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SASIA, A COMPUTER CODE FOR THE ANALYSIS
OF FAST-REACTOR POWER AND FLOW TRANSIENTS

by

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ABSTRACT

The SAS1A computer code is a comprehensive code designed for analyzing both flow and power transients for the large LMFBR cores. This report describes the models, numerical methods, and programming details used in its development as well as the input-output, including a sample problem. Accordingly, the report should meet the needs of both casual users and those more ambitious who desire to make programming changes. Since SAS1A is intended to be a complete accident package, the analysis can be carried from a normal operating state of the reactor up to and through thresholds for ineversible fuel and/or cladding damage, finally terminating in core disassembly (if prior calculated events so dictate). SAS1A is the first in a planned series of SAS codes which are currently under development. These codes are aimed toward more realistic computer simulation of LMFBR dynamics via more accurate models and, also, development of models for processes which are not treated in SAS1A. The code is available in CDC-3600 and IBM-360 (75) versions from the Argonne Code Center.

I. INTRODUCTION

In the last five or six years a great deal of analytic effort has been devoted to the study of safety problems for the large LMFBR cores. Only in the past several years, however, with the increases in digital-computer speed and capacity, has it been practical to consider performing a complete calculation of the dynamic behavior of a reactor core (including heat transfer and a fairly detailed description of feedback mechanisms) in a single, integrated computer calculation. The SAS1A computer code, described in this report, is the result of such efforts in conjunction with the development of analytical techniques and models to be used in evaluating the importance of design parameters which have a bearing on the safety of large LMFBRs. Accordingly, the code represents a major step within the

safety program at Argonne toward the development of a new generation of computer codes directed toward more accurate and credible computation of fast breeder reactor accident histories.

One objective in developing this code was to provide a flexible analytic tool which could be used in fast reactor safety analyses and updated easily as new information became available from experiments (which presumably would allow improvements in the various computational models). Furthermore, it was desired to keep the code simple enough so that the computer running time would not exceed 5 min or so for running a complete problem on the IBM-360, Model 75 computer, a representative current computer. The code is written entirely in Fortran IV, and it is presently available through the Argonne Code Center in both CDC-6600 and IBM-360 (Model 75) versions.

Because of the desire to allow ready incorporation of improvements in calculational models and, also, because a number of different groups and individuals were involved in developing various segments of the calculation, a modular structure similar to that employed in the ARC system¹ was employed in setting up the code. In this arrangement a main program calls four driver programs. These drivers handle the areas of 1) input-output, with diagnostics, 2) steady-state initialization, to define the core operating conditions before the initiation of the transient, 3) the transient portion (the largest part of the code), and 4) the disassembly (weak explosion) analysis. In total 26 subprograms are used.

The code in its present form proceeds from steady-state preaccident conditions through the calculation of the consequences of a disassembly which might result from computed initial accident events. It initializes the thermohydraulic conditions of the core, via a steady-state initialization search, to the users' specifications and thus defines the preaccident steady operating state of the system (normally the reactor steady-state design power). A calculation is then commenced of the transient history of the reactor response to power/flow perturbations resulting from either a reactivity insertion (or a specified power increase) and/or a specified reduction of coolant flow. Throughout this portion of the calculation a basic assumption in the computer model is that the reactor core geometry remains intact, that is, coolant channels are still well-defined and there has been no melting of clad or slumping of fuel (even though a significant portion of the fuel may be molten at the center of a fuel pin). Some important features of this portion of the calculation are:

1. The two-phase flow and vapor (void) fraction during coolant boiling is calculated explicitly, and the reactivity feedback due to boiling is then obtained from the detailed void-fraction profile. Corresponding changes in the Doppler coefficient are also computed.

2. Mechanical deformations of the fuel and cladding are calculated in the elastic and plastic regions, giving an estimate of the cladding failure point.

3. Axial expansion of the fuel and radial expansion of the core, along with the corresponding reactivity effects, are computed.

If the transient calculations lead to situations wherein an explosion or disassembly of the reactor core is imminent as a result of the reactivity approaching prompt critical with concomitant high fuel temperatures and pressures, then the history of the disassembly of the core is calculated along with an estimate of the total energy yield during this phase of the accident. Thus, besides the advantage of convenience to the user in performing all of the calculations in an integrated manner, severe accidents computed with SAS1A for the "design basis accident" portion of safety evaluation studies will use initial conditions for the disassembly calculation which are computed as a direct consequence of the previous history of the accident. Therefore, they need no longer be hypothetical and exceptionally pessimistic, as is often the case at present.

Section II of this report describes the models and presents the basic equations and their finite difference representations which are used for the various computations in the code. An attempt is made in this section to acquaint the user with the basic ideas and assumptions underlying the calculations without burdening him unduly with the details of programming and code structure at this point. Section III gives some details of programming and describes the overall code structure and logic by means of which the various drivers and subroutines are linked together through the main program. Although the basic functions of the subprograms as well as a summary description of their structures are given in this section, the actual programming details are described in the Appendices. In Sect. IV detailed descriptions of the input format for the code and plot package as well as options available to the user are presented. Finally, the practical use of the code in performing calculations is illustrated in Sect. V by presenting and describing the output, both printed and plotted, from a sample problem.

The development of the SAS series of safety-analysis codes is a continuing effort in which the completion of SAS1A, described herein, represents a major milestone. Improved versions are being completed and will be available during the next year. For example, SAS2A, which is due to be released next, includes a multichannel core description, thus permitting a more realistic calculation of behavior across the core radius than is possible with the single-channel model in SAS1A. Also, it will have the option of using either the VENUS¹⁸ or the MARS code for the weak-explosion part of the calculation. VENUS is much more sophisticated than MARS¹⁴ and allows the use of an equation of state for the expanding core which recognizes the presence of sodium in the core during disassembly.

Other features and improvements which are planned for future SAS versions are:

1. A model of fuel-coolant interaction which will calculate pressures and voiding rates, etc., in the event that molten UO_2 should come in contact with sodium coolant.
2. A complete primary-coolant-loop model which includes all elements of the loop rather than just the reactor core as in SAS1A.
3. An improved voiding (boiling) analysis which comprises an improved two-phase flow model and a slug-expulsion model. The new two-phase model will allow the local saturation temperature to change with pressure during boiling rather than being held constant as in SAS1A. The new slug-expulsion model includes a pressure balance coupled with a heat balance to obtain a vapor production rate, rather than just considering a pressure balance as with the current slug model in SAS1A.
4. A model of fission-product (FP) gas voiding which will handle those cases where clad rupture and release of FP gas occurs before or concurrently with coolant boiling.
5. A more sophisticated model of fuel deformation which accounts for restructuring in irradiated oxide fuel. Fission-gas release due to heating of the fuel during a transient will also be accounted for. Three radial zones with different fuel structure (and, hence, physical properties) will be allowed within a fuel pin. The model will predict the time and position of clad rupture, in addition to the states of the fuel versus time.

Throughout the development of new models, a paramount objective is to test SAS against experimental results in order to achieve a maximum basis for the credibility of the analysis.

II. PHYSICAL MODELS AND BASIC EQUATIONS

The basic calculational model used in SAS1A is designed to treat the configurations most commonly found in the current, large LMFBR re-

Fig. 1. Single Fuel Pin, Coolant Channel, and Structure

actor designs. This includes reactor cores ranging from extreme pancake designs to those with length-to-diameter ratios closer to one and which have axial and radial breeding blankets. In addition, an unheated segment of core can be included above the upper axial blanket; the purpose of this is to attempt to simulate the hydrodynamic properties of the coolant channel when there are fission gas reservoirs, or other structural material, at the upper ends of the fuel pins. The analysis is predicated on the assumption that the behavior of the entire core (prior to the disassembly phase) can be represented by a single fuel pin and its associated coolant (see Fig. 1). This is the basic approach which has been used; however, the non-coherence of coolant boiling across the core radius has been accounted for in an approximate way which is described later. Because of the modular form in which SAS1A has been created, the intended upgrading of the code to include an option for explicit computation of several channels can be provided with a minimal programming effort.

The types of situations for which the analysis is designed are the following:

1. Whole-core power perturbations which result from reactivity insertions due to control-system malfunction or other source, and
2. Gross failure of coolant flow due to pump or piping-system failures. Typically these accident-initiating events are assumed to occur relatively slowly, that is, the power transients usually result from rates of reactivity insertion up to several dollars per second. Similarly, for cases of coolant flow coastdown it is usually assumed that the rates are such that 50% flow is achieved in times of several seconds or longer (a reasonable assumption for large LMFBR coolant loops). Moreover, as stated, the calculational model is based on the assumption that the core fuel elements and coolant channels are essentially intact throughout the calculation (until the disassembly calculation is started) even though the center

portion of the fuel pin may have a considerable fraction of molten fuel. At the present time, there is no provision for treating any effects due to fuel-coolant interaction when the cladding has failed and allowed molten fuel to contact the coolant. Sudden blockages of flow or partial blockage of the core (single-subassembly accident) can be simulated by holding the power constant during the flow reduction. However, it is not possible to represent radial interaction or propagation of disturbances across the reactor core. Reactor dynamic behavior is calculated using a point kinetics model.

Some of the salient features of the SAS1A code are as follows:

1. Sodium voiding is calculated explicitly within the code when the coolant temperature exceeds the saturation temperature. A corresponding feedback reactivity due to sodium voiding is computed using tabular input values of sodium-density reactivity as a function of axial core position.
2. The fuel-heat-transfer model can treat fuel pins which have a central void; in addition, it incorporates a reasonably rigorous treatment of nonlinearities introduced when thermal conductivity varies strongly with temperature.
3. A fuel-deformation module computes the stresses and deformations occurring during transients, and treats both elastic and plastic deformation of the cladding.
4. The moment of possible fuel-cladding rupture can be badly miscalculated if the possibility of relief of the internal pressures (calculated by the fuel-deformation module) due to the displacement of highly molten UO_2 is not taken into account. The fuel dynamics model attempts to do this and, since cladding rupture could lead to fuel-coolant interaction and very rapid sodium expulsion and reactivity change, this could supply important input to the future fuel-coolant interaction module.
5. The reactivity feedbacks due to Doppler effect, and axial and radial core expansions are computed. There is also an input option for adding the reactivity change due to control-rod scram.
6. A two-dimensional (r,z) weak-explosion routine is included as an integral part of the code and is called to calculate the energy release in a disassembly when certain criteria (specified as input by the user) are met.

Thus, in developing the code an attempt has been made to include all of the important phenomena (with the exception of the fuel-coolant interaction and fission gas release) which would be likely to occur in a transient of the type specified above.

As stated earlier, a modular approach was followed in the development of the SAS1A computer code. In this context a module is defined as all of the calculations pertaining to a specific model, such as heat-transfer coolant dynamics. This was done because it is a logical and convenient way of breaking down the calculations so that the various portions of the code could be developed more or less independently by the persons working in these different areas. In actual operation the code is made up into a series of subroutines (described in Sect. III) which do not have a one-to-one correspondence to the modules as defined here. Specifically, the subroutine structure is set up along functional lines and for convenience in manipulations within the code. Typically, the calculations which fall within one module are carried out by a group of subroutines (e.g., heat transfer comprises the steady-state and transient subroutines, each of which is under control of a separate driver routine), explained in more detail in Sect. III.

The following material in this section describes the basic models and differential equations used in the code. The discussion is organized along the modular lines.

A. Fuel Heat Transfer Module

Since axial and angular conduction of heat are relatively unimportant for the class of problems under consideration with SAS1A, a one-dimensional (radial, r) heat-flow model is employed. The channel is divided into axial segments (up to 200 in the coolant), and the temperature calculations are made for each of the sections in succession following the direction of coolant flow. Since successive sections are thermally coupled through the coolant, the Storrer effect of heat transfer from downstream coolant to the fuel in the axial blanket is automatically included. Calculations made thus far show that the neglect of axial conduction is quite reasonable. The advantage gained thereby, namely, of not having to solve the heat-flow equations in a two-dimensional space, represents a large saving in computing time.

The model used here is similar to those usually employed in reactor fuel-temperature calculations (e.g., Refs. 2 and 3). The numerical methods previously employed, however, have the following limitations:

1. Time increments must be kept small to assure numerical stability, because the differencing schemes are explicit.
2. Temperatures are computed neglecting thermal expansions of the fuel. The method of analysis developed for SAS1A tries to eliminate these disadvantages. The transient heat-conduction equations are discretized in space, r , and time, t , by means of an extrapolated Crank-Nicolson scheme.⁴ This scheme was chosen because it is numerically stable for reasonably large increments of time, and also because it is

efficient in handling the nonlinearities in the diffusion equation resulting from the wide variation of fuel thermal conductivity with temperature. In addition to the use of the new differencing scheme, the numerical model also takes the following into account:

1. dimensional changes due to thermal expansion and phase change (fuel melting);
2. latent heat absorption due to the phase change;
3. variable bond-gap size and the associated variable thermal resistance at the fuel-clad interface;
4. the desirability of being able to use widely varying time increments for different portions of a transient;
5. temperature dependence of fuel thermal conductivity, $k_f(T)$, and heat capacities, $C_f(T)$.

1. Initial Conditions

In all the calculations described here, it is assumed that a transient commences from some known steady state. The steady-state fuel and coolant temperatures are computed separately before starting the transient calculations. Given the dimensions, material composition, thermal properties of the materials, the steady volumetric rate of heat generation, coolant flow rate, and inlet coolant temperature of a fuel cell, the steady-state portion of the Heat Transfer Module computes the radial and axial temperature profiles, the unrestricted thermal expansion in the axial increments, and the average temperature and the volume fraction of the various materials in the different axial regions. The height of the interface between the various axial regions, the position of the liquid-solid interface in each axial increment, and the percentage of the total fuel melted are also calculated.

The axial coolant temperatures are first calculated explicitly from a knowledge of the fuel power density and coolant flow rate. A heat balance is then applied to the various radial increments. The resulting set of nonlinear algebraic equations for the fuel (steady-state forms of Eqs. A.2-A.9; see below in Sect. II.A.3) are solved simultaneously using a Gauss-Seidel iterative scheme. If the fuel-clad bond consists of a gas, the temperature drop in the bond is usually large and the drop is strongly dependent upon the gap size. Consequently, an iteration is necessary to make the radial temperature profile in an axial increment and the corresponding thermal expansion and bond-gap size compatible. Since axial conduction of heat is neglected, the axial increments are thermally coupled only via the coolant temperature. Therefore, a straightforward marching procedure (starting from the inlet segment) is used to determine the radial temperature profile in all the axial segments. This procedure is repeated on successive sweeps through the axial mesh until the desired compatibility

between the temperatures and thermal expansions (unrestrained) are achieved in accordance with a specified convergence criterion.

The steady-state conditions (power level and flow rate) may be input directly or, if desired, they can be calculated using the steady-state search option in the code. When using this option the user supplies constraints on fuel centerline temperature, coolant inlet and outlet temperatures, and core pressure drop. The code then maximizes fuel thermal rating within these limitations in setting up the steady-state conditions.

2. Variable Radial Space Mesh due to Fuel Expansion

In performing the steady-state calculations, Δr_{i+1} and Δr_i (in Eqs. A.2-A.9) are obtained from the knowledge of the temperatures T_{i+1}^k and T_i^k , respectively. In other words, the spatial dimensions at the end of the k th time increment are used for the computations in the $(k+1)$ st increment. A projection of the spatial increment lengths themselves to the middle of the time increment $k+1$ (as was done with temperatures) is found to be necessary in practice. The Δr_i 's are computed as follows:

$$\Delta r_i^k = \Delta r_i^0 [1 + \alpha_s (T_i^k - T_i^0)].$$

If T_i^k is at the melting point,

$$\Delta r_i^k = \Delta r_i^0 [1 + \alpha_s (T_{\text{melt}} - T_i^0)] [1 + \chi_i \alpha_{\text{melt}}].$$

If T_i^k is above the melting point,

$$\Delta r_i^k = \Delta r_i^0 [1 + \alpha_s (T_{\text{melt}} - T_i^0)] [1 + \alpha_{\text{melt}}] [1 + \alpha_l (T_i^k - T_{\text{melt}})],$$

where

α_s = linear coefficient of expansion of the solid;

α_{melt} = expansion due to melting;

α_l = coefficient of expansion of the liquid.

The above procedure is used only for the initial values of the Δr_i 's in the steady-state calculation. In the transient calculations the Δr_i 's are obtained from the calculations performed in the Fuel Deformation Module.

3. Transient Solution

Figure 1 shows the cross section of a typical fuel element under consideration. The bond may either be filled with a gas such as helium or

a liquid metal such as sodium. The time-dependent radial temperature profile is obtained by solving the diffusion equation in cylindrical geometry:

$$\frac{1}{r} \frac{\partial}{\partial r} \left[k_f(T_f) r \frac{\partial T_f}{\partial r} \right] + Q(t) = C_f \rho_f(T) \frac{\partial T_f}{\partial t}, \quad (\text{A.1})$$

where

T_f = fuel temperature;

C_f = fuel heat capacity;

ρ_f = fuel density;

k_f = fuel thermal conductivity;

$Q(t)$ = volumetric heat-generation rate.

Figure 2 shows the manner in which the radius of the fuel element is discretized for performing the numerical solution. The various discretized forms of Eq. A.1 obtained when one uses the extrapolated Crank-Nicolson differencing scheme are:

a. Inner Fuel Surface Temperature. Refer to Fig. 2 for the location of the various radii and temperatures. The approximation to Eq. A.1 is based on the heat balance

Heat stored = Heat in - Heat out + Heat generated,

which is written

$$C_p(T_1) \frac{\partial T_1}{\partial t} (r_2^2 - r_1^2) \pi H = k(\bar{T}_2) \frac{\partial T}{\partial r} \bigg|_{r=r_2} (2\pi r_2 H) + Q_1(r_2^2 - r_1^2) \pi H,$$

Fig. 2. Radial and Axial Nodes in Reactor Channel. ANL Neg. No. 900-174.

where

$\bar{T}$ = linear average temperature at the location shown;

H = axial height of fuel segment;

C , ρ , T , and Q have the same definitions as above, and the subscripts denoting fuel have been dropped for simplicity.

