNEL LOSS OF AREA EFFECT IN INNER RADIAL CORE POWER ZONE
302D 0, 'AREA', .F.
C NO OF NODES/CHANNELS IN
C CENTRAL REFL, ACT CORE REGN 1, REGN2, REGN3, SIDE REFLECTORS
303D 6, 2, 2, 2, 6
C INITIAL AXIAL INTERFACE POINT ( TOP OF ACTIVE CORE ), NO OF
C AXIAL NODES PER FUEL ELEMENT, TOP & BOT REFL NODE MULTIPLIER
C                ( MULTIPLES OF 4 NODES EACH )
304D 12, 2, 1, 1
C BASE RADIAL POWER PROFILE
305D 1, 'D'
C POINT KINETICS RADIAL POWER PROFILE
306D 0, 'F'
C BASE AXIAL POWER PROFILE
307D 10, 'D'

```

```

C POINT KINETICS AXIAL POWER PROFILE
308D 0, 'F'
C
C UNITS ( SECTION 2 ) ** ** ** **
C GEOMETRY (LENGTHS) ** **
401D 'M'
C INPUT TEMPERATURES ** **
403D 'C'
C OUTPUT TEMPERATURES ** **
404D 'C'
C GEOMETRY ( SECTION 3 ) ** ** **
C RADIAL INTERFACE ** **
501D 21
502D 0.336352, 0.475674, 0.582579, 0.672704, 0.752106, 0.823891
    1.000166, 1.149724, 1.323095, 1.476243, 1.614932, 1.742619
    1.982994, 2.197229, 2.413, 2.572724, 2.741251, 2.900000
    3.275, 3.342, 3.408
C RADIAL POINT 0 ** **
503D 0.
C AXIAL INTERFACE ** **
504D 45
505D -5.29, -5.21, -4.653, -4.603, -4.59, -3.59, -2.59, -1.59
    -1.2, -.8, -.4, 0.
    0.396500, 0.793000, 1.189500, 1.586000, 1.982500, 2.379000
    2.775500, 3.172000, 3.568500, 3.965000, 4.361500, 4.758000
    5.154500, 5.551000, 5.947500, 6.344000, 6.740500, 7.137001
    7.533500, 7.930000
    8.38, 8.83, 9.28, 9.73, 10.33
    10.93, 11.10, 11.28, 11.43, 12.28, 15.13, 15.19, 15.26
C BLOCKS ( SECTION 4 ) ** ** **
601D 20
C BLOCK 1 ** **
602D 1 'CENTRAL REFLECTOR'
603D 1 0, 6, 8, 36, 1
604D 1 4
605D 1 1
606D 1 7
C BLOCK 2 ** **
602D 2 'ACTIVE CORE'
603D 2 6, 12, 12, 32, 2
604D 2 5
605D 2 2
606D 2 6
607D 2 1
C BLOCK 3 ** **
602D 3 'INNER SIDE REFLECTORS'
603D 3 12, 15, 8, 36, 1
604D 3 4
605D 3 13
606D 3 7

```

607D 3 2
 C BLOCK 4 ** **
 602D 4 'PERMANENT SIDE REFLECTORS'
 603D 4 15, 18, 8, 36, 4
 604D 4 4
 605D 4 3
 606D 4 7
 607D 4 13
 C BLOCK 5 ** **
 602D 5 'TOP REFLECTOR'
 603D 5 6, 12, 9, 12, 3
 604D 5 13
 605D 5 2
 606D 5 5
 607D 5 1
 C BLOCK 6 ** **
 602D 6 'UPPER PLENUM ELEMENTS'
 603D 6 6, 12, 8, 9, 15
 604D 6 4
 605D 6 2
 606D 6 13
 607D 6 1
 C BLOCK 7 ** **
 602D 7 'UPPER BOTTOM REFLECTORS'
 603D 7 6, 12, 32, 34, 3
 604D 7 6
 605D 7 2
 606D 7 16
 607D 7 1
 C BLOCK 8 ** **
 602D 8 'LOWER BOTTOM REFLECTORS'
 603D 8 6, 12, 34, 36, 5
 604D 8 16
 605D 8 2
 606D 8 7
 607D 8 1
 C BLOCK 9 ** **
 602D 9 'CORE BARREL'