In addition,

$$T = \frac{T^k + T^{k+1}}{2},$$

$$\frac{\partial T}{\partial t} = \frac{T^{k+1} - T^k}{\Delta t},$$

and

$$\frac{\partial T}{\partial r} = \frac{\Delta T}{\Delta r},$$

where

the superscripts k denote time nodes;

the subscripts i denote radial space nodes.

Substitution of these expressions into the above equation gives

$$C\rho\left(T_1^{k+\frac{1}{2}}\right) \frac{T_1^{k+1} - T_1^k}{\Delta t} (r_2^2 - r_1^2) = \left(T_2^{k+1} + T_2^k - T_1^{k+1} - T_1^k\right) \frac{2k\left(\bar{T}_2^{k+\frac{1}{2}}\right)r_2}{r_2 + r_3 - 2r_1} + Q_1(r_2^2 - r_1^2),$$

where the time-dependent fuel properties $C\rho$ and k are evaluated by extrapolation to $k + \frac{1}{2}$ (the midpoint of the next time interval) and

$$\Delta r_{1,2} = \frac{1}{2}(r_2 + r_3 - 2r_1).$$

Rearranging the equation so that the $k+1$ superscripts appear on the left side, one obtains

$$\begin{aligned}
& T_1^{k+1} \left[\frac{C\rho(T_1^{k+\frac{1}{2}})}{2\Delta t} (r_2^2 - r_1^2) + \frac{k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_2 + r_3 - 2r_1} \right] + T_2^{k+1} \left[- \frac{k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_2 + r_3 - 2r_1} \right] = \\
& T_1^k \left[\frac{C\rho(T_1^{k+\frac{1}{2}})}{2\Delta t} (r_2^2 - r_1^2) - \frac{k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_2 + r_3 - 2r_1} \right] + T_2^k \left[\frac{k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_2 + r_3 - 2r_1} \right] \\
& + Q_1 \frac{r_2^2 - r_1^2}{2}. \tag{A.2}
\end{aligned}$$

b. Second Fuel Node. Based on Fig. 2, the heat balance for the second fuel temperature is

$$\begin{aligned}
C\rho(T_2) \frac{\partial T_2}{\partial t} (r_3^2 - r_2^2) \pi H = & -k(\bar{T}_2) \frac{\partial T}{\partial r} \bigg|_{r_2} (2\pi r_2 H) + k(\bar{T}_3) \frac{\partial T}{\partial r} \bigg|_{r_3} (2\pi r_3 H) \\
& + Q_2 \pi (r_3^2 - r_2^2) H.
\end{aligned}$$

Upon inserting the expressions for the derivatives this becomes

$$\begin{aligned}
C\rho(T_2^{k+\frac{1}{2}}) \frac{T_2^{k+1} - T_2^k}{\Delta t} (r_3^2 - r_2^2) = & (T_1^{k+1} + T_1^k - T_2^{k+1} - T_2^k) \frac{2k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_2 + r_3 - 2r_1} \\
& - (T_2^{k+1} + T_2^k - T_3^{k+1} - T_3^k) \frac{2k(\bar{T}_3^{k+\frac{1}{2}})r_3}{r_4 - r_2} \\
& + Q_2(r_3^2 - r_2^2),
\end{aligned}$$

where

$$\Delta r_{2,3} = \frac{1}{2}(r_4 - r_2).$$

This equation, as above, is rearranged to give

$$\begin{aligned}
& T_1^{k+1} \left[- \frac{k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_2 + r_3 - 2r_1} \right] + T_2^{k+1} \left[\frac{C\rho(T_2^{k+\frac{1}{2}})}{2\Delta t} (r_3^2 - r_2^2) + \frac{k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_2 + r_3 - 2r_1} + \frac{k(\bar{T}_3^{k+\frac{1}{2}})r_3}{r_4 - r_2} \right] \\
& + T_3^{k+1} \left[- \frac{k(\bar{T}_3^{k+\frac{1}{2}})r_3}{r_4 - r_2} \right] = T_1^k \left[\frac{k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_2 + r_3 - 2r_1} \right] + T_2^k \left[\frac{C\rho(T_2^{k+\frac{1}{2}})}{2\Delta t} (r_3^2 - r_2^2) \right. \\
& \left. - \frac{k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_2 + r_3 - 2r_1} - \frac{k(\bar{T}_3^{k+\frac{1}{2}})r_3}{r_4 - r_2} \right] + T_3^k \left[\frac{k(\bar{T}_3^{k+\frac{1}{2}})r_3}{r_4 - r_2} \right] + Q_2 \frac{r_3^2 - r_2^2}{2}. \tag{A.3}
\end{aligned}$$

c. Nodes 3 through NN-1. The heat balance for these nodes is (see Fig. 2)

$$C\rho(T_i) \frac{\partial T_i}{\partial t} (r_{i+1}^2 - r_i^2) \pi H = -k(\bar{T}_i) \frac{\partial T}{\partial r} \Big|_{r_i} (2\pi r_i H) \\ + k(\bar{T}_{i+1}) \frac{\partial T}{\partial r} \Big|_{r_{i+1}} (2\pi r_{i+1} H) + Q_i (r_{i+1}^2 - r_i^2) \pi H,$$

which, as above, is rearranged to give

$$T_{i-1}^{k+1} \left[-\frac{k(\bar{T}_i^{k+\frac{1}{2}}) r_i}{r_{i+1} - r_{i-1}} \right] + T_i^{k+1} \left[\frac{C\rho(T_i^{k+\frac{1}{2}})}{2\Delta t} (r_{i+1}^2 - r_i^2) + \frac{k(\bar{T}_i^{k+\frac{1}{2}}) r_i}{r_{i+1} - r_{i-1}} + \frac{k(\bar{T}_{i+1}^{k+\frac{1}{2}}) r_{i+1}}{r_{i+2} - r_i} \right] \\ + T_{i+1}^{k+1} \left[-\frac{k(\bar{T}_{i+1}^{k+\frac{1}{2}}) r_{i+1}}{r_{i+2} - r_i} \right] = T_{i-1}^k \left[\frac{k(\bar{T}_i^{k+\frac{1}{2}}) r_i}{r_{i+1} - r_{i-1}} \right] + T_i^k \left[\frac{C\rho(T_i^{k+\frac{1}{2}})}{2\Delta t} \right. \\ \left. - \frac{k(\bar{T}_i^{k+\frac{1}{2}}) r_i}{r_{i+1} - r_{i-1}} - \frac{k(\bar{T}_{i+1}^{k+\frac{1}{2}}) r_{i+1}}{r_{i+2} - r_i} \right] + T_{i+1}^k \left[\frac{k(\bar{T}_{i+1}^{k+\frac{1}{2}}) r_{i+1}}{r_{i+2} - r_i} \right] + Q_i \frac{r_{i+1}^2 - r_i^2}{2}, \quad (A.4)$$

where

$$\Delta r_{i,i+1} = \frac{1}{2}(r_{i+2} - r_i); \\ \Delta r_{i-1,i} = \frac{1}{2}(r_{i+1} - r_{i-1}).$$

d. Node NN. The heat balance for this node is

$$C\rho(T_{NN}) \frac{\partial T_{NN}}{\partial t} (r_{NT}^2 - r_{NN}^2) \pi H = -k(\bar{T}_{NN}) \frac{\partial T}{\partial r} \Big|_{r_{NN}} (2\pi r_{NN} H) \\ + k(\bar{T}_{NT}) \frac{\partial T}{\partial r} \Big|_{r_{NT}} (2\pi r_{NT} H) + Q_{NN} (r_{NT}^2 - r_{NN}^2) \pi H,$$

which, on inserting the expressions for the derivatives and rearranging, gives

$$\begin{aligned}
& T_{NN-1}^{k+1} \left[-\frac{k \left(\bar{T}_{NN}^{k+\frac{1}{2}} \right) r_{NN}}{r_{NT} - r_{NN-1}} \right] + T_{NN}^{k+1} \left[\frac{C\rho \left(\bar{T}_{NN}^{k+\frac{1}{2}} \right)}{2\Delta t} (r_{NT}^2 - r_{NN}^2) + \frac{k \left(\bar{T}_{NN}^{k+\frac{1}{2}} \right) r_{NN}}{r_{NT} - r_{NN-1}} \right. \\
& \quad \left. + \frac{k \left(\bar{T}_{NT}^{k+\frac{1}{2}} \right) r_{NT}}{2r_{NR} - r_{NT} - r_{NN}} \right] + T_{NT}^{k+1} \left[-\frac{k \left(\bar{T}_{NT}^{k+\frac{1}{2}} \right) r_{NT}}{2r_{NR} - r_{NT} - r_{NN}} \right] = T_{NN-1}^k \left[\frac{k \left(\bar{T}_{NN}^{k+\frac{1}{2}} \right) r_{NN}}{r_{NT} - r_{NN-1}} \right] \\
& \quad + T_{NN}^k \left[\frac{C\rho \left(\bar{T}_{NN}^{k+\frac{1}{2}} \right)}{2\Delta t} (r_{NT}^2 - r_{NN}^2) - \frac{k \left(\bar{T}_{NN}^{k+\frac{1}{2}} \right) r_{NN}}{r_{NT} - r_{NN-1}} - \frac{k \left(\bar{T}_{NT}^{k+\frac{1}{2}} \right) r_{NT}}{2r_{NR} - r_{NT} - r_{NN}} \right] \\
& \quad + T_{NT}^k \left[\frac{k \left(\bar{T}_{NT}^{k+\frac{1}{2}} \right) r_{NT}}{2r_{NR} - r_{NT} - r_{NN}} \right] + Q_{NN} \frac{r_{NT}^2 - r_{NN}^2}{2}, \tag{A.5}
\end{aligned}$$

where

$$\begin{aligned}
\Delta r_{NN-1} &= \frac{1}{2}(r_{NT} - r_{NN-1}); \\
\Delta r_{NN,NT} &= \frac{1}{2}(2r_{NR} - r_{NT} - r_{NN}).
\end{aligned}$$

e. Outer Fuel Surface Temperature (NT). The outer fuel surface temperature is derived from the following equation (see Fig. 2):

$$\begin{aligned}
C\rho(T_{NT}) \frac{\partial T_{NT}}{\partial t} (r_{NR}^2 - r_{NT}^2) \pi H &= -k(\bar{T}_{NT}) \frac{\partial T}{\partial r} \bigg|_{r_{NT}} (2\pi r_{NT} H) \\
&\quad - (T_{NE} - T_{NE''}) h_b (2\pi r_{NR} H) - \epsilon \sigma (T_{NT}^4 - T_{NE''}^4) (2\pi r_{NR} H) \\
&\quad + Q_{NT} (r_{NR}^2 - r_{NT}^2) \pi H,
\end{aligned}$$

where

$$h_b = \text{bond conductance} = h_{\text{cond}}/\tau^k \text{ (see Eq. A.14);}$$

$$\epsilon = \text{thermal emissivity;}$$

$$\sigma = \text{Stefan-Boltzmann Constant,}$$

which, on inserting the expressions for the derivatives and rearranging, gives

$$\begin{aligned}
& T_{NN}^{k+1} \left[- \frac{k \left(\bar{T}_{NT}^{k+\frac{1}{2}} \right) r_{NT}}{2r_{NR} - r_{NT} - r_{NN}} \right] + T_{NT}^{k+1} \left[\frac{C\rho \left(T_{NT}^{k+\frac{1}{2}} \right)}{2\Delta t} (r_{NR}^2 - r_{NT}^2) + \frac{k \left(\bar{T}_{NT}^{k+\frac{1}{2}} \right) r_{NT}}{2r_{NR} - r_{NT} - r_{NN}} \right. \\
& \left. + \frac{h_b r_{NR}}{2} \right] + T_{NE''}^{k+1} \left[- \frac{h_b r_{NR}}{2} \right] = T_{NN}^k \left[\frac{k \left(\bar{T}_{NT}^{k+\frac{1}{2}} \right) r_{NT}}{2r_{NR} - r_{NT} - r_{NN}} \right] \\
& + T_{NT}^k \left[\frac{C\rho \left(T_{NT}^{k+\frac{1}{2}} \right)}{2\Delta t} (r_{NR}^2 - r_{NT}^2) - \frac{k \left(\bar{T}_{NT}^{k+\frac{1}{2}} \right) r_{NT}}{2r_{NR} - r_{NT} - r_{NN}} - \frac{h_b r_{NR}}{2} \right] \\
& + T_{NE''}^k \left[\frac{h_b r_{NR}}{2} \right] - \epsilon \sigma r_{NR} \left[\left(T_{NT}^{k+\frac{1}{2}} \right)^4 - \left(T_{NE''}^{k+\frac{1}{2}} \right)^4 \right] + Q_{NT} \frac{r_{NR}^2 - r_{NT}^2}{2}.
\end{aligned} \tag{A.6}$$

f. Inner Surface Temperature of Cladding. The inner surface temperature of the cladding is derived as follows (see Fig. 2). Unlike the fuel, the cladding heat capacity and thermal conductivity are taken as constant. The heat balance is

$$\begin{aligned}
C\rho_c \frac{\partial T_{NE''}}{\partial t} (\bar{r}_{NE}^2 - r_{NE}^2) \pi H &= (T_{NT} - T_{NE''}) h_b (2\pi r_{NR} H) \\
&+ \epsilon \sigma (T_{NT}^4 - T_{NE''}^4) (2\pi r_{NR} H) \\
&+ k_c \frac{\partial T}{\partial r} \bigg|_{\bar{r}_{NE}} (2\pi \bar{r}_{NE} H),
\end{aligned}$$

which, on inserting the values for the derivatives, becomes

$$\begin{aligned}
C\rho_c \frac{T_{NE''}^{k+1} - T_{NE''}^k}{\Delta t} (\bar{r}_{NE}^2 - r_{NE}^2) &= (T_{NT}^{k+1} + T_{NT}^k - T_{NE''}^{k+1} - T_{NE''}^k) h_b r_{NR} \\
&+ 2r_{NR} \epsilon \sigma \left[\left(T_{NT}^{k+\frac{1}{2}} \right)^4 - \left(T_{NE''}^{k+\frac{1}{2}} \right)^4 \right] - (T_{NE''}^{k+1} + T_{NE''}^k - T_{NE''}^{k+1} - T_{NE''}^k) \\
&\cdot \frac{2k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}},
\end{aligned}$$

where

$$\Delta r = \frac{1}{2}(r_{NE'} - r_{NE});$$

$$\bar{r}_{NE} = r_{NE} + \frac{1}{4}(r_{NE'} - r_{NE}).$$

This equation is rearranged in the usual way to give

$$\begin{aligned} T_{NT}^{k+1} \left[-\frac{h_b r_{NR}}{2} \right] + T_{NE''}^{k+1} \left[\frac{C\rho_c}{2\Delta t} (r_{NE}^2 - r_{NE'}^2) + \frac{h_b r_{NR}}{2} + \frac{k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}} \right] \\ + T_{NE}^{k+1} \left[-\frac{k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}} \right] = T_{NT}^k \left[\frac{h_b r_{NR}}{2} \right] + T_{NE''}^k \left[\frac{C\rho_c}{2\Delta t} (\bar{r}_{NE}^2 - r_{NE}^2) \right. \\ \left. - \frac{h_b r_{NR}}{2} - \frac{k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}} \right] + T_{NE}^k \left[\frac{k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}} \right] + r_{NR} \epsilon_O \left[\left(T_{NT}^{k+\frac{1}{2}} \right)^4 - \left(T_{NE''}^{k+\frac{1}{2}} \right)^4 \right]. \end{aligned} \quad (A.7)$$

g. Cladding Central Node. The heat balance for the central clad node is

$$C\rho_c \frac{\partial T_{NE}}{\partial t} (\bar{r}_{NE'}^2 - \bar{r}_{NE}^2) \pi H = -k_c \left. \frac{\partial T}{\partial r} \right|_{\bar{r}_{NE}} (2\pi r_{NB} H) + k_c \left. \frac{\partial T}{\partial r} \right|_{\bar{r}_{NE'}} (2\pi \bar{r}_{NE'} H),$$

which, on inserting the expressions for the derivatives and rearranging, gives

$$\begin{aligned} T_{NE''}^{k+1} \left[-\frac{k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}} \right] + T_{NE}^{k+1} \left[\frac{C\rho_c}{2\Delta t} (\bar{r}_{NE'}^2 - \bar{r}_{NE}^2) + \frac{k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}} + \frac{k_c \bar{r}_{NE'}}{r_{NE'} - r_{NE}} \right] \\ + T_{NE'}^{k+1} \left[-\frac{k_c \bar{r}_{NE'}}{r_{NE'} - r_{NE}} \right] = T_{NE''}^k \left[\frac{k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}} \right] + T_{NE}^k \left[\frac{C\rho_c}{2\Delta t} (\bar{r}_{NE'}^2 - \bar{r}_{NE}^2) \right. \\ \left. - \frac{k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}} - \frac{k_c \bar{r}_{NE'}}{r_{NE'} - r_{NE}} \right] + T_{NE'}^k \left(\frac{k_c \bar{r}_{NE'}}{r_{NE'} - r_{NE}} \right), \end{aligned} \quad (A.8)$$

where

$$\bar{r}_{NE'} = r_{NE'} - \frac{1}{4}(r_{NE'} - r_{NE});$$

$$\Delta r = \frac{1}{2}(r_{NE'} - r_{NE}).$$

h. Cladding Outer Surface Temperature. The outer surface temperature of the cladding is derived from the following equation:

$$C\rho_c \frac{\partial T_{NE'}}{\partial t} (r_{NE'}^2 - r_{NE}^2) \pi H = -k_c \frac{\partial T}{\partial r} \bigg|_{\bar{r}_{NE'}} (2\pi \bar{r}_{NE'} H) \\ - (T_{NE'} - T_{NC}) h_c (2\pi r_{NE'} H),$$

where

h_c = coolant film heat-transfer coefficient.

On inserting the expressions for the derivatives and rearranging, we obtain

$$T_{NE}^{k+1} \left[-\frac{k_c \bar{r}_{NE'}}{r_{NE'} - r_{NE}} \right] + T_{NE'}^{k+1} \left[\frac{C\rho_c}{2\Delta t} (\bar{r}_{NE'}^2 - \bar{r}_{NE}^2) + \frac{k_c \bar{r}_{NE'}}{r_{NE'} - r_{NE}} + \frac{h_c r_{NE'}}{2} \right] = \\ T_{NE}^k \left[\frac{k_c r_{NE'}}{r_{NE'} - r_{NE}} \right] + T_{NE'}^k \left[\frac{C\rho_c}{2\Delta t} (\bar{r}_{NE'}^2 - \bar{r}_{NE}^2) - \frac{k_c \bar{r}_{NE'}}{r_{NE'} - r_{NE}} - \frac{h_c r_{NE'}}{2} \right] \\ + \left(T_{NE}^{k+1} + T_{NE}^k \right) \frac{h_c r_{NE'}}{2}. \quad (A.9)$$

Equations A.2-A.9 are then recast using the following definitions:

$$\alpha_i = \frac{2\Delta t(r_{i+1}^2 - r_i^2)}{C\rho(T_i^{k+\frac{1}{2}})} \quad \text{for } i = 1 \text{ to } NT; \\ \alpha_{NEPP} = \frac{2\Delta t(\bar{r}_{NE}^2 - r_{NE}^2)}{C\rho_c}, \quad \text{where } NEPP = NE''; \\ \alpha_{NE} = \frac{2\Delta t(\bar{r}_{NE'}^2 - \bar{r}_{NE}^2)}{C\rho_c}; \\ \alpha_{NEP} = \frac{2\Delta t(\bar{r}_{NE'}^2 - \bar{r}_{NE'}^2)}{C\rho_c}, \quad \text{where } NEP = NE'; \\ \beta_2 = \frac{k(\bar{T}_2^{k+\frac{1}{2}})r_2}{r_3 + r_2 - 2r_1};$$

$$\beta_i = \frac{k \left(\bar{T}_i^{k+\frac{1}{2}} \right) r_i}{r_{i+1} - r_{i-1}} \quad \text{for } i = 3 \text{ to } NN = NT-1;$$

$$\beta_{NT} = \frac{k \left(\bar{T}_{NT}^{k+\frac{1}{2}} \right) r_{NT}}{2r_{NR} - r_{NT} - r_{NN}};$$

$$\beta_{NEPP} = \frac{r_{NR} h_b}{2};$$

$$\beta_{NE} = \frac{k_c \bar{r}_{NE}}{r_{NE'} - r_{NE}};$$

$$\beta_{NEP} = \frac{k_c \bar{r}_{NE'}}{r_{NE'} - r_{NE}};$$

$$\beta_{NC} = \frac{r_{NE'} h_c}{2}.$$

Equation A.2 becomes

$$T_1^{k+1} \left[\frac{1}{\alpha_1} + \beta_2 \right] + T_2^{k+1} [-\beta_2] = T_1^k \left[\frac{1}{\alpha_1} - \beta_2 \right] + T_2^k [\beta_2] + Q_1. \quad (\text{A.2}')$$

Equations A.3-A.8 are written as

$$\begin{aligned} T_{i-1}^{k+1} [-\beta_i] + T_i^{k+1} \left[\frac{1}{\alpha_i} + \beta_i + \beta_{i+1} \right] + T_{i+1}^{k+1} [-\beta_{i+1}] &= T_{i-1}^k [\beta_i] + T_i^k \left[\frac{1}{\alpha_i} - \beta_i - \beta_{i+1} \right] \\ &+ T_{i+1}^k [\beta_{i+1}] + \psi_i \quad \text{for } i = 2 \text{ to } NE, \end{aligned} \quad (\text{A.3}'-\text{A.8}')$$

and Eq. A.9 becomes

$$\begin{aligned} T_{NE}^{k+1} [-\beta_{NEP}] + T_{NE'}^{k+1} \left[\frac{1}{\alpha_{NEP}} + \beta_{NEP} + \beta_{NC} \right] &= T_{NE}^k [\beta_{NEP}] \\ &+ T_{NE'}^k \left[\frac{1}{\alpha_{NEP}} - \beta_{NEP} - \beta_{NC} \right] + \left[T_{NC}^{k+1} + T_{NC}^k \right] \beta_{NC} + \psi_{NE'}, \end{aligned} \quad (\text{A.9}')$$

where

$$\psi_i = Q_i \frac{r_{i+1}^2 - r_i^2}{2} \quad \text{for } i = 1 \text{ to } NN;$$

$$\psi_{NT} = Q_{NT} \frac{r_{NR}^2 - r_{NT}^2}{2} - \epsilon \sigma \left[\left(T_{NT}^{k+\frac{1}{2}} \right)^4 - \left(T_{NE''}^{k+\frac{1}{2}} \right)^4 \right];$$

$$\psi_{NE''} = \epsilon \sigma r_{NR} \left[\left(T_{NT}^{k+\frac{1}{2}} \right)^4 - \left(T_{NE'}^{k+\frac{1}{2}} \right)^4 \right];$$

$$\psi_{NE} = \psi_{NE'} = 0.$$

The system of Eqs. A.2'-A.9' can be written in matrix form, yielding a tridiagonal matrix:

$$\begin{bmatrix} \frac{1}{\alpha_1} + \beta_2 & -\beta_3 & 0 & 0 & \dots \\ -\beta_2 & \frac{1}{\alpha_2} + \beta_2 + \beta_3 & -\beta_3 & 0 & \dots \\ 0 & -\beta_3 & \frac{1}{\alpha_3} + \beta_3 + \beta_4 & -\beta_4 & \dots \\ \dots & 0 & -\beta_{NE} & \frac{1}{\alpha_{NE}} + \beta_{NE} + \beta_{NEP} & -\beta_{NEP} \\ \dots & 0 & 0 & -\beta_{NEP} & \frac{1}{\alpha_{NEP}} + \beta_{NEP} + \beta_{NC} \end{bmatrix} \begin{bmatrix} T_1^{k+1} \\ T_2^{k+1} \\ T_3^{k+1} \\ \vdots \\ T_{NE}^{k+1} \\ T_{NE'}^{k+1} \end{bmatrix} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ \vdots \\ d_{NE} \\ d_{NE'} \end{bmatrix}, \quad (\text{A.10})$$

where

$$d_1 = T_1^k \left[\frac{1}{\alpha_1} - \beta_2 \right] + T_2^k [\beta_2] + Q_1;$$

$$d_i = T_{i-1}^k [\beta_i] + T_i^k \left[\frac{1}{\alpha_i} - \beta_i - \beta_{i+1} \right] + T_{i+1}^k [\beta_{i+1}] + \psi_i \quad \text{for } i = 2, NE;$$

$$\begin{aligned} d_{NE'} &= T_{NE}^k [\beta_{NEP}] + T_{NE'}^k \left[\frac{1}{\alpha_{NEP}} - \beta_{NEP} - \beta_{NC} \right] \\ &\quad + \beta_{NC} \left[T_{NC}^{k+1} + T_{NC}^k \right] + \psi_{NE'}. \end{aligned}$$

If there are NE' radial nodes, Eq. A.10 represents NE' coupled algebraic equations that have to be solved simultaneously to obtain T_i^{k+1} for all i at each axial node. The differencing scheme, therefore, is implicit, and since k_f and $C_f \rho_f$ are functions of temperature, the equation is nonlinear. Consequently, an exact solution of the coupled finite-difference equations is not easily possible.

The following method⁴ is very effective for treatment of the nonlinearity. Temperatures at the middle of the $(k+1)$ st time interval which are needed to evaluate k_f and $C_f \rho_f$ are obtained by a linear extrapolation of the temperature T_i^k and T_i^{k-1} , that is,

$$T_i^{k+\frac{1}{2}} = T_i^k + \frac{T_i^k - T_i^{k-1}}{2\Delta t^k} \Delta t^{k+1}, \quad (\text{A.11})$$

where, in general, $\Delta t^k \neq \Delta t^{k+1}$. By means of values thus obtained for the $T_i^{k+\frac{1}{2}}$ ($i = 1, \text{NE}$), the values of $C_f \rho_f$ and k_f are computed and used to calculate the matrix elements. This reduces Eq. A.10 to a set of linear algebraic equations in the T_i^{k+1} 's, which can be solved directly by the Gauss elimination procedure. The matrix coefficients are reevaluated and the matrix equation is solved again for the next time step. The effectiveness of this approach results from the smooth variation of the temperature with respect to time.

In the actual programming of the solution described in Appendix A, the following further combination of coefficients is made. Define

$$A_1 = \frac{1}{\alpha_1} + \beta_2;$$

$$A_i = \frac{1}{\alpha_i} + \beta_i + \beta_{i+1} - \frac{\beta_i^2}{A_{i-1}} \quad \text{for } i = 2 \text{ to NEP};$$

$$S_1 = d_1;$$

$$S_i = d_i + \frac{\beta_i S_{i-1}}{A_{i-1}} \quad \text{for } i = 2 \text{ to NEP}.$$

Then

$$T_i^{k+1} = \frac{S_i + \beta_{i+1} T_{i+1}^k}{A_i} \quad \begin{array}{l} \text{for } i = 1 \text{ to NEP} \\ \text{(in reverse order).} \end{array}$$

In the calculations, $\Delta r_i = r_i - r_{i-1}$ is set up for equal-volume nodes in the fuel.

4. Fraction of Fuel Melted

The fraction of fuel melted at the i th node, χ_i , is computed as follows. Temperatures are first calculated neglecting any melting during the time increment, and an apparent temperature rise, $(\Delta T_i)_{app}$, above the melting temperature, T_{melt} , is obtained. The fraction of fuel melted is then given by

$$\chi_i = C_f(\Delta T_i)_{app}/L, \quad (A.12)$$

where

L = heat of fusion of fuel.

However, when $C_f(\Delta T_i)_{app} > L$, then

$$\chi_i = 1,$$

and the rise in temperature, $(\Delta T_i)_\ell$, in the all-liquid phase above the melting point is computed using the equation

$$(\Delta T_i)_\ell = \frac{C_f(\Delta T_i)_{app} - L}{C_f}. \quad (A.13)$$

The procedure is reversed during a cooling process.

5. Bond-gap and Cladding Equations

When the bond consists of a gas, there is usually a large drop in temperature through the bond, and this sharp gradient of temperature may introduce numerical instabilities. A method suggested by Back⁵ for treating the boundary between the fuel and clad was found quite adequate for such a situation. The heat flux through the bond is assumed to consist of a conductive and a radiative component. The conductive component, which is usually much larger, is expressed implicitly as

$$\phi_c = \frac{h_{cond}}{\tau^k} \left[\frac{T_{NT}^{k+1} + T_{NT}^k - T_{NE}^{k+1} + T_{NE}^k}{2} \right], \quad (A.14)$$

where

ϕ_c = conductive heat flux;

h_{cond} = bond-conductance parameter;

τ^k = gap width (variable) at the end of the k th time increment;

T_{NT} = temperature of surface of outer fuel node;

$T_{NE''}$ = clad temperature at inner surface;

h_b = bond conductance = h_{cond}/τ^k .

The radiative component (being small) is calculated explicitly

$$\phi_R = \epsilon \sigma \left[\left(T_{NT}^{k+\frac{1}{2}} \right)^4 - \left(T_{NE''}^{k+\frac{1}{2}} \right)^4 \right], \quad (A.15)$$

where

ϕ_R = radiative heat flux;

ϵ = thermal emissivity;

σ = Stefan-Boltzmann constant.

The gap width, τ , is calculated as a function of time in the Fuel Deformation Module. When the prediction is made that the fuel and clad have come into contact, the thermal conductance of the bond, h_b , is set equal to a maximum value $(h_b)_{max}$. The value of $(h_b)_{max}$ can be pressure-dependent if desired. In this case the maximum bond conductance varies with the fuel pressure calculated in the Fuel Deformation Module according to a specified input gradient.

The coupling of the clad (Heat Transfer Module) and coolant (Coolant Dynamics Module) temperatures is as follows. The heat fluxes (at the clad surface) at the k th time interval are used by the Coolant Dynamics Module to calculate new coolant temperatures, $T_{NC}^{k+1,j}$, at the $(k+1)$ st interval. Once $T_{NC}^{k+1,j}$'s are known, the set of Eqs. A.10 is solved directly by Gauss elimination.

6. Heat Transfer to Core Structural Material

An approximate calculation of the temperature of structural material which may be in the reactor core (subassembly cans, supporting structure, etc.) is also performed by the Heat Transfer Module if desired. This calculation is based on a simple model which considers the transport of heat from the coolant at the various axial nodes.

The structure heat-balance equation is

$$V_s C_{p,s} \frac{\partial T_{NS}}{\partial t} = \bar{h}_c (T_{NC} - T_{NS}) A_s$$

or

$$C\rho_s \frac{T_{NS}^{k+1} - T_{NS}^k}{\Delta t} \tau_s = \frac{\bar{h}_c}{2} (T_{NC}^{k+1} + T_{NC}^k - T_{NS}^{k+1} - T_{NS}^k),$$

where

R_{st} = structure thermal resistance;

$\bar{h}_c$ = equivalent heat transfer = $\frac{1}{h_c} + R_{st}$;

$\tau_s = \frac{V_s}{A_s} \frac{\text{structure volume}}{\text{structure area in contact with coolant}}.$

The equation is rearranged to give T_{NS}^{k+1} explicitly in terms of the other temperatures:

$$T_{NS}^{k+1} = \frac{T_{NS}^k + \frac{h_c \Delta t}{2C\rho_s \tau_s} (T_{NC}^{k+1} + T_{NC}^k - T_{NS}^k)}{1 + \frac{\bar{h}_c \Delta t}{2C\rho_s \tau_s}}. \quad (A.16)$$

B. Coolant Dynamics Module

The main function of the coolant-dynamics module in SAS1A is to provide a reasonable detailed profile of vapor voiding, based on the single-channel model shown in Fig. 1. The calculated temporal and spatial void distribution, along with input void-reactivity coefficients, is then used to obtain the coolant-voiding component of feedback reactivity, which is input to the Point Kinetics Module. Coupling of the Coolant Dynamics and Heat Transfer Modules arises naturally via the heat flux at the cladding surface.

Two different models are used for different parts of the boiling expulsion. A slip-flow, two-phase model is used for the initial portion and up to a short time after flow reversal (ejection of coolant from the channel inlet) when a reasonably large void fraction (>0.90) exists. Since the slip-flow model is less meaningful from a physical standpoint when the vapor-void fraction is approaching 1.0 and coolant is being expelled from both ends of the channel, a switch is then made to a simple slug model to continue the voiding calculation. Throughout all the coolant-dynamics calculations, the coolant channel geometry is assumed to remain intact, that is, there are presently no models for considering vapor blanketing of the fuel rods and subsequent interaction of molten fuel (produced by clad melting or other mechanisms, e.g., failure of clad due to excessive pin internal pressure) with the coolant.

1. Sodium-void Model

In the slip-flow model used in the treatment of the two-phase fluid, it is assumed that the vapor and liquid each move at a separate characteristic velocity. Since the vapor velocity is higher, it "slips" past the liquid. The following assumptions are made in the formulation of the voiding model:

1. No subcooled boiling or liquid superheat occurs; vapor is formed only when the local bulk coolant temperature exceeds the local saturation temperature.

2. There is thermodynamic equilibrium between phases, and liquid and vapor temperatures equal the local saturation temperature after boiling starts.

Heat transfer in the boiling region is treated in a simple manner wherein the heat-transfer coefficient is calculated by assuming that the liquid film stays in contact with the channel wall; hence, cooling of the cladding is maintained during boiling and expulsion of coolant.

2. Hydrodynamics Equations for Two-phase Flow

The conservation equations for the two-phase mixture are:

Continuity

$$\frac{\partial}{\partial t} [\alpha \rho_g + (1 - \alpha) \rho_\ell] + \frac{\partial G}{\partial z} = 0; \quad (B.1)$$

Momentum

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial z} \left[\alpha \frac{G_g^2}{\rho_g} + (1 - \alpha) \frac{G_\ell^2}{\rho_\ell} \right] + \frac{\partial p}{\partial z} + g[\alpha \rho_g + (1 - \alpha) \rho_\ell] + \left(\frac{\partial p}{\partial z} \right)_{fr} = 0; \quad (B.2)$$

Energy

$$\frac{\partial}{\partial t} [\alpha \rho_g H_g + (1 - \alpha) \rho_\ell H_\ell] + \frac{\partial}{\partial z} G[x H_g + (1 - x) H_\ell] = \gamma \phi(z, t), \quad (B.3)$$

where

α = volume fraction of vapor;

x = vapor quality;

ρ_g = vapor density;

ρ_ℓ = liquid density;

$G = \alpha G_g + (1 - \alpha) G_\ell$ = total mass flow rate;

$\left(\frac{\partial p}{\partial z}\right)_{fr}$ = frictional pressure gradient;

H_g = vapor enthalpy;

H_ℓ = liquid enthalpy;

γ = ratio of channel perimeter to cross-sectional area;

p = pressure;

$\phi(z,t)$ = heat flux at channel wall;

g = acceleration of gravity.