 603D 9 18, 19, 8, 43, 10
 604D 9 14
 /605D 9 114,9,10, 4,11,43
 605D 9, 14,9,10, 4,11,43
 905D 14, 16, .025
 606D 9 15
 607D 9 3,9,36, 11,37,38, 12,39,43
 C ** ** BLOCK 10 ** ** ** **
 602D 10 'VESSEL (SIDE)'
 603D 10 19, 21, 1, 45, 6
 604D 10 1
 605D 10 7,2,43, 8,44,45

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606D 10 12
607D 10 5,2,3, 6,44,45
C  ** ** BLOCK 11 ** ** ** ** ** ** ** ** ** ** 
602D 11 'VESSEL (TOP)'
603D 11 0, 19, 1, 3, 6
604D 11 1
605D 11 5
C  ** ** BLOCK 12 ** ** ** 
602D 12 'VESSEL (BOTTOM)'
603D 12 0, 19, 43, 45, 6
604D 12 11,1,18, 15,19,19
605D 12 6
606D 12 12
C  ** ** BLOCK 13 ** ** ** 
602D 13 'SHROUD (SIDE)'
603D 13 18, 19, 3, 8, 11
604D 13 18
/605D 13 116,4,7, 115, 8,8
605D 13 16,4,7, 15, 8,8
905D 16 17, .024
905D 15 17, .024
606D 13 14
607D 13 10,4,5, 9,6,8
C  ** ** BLOCK 14 ** ** ** 
602D 14 'SHROUD (TOP)'
603D 14 0, 18, 3, 5, 10
/604D 14 102,1,18
604D 14 2,1,18
904D 2 7, .037
605D 14 10
606D 14 3

C  ** ** BLOCK 15 ** ** ** 
602D 15 'UPPER CORE FLOOR'
603D 15 0, 18, 38, 40, 4
604D 15 8
605D 15 12
606D 15 17

C  ** ** BLOCK 16 ** ** ** 
602D 16 'LOWER CORE FLOOR'
603D 16 0, 18, 40, 41, 8
604D 16 17
605D 16 12
606D 16 9

C  ** ** BLOCK17 ** ** ** 
602D 17 'FLOOR SUPPORT 1'
603D 17 0, 18, 41, 42, 6
604D 17 9

```

```

605D 17 12
606D 17 10
C ** ** BLOCK18 ** ** ** ** ** ** ** ** ** ** ** ** 
602D 18 'FLOOR SUPPORT 2'
603D 18 0, 18, 42, 43, 6
604D 18 10
605D 18 12
606D 18 11
C ** ** BLOCK 19 ** ** ** 
602D 19 'UPPER PLENUM'
603D 19 0, 18, 5, 8, 101
651D 19 'CYLIN'
C ** ** BLOCK 20 ** ** ** 
602D 20 'LOWER PLENUM'
603D 20 0, 18, 36, 38, 102
651D 20 'CYLIN'
C RADIATION PLENA ( SECTION 5 ) ** ** ** 
701D 'NEWTON', 1.0E-04, 0.01, 20, 0.4, 0.0
C UPPER PLENUM CONVECTION HT CONTROL
C ( IF FLOXI IS SPECIFIED FALSE BELOW, THEN A VALUE OF TRUE GIVEN
C   HERE IS OVERRIDDEN, I.E. UPLCNV = .T. REQUIRES FLOXI = .T.)
702D .F., 1.
C ADDITIONAL RADIAL GAPS
801D 5
802D 1 17, 2, 9,36
802D 2 18, 4, 9,36
802D 3 19, 8, 9,36
802D 4 20, 10, 9,36
802D 5 21, 14, 9,36
C ADDITIONAL AXIAL GAPS
803D 8
804D 1 19, 12, 1,6
804D 2 20, 12, 13,15
804D 3 21, 32, 1,6
804D 4 22, 32, 13,15
804D 5 23, 16, 1,15
804D 6 24, 20, 1,15
804D 7 25, 24, 1,15
804D 8 26, 28, 1,15
C BOUNDARIES/GAPS ( SECTION 6 ) ** ** ** 
C ** ** RADIAL ** ** ** 
901D 1,3,102,.001,.82,0.
901D 2,3,102,.001,.82,0.
901D 3,3,102,.001,.82,0.
901D 4,3,106,.295,.485,0.
901D 5,1,0,0.,0.,0.
901D 6,1,0,0.,0.,0.