The continuity and energy equations (Eqs. B.1 and B.3) are put in a more useful form for numerical solution by the following manipulations. Performing the differentiation indicated in the first term of Eq. B.1 yields

$$(\rho_g - \rho_\ell) \frac{\partial \alpha}{\partial t} + \frac{\partial G}{\partial z} = 0 \quad (B.4)$$

if the terms $\alpha \partial \rho_g / \partial t$ and $(1 - \alpha) \partial \rho_\ell / \partial t$ are neglected. This is permissible since these terms are small with respect to $(\rho_g - \rho_\ell) \partial \alpha / \partial t$ in a boiling sodium system. Similarly, the energy equation can be written as

$$(\rho_g H_g - \rho_\ell H_\ell) \frac{\partial \alpha}{\partial t} + \frac{\partial G}{\partial z} (x\lambda + H_\ell) + G\lambda \frac{\partial x}{\partial z} + G \frac{\partial H_\ell}{\partial z} = \gamma \phi(z,t), \quad (B.5)$$

where λ = heat of vaporization = $H_g - H_\ell$. In the derivation of Eq. B.5, it is assumed that the terms $\alpha \frac{\partial}{\partial t} (\rho_g H_g)$ and $(1 - \alpha) \frac{\partial}{\partial t} (\rho_\ell H_\ell)$ can also be neglected (a reasonable assumption for a boiling sodium system). Combining Eqs. B.4 and B.5 gives

$$[\lambda \rho_g + \lambda x \rho_\ell - \lambda x \rho_g] \frac{\partial \alpha}{\partial t} + G\lambda \frac{\partial x}{\partial z} + G \frac{\partial H_\ell}{\partial z} = \gamma \phi(z,t).$$

Since $\rho_g \ll \rho_\ell$ this can be approximated as

$$(\rho_g + \rho_\ell x) \frac{\partial \alpha}{\partial t} + G \frac{\partial x}{\partial z} + \frac{G}{\lambda} \frac{\partial H_\ell}{\partial z} = \frac{\gamma \phi(z,t)}{\lambda}. \quad (B.6)$$

Momentum Eq. B.2 is rewritten in the following way. The second term, representing the momentum pressure gradient, can be written in terms of the total flow rate as

$$\left[\frac{\partial p}{\partial z} \right]_{\text{mom}} = \frac{\partial}{\partial z} \left[\alpha \frac{G_g^2}{\rho_g} + (1 - \alpha) \frac{G_\ell^2}{\rho_\ell} \right] = \frac{\partial}{\partial z} \left\{ \frac{G^2}{\rho_\ell} \left[\frac{\beta x^2}{\alpha} + \frac{(1 - x)^2}{1 - \alpha} \right] \right\},$$

where

$$\beta = \rho_\ell / \rho_g.$$

Also, the static-head term can be written in terms of β as

$$\left[\frac{\partial p}{\partial z} \right]_{\text{stat}} = g[\alpha \rho_g + (1 - \alpha) \rho_\ell] = g \rho_\ell [(\alpha / \beta) - \alpha + 1].$$

Further, the friction gradient is

$$\left[\frac{\partial p}{\partial z} \right]_{\text{fr}} = \frac{f_{\text{sp}} G^2}{2 \rho_\ell D_h} (1 - x)^{2-a} \phi_\ell^2,$$

where

$$\phi_\ell^2 = \text{two-phase friction multiplier} = f_1(X_{\text{tt}});$$

$$X_{\text{tt}} = \text{Lockhart-Martinelli flow parameter (see Eq. B.21),}$$

$$a = 0.2;$$

$$f_{\text{sp}} = \text{single-phase friction factor};$$

$$D_h = \text{channel equivalent diameter.}$$

Thus, the momentum equation becomes

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial z} \left\{ \frac{G^2}{\rho_\ell} \left[\frac{\beta x^2}{\alpha} + \frac{(1 - x)^2}{1 - \alpha} \right] \right\} + g \rho_\ell [(\alpha / \beta) - \alpha + 1] + \frac{f_{\text{sp}} G^2}{2 \rho_\ell D_h} (1 - x)^{2-a} \phi_\ell^2 + \frac{\partial p}{\partial z} = 0. \quad (\text{B.7})$$

The most rigorous solution to Eqs. B.4, B.6, and B.7 would be given by the "sectionalized compressible model" as described by Meyer.⁶ However, a numerical solution using this model requires a knowledge of the maximum signal, or sonic, velocity in the fluid. Since the sonic velocity in two-phase sodium cannot be accurately predicted and the computer solution is very much slower, sonic effects were omitted and the momentum equation was used in the so-called "momentum integral" form. Hence, integrating Eq. B.7 over the length of the channel gives

$$\begin{aligned}
& \int_0^L \frac{\partial G}{\partial t} dz + \frac{G^2}{\rho_\ell} v' \Big|_0^L + g \int_0^L \rho_\ell [(\alpha/\beta) - \alpha + 1] dz \\
& + \int_0^L \frac{f_{sp} G^2 (1-x)^{2-a}}{2\rho_\ell D_h} \phi_\ell^2 dz + p \Big|_{P_0}^{P_N} = 0,
\end{aligned} \tag{B.8}$$

where

$$v' = \frac{\beta x^2}{\alpha} + \frac{(1-x)^2}{1-\alpha};$$

L = channel length;

P_0 = channel pressure just inside the inlet;

P_N = channel pressure just inside the exit;

In this form the transfer of momentum across the control-volume boundaries (ends of the reactor channel) is treated explicitly while the details of momentum transfer within the channel are suppressed. In contrast to the work of Meyer and others using the momentum integral model, however, the fluid properties used in evaluating the various integrals in Eq. B.8 are pressure-dependent, rather than being evaluated at a constant reference pressure. In order to include cases where boiling starts at an arbitrary point in the channel, the momentum integral (Eq. B.8) is broken into two parts as follows:

Lower nonboiling leg and boiling portions

$$\begin{aligned}
& \int_0^{z_{ub}} \frac{\partial G}{\partial t} dz + \frac{G^2}{\rho_\ell} v' \Big|_0^{z_{ub}} + g \int_0^{z_{ub}} \rho_\ell [(\alpha/\beta) - \alpha + 1] dz \\
& + \int_0^{z_{ub}} \frac{f_{sp} G^2 (1-x)^{2-a}}{2\rho_\ell D_h} \phi_\ell^2 dz + p \Big|_{P_0}^{P_{z_{ub}}} = 0,
\end{aligned} \tag{B.9}$$

where

$z_{ub} = z_{ub}(t)$ = length of lower nonboiling leg at time t .

Upper nonboiling leg

$$\int_{z_{ub}}^L \frac{\partial G}{\partial t} dz + \frac{G^2}{\rho_\ell} \Big|_{z_{ub}}^L + g \int_{z_{ub}}^L \rho_\ell dz + \int_{z_{ub}}^L \frac{f_{sp} G^2}{2\rho_\ell D_h} dz + p \Big|_{P_{z_{ub}}}^{P_N} = 0. \tag{B.10}$$

Since the mass flow rate and liquid properties are approximately constant with position in the upper nonboiling leg, integration of Eq. B.10 gives

$$P_{z_{ub}} = \frac{\partial G}{\partial t} (L - z_{ub}) + g\rho_\ell(L - z_{ub}) + \frac{f_{sp}G^2}{2\rho_\ell D_h} (L - z_{ub}) + P_N. \quad (B.11)$$

In this manner the upstream single-phase liquid leg and the two-phase boiling portion of the channel are treated using one momentum integral (Eq. B.9), and the downstream liquid leg being expelled from the channel exit is treated by a second integral (Eq. B.10). The boundary condition for the downstream pressure $P_{z_{ub}}$ for Eq. B.9 is time varying as determined by Eq. B.11. Thus the rate of change of average channel velocity is given as the difference between the imposed pressure drop in the channel and the various integrals in Eq. B.9.

3. Equations for Single-phase Flow

The conservation equations for the single-phase fluid in the subcooled portion of the channel are readily obtained from the two-phase Eqs. B.1 and B.3 by setting $\alpha = 0$. They are:

Continuity

$$\frac{\partial \rho}{\partial t} + \frac{\partial G}{\partial z} = 0; \quad (B.12)$$

Momentum

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial z} \left(\frac{G^2}{\rho} \right) + \frac{\partial p}{\partial z} + g\rho + \left(\frac{\partial p}{\partial z} \right)_{fr} = 0; \quad (B.13)$$

Energy

$$\frac{\partial}{\partial t} (\rho H) + \frac{\partial}{\partial z} (GH) = \gamma \phi(z, t). \quad (B.14)$$

Combining Eqs. B.12 and B.14 gives the energy equation in the form

$$\rho \frac{\partial H}{\partial t} + G \frac{\partial H}{\partial z} = \gamma \phi(z, t); \quad (B.15)$$

since the liquid phase is assumed to be incompressible, the continuity equation reduces to $\partial G / \partial z = 0$.

4. Boundary Conditions and Equation of State for Two-phase Fluid

The heat flux at the fuel-rod surface as a function of axial position and time is given in the usual way by an equation of the form

$$\phi(z,t) = h(G,T_c)[T_{NE}' - T_{NC}], \quad (B.16)$$

where

T_{NE}' = surface temperature of the fuel cladding;

T_{NC}' = bulk coolant temperature.

The convection film coefficient is calculated by the expression

$$\frac{hD_h}{k} = C_1 \left[\frac{D_h G C_\ell}{k} \right]^{C_2} + C_3, \quad (B.17)$$

which is the form of correlation used for calculation of convection heat-transfer coefficients for fluids of low Prandtl number (such as liquid metals). Here

D_h = channel equivalent diameter;

k = coolant thermal conductivity;

G = coolant mass flow rate;

C_ℓ = coolant heat capacity;

C_1, C_2, C_3 = constants depending on particular correlation;

$h = h(G, T_c)$ = convection film coefficient.

The additional boundary conditions required to complete the problem formulation are:

a. Temperatures at $t = 0$ in the coolant and fuel, calculated from the steady-state forms of the appropriate equations.

b. Coolant temperature at the channel inlet as a function of time, assumed constant in calculations (except after flow reversal).

c. Channel outlet pressure as a function of time.

In computing the exit pressure loss, we assumed that none of the potential pressure increase is recovered and that there is a further loss of one velocity head due to the fuel bundle and fittings, etc. The exit pressure-loss term is given by

$$P_N - P_{ex} = \frac{G_N |G_N|}{2\rho_N}, \quad (B.18)$$

where

P_{ex} = exit plenum pressure.

d. Channel inlet pressure as a function of time determined by the inlet pressure loss, given by

$$P_I - P_o = \frac{G_o |G_o|}{2\rho_o}, \quad (\text{B.19})$$

where

P_I = inlet plenum pressure.

This is the single-phase pressure loss at the channel inlet for an area ratio of 0.5 (corresponds to a core coolant fraction of 0.5) according to data given by Lottes.⁷ The channel driving pressure head ($P_I - P_{ex}$) is either constant (power transient) or exponentially decreasing (flow-coastdown transient) in time. An alternative means of specifying a flow-reduction transient in SAS1A is by a tabular input of flow rate versus time.

It is necessary to have an expression which gives the vapor volume fraction, α , in a two-phase flow system. The experimental vapor fraction is most frequently correlated by an expression of the form

$$\alpha = f_2(X_{tt}), \quad (\text{B.20})$$

where

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\rho_g}{\rho_l} \right)^{0.5} \left(\frac{\mu_l}{\mu_g} \right)^{1.1} \quad (\text{B.21})$$

μ_g = vapor viscosity;

μ_l = liquid viscosity;

and the quantity X_{tt} is the Lockhart-Martinelli two-phase flow parameter.⁸ The correlation represented by Eq. B.20 defines the vapor-liquid slip-velocity ratio since the slip ratio is implicit within it. Equation B.20 and the assumption that the channel is completely filled with the fluid mixture, i.e.,

$$\alpha_g + \alpha_l = 1.0,$$

fix the fraction of the channel cross section occupied by the liquid. Thus, Eq. B.20 is used to relate the variables x and α in Eq. B.6. The particular $f_2(X_{tt})$ built into the code at present is

$$\alpha = 1.0 - \frac{1.0}{\sqrt{1.0 + \frac{21.0}{X_{tt}}}};$$

5. Slug-expulsion Model

In general, the core is only partially voided at the time the two-phase boiling calculation breaks down (i.e., the limitation of the model is exceeded) and, in many cases, significant rates of reactivity due to coolant voiding are being introduced at this point in time. Therefore, a different model was devised to continue the voiding beyond this point. One of the most straightforward and direct ways of doing this is to continue the voiding calculation by means of a so-called slug-ejection model. The basic assumption in developing the model is that there is a differential pressure across the liquid slug which tends to move it out of the core. This driving pressure for ejection is generated by the coolant vapor pressure. The saturation pressure used in the model corresponds to a temperature midway between those of the coolant and the clad. Accordingly, the driving forces are given by the difference between the saturation pressure and the pressure at the end of the channel.

The equation which describes the motion is derived by writing a force balance on the slug, which includes inertial and frictional terms. Considering a force balance (neglecting gravitational forces and spatial acceleration terms) on the slug, one obtains from Eq. B.13,

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial p}{\partial z} + \left(\frac{\partial p}{\partial z} \right)_{fr} = 0.$$

At any instant

$$\frac{dp}{dz} = \frac{P_e - P_s}{L(t)},$$

where

P_s = saturation pressure;

P_e = channel exit pressure;

$L(t)$ = slug length as function of time;

v = slug velocity;

ρ = liquid density;

t = time.

Since we assume incompressible flow in the slug, $\partial \rho / \partial t = 0$, which gives

$$\frac{dv}{dt} = -\frac{1}{\rho} \frac{dp}{dz} - \frac{1}{\rho} \frac{fv^2 \rho^2}{2\rho D_h} \quad (B.22)$$

Substituting the above equation into Eq. B.22 along with

$$L(t) = L_0 - \int_{t_0}^t v(t') dt'$$

gives

$$\frac{dv}{dt} = \frac{P_s - P_e}{\rho \left[L_0 - \int_{t_0}^t v(t') dt' \right]} - \frac{fv^2}{2D_h}, \quad (B.23)$$

where

D_h = channel hydraulic diameter;

f = friction factor = $A(Re)^b$;

Re = Reynolds No. = $D_h v \rho / \mu$;

μ = liquid viscosity.

Thus Eq. B.23 describes the motion of the liquid slug as a function of time, and its solution gives the propagation rate of the voiding pattern in the coolant channel. Equation B.23 is solved in SAS1A using the Runge-Kutta method. The integral in the equation is evaluated using the trapezoidal rule. Boundary values required for solution of the problem are

L_0 = initial length of liquid slug

and

v_0 = initial velocity of slug.

These values are obtained from the two-phase calculation at the time the switch over to the calculation for slug expulsion is made.

6. Finite-difference Equations for Numerical Solution

As stated earlier, the coolant channel is divided into axial segments (j nodes) for writing the finite-difference equations.

a. Single-phase Equations. Solving problems in which the coolant is greatly subcooled initially may require relatively long periods of real time in the single-phase part of the calculation before boiling starts. Therefore, a stable representation for Eq. B.15 was desired, permitting time steps in this region which would not be inordinately small. After a good deal of experimentation with other methods, the "box method" representation⁹ was chosen. Thus, Eq. B.15 is represented as

$$\begin{aligned}
& \frac{\bar{\rho}\bar{C}}{2\Delta t} \left[T_j^{k+1} + T_{j-1}^{k+1} - T_j^k - T_{j-1}^k \right] + \frac{\bar{C}}{2\Delta z} \left[\hat{G}^{k+1} \left(T_j^{k+1} - T_{j-1}^{k+1} \right) + \hat{G}^k \left(T_j^k - T_{j-1}^k \right) \right] = \\
& \frac{\gamma}{2} \left[\bar{h}c_j \bar{T}_{NE'j} - \bar{h}c_j \left(\frac{T_j^k + T_j^{k+1}}{2} \right) + \bar{h}c_j \bar{T}_{NE'j-1} - \bar{h}c_{j-1} \left(\frac{T_{j-1}^k + T_{j-1}^{k+1}}{2} \right) \right. \\
& \left. + \frac{\gamma_2}{\frac{1}{\bar{h}c_j} + R_{st}} \cdot \left(\bar{T}_{sj} - \frac{T_j^k + T_j^{k+1}}{2} \right) + \frac{\gamma_2}{\frac{1}{\bar{h}c_{j-1}} + R_{st}} \cdot \left(\bar{T}_{sj-1} - \frac{T_{j-1}^k + T_{j-1}^{k+1}}{2} \right) \right],
\end{aligned}
\tag{B.24}$$

where

$\bar{T}_{NE'j}$ = extrapolated surface temperature of clad =

$$T_{NE'j}^k + \frac{\Delta t^k}{2\Delta t^{k-1}} \left(T_{NE'j}^k - T_{NE'j}^{k-1} \right);$$

$\bar{T}_{sj}$ = extrapolated structure temperature = $T_{sj} + \frac{\Delta t^k}{2\Delta t^{k-1}} \left(T_{sj}^k - T_{sj}^{k-1} \right);$

$\bar{h}c_j$ = average heat-transfer coefficient of film = $\frac{hc_j^k + hc_j^{k+1}}{2};$

$\gamma_2 = \frac{\text{surface area of structure}}{\text{surface area of clad}};$

R_{st} = effective thermal resistance of the structure;

$\bar{\rho} = \rho_\ell(T = \bar{T});$

$\bar{C} = C_\ell(T = \bar{T});$

$\bar{T}$ = space- and time-average coolant temperature =

$$\frac{1}{2} \left[T_j^k + \frac{\Delta t^k}{2\Delta t^{k-1}} \left(T_j^k - T_j^{k-1} \right) + T_{j-1}^k + \frac{\Delta t^k}{2\Delta t^{k-1}} \left(T_{j-1}^k - T_{j-1}^{k-1} \right) \right];$$

G^k = channel time-averaged coolant mass flow rate over time step Δt^k .

In the single-phase region, the mass flow rate is independent of position; therefore,

$$\bar{G}^{k+1} = G_j^{k+1}; \quad j = 0, 1, 2, \dots, n.$$

The value of $\bar{G}^{k+1}$ is obtained from the derivative at k :

$$\bar{G}^{k+1} = \bar{G}^k + \left(\frac{\partial \bar{G}}{\partial t} \right)_k \Delta t^k, \quad (\text{B.25})$$

where Δt^k is the time step at k and $\left(\frac{\partial \bar{G}}{\partial t} \right)_k$ is obtained from Eq. B.13, which is used in integrated form (see Eq. B.10). The various integrals in the equation are evaluated using the trapezoidal rule. When $\bar{G}^{k+1}$ is obtained from Eq. B.25, the flow rate at the end of the time step is found by use of a relationship which is derived as follows.* We make use of the fact that the frictional pressure gradient is proportional to the square of the mass flow rate; thus the ΔG based on Eq. B.25 is

$$\Delta G_o = \bar{G}^{k+1} - \bar{G}^k = A + B(\bar{G}^k)^2, \quad (\text{B.26})$$

where $\bar{G}^{k+1}$ and $\bar{G}^k$ are the mass flow rates at k and $k + 1$; and A and B are constants for the Δt^k time step. The corrected ΔG based on the average mass flow rate between k and $k + 1$ is

$$\Delta G = A + \frac{B}{2} \{ (\bar{G}^k)^2 + [(\bar{G}^k) + \Delta G] \},$$

which on expanding and neglecting terms of order $(\Delta G)^2$ becomes

$$\Delta G = A + B(\bar{G}^k)^2 + B\bar{G}^k \Delta G. \quad (\text{B.27})$$

Combining Eqs. B.26 and B.27, and rearranging, gives

$$\Delta G = \frac{\Delta G_o}{1 - B\bar{G}^k}.$$

Hence, the corrected value for the flow rate at $k + 1$ is

$$(\bar{G}^{k+1})_{\text{corr}} = \bar{G}^k + \frac{\Delta G_o}{1 - B\bar{G}^k}, \quad (\text{B.28})$$

where the $B\bar{G}^k$ term is evaluated by subtracting the channel driving pressure and static head gradients (A in Eq. B.26) from the ΔG_o .

*Derivation by Floyd Dunn.

b. Two-phase Equations. The finite-difference form of the continuity equations, B.1, uses backward differences to represent both space and time derivatives; thus,

$$\frac{\bar{\rho}^{k+1} - \bar{\rho}^k}{\Delta t^k} + \frac{G_j^{k+1} - G_{j-1}^{k+1}}{\Delta z} = 0, \quad (\text{B.29})$$

where terms of order Δt and Δz and higher are neglected,

$$\bar{\rho}_j^k = \rho_j^k \left[\left(\alpha_j^k / \beta_j^k \right) - \alpha_j^k + 1 \right],$$

and ρ_j^k is the liquid density.

The energy equation, B.6, is represented using an implicit characteristic method wherein the space derivatives and dependent variables are averaged over the time step, and the fluid properties are the values calculated at the previous time step; thus,

$$\begin{aligned} & \left[\rho_j^k \left\{ \left(1/\beta_j^k \right) + x_j^k \right\} + \rho_j^k \left\{ \left(1/\beta_j^k \right) + x_j^{k+1} \right\} \right] \frac{\alpha_j^{k+1} - \alpha_j^k}{\Delta t^k} + G_j^k \frac{x_j^k - x_{j-1}^k}{\Delta z} \\ & + G_j^{k+1} \frac{x_j^{k+1} - x_{j-1}^{k+1}}{\Delta z} + \frac{(G_j^{k+1} + G_j^k)}{\lambda_j^{k+1}} \frac{(T_{s_j} - T_{s_{j-1}}) C_\ell}{\Delta z} = \gamma \frac{\phi_j^{k+\frac{1}{2}} + \phi_{j-1}^{k+\frac{1}{2}}}{\lambda_j^{k+1}}, \end{aligned} \quad (\text{B.30})$$

where terms of order $(\Delta t)^2$, Δz , and higher powers are neglected. This equation, on rearranging, gives

$$\begin{aligned} \alpha_j^{k+1} = \alpha_j^k + & \left\{ \frac{\gamma \Delta t^k (\phi_j^{k+\frac{1}{2}} + \phi_{j-1}^{k+\frac{1}{2}})}{\lambda_j^{k+1}} - \frac{\Delta t^k}{\Delta z} \left[G_j^k (x_j^k - x_{j-1}^k) \right. \right. \\ & \left. \left. + G_j^{k+1} (x_j^{k+1} - x_{j-1}^{k+1}) \right] \right\} / (\Gamma_j^{k+1} + \Gamma_j^k), \end{aligned} \quad (\text{B.31})$$

where

$$\Gamma_j^k = \rho_j^k \left[\left(1/\beta_j^k \right) + x_j^k \right];$$

$$\Gamma_j^{k+1} = \rho_j^k \left[\left(1/\beta_j^k \right) + x_j^{k+1} \right].$$

Equations B.29 and B.31 evolved from experimenting with various differencing schemes to find stable convergent equations. In the course of these studies, it was found that the convergence of the iterative scheme used to solve the two-phase energy, continuity, and momentum equations was accelerated by use of the step

$$\left(\alpha_j^{k+1} \right)_{\text{est}} = \left[\left(\alpha_j^{k+1} \right)^{n+1} + \left(\alpha_j^{k+1} \right)^n \right] / 2,$$

where n denotes the iteration number, that is, the new estimate for α_j^{k+1} is obtained by averaging the value from Eq. B.31 for the current iterations with the value from the previous iteration.

The momentum integral equation, B.9, is evaluated by a simple trapezoidal-integration scheme and thus poses no direct stability problems.

To develop a practical scheme of solution, the continuity difference equation, B.29, is rearranged as suggested by Meyer,¹⁰ obtaining

$$G_j^{k+1} = G_{j-1}^{k+1} \pm \frac{\Delta z}{\Delta t^k} \left(\bar{\rho}_j^k - \bar{\rho}_j^{k+1} \right) = G_{j-1}^{k+1} + \sigma_j^{k+1},$$

where terms of order Δt , Δz , $(\Delta z)^2$, and higher powers have been neglected, and

$$\sigma_j^{k+1} = \frac{\Delta z}{\Delta t^k} \left(\bar{\rho}_j^k - \bar{\rho}_j^{k+1} \right).$$

One can then write

$$G_j^{k+1} = G_o^{k+1} + \sum_{\ell=1}^j \sigma_{\ell}^{k+1} = G_o^{k+1} + \eta_j^{k+1}, \quad (\text{B.32})$$

where terms of order Δz , Δt , and higher powers have been neglected, and

$$\eta_j^{k+1} = \sum_{\ell=1}^j \sigma_{\ell}^{k+1}.$$

Then the average channel mass flow rate is given by

$$\bar{G}^{k+1} = \frac{1}{2L} \sum_{j=1}^n \left(G_j^{k+1} + G_{j-1}^{k+1} \right) \Delta z. \quad (\text{B.33})$$

Substituting Eq. B.32 into B.33 gives

$$\bar{G}^{k+1} = \frac{1}{2L} \sum_{j=1}^n \left(G_o^{k+1} + \eta_j^{k+1} + G_o^{k+1} + \eta_{j-1}^{k+1} \right) \Delta z,$$

which on rearranging yields

$$G_o^{k+1} = \bar{G}^{k+1} - \frac{1}{2L} \sum_{j=1}^n \left(\eta_j^{k+1} + \eta_{j-1}^{k+1} \right) \Delta z. \quad (\text{B.34})$$

Thus, Eq. B.34 gives G_o^{k+1} directly in terms of the known $\bar{G}^{k+1}$ (determined from Eq. B.28 above) and the σ_j^{k+1} 's. Equation B.32 can then be used to calculate all the remaining G_j^{k+1} 's.

The steps in the iterative numerical solutions involving Eqs. B.20, B.28, B.29, B.31, B.32, and B.34 are:

(1) By use of values of temperature- and pressure-dependent fluid properties from the previous time step, use Eq. B.28 to obtain $\bar{G}^{k+1}$.

(2) Obtain first estimates for the α_j^{k+1} 's using Eq. B.31.

(3) Use the explicit Eqs. B.34 and B.32 to calculate G_o^{k+1} and new G_j^{k+1} 's, respectively.

(4) Use the Martinelli void correlation (Eq. B.20) inverted to be explicit in terms of x instead of α to evaluate: the new x_j^{k+1} 's from the α_j^{k+1} 's, and fluid physical properties evaluated at k .

(5) Repeat the cycle of steps from 2 on until the x_j^{k+1} 's agree between two successive iterations within a specified convergence criterion.

(6) The new pressure profile at $k + 1$ is then calculated by the trapezoidal integration of Eqs. B.9 and B.10, and then the cycle of steps starting with 1 is repeated for the next time step.

c. Equations for Slug-expulsion Model. The numerical integration of Eq. B.23 to give the motion of the upper coolant slug is performed using a Runge-Kutta Scheme; thus,

$$v^{k+1} = v^k + \frac{1}{6}(C_5 + 2C_6 + 2C_7 + C_8),$$

where

$$\begin{aligned} C_5 &= \Delta t^k \left\{ \frac{P_s - P_e}{\rho[L^k - v^k \Delta t]} - \frac{f}{2D_h} (v^k)^2 \right\}; \\ C_6 &= \Delta t^k \left\{ \frac{P_s - P_e}{\rho \left[L^k - \left(v^k + \frac{C_5}{2} \right) \Delta t \right]} - \frac{f}{2D_h} \left(v^k + \frac{C_5}{2} \right)^2 \right\}; \\ C_7 &= \Delta t^k \left\{ \frac{P_s - P_e}{\rho \left[L^k - \left(v^k + \frac{C_6}{2} \right) \Delta t \right]} - \frac{f}{2D_h} \left(v^k + \frac{C_6}{2} \right)^2 \right\}; \\ C_8 &= \Delta t^k \left\{ \frac{P_s - P_e}{\rho \left[L^k - \left(v^k + \frac{C_7}{2} \right) \Delta t \right]} - \frac{f}{2D_h} (v^k + C_7)^2 \right\}. \end{aligned}$$

This solution is applied to the upper slug when the switch to slug expulsion is made. The motion of the lower coolant slug is calculated in the same way as before the switch, i.e., using the momentum integral equation.

C. Fuel Deformation Module

This module in the SAS1A code calculates the thermoelastic deformation of the fuel and the elastic-plastic deformation of the cladding, using the fuel and cladding temperature profiles from the Heat Transfer Module. A quasi-static deformation analysis is employed which implies that there is no explosive loading on the fuel elements to produce shock effects. On the other hand, it is assumed that the time scale of the loading is short enough that such long-term effects as radiation growth and viscoelastic creep can be neglected. Fuel and cladding stresses and deformations are calculated by assuming a stress-free configuration at normal operating conditions. This assumption is justified if the stresses produced by the change from room temperature to operating conditions are annealed out. Therefore, in the following description the temperature at a point is the difference between the actual temperature and the temperature corresponding to the steady-state operating conditions.

In this module, as in the Heat Transfer Module, the fuel element is divided into axial segments. Since the radial temperature variations for a reactor fuel rod are much more severe than the axial, the field equations of elasticity with the appropriate boundary conditions are solved exactly in closed form with respect to radial variations, but only approximately by iteration with respect to axial variations of stress and deformation. Depending upon the conditions of the fuel and the clad, any one of nine cases may pertain to each of these axial segments. Deformation cases 1, 2, and 3 refer to the solid fuel; 4, 5, and 6 refer to a central cavity in the fuel with either no melting or not enough to fill the central hole; and 7, 8, and 9 correspond to the case when fuel melting has occurred and the resultant liquid is exerting expansion-derived pressures on the remaining solid fuel. The three options in each set of above cases correspond, respectively, to the existence of a radial gap (Cases 1, 4, 7), the elastic deformation of the clad due to closing of the gap (Cases 2, 5, 8), and the plastic deformation of the clad due to excessive loading (Cases 3, 6, 9).

1. Reference Configuration (Steady-state Conditions)

Let the reference state of the fuel element be divided into axial segments as in the heat-transfer module. Figure 3 shows a typical segment.

Fig. 3. Fuel-element Segment in Reference Configuration

In the following, the subscript c refers to the clad, f to the fuel, s to the solid part of the fuel, and ℓ to the liquid or partially melted part of the fuel. The superscript j identifies the axial segment. The clad thickness δ_c is given by

$$\delta_c = b_c - a_c. \quad (C.1)$$

The gap between the clad and fuel is assumed to be occupied by a bonding material or inert gas which squeezes out as the fuel expands. Since in the reference configuration no fuel has melted, the inside radius a_s and outside radius b_s of the solid part of the fuel are equal initially to a_f and b_f , respectively.

The Young's modulus, shear modulus, Poisson's ratio, and coefficient of thermal expansion of the clad material are denoted by E_c , μ_c , ν_c , and $\alpha_c(T)$, respectively; the corresponding quantities for the solid fuel are denoted by E_s , μ_s , ν_s , and $\alpha_s(T)$. The bulk moduli and densities of the solid and liquid fuel are denoted by K_s , $\rho_s(T)$, K_ℓ , and $\rho_\ell(T)$, and $\sigma_{co}(T)$ is the yield stress. Where indicated by the temperature argument the above material constants may be taken as functions of temperature. The elastic constants for a solid material are related through the expressions

$$\mu = \frac{E}{2(1+\nu)}; \quad K = \frac{E}{3(1-2\nu)}. \quad (C.2)$$

2. Elastic Deformation Model of the Fuel with No Melting

The thermoelastic field equations of equilibrium in cylindrical coordinates r , θ , z are, for axisymmetric deformations (no θ dependence),

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{\partial \sigma_{rz}}{\partial z} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r} = 0; \quad (C.3)$$

$$\frac{\partial \sigma_{rz}}{\partial r} + \frac{\partial \sigma_{zz}}{\partial z} + \frac{\sigma_{rz}}{r} = 0; \quad (C.4)$$

$$\sigma_{rr} = \frac{E}{1+\nu} \frac{\partial u_r}{\partial r} + \phi; \quad (C.5)$$

$$\sigma_{\theta\theta} = \frac{E}{1+\nu} \frac{u_r}{r} + \phi; \quad (C.6)$$

$$\sigma_{zz} = \frac{E}{1+\nu} \frac{\partial u_z}{\partial z} + \phi; \quad (C.7)$$

$$\sigma_{rz} = \frac{E}{2(1+\nu)} \left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} \right), \quad (C.8)$$

with

$$\phi = \frac{E\nu}{(1+\nu)(1-2\nu)} \left(\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_z}{\partial z} \right) - \frac{E\alpha T}{1-2\nu}, \quad (C.9)$$

where

σ_{rr} = radial normal stress;

$\sigma_{\theta\theta}$ = circumferential (hoop) stress;

σ_{zz} = axial normal stress;

σ_{rz} = shearing stress on planes $z = \text{constant}$;

u_r = radial displacement;

u_z = axial displacement,

all measured from the steady-state configuration.

The present method of solving the partial differential equations, C.3 and C.4, for the solid fuel region $a_s \leq r \leq b_s$; $0 \leq z \leq H_f$, where H_f is the total height of the fuel, subject to boundary conditions on the

surface and the prescribed $T(r, z)$, assumes that within each axial segment ($z^j \rightarrow z^{j+1}$) each of the quantities T^j , σ_{rr}^j , $\sigma_{\theta\theta}^j$, σ_{zz}^j , σ_{rz}^j , and u_r^j does not vary significantly with z . These quantities are permitted to vary from segment to segment; however, Eqs. C.3 and C.4 are now solved analytically for each axial segment. For the radial displacement and axial elongation

$$\begin{aligned} \frac{u_r^j(r)}{r} = & -\frac{\nu_s F_{zs}^j}{E_s A_s} + \tau_s^j(b_s) - \frac{(1 + \nu_s)(r^2 - a_s^2)}{2(1 - \nu_s) r^2} [\tau_s^j(b_s) - \tau_s^j(r)] \\ & + \frac{\pi}{E_s A_s} \left\{ (1 - \nu_s) [b_s^2 \sigma_{rr}^j(b_s) - a_s^2 \sigma_{rr}^j(a_s)] \right. \\ & \left. + (1 + \nu_s) \frac{b_s^2 a_s^2}{r^2} [\sigma_{rr}^j(b_s) - \sigma_{rr}^j(a_s)] \right\}; \quad a_s \leq r \leq b_s, \end{aligned} \quad (C.10)$$

and

$$\begin{aligned} \frac{u_{zs}^j}{h^j} & \equiv \frac{u_z^j(z^{j+1}) - u_z^j(z^j)}{h^j} \\ & = \frac{F_{zs}^j}{E_s A_s} + \tau_s^j(b_s) + \frac{2\pi\nu_s}{A_s E_s} [a_s^2 \sigma_{rr}^j(a_s) - b_s^2 \sigma_{rr}^j(b_s)], \end{aligned} \quad (C.11)$$

where

$$\begin{aligned} \tau_s^j(r) & \equiv \frac{2}{r^2 - a_s^2} \int_{a_s}^r \alpha_s T^j(r) r \, dr; \quad a_s < r \leq b_s, \\ \tau_s^j(a_s) & \equiv \lim_{r \rightarrow a} \tau_s^j(r) = \alpha_s T^j(a_s), \end{aligned} \quad (C.12)$$

and

$$F_{zs}^j = 2\pi \int_{a_s}^{b_s} r \sigma_{zz}^j(r) \, dr. \quad (C.13)$$

The circumferential stresses at the inner and outer radii are

$$\sigma_{\theta\theta}^j(a_s) = \frac{E}{1 - \nu_s} \left[-\alpha_s T^j(a_s) + \tau_s^j(b_s) \right] + \frac{\pi}{A_s} \left[2b_s^2 \sigma_{rr}^j(b_s) - (b_s^2 + a_s^2) \sigma_{rr}^j(a_s) \right] \quad (C.14)$$

and

$$\sigma_{\theta\theta}^j(b_s) = \frac{E_s}{1 - \nu_s} \left[-\alpha_s T^j(b_s) + \tau_s^j(b_s) \right] + \frac{\pi}{A_s} \left[(b_s^2 + a_s^2) \sigma_{rr}^j(b_s) - 2a_s^2 \sigma_{rr}^j(a_s) \right]. \quad (C.15)$$

The quantities $\sigma_{rr}^j(a_s)$, $\sigma_{rr}^j(b_s)$, and $\sigma_{zz}^j(r)$ are determined from the boundary conditions pertaining to the nine deformation cases described above. In this way radial displacements, axial elongations, and circumferential stresses are evaluated for each axial segment.