901D 7,32,0,0.,0.,0.
901D 8,13,0,0.,0.,0.
901D 9,21,0,0.,0.,0.

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901D 10,1,0,0.,0.,0.
901D 11,21,0,0.,0.,0.
901D 12,1,0,0.,0.,0.
901D 13,3,102,.001,.82,0.
901D 14,3,106,.270,.68,0.
901D 15,3,106,.271,.68,0.
901D 16,3,106,.271,.68,0.
901D 17,3,102,.001,.82,0.
901D 18,3,102,.001,.82,0.
901D 19,3,102,.001,.82,0.
901D 20,3,102,.001,.82,0.
901D 21,3,102,.001,.82,0.
C   ** ** AXIAL ** ** **
902D 1,12,0,0.,0.,0.
902D 2,3,107,.477,.68,0.
902D 3,21,0,0.,0.,0.
902D 4,21,0,0.,0.,0.
902D 5,3,102,.0005,.82,0.
902D 6,3,102,.0005,.82,0.
902D 7,21,0,0.,0.,0.
902D 8,21,0,0.,0.,0.
902D 9,1,0,0.,0.,0.
902D 10,3,102,.7,.68,0.
902D 11,3,102,2,.68,0.
902D 12,13,0,0.,0.,0.
902D 13,3,102,.0005,.82,0.
902D 14,1,0,0.,0.,0.
902D 15,3,102,2,.68,0.
902D 16,3,102,.0005,.82,0.
902D 17,1,0,0.,0.,0.
902D 18,5,0,0.,0.,0.
902D 19,3,102,.0005,.82,0.
902D 20,3,102,.0005,.82,0.
902D 21,3,102,.0005,.82,0.
902D 22,3,102,.0005,.82,0.
902D 23,3,102,.0005,.82,0.
902D 24,3,102,.0005,.82,0.
902D 25,3,102,.0005,.82,0.
902D 26,3,102,.0005,.82,0.
C   IRRADIATION AND ANNEALING DATA
C   IF FIRST PARAMETER ( IRRADN IS FALSE, THEN THIS SECTION IS BYPASSED )
1001D .T.
1002D .T.
1003D 3
C   ASSUMED BASE CASE IRRADIATION DAMAGE
1004D 3,15, 12,33
1005D 12 0.0,4R, 1.0,6R, 0.0,3R/
1005D 13 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 14 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 15 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R

```

```

1005D 16 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 17 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 18 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 19 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 20 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 21 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 22 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 23 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 24 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 25 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 26 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 27 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 28 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 29 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 30 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 31 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 32 0.6,2R, 0.95,2R, 1.0,6R, .95, 0.6,2R
1005D 33 0.0,4R, 0.82,6R, 0.0,3R/
1006D 1000., 1300.
C
C ** ** AFTERHEAT DATA (SECTION 7 ) ** ** ** ** ** ** ** ** ** ** ** ** ** ** 
C INITIAL POWER ** ** ** 
1101D 350.E6, 0., 1.4, 1., 2
C AFTERHEAT REGION ** ** ** 
1102D 7,12, 13,32
C REFLECTOR REGION ** ** ** 
1103D 1, 15, 10, 34
C ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** 
C BASE RADIAL POWER PROFILE ( IHI - (ILO-1) ENTRIES )
1104D 1.0,6R/
C POINT KINETICS RADIAL POWER PROFILE ( IHI - (ILO-1) ENTRIES )
1105D 0.7121,2R, 1.053,2R, 1.163,2R/
C BASE AXIAL POWER PROFILE ( JHI - (JLO-1) ENTRIES )
1106D 1.36,10R, 0.77,6R, 0.445,4R/
C POINT KINETICS AXIAL POWER PROFILE ( IHI - (ILO-1) ENTRIES )
1107D 1.36,10R, 0.77,6R, 0.445,4R/
C ** AFTER HEAT OPTIONS
1108D 'NOML'
C ** ** TIME CONTROL ( SECTION 8A ) ** ** ** 
C START TIME (HR) ** ** ** 
1201D 0.
C TIME PERIODS ** ** ** 
1202D 8
C NORMAL TIME STEPS FOR DEPRESSURIZED TRANSIENTS
1203D 0,240.,15.,240.,240.
      1,10.,1.,10.,6.
      1,60.,5.,50.,25.
      2, 5.,.25,4.,1.