The above solutions assume zero shearing stresses, σ_{rz} , throughout each tube segment. Actually, the relative radial displacements of adjacent tube segments produce shearing stresses and an accompanying shear-displacement field. We will approximate the effect of the omitted shearing stresses by applying equivalent fictitious normal tractions to the tube surface $r = b_s$. Let S_s^j be the fictitious applied stress. Then

$$S_s^j = \frac{F_{rs}^{j,j+1} - F_{rs}^{j-1,j}}{2\pi b_s h^j}, \quad (C.16)$$

where $F_{rs}^{j,j+1}$ is the outward radial force exerted by segment $j+1$ on segment j (see Fig. 4) and is given by

$$F_{rs}^{j,j+1} = 2\pi \int_{a_s}^{b_s} r \sigma_{rz}^{j,j+1}(r) dr. \quad (C.17)$$

Shearing stress σ_{rz} is calculated from Eq. C.8 by neglecting $\partial u_z / \partial r$ compared to $\partial u_r / \partial z$. Thus,

$$\sigma_{rz}^{j,j+1}(r) = 2\mu_s \frac{u_r^{j+1}(r) - u_r^j(r)}{h^{j+1} + h^j}, \quad (C.18)$$

where Eq. C.2 is used. The fictitious force S_s^j can now be obtained by combining Eqs. C.16, C.17, and C.18.

Fig. 4
Shearing Reactions and
Relative Displacements

The calculational procedure for the solid fuel is started by setting $F_{zf} = F_{zs}$ (since no melting occurs) and $S_s^j = 0$, and using the boundary conditions to obtain a new value for U_{zs}^j and S_s^j from Eqs. C.11 and C.16. This axial iteration is repeated until the values of F_{zf} and S_s^j converge. The desired displacements and stresses are then calculated using the final values.

3. Elastic Deformation Model of the Fuel for Partial Melting

The structural response in a cell in which partial melting has occurred is calculated under the following assumptions: 1) the material in the cell behaves mechanically as a liquid with density and bulk modulus between those for the liquid and solid states; 2) all the cells where melting has occurred in any given axial segment are acted on by the same fluid pressure (this pressure can vary axially, however); 3) consistent with the Heat Transfer Module, the fuel does not cross cell boundaries; 4) the axial expansion of an axial segment does not vary radially. The implication of the last two assumptions is that migration of liquid fuel through a central cavity is not permitted.

Consider the partially melted fuel cell ij ($r^i \leq r \leq r^{i+1}$; $z^j \leq z \leq z^{j+1}$). The equivalent density $\bar{\rho}^{ij}$ of the fuel in this cell is given by

$$\frac{1}{\bar{\rho}^{ij}} = \frac{f_\ell^{ij}}{\rho_\ell^{ij}} + \frac{1 - f_\ell^{ij}}{\rho_s^{ij}}, \quad (C.19)$$

where f_ℓ^{ij} is the mass fraction of the melted fuel; ρ_ℓ^{ij} and ρ_s^{ij} are, respectively, the liquid and solid fuel densities at the average temperature T^{ij} of the cell. The partially melted cells are then allowed to expand freely into the empty central cavity, if one exists. If the expansion into the central cavity is not enough to accommodate the increased volume of the partially melted fuel, the resulting pressure p^j exerted by the solid fuel on each cell of partially melted fuel in axial segment j is found to be

$$p^j = -\bar{K}^{ij} \frac{\Delta V^{ij}}{V^{ij}}, \quad (C.20)$$

where the average bulk modulus of the cell ij is

$$\frac{V^{ij}}{\bar{K}^{ij}} = \frac{V_L^{ij}}{K_\ell} + \frac{V_s^{ij}}{K_s}, \quad (C.21)$$

and the change in volume ΔV^{ij} is equal to the sum of the changes in liquid and solid fuel.

For small elastic deformations of the heated cell boundaries the fractional change in the volume is related to the (fictitious) unstressed inner and outer radii $R^{i+1,j}$ and R^{ij} and their deformations:

$$\frac{\Delta V^{ij}}{V^{ij}} = \frac{2[R^{i+1,j}u_r^j(R^{k+1,j}) - R^{ij}u_r^j(R^{ij})]}{[(R^{i+1,j})^2 - (R^{ij})^2]} + \frac{U_{z\ell}^j}{h^j}, \quad (C.22)$$

where

$$\begin{aligned} U_{z\ell}^j &= u_z^j(z^{j+1}) - u_z^i(z^j), \\ h^j &= z^{j+1} - z^j, \\ u_r^j(R^{ij}) &= u_r^j(0) = 0, \end{aligned} \quad (C.23)$$

$$u_r^j(R^{i+1,j}) = -\frac{R^{i+1,j}}{2} \left\{ \frac{p^j}{(R^{i+1,j})^2} \sum_{n=1}^i \frac{\rho_{sR}^{nj} [(r^{n+1})^2 - (r^n)^2]}{\bar{\rho}^{nj} \bar{K}^{nj}} + \frac{U_{zL}^j}{h^j} \right\}, \quad (C.24)$$

and

$$(R^{i+1,j})^2 = \sum_{n=1}^i \frac{\rho_{sR}^{nj}}{\bar{\rho}^{nj}} [(r^{n+1})^2 - (r^n)^2]; \quad 1 \leq i \leq k, \quad (C.25)$$

where k is the number of radial cells of axial segment j up to which a partial melting occurs.

Now we need a relationship between p^j and the exterior surface displacements of the partially melted block of cells lj through kj . Let b_ℓ^j denote the outer unstressed radius of the partially melted cells. We then have

$$b_\ell^j = \left[\frac{1}{\pi h^j} \sum_{i=1}^k V^{ij} \right]^{\frac{1}{2}}, \quad (C.26)$$

$$u_r^j(b_\ell^j) = -\frac{b_\ell^j}{2} \left[\frac{p^j}{\bar{K}^j} + \frac{U_{z\ell}^j}{h^j} \right], \quad (C.27)$$

and

$$\frac{1}{\bar{K}^j} = \frac{1}{(b_\ell^j)^2} \sum_{i=1}^k \frac{\rho_{sR}^{ij} [(r^{i+1})^2 - (r^i)^2]}{\bar{\rho}^{ij} \bar{K}^{ij}}. \quad (C.28)$$

The net axial force on cells ij through kj , for small deformations, is

$$F_{z\ell}^j = -\pi(b_\ell^j)^2 p^j. \quad (C.29)$$

The axial restraint on the fuel F_{zf} is

$$F_{zf} = F_{zs}^j + F_{z\ell}^j, \quad (C.30)$$

where F_{zs}^j , the net axial force on the solid part of the fuel, is calculated by the method outlined in the preceding section.

The boundary conditions at the partially melted cell and the adjacent solid cell are

$$\sigma_{rr}^j(a_s^j) = -p^j \quad (C.31)$$

and

$$a_s^j + u_r^j(a_s^j) = b_\ell^j + u_r^j(b_\ell^j). \quad (C.32)$$

From our assumption,

$$U_{z\ell}^j = U_{zs}^j. \quad (C.33)$$

Then, by combining Eqs. C.26, C.27, C.32, and C.33 with Eq. C.11, one obtains a relationship between p^j and $\sigma_{rr}^j(a_s^j)$. This relationship when combined with Eq. C.31 yields a value for p^j . The computer calculations are essentially the same as for the solid fuel rod as discussed in the preceding section. Initially F_{zf} and S_s^j are taken to be zero and p^j is calculated from Eq. C.20. New values for F_{zf} and S_s^j are then found by using Eqs. C.11, C.30, and C.16. The axial iteration is continued until the values of F_{zf} and S_s^j converge, and the desired displacements and stresses are then calculated from the final values.

4. Elastic Deformation Model of the Clad

Equations governing the elastic deformation of the clad are exactly the same as for the elastic deformation of the solid fuel, namely, Eqs. C.3-C.9. The radial displacements and axial elongation, therefore, are given by Eqs. C.10 and C.11, with subscript c replacing s . The circumferential stresses at the inner and outer clad radii are obtained from

Eqs. C.14 and C.15. The axial iteration is carried on in a way identical to the elastic deformation of the solid fuel. The desired displacements and stresses are then calculated using the final values.

Another quantity of interest is the change in the clad thickness, which is given by

$$u_{\delta}^j \equiv u_r^j(b_c) - u_r^j(a_c). \quad (C.34)$$

The interior and surface radial displacements $u_r^j(a_c)$ and $u_r^j(b_c)$ can be obtained from Eq. C.10. Combining these with Eq. C.34, we obtain

$$\begin{aligned} \frac{u_{\delta}^j}{\delta_c} = & -\frac{\nu_c F_{zc}}{E_c A_c} + \tau_c^j(b_c) + \frac{\pi}{E_c A_c} \left\{ (1 - \nu_c) \left[b_c^2 \sigma_{rr}^j(b_c) - a_c^2 \sigma_{rr}^j(a_c) \right] \right. \\ & \left. + (1 + \nu_c) a_c b_c \left[\sigma_{rr}^j(a_c) - \sigma_{rr}^j(b_c) \right] \right\}, \end{aligned} \quad (C.35)$$

where the design-temperature clad thickness δ_c is given by Eq. C.1.

5. Elastic-Plastic Deformation Model of the Clad

The constitutive relations for plasticity theory are an assortment of equalities and inequalities which determine a yield surface in stress space for each point of the material, with accompanying relations (flow rules) between stress and strain-rate components. The choice of the correct flow rule to use at each point depends on the portion of the yield surface that pertains there. As a result, final states of stress and strain are strongly history-dependent, unlike the situation in an elasticity problem in which the state of stress at a point is determined completely by the state of strain there, and vice versa. Consequently, the exact solution of a plasticity problem normally requires an enormous computational effort. In order to have a computer program which is not inordinately large compared with the other parts of the SASIA, it was necessary to make some significant simplifications in the calculations for plastic deformation of the clad. The plasticity analysis used here should be qualitatively correct and quantitatively accurate enough for our purposes.

The clad tube is treated essentially as if it were an elastic-plastic membrane made of an elastic, perfectly plastic material (see Fig. 5). It is assumed that the circumferential stress $\sigma_{\theta\theta}$ is constant across the tube wall thickness and that plastic yielding occurs when $\sigma_{\theta\theta} = \sigma_{co}$. The plastic stretching of the tube cross section is limited because as the tube gets larger, the radial pressure exerted by the thermally expanded fuel

Fig. 5. Stress-Strain Diagram for Ideal Elastic, Perfectly Plastic Clad Material in Uniaxial Tension

decreases until an equilibrium state is reached. The clad material is assumed to be incompressible during the plastic part of its deformation; this assumption is normally made in plasticity analysis and has been justified by experimental observations. Consequently, as the tube diameter grows larger, its wall thickness decreases, resulting eventually in clad rupture. The present analysis also assumes that the wall thins uniformly around the circum-

ference; what actually happens is that the wall thins locally at a random spot on the circumference and fails there.

Consider the half segment of a clad tube shown in Fig. 6. If we assume $\sigma_{\theta\theta}^j$ to be constant across the clad, the equilibrium of the deformed tube segment requires that

$$\sigma_{\theta\theta}^j [\delta_c + u_{\delta}^j] = \sigma_{rr}^j(b_c)[b_c + u_r^j(b_c)] - \sigma_{rr}^j(a_c)[a_c + u_r^j(a_c)]. \quad (C.36)$$

The external radial stress $\sigma_{rr}^j(b_c)$ is determined from the boundary conditions. Equation C.36 determines the circumferential stress assuming elastic deformation of the clad. At some time $\sigma_{\theta\theta}^j$ may be at the verge of going plastic (i.e., $\sigma_{\theta\theta}^j = \sigma_{c0}$); then Eq. C.36 gives

$$\left(\sigma_{rr}^j(a_c)\right)^{ev} = - \frac{\delta_c + \left(u_{\delta}^j\right)^{ev}}{a_c + \left(u_r^j(a_c)\right)^{ev}} \sigma_{c0} + \frac{b_c + \left(u_r^j(b_c)\right)^{ev}}{a_c + \left(u_r^j(a_c)\right)^{ev}} \left(\sigma_{rr}^j(b_c)\right)^{ev}, \quad (C.37)$$

where $\left(u_r^j(a_c)\right)^{ev}$, $\left(u_r^j(b_c)\right)^{ev}$, and $\left(u_{\delta}^j\right)^{ev}$ are obtained from the preceding section assuming that the axial elongation of the clad u_{zc}^j does not change due to plastic flow. For times beyond the elastic verge point, $\sigma_{\theta\theta}^j$ stays constant at the value σ_{c0} (in accordance with the assumption) and the equilibrium equation C.36 is satisfied.

Fig. 6
Segment of Clad Tube

The requirement of constant volume during the plastic yielding gives

$$b_c u_r^j(b_c) - a_c u_r^j(a_c) \approx b_c \left(u_r^j(b_c) \right)^{ev} - a_c \left(u_r^j(a_c) \right)^{ev}. \quad (C.38)$$

By eliminating $u_r^j(b_c)$ from Eqs. C.36 and C.38 we obtain a relationship between $u_r^j(a_c)$ and $\sigma_{rr}^j(a_c)$. Another relation between these two quantities is obtained from the fuel behavior. By solving these equations one then gets $u_r^j(a_c)$ and $\sigma_{rr}^j(a_c)$. The permanent deformation of the tube segment is evaluated by partitioning the displacements into their elastic and plastic parts. For the next time step, the tube-segment dimensions are then altered by the permanent plastic deformation. This incorporates a history-dependent effect into the analysis. Proceeding from an initial loading state through intermediate loading states and then back to the original state will not and should not return the clad to its original conditions.

For the purpose of studying clad deformation, the following quantity is calculated for both the inner and outer clad radius:

$$\text{Total permanent deformation} = r_c(t) - r_c(t_0),$$

where $r_c(t)$ is the radius (inner or outer) of the clad at time t (measured from the steady-state operation) and t_0 is the time when the clad is at the verge of plastic deformation.

D. Fuel Dynamics Module

The purpose of this module in SAS1A is to calculate the axial motion and fuel displacement after gross melting occurs in the central region of a fuel pin. Presumably, at this time, the calculations in the Fuel Deformation Module are inadequate since the model which they are based upon no longer applies if there is gross fuel motion. For this reason, the Fuel Dynamics Module was developed to extend the range of validity of the calculations somewhat and to form a starting point for later development of modules which would attempt to calculate phenomena occurring when the fuel (and core) geometry is no longer intact (e.g., molten fuel-coolant interaction). Of course, a main objective in addition to obtaining an estimate of thresholds for fuel-element failure is to calculate the feedback reactivity due to fuel displacements. Since the Fuel Dynamics Model does not allow for plastic flow of the cladding, in cases where there is plastic flow calculated by the Fuel Deformation Module, the cladding fails immediately on entering Fuel Dynamics.

Fig. 7. Fuel Dynamics Model

1. Model of Fuel Motion

A diagram of the physical model upon which the analysis is based is given in Fig. 7. The approach taken in the modeling is to assume that the fuel is in the form of a partially molten "slurry" within the still intact cladding at the time the Fuel Dynamics Module starts its calculations. Axial pressure gradients, according to the model, arise from the radial restraining force of the cladding which is imposed on the expanding solid-liquid fuel material. Since the fuel is in a partially molten state, the pressure gradient produces axial motion. Also, the axial motion is resisted by frictional forces between the fuel and cladding. Pressure buildup continues to a point where the developed stress exceeds the ultimate stress of the cladding at the temperature involved. In formulating the mathematical model the following assumptions are made:

1. The fuel behaves like a fluid in that it offers no resistance to change of shape.
2. The frictional force is broken down into two components: a dynamic frictional component which is velocity-dependent and a static (or stiction) component which must be exceeded before motion can take place.
3. The internal energy of the fuel in its solid and liquid phases is a function only of temperature.
4. The cladding can be considered to be a thin-walled cylinder for purposes of stress calculation.
5. The fuel has expanded and closed the bond gap at the time the calculations start; hence, only the core fuel is involved.
6. The heat loss from the fuel is neglected for purposes of temperature calculation.

2. Equation of Motion

The equation of motion for an incremental axial segment of fuel is

$$\frac{d^2 z}{dt^2} = - \frac{1}{\rho_f} \frac{dp_f}{dz} - F \frac{dz}{dt} - g, \quad (D.1)$$

where

p_f = pressure in the fuel;

ρ_f = average fuel density;

F = friction factor;

g = gravitational acceleration.

The pressure in the fuel at any axial point is derived by calculating a required cladding internal pressure from the cladding strain. The net clad circumferential strain due to internal pressure is

$$\epsilon_c = \frac{\Delta a_c}{a_c} - \alpha_c \Delta T_e,$$

where

ϵ_c = cladding circumferential strain due to internal pressure;

a_c = clad inner radius at time zero;

α_c = cladding coefficient of thermal expansion;

ΔT_e = temperature of clad at time t minus its temperature at time zero.

Using the stress-strain relationship

$$\sigma_c = \frac{E_c}{\left(1 - \frac{\nu_c}{2}\right)} \epsilon_c,$$

where

$1 - (\nu_c/2)$ = correction to the uniaxial stress strain slope, E_c , for the case of circumferential strain in a thin-walled cylinder;¹¹

and the stress formula for a thin-walled cylinder:

$$\sigma_c = p a_c / \delta_c,$$

one obtains the following equation for the pressure in the fuel at any axial point:

$$p_f = (\Delta a_c - a_c \alpha_c \Delta T_e) \frac{E_c \delta_c}{a_c^2 \left(1 - \frac{\nu_c}{2}\right)}, \quad (D.2)$$

where

δ_c = cladding thickness at time zero;

E_c = clad Young's Modulus;

ν_c = Poisson's ratio for clad.

The axial pressure gradient, dp_f/dz , used in Eq. D.1 is then obtained by taking differences of pressures calculated at adjacent axial nodes using Eq. D.2; hence,

$$\left(\frac{dp_f}{dz}\right)_j \approx [(p_f)_j - (p_f)_{j-1}]/\Delta z. \quad (D.3)$$

In actually performing the calculation, the static Coulomb friction (stiction) effect is accounted for by specifying that the acceleration (Eq. D.1) of the fuel be zero until a specified threshold pressure gradient is exceeded, that is,

$$\frac{d^2z}{dt^2} = 0; \quad |(p_f)_j - (p_f)_{j-1}| < (\delta p_f)_j.$$

The acceleration is computed using Eq. D.1 if

$$|(p_f)_j - (p_f)_{j-1}| \geq \delta(p_f)_j,$$

where the $\delta(p_f)_j$'s are inputs to the computation.

3. Energy Equations

The time-dependent temperatures in the fuel are available from the Heat Transfer Module. A switch to the Fuel Dynamics Module for calculations of fuel temperature and motion is made when the maximum fuel-centerline temperature exceeds a specified input value. Presumably, at the time the switch is made, a major fraction of the fuel in the core region of the fuel rod is in contact with the clad. Therefore, the pressure calculations using Eq. D.2 and fuel-motion calculations (Eq. D.1) begin from this point. Further calculations of fuel temperature are no longer made in the Heat Transfer Module, but are performed in the Fuel Dynamics Module and are based on the assumption that the heat losses from the fuel can be neglected during this phase of the calculation. Thus, the temperature of a given axial segment of fuel is given by

$$\bar{T}_f(t) = \bar{T}_f(t_0) + \int_{t_0}^t \frac{Q(t')}{C_f(\bar{T})} dt', \quad (D.4)$$

where

- t_0 = time when switch to fuel dynamics is made;
- $Q(t')$ = heat generation rate in axial fuel segment;
- $\bar{T}_f$ = volume-averaged fuel temperature.

The specific volume of the fuel is obtained using this temperature in an equation of state of the form

$$v_f = a + b\bar{T}_f,$$

where

- b = an input constant for all axial segments (can be adjusted to allow for added swelling due to fission gas release);
- a = constant calculated for each axial segment from the mass and volume of the segment when the Fuel Dynamics Module is called.

The fuel specific volume, v_f , thus obtained is then used to calculate the change in cladding radius, Δa_c , which is input to Eq. D.2 to calculate the fuel pressure.

The calculation of the cladding and coolant temperatures is performed using the following equations. The fuel surface temperature is given by

$$T_{NT}(t) = T_{NT}(t_0) + \int_{t_0}^t \frac{Q(t')}{C_f(T)} dt'. \quad (D.5)$$

The cladding temperature is then obtained by solving the equation

$$\frac{dT_{NE}}{dt} = \frac{1}{\delta_c C_c \rho_c} [h_b(T_{NT} - T_{NE}) - h_c(T_{NE} - T_{NC})], \quad (D.6)$$

where

- T_{NE} = temperature at midpoint of cladding;
- C_c = heat capacity of cladding;
- ρ_c = density of cladding;
- h_c = heat-transfer coefficient between clad and coolant;
- h_b = heat-transfer coefficient between fuel and clad;
- T_{NC} = coolant temperature.

The contact bond conductance, h_b , between the fuel and cladding is assumed to increase linearly with internal pressure, that is,

$$h_b = (h_b)_0 + (h_b)_{\text{grad}}(p_f - p_f^0),$$

where

$(h_b)_0$ = the initial value of bond conductance when $p_f = p_f^0$ (user input quantity);

$(h_b)_{\text{grad}}$ = change of bond conductance with pressure (user input quantity).

4. Boundary Conditions

As already stated, the initial fuel and clad temperatures for Fuel Dynamics are obtained from the Heat Transfer Module when the Fuel Dynamics Module is called to take over the functions of the Heat Transfer and Fuel Deformation Modules. The initial fuel pressure, p_f^0 , at all axial nodes is set equal to the exit coolant plenum pressure. Boundary conditions on the motion of the core fuel column are:

1. The lower interface of the bottom core node is held fixed in time.
2. The motion of the upper core node is assumed to be restrained by a spring, such that the restraining force is proportional to the displacement (the spring constant is an input parameter). In addition, the motion of this upper node is restrained by the inertia of the fuel in the upper blanket. The portion that calculates the pressure and axial motion is terminated when either of the following conditions occur at any fuel node:
 - a. The calculated cladding stress at any axial node exceeds the yield point.
 - b. The cladding temperature exceeds the melting point.
 - c. Fuel surface temperature exceeds the melting point.

The fuel and cladding temperature calculations are continued until a switch is made to the Weak Explosion Module or the problem is otherwise terminated.

5. Numerical Solution Scheme

This topic is only treated briefly here since a detailed description of the equations and iteration schemes used is given in Appendix D. In obtaining the solutions in this module an iteration is necessary to achieve compatibility between the pressure given by Eq. D.2 and the axial height

(and hence radius) of a given axial node as determined by Eq. D.1. In the early attempts to solve these equations some difficulties were encountered with numerical instability. These problems were circumvented by adopting a Lagrangian coordinate system for representing Eq. D.1 by finite differences. In this method, the motion of the axial interfaces between nodes are determined, successively, from the pressure difference between adjacent nodes. The interface motions are thus accounted for on a variable space mesh. In practice this method of representing the equation of motion has been found to be satisfactory over a reasonable range of parameters. Since the other equations in the scheme are explicit algebraic equations, no problems are encountered with them in the calculations.

E. Point Kinetics Module

1. Basic Equations

A one-group, space-independent (point) kinetics model is used to describe the neutron kinetics of the reactor. The power is separated in space and time:

$$Q(\vec{r}, t) = n(t)S(\vec{r}), \quad (\text{E.1})$$

where $S(\vec{r})$ is a specified shape function and $n(t)$ is a solution of the point kinetics equations

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^6 \lambda_i C_i \quad (\text{E.2})$$

and

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} n - \lambda_i C_i; \quad i = 1, 6. \quad (\text{E.3})$$

In these equations,

n = neutron density;

C_i = concentration of i th delayed-neutron precursor;

β_i = delayed-neutron fraction from the i th group;

$\beta = \sum_{i=1}^6 \beta_i$ = delayed-neutron fraction;

λ_i = decay constant for the i th precursor;

Λ = prompt-neutron generation time = ℓ/k_{eff} ;

ℓ = prompt-neutron lifetime;

k_{eff} = effective multiplication factor;

ρ = reactivity = $(k_{\text{eff}} - 1)/k_{\text{eff}}$;

Most stepwise integration procedures for solving Eq. E.2 involve the use of previously calculated values of n to obtain the next value. Thus, to compute n^{k+1} , knowledge of n^k , n^{k-1} , n^{k-2} , ... is required (k denotes time nodes). These methods have the disadvantage that several initial values of n , needed to start the calculations, must be obtained by an auxiliary process. This disadvantage can be eliminated by using one of the Runge-Kutta integration methods. Even then, the fact that Λ in Eq. E.2 is very small ($\sim 10^{-7}$ sec) in fast reactors limits the size of the time step, Δt^k , to about 1000Λ for stable integration.¹²

2. Method of Solution

The method used here for the solution of Eqs. C.2 and C.3 was formulated by Kaganove.¹³ It has the advantages of being self-starting, of being stable for large integration intervals, and of having a procedure for changing the integration interval as the nature of the problem changes. Kaganove's method is described briefly here; for further details see Ref. 13. Equation E.3 is solved for $\lambda_i C_i$ and the results are substituted in Eq. E.2, giving

$$\frac{dn}{dt} = \frac{\rho}{\Lambda} n - \sum_{i=1}^6 \frac{dC_i}{dt} \quad (\text{E.4})$$

Equation E.4 is numerically integrated across a time interval τ :

$$n(\tau) - n^k = \int_{t^k}^{t^k + \tau} \frac{\rho n}{\Lambda} dt - \sum_{i=1}^6 [C_i(\tau) - C_i^k], \quad (\text{E.5})$$

where n^k and C_i^k are $n(t^k)$ and $C_i(t^k)$, respectively. By making the transformation $t' = t - t^k$, Eq. E.5 becomes

$$n(\tau) - n^k = \int_0^\tau \frac{\rho n}{\Lambda} dt' - \sum_{i=1}^6 [C_i(\tau) - C_i^k], \quad (\text{E.6})$$

where

$$n(0) = n^k$$

and

$$C_i(0) = C_i^k. \quad (\text{E.7})$$

Equation E.3 can be solved in functional form:

$$C_i(\tau) - C_i^k = -C_i^k(1 - e^{-\lambda_i \tau}) + \frac{\beta_i}{\Lambda} \int_0^\tau e^{-\lambda_i(\tau-\tau')} n \, d\tau'. \quad (E.8)$$

Substituting Eq. E.8 in Eq. E.6 yields

$$\begin{aligned} n(\tau) - n^k = & \int_0^\tau \frac{\rho n}{\Lambda} dt' - \sum_{i=1}^6 \frac{\beta_i}{\Lambda} \int_0^\tau e^{-\lambda_i(\tau-\tau')} n \, d\tau' \\ & + \sum_{i=1}^6 C_i^k(1 - e^{-\lambda_i \tau}). \end{aligned} \quad (E.9)$$

For the time interval under consideration, let ρ and n be represented by second-order polynomials, that is,

$$\rho = \rho^k + \rho_1 t' + \rho_2 (t')^2 \quad (E.10)$$

and

$$n = n^k + n_1 t' + n_2 (t')^2. \quad (E.11)$$

Substitution of Eqs. E.10 and E.11 in Eq. E.9, with the condition that Eq. E.9 be satisfied both at $\tau = \Delta t^{k+1}$ and at $\tau = \Delta t^{k+1}/2$, yields two linear equations in the two unknowns n_1 and n_2 . Substitutions of the values of n_1 and n_2 in Eq. E.11 gives $n(t)$ for this time interval.

The net reactivity, ρ , in Eq. E.10 is the sum of five contributions:

$$\rho = \rho_p + \rho_D + \rho_c + \rho_e + \rho_d, \quad (E.12)$$

where

ρ_p = programmed reactivity input (initial ramp and scram);

ρ_D = Doppler feedback reactivity;

ρ_c = sodium-void feedback reactivity;

ρ_e = structural (radial) expansion feedback reactivity;

ρ_d = fuel-density feedback reactivity.

The net reactivity is a function of $n(t)$. From Eqs. E.9 and E.12, $n(t)$ is a function of ρ . These two functions must be compatible. Due to the

interdependence of the functions and the fact that ρ is not known explicitly, an iterative scheme is used to achieve compatibility. The sequence of events in the calculation of n and ρ across any time interval Δt^{k+1} is described in Sect. III, which gives the details of the operation of the complete computer program.

F. Feedback Reactivity Calculations

The current version of SASIA includes four feedback-reactivity components: Doppler, axial fuel expansion (density reduction), coolant density (voiding), and structural (radial) core expansion reactivities. A brief description of the method of calculating each of these follows.

1. Doppler Reactivity

The Doppler reactivity is based on the volume-averaged temperature over a fuel-pin segment. The total Doppler reactivity for the reactor at any time is then given by the expression

$$\rho_D(t) = \sum_{j=1}^N A_j^k \ln \frac{\bar{T}_j^k}{\bar{T}_j^0}, \quad (\text{F.1})$$

where

$\bar{T}_j^k$ = volume-averaged temperature over the j th axial segment at time node k ($^{\circ}\text{K}$);

$\bar{T}_j^0$ = volume-averaged temperature over the j th axial segment at time zero ($^{\circ}\text{K}$);

N = number of axial segments.

The local Doppler coefficient, A_j^k , is given by

$$A_j^k = \omega_j [A_D + (B_D - A_D) \alpha_j^k],$$

where

ω_j = local Doppler (axial) weighting factor;

A_D = Doppler coefficient for core with all sodium present;

B_D = Doppler coefficient for core with no sodium present;

α_j^k = local sodium-void fraction at time node k .

The foregoing is based on the assumption that A_D and B_D are given by equations of the form

$$A_D = \bar{T}_j \frac{d\rho_D}{d\bar{T}_j} = \text{constant.}$$

The coefficients A_D and B_D as well as the axial weighting-factor vector, $\vec{\omega}$, are specified in the problem input.

2. Axial Fuel Expansion

The fuel-density-change feedback due to axial fuel expansion is given by the equation

$$\rho_d(t) = \sum_{j=1}^N w_j \left(1 - \frac{\Delta z_j^0}{\Delta z_j^k} \right), \quad (F.2)$$

where

w_j = material worth (everything except coolant) of axial segment j ;^{*}

Δz_j^k = height of axial segment j at time k ;

Δz_j^0 = height of axial segment j at time zero.

3. Structural Expansion (Radial)

The model used for calculating the reactivity due to core radial expansion is based on the assumption that this feedback can be described qualitatively as shown in Fig. 8. The total expansion reactivity is given by

$$\rho_e(t) = \sum_{j=1}^N w_j^! \rho(U^{j,k}), \quad (F.3)$$

where

$w_j^!$ = axial weighting factor for structural (radial) expansion;

$\rho(U^{j,k})$ = function type depicted in Fig. 8;

^{*}These values are derived from the material-worth data input for the Weak Explosion Module. If weak explosion is not used in a particular calculation, the w_j 's must be input separately.

$$U_{j,k} = \alpha_{st} (T_{st}^{j,k} - T_{st}^{j,0});$$

α_{st} = coefficient of linear thermal expansion of structure;

$T_{st}^{j,k}$ = structure temperature at jth node at time k;

$T_{st}^{j,0}$ = structure temperature at jth node at time zero.

The rationale behind the form for $\rho(U^{j,k})$ shown in Fig. 8 is that, initially, there would be no reactivity effect until the structure (fuel-subassembly cans) has expanded enough to take up the core clearances. Once this point, U_{min} , is reached, the reactivity is added at a specified rate per unit of further expansion (slope S_1 in Fig. 8). Finally, enough expansion has occurred so that the outer core-restraining structure is contacted (U_{max}) and then reactivity is added at a decreased rate (slope S_2 in Fig. 8). In running problems, the parameters which described the reactivity curve in Fig. 8 must be supplied as input.

Fig. 8

Model of Radial Core-expansion Feedback

4. Coolant Density/Voiding

The reactivity due to changes of coolant density prior to boiling is calculated by translating the single-phase density change due to heating into an equivalent void fraction; thus,

$$\rho_c(t) = \sum_{j=1}^N (\rho_c)_j \alpha_j^k, \quad (F.4)$$

where

$(\rho_c)_j$ = whole-core reactivity worth of sodium in axial segment j
(given as tabular input, determined from a separate diffusion or transport calculation);

α_j^k = average sodium-void fraction in segment j at time node k.

After boiling starts in the hot channel, the coolant reactivity is broken down into four equal components which are successively delayed in time to allow for the noncoherence of boiling initiation across the core radius. Thus, the total coolant reactivity after boiling starts is given by

$$\begin{aligned} \rho_c(t) = & \rho_c(t_b) + \rho_{cb}(t - t_b) + \rho_{cb}(t - t_b - \sigma_1) + \rho_{cb}(t - t_b - \sigma_2) \\ & + \rho_{cb}(t - t_b - \sigma_3), \end{aligned} \quad (F.5)$$

where

$$\rho_{cb}(t) = \frac{1}{4} \left[\sum_{j=1}^N (\rho_c)_j \alpha_j^k - \rho_c(t_b) \right]; \quad (F.6)$$

t_b = time when boiling starts in hot region;

σ_1 , σ_2 , and σ_3 are time delays (relative to the hot channel) for the boiling to start in other (radial) channels of the core.

In Eq. F.5 the contribution from each term is zero when the argument is negative. In performing the computations, the values of the time delays are determined by specifying overpower factors for the hot channels. Thus, when the hot-channel power has increased by specific amounts above the power level when boiling started, boiling is triggered successively in the other channels. The function $\rho_{cb}(t)$ of Eq. F.6 is stored, and the reactivity contributions from the other later boiling channels are then obtained from this stored information. In this manner the feedback reactivity based on the single hot-channel fluid flow and heat-transfer analysis is modified to be more representative of that in a multichannel reactor having radial power gradients and fuel subassemblies with different burnup histories.

G. Weak Explosion Module

The primary objective of this module is to estimate the magnitude of the energy release in the event that prior events as calculated in other modules of the code lead to a superprompt critical reactor excursion. Parameters which describe the condition of the reactor core are the input to the module at the time the disassembly excursion begins. The basic method of analysis used is a modified version of the MARS¹⁴ code, that is, a number of improvements were made to the original MARS code in developing this module. They are:

1. Incorporation of a method of correcting for the discontinuous derivatives of material reactivity worth at the interface between two core regions (or between core and blanket) with different enrichments (zoned core), thereby eliminating the need for the usual assumption that the derivative of material worth is continuous across such interfaces.

2. Modification of the method of solving the point kinetics equations so that numerical stability has been considerably improved.

3. Made the input data format more general so that the spatial detail in specifying the material-worth and power-distribution functions is at the option of the user.

4. Changed the calculation scheme so that the initial core temperature distribution need not be uniform.

1. Mathematical Model

The MARS code was developed by APDA for analyzing destructive excursions in mixed oxide-fueled cylindrical cores. In order to perform calculations using more realistic geometry, the development of a two-dimensional (r,z geometry) code was undertaken. As in the models generally employed in explosion calculations, use is made of the fact that a power excursion is usually terminated by Doppler feedback plus the small displacement of core material due to the high pressure produced in the core during the excursion. Since actual motion of the core material is quite small before termination, it is assumed that both the initial power distribution (which determines the pressure distribution) and the reactivity-worth distribution are unchanged throughout the problem. The latter assumption means that fuel-motion reactivity feedback can be calculated by a perturbation treatment rather than requiring direct k_{eff} calculations at subsequent time intervals during the excursion. The module is designed to treat a cylindrical reactor which is separated into as many as sixty annular regions. Each region must be a cylinder or annular cylinder having a common z axis, and each may have different material properties. The power and material-worth distributions are tabulated and input separately for each region. A one-group, space-independent point kinetics model is used to describe the neutron kinetics of the reactor in this module as in the earlier portion of the calculation.

2. Input Reactivity

When the switch over to the Weak Explosion Module is made, the input reactivity is calculated by extrapolating the reactivity versus time curve developed in the previous portion of the calculation. The extrapolation is made using the linear equation

$$\rho_{ce}(t) = \rho_{ce}(T_0) + a(t - t_0), \quad (G.1)$$

where

$$\rho_{ce}(t) = \rho_c(t) + \rho_e(t) = \text{reactivity due to coolant voiding} + \text{radial core expansion};$$

t_0 = time when the weak explosion calculation starts;

a = constant calculated from previous reactivity history.

The other reactivity terms, which are computed within the module, are added to this and the programmed reactivity (if any) to obtain the net reactivity:

$$\rho(t) = \rho_{ce}(t) + \rho_p(t) + \rho_D(t) + \rho_d(t), \quad (G.2)$$

where

$\rho_p(t)$ = programmed reactivity input (including scram);

$\rho_D(t)$ = Doppler-feedback reactivity calculated in Weak Explosion Module;

$\rho_d(t)$ = feedback reactivity due to reactor expansion (material displacement) calculated in Weak Explosion Module.

The methods of calculating $\rho_D(t)$ and $\rho_d(t)$ in the module are described in the following two sections. The major portion of the computations in the module are devoted to calculating $\rho_d(t)$.

3. Doppler-feedback Reactivity

The doppler reactivity effect is given by

$$\left(\frac{\partial \rho_D}{\partial \bar{T}} \right)_m = A_m \bar{T}_m^{-3/2} + \frac{B_m}{\bar{T}_m} + \frac{C_m}{\bar{T}_m^{1-n}}, \quad (G.3)$$

where

A_m, B_m, C_m = input constants for m th core region evaluated from experimental data or nuclear calculations;

$\bar{T}_m$ = average fuel temperature in m th region, °K;

n = an input integer.

Equation G.3 is used in the module in the integrated form:

$$(\rho_D)_m = -2A_m \bar{T}_m^{-1/2} + B_m \ln \bar{T}_m + \frac{C_m}{n} \bar{T}_m^n. \quad (G.4)$$

Summing the contributions of all the core regions gives the total Doppler feedback:

$$\rho_D = \sum_m [\rho_D(\bar{T}_m) - \rho_D(\bar{T}_m^0)], \quad (G.5)$$

where

$\bar{T}_m^0$ = initial average temperature in mth region.

4. Reactivity Feedback from Core Expansion

The equations of hydrodynamics which are applied to an expanding core are:

Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \frac{\partial \vec{u}}{\partial t} \right) = 0; \quad (G.6)$$

Momentum

$$\frac{\partial^2 \vec{u}}{\partial t^2} = -\frac{1}{\rho} \nabla p; \quad (G.7)$$

Energy (neglecting heat loss to coolant)

$$T_f = \int_{t_0}^t \frac{Q}{C_f} dt' + T_f^0, \quad (G.8)$$

where

ρ = core-averaged material density;

$\vec{u} = \vec{u}(\vec{r}, t)$ = core material displacement vector;

$p = p(\vec{r}, t)$ = pressure in core;

$Q = Q(\vec{r}, t)$ = power density;

C_f = fuel heat capacity;

T_f = local fuel temperature, °K.

In the analysis, the small change in density due to material motion is neglected, and the density is assumed constant for each region. Therefore the continuity equation can be dropped, and ρ becomes a constant in the momentum equation. The pressure and temperature relationship in each core region is given by the equation of state

$$p(\vec{r}, t) = a_m \exp\left(-\frac{b_m}{T_f} + c_m\right), \quad (\text{G.9})$$

where

a_m , b_m , and c_m are input parameters for each region.

Using the perturbation treatment, which is based on the assumption that the reactivity-worth distribution for core material is constant in time, one obtains for the reactivity change due to motion in a region

$$(\rho_d)_m = \int_{V_m} \vec{u}(\vec{r}, t) \cdot \nabla D(\vec{r}) dV, \quad (\text{G.10})$$

where

ρ_d = expansion reactivity for mth region;

$D(\vec{r})$ = reactivity change which would occur if a unit volume of homogenized core material at position $\vec{r}$ were to be removed from the core.

Therefore, $\vec{u}(\vec{r}, t) \cdot \nabla D(\vec{r})$ is the reactivity change which occurs when a unit volume of material is displaced from its initial location $\vec{r}$ to the position $\vec{r} + \vec{u}(\vec{r}, t)$. Differentiating Eq. G.10 twice with respect to time and combining with Eq. G.7, one obtains

$$\left(\frac{d^2 \rho_d}{dt^2}\right)_m = -\frac{1}{\rho_m} \int_{V_m} \nabla p(\vec{r}, t) \cdot \nabla D(\vec{r}) dV, \quad (\text{G.11})$$

where

ρ_m = density of core material in mth region.

The total change over the reactor is obtained by summing over all regions, giving

$$\frac{d^2 \rho_d}{dt^2} = -\sum_m \frac{1}{\rho_m} \int_{V_m} \nabla p(\vec{r}, t) \cdot \nabla D(\vec{r}) dV. \quad (\text{G.12})$$

In considering the evaluation of Eq. G.11 for regions which include an outer surface of the core (adjacent to a blanket or reflector), a model is necessary to treat the boundary condition of $\nabla p(r, t) \rightarrow -\infty$ which arises because of the abrupt reduction in energy density across the boundary. As discussed by Nicholson¹⁵ these models are:

- (a) The core surface is free to move unimpeded by the reflector, or
- (b) The existence of the core surface is completely ignored.

In evaluating the integral based on model (b), the pressure gradient is assumed to be continuous through the boundary and then the integral in Eq. G.11 is simply carried up to the surface. In the treatment by model (a) it is assumed that there is a rapid drop in pressure, from the asymptotic value to zero, through a thin surface layer. As long as the layer is sufficiently thin that the gradient of the reactivity distribution does not change much through it, the layer can be treated as a unit, and the rate of reactivity change due to the motion of this material is proportional to the total momentum of the material. This means that the result is independent of the actual magnitude of the thickness of the layer (as long as it is thin), and it is permissible to go to the limit of an infinitesimally thin layer in which $\nabla p(\vec{r}, t)$ in Eq. G.11 becomes the sum of a smooth function plus a delta function at the surface, that is,

$$\nabla p(\vec{r}, t) = \nabla p_m(\vec{r}, t) - \vec{n} p_s(\vec{r}, t) \delta(r - r_s), \quad (G.13)$$

where $p_m(\vec{r}, t)$ is always evaluated inside the core and is a continuous function approaching the value $p_s(\vec{r}_s, t)$ at the surface, and $\vec{n}$ is a unit vector in the direction of the outward normal to the surface. Therefore, in the free surface, model (a) approximation, Eq. G.11 becomes

$$\begin{aligned} \left(\frac{d^2 \rho_d}{dt^2} \right)_m &= - \frac{1}{\rho_m} \int_{V_m} \nabla p_m(\vec{r}, t) \cdot \nabla D(\vec{r}) dV \\ &+ \frac{1}{\rho_m} \int_{S_m} \nabla D(\vec{r}_s) \cdot p_{sm}(\vec{r}_s, t) d\vec{s}. \end{aligned} \quad (G.14)$$

In some cases it may be preferable not to include the surface-integration term; in any event it should not be used along the reactor vertical center-line since, analytically, $\partial D(0, z) / \partial r = 0$ along this axis. For a detailed discussion of the effect of including the surface-integral term on the estimate of total energy release, see Ref. 15.

An additional correction term to treat the discontinuous gradient of material worth $[\nabla D(\vec{r}, t)]$ at the interface between core regions (in the case of a zoned reactor with different enrichments) has been incorporated into the weak-explosion calculation. During a severe prompt critical power excursion, the pressure distribution in a zoned reactor has the following characteristics. Well away from zone boundaries the pressure is approximately defined by the energy deposition, the heat capacity, and the equation

of state, and is only slightly dependent upon material movement and density changes. Discontinuities of fissile-material enrichment at zone boundaries, and therefore of power density, tend to produce pressure discontinuities. This is treated through use of the acoustic approximation in which the pressure must be continuous, and the continuity is accomplished by local movement and density changes. The interface is the source of a pressure wave, and a compression wave moves into the region of lower pressure while a rarefaction wave moves into the region of high pressure. If the time scale of the power excursion is short enough, then the wave can move only a short distance. For purposes of analysis, the reactor volume is divided into two regions as shown in Fig. 9. One is a small region which

Fig. 9.. Model of Interface between Core Regions with Different Enrichments

brackets the interface (the transition region); the other is the remainder of the reactor (the asymptotic region). The analysis is accurate only if the power excursion is sufficiently sharp so that the transition region is small; in fact, the approximation is effected by taking the limit as the transition region thickness goes to zero.

Figure 9 shows the nature of the pressure distribution near a zone boundary and the division into transition and asymptotic regions. For convenience we also distinguish between the left and right side of the boundary by subscripts 1 and 2, respectively. The symbols p' and p'' designate the pressure distribution inside the transition region and the pressure at the zone boundary, respectively.

Equation G.11 can be rewritten in terms of the asymptotic region and the two sections of the transition region (T_1 and T_2):

$$\begin{aligned} \frac{d^2 \rho_d}{dt^2} = & - \int_{V_A} \frac{1}{\rho_A} \nabla D_A \cdot \nabla p \, dV - \int_{V_{T_1}} \frac{1}{\rho_1} \nabla D_1 \cdot \nabla p'_1 \, dV \\ & - \int_{V_{T_2}} \frac{1}{\rho_2} \nabla D_2 \cdot \nabla p'_2 \, dV. \end{aligned} \quad (G.15)$$

By manipulations of Eq. G.15 using the divergence theorem, taking appropriate limits as the volumes of the transition regions approach zero, and introducing estimates of the pressure p'' at the zone boundary from acoustic theory, one obtains the result

$$\frac{d^2 \rho d}{dt^2} \approx - \int_V \frac{1}{\rho} \nabla D \cdot \nabla p \, dV + \int_S (p_1 - p_2) \frac{\nabla D_1(\vec{r}_s) + \gamma \nabla D_2(\vec{r}_s)}{\rho_1 + \gamma \rho_2} \cdot d\vec{S}, \quad (G.16)$$

where

$$\gamma = c_2/c_1 = \text{ratio of sonic velocities in the two zones.}$$

For details of the intermediate steps in obtaining Eq. G.16 see the derivation by Sha and Nicholson.¹⁶ This result was also obtained by Hicks and Menzies.¹⁷

On the assumption that the various zones of the reactor have similar acoustic properties, a value of $\gamma = 1.0$ is suggested, unless the program user has a better estimate for this parameter. Thus Eq. G.16 is Eq. G.11 with the correction term involving the surface integral, which can now be evaluated in a practical numerical scheme. In practice this correction term can be applied whenever there is a discontinuous gradient of material worth, i.e., between core and blanket as well as between different core zones. In the numerical solution, the two surface-integral correction terms to the basic calculation, which are given in Eqs. G.14 and G.16, respectively, may be included or omitted at the option of the user. In any case, the term in Eq. G.14 should be used at the outermost boundaries of the reactor; the correction in Eq. G.16 is for interfaces between regions within the reactor core and blanket.

The foregoing discussion has given a description of the model and basic equations used in the Weak Explosion Module. The following describes the manipulation of the equations required to get them in a form for numerical solution and is to some extent a repeat of material given in the original MARS writeup.¹⁴

The volume-integration term in Eq. G.14 in terms of r, z geometry becomes

$$\begin{aligned} \int_{V_m} \nabla p \cdot \nabla D \, dV &= 2\pi \iint r \left(\frac{\partial p}{\partial r} \frac{\partial D}{\partial r} + \frac{\partial p}{\partial z} \frac{\partial D}{\partial z} \right) dr dz \\ &= 2\pi \iint r \frac{\partial p}{\partial T_f} \left(\frac{\partial T_f}{\partial r} \frac{\partial D}{\partial r} + \frac{\partial T_f}{\partial z} \frac{\partial D}{\partial z} \right) dr dz, \end{aligned} \quad (G.17)$$

and since from the equation of state (Eq. G.9)

$$\frac{\partial p}{\partial T_f} = \frac{a_m b_m}{T_f^2} \exp\left(-\frac{b_m}{T_f} + c_m\right),$$

which upon substitution into Eq. G.17 gives

$$\int_{V_m} \nabla p \cdot \nabla D \, dV = 2\pi a_m b_m \iint \frac{r}{T_f^2} \exp\left(-\frac{b_m}{T_f} + c_m\right) \left(\frac{\partial T_f}{\partial r} \frac{\partial D}{\partial r} + \frac{\partial T_f}{\partial z} \frac{\partial D}{\partial z} \right) dr dz. \quad (G.18)$$

The fuel temperature at any point is determined by the energy equation G.8, which is rewritten as

$$T_f(r, z, t) = T_f(r, z, 0) + \frac{\sigma(r, z)}{\rho_0} \int_{t_0}^t \frac{Q(t')}{C_f(T_f)} dt', \quad (G.19)$$

where

ρ_0 = density of material at $t = t_0$;

$\sigma(r, z)$ = power-shape function, normalized so that

$$\int_V \sigma(r, z) \, dV = 1;$$

$$C_f(T_f) = C_0 + C_1 T_f + C_2 T_f^2.$$

If it is assumed that the specific heat C_f has no gradient in the region, then differentiation of Eq. G.19 with respect to r gives

$$\frac{\partial T_f(r, z, t)}{\partial r} = \frac{1}{\rho_0} \frac{\partial \sigma(r, z)}{\partial r} \int_{t_0}^t \frac{Q(t')}{C_f(T_f)} dt' + \frac{\partial T_f(r, z, 0)}{\partial r},$$

which, combining with Eq. G.19, can be written as

$$\frac{\partial T_f(r, z, t)}{\partial r} = \frac{1}{\sigma(r, z)} \frac{\partial \sigma(r, z)}{\partial r} [T_f(r, z, t) - T_f(r, z, 0)] + \frac{\partial T_f(r, z, 0)}{\partial r}. \quad (G.20)$$

A similar result is obtained for z :

$$\begin{aligned} \frac{\partial T_f(r, z, t)}{\partial z} &= \frac{1}{\sigma(r, z)} \frac{\partial \sigma(r, z)}{\partial z} [T_f(r, z, t) - T_f(r, z, 0)] \\ &\quad + \frac{\partial T_f(r, z, 0)}{\partial z}. \end{aligned} \quad (G.21)$$

Substituting Eqs. G.20 and G.21 into Eq. G.18 gives

$$\begin{aligned}
\int_{V_m} \nabla p \cdot \nabla D \, dV &= 2\pi a_m b_m \iint \frac{r}{T_f^2} \exp\left(-\frac{b_m}{T_f} + c_m\right) \\
&\cdot \left\{ \frac{\partial D}{\partial r} \left[\frac{1}{\sigma(r,z)} \frac{\partial \sigma(r,z)}{\partial r} (T_f(r,z,t) - T_f(r,z,0)) + \frac{\partial T_f(r,z,0)}{\partial r} \right] \right. \\
&+ \left. \frac{\partial D}{\partial z} \left[\frac{1}{\sigma(r,z)} \frac{\partial \sigma(r,z)}{\partial z} (T_f(r,z,t) - T_f(r,z,0)) + \frac{\partial T_f(r,z,0)}{\partial z} \right] \right\} dr dz \quad (G.22)
\end{aligned}$$

for the contribution $d^2\rho_d/dt^2$ from the m th region. In performing the numerical solution, the integral on the right side of Eq. G.22 is evaluated at each time step for each region by a trapezoidal-integration scheme. The total volume integral over the whole reactor is then obtained by summing over all regions, as indicated by Eq. G.12. Similarly, the surface-integral correction terms in Eqs. G.14 and G.16 (if included) are evaluated by trapezoidal integration and summation over the whole reactor at each time interval. Prior to performing the spatial integrations the input tables of material reactivity worth, $D(\vec{r})$, are smoothed by representing each triplet of adjacent points on the axial and radial grid lines as a second-degree polynomial function of z or r , respectively. The data are fit both axially and radially, and the quadratic functions of r and z so generated are differentiated analytically to give expressions for $\partial D(r,z)/\partial z$ and $\partial D(r,z)/\partial r$. These expressions are then used directly in evaluating the integral of Eq. G.22.

5. Method of Solution of Equations

To summarize, the equations which must be solved at each time step are the point kinetics equations E.2 and E.3 with the reactivity-feedback terms for the Doppler and core-expansion reactivities given by Eqs. G.5 and G.22. The method of solution employed in the Weak Explosion Module abandons the Runge-Kutta-Gill scheme used in the original MARS code and uses the following scheme instead. The feedback reactivities are expressed as second-order polynomials:

$$\rho_D(t) = \alpha_1 + \beta_1 t + \gamma_1 t^2; \quad (G.23)$$

$$\rho_d(t) = \alpha_2 + \beta_2 t + \gamma_2 t^2, \quad (G.24)$$

where $\rho_D(t)$ and $\rho_d(t)$ are the two contributions to total reactivity in Eq. G.2; they are functions of integrated