      2, 20., .5,15.,1.
      2,100., 1.,20.,1.

```



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      2,120., 1.,20.,1.
      2,200., .5,20.,1.
C  OUTPUT FORMATS ( SECTION 8B ) ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** 
1301D 4,0, 8,1
C  BLOCK SURFACES OUTPUT ( SECTION 8C ) ** ** ** ** 
1401D 2
1402D 10,2, 10,4
C  DEBUG ( SECTION 8D ) ** ** ** 
C  DEBUG CONTROL VARIABLE
1403D 0
C  DEBUG SET DATA ( BYPASS AT THIS TIME, SETTING NO OF SETS = 0
/ 0
C  ** ** INITIAL TEMPERATURES ( SECTION 9 ) ** ** ** 
1501D 'READRUN '
C  'OTHER'
1502D 100.0,21R
1503D 100.0,35R, 80.0,9R
1504D 100.0,21R
C  BLOCK TEMPERATURES ** ** ** 
1505D B1;24*258.
      B1;6*269.
      B1;6*290.
      B1;6*312.
      B1;6*333.
      B1;6*355.
      B1;6*376.
      B1;6*397.
      B1;6*419.
      B1;6*440.
      B1;6*462.
      B1;6*483.
      B1;6*505.
      B1;6*526.
      B1;6*548.
      B1;6*569.
      B1;6*590.
      B1;6*612.
      B1;6*633.
      B1;6*655.
      B1;6*676.
      B1;24*687.
      B2;6*269.
      B2;6*290.
      B2;6*312.
      B2;6*333.
      B2;6*355.
      B2;6*376.
      B2;6*397.
      B2;6*419.
      B2;6*440.

```

B2;6*462.
 B2;6*483.
 B2;6*505.
 B2;6*526.
 B2;6*548.
 B2;6*569.
 B2;6*590.
 B2;6*612.
 B2;6*633.
 B2;6*655.
 B2;6*676.
 B3;24*258.,120*400.,24*470.
 B4*258.
 B5*687.
 B6*258.
 B7*219.
 B8*219.
 B9*219.
 B10*258.
 B11*258.
 B12*500.
 B13*400.
 B14*258.

1000*777. /

C

C WATER COOLED RCCS INPUT DATA

C NFIRST, NLAST

7001D 1 43

C NLOOP

7002D 1

7003D 0.2 0.2

7004D 60.77 60.77 39.47 13.56

7005D 120 21.3 4.113E-2 1.6E-2 1.005E-4 1.5E-4

7006D 3000 15 3.658 0.01 1.E-3 0.06 37.16 32. 5.625

7007D 0 .015 .002 5.E-4 5.E-4 1. .824

7008D 0 0 0. 0. 0.2 0.2

7009D 3.E-4 7.767

7010D 1.E5 1.E5

7011D 311.3 1.E5

7012D 40. 20. 1. 20. -10.

7013D 21.3 21.3

7014D 0.8 0.8

7015D 0.7E6

7016D 1.E-6 1.E-6 40 0.15 1.E-4

C END OF MODULAR HTGR AIR INGRESS CASE INPUT DATA

STOP

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11. ABSTRACT <i>(200 words or less)</i> <p style="margin-left: 40px;">This report documents the THATCH code, which models thermal and flow networks of solids and coolant channels in two-dimensional geometries.</p> <p style="margin-left: 40px;">The main application of THATCH is for reactor thermo-hydraulic transients in High-Temperature Gas-Cooled Reactors (HTGRs). The code simulates core heatup transients, heat transfer to general sinks or to specific air or water-cooled reactor cavity cooling systems. Graphite oxidation during air or water ingress can be modelled, including the chemical energy release. A point kinetics model is available for reactivity excursions. For most slow HTGR transients a user-selected nodalization of the core in r-z geometry is used. A separate model of heat transfer in the symmetry element of each fuel element is available for rapid transients.</p> <p style="margin-left: 40px;">The report describes the mathematical models and the method of solution. It describes the code structure and its various procedures. Details of the input data and file usage, is given for the code and for the preprocessing and postprocessing options. The THATCH model of the current 350 MW_{th} reactor is described. Input data for four sample cases are given, with output available in fiche form. Installation requirements, code limitations, and some common error indications are listed.</p>						
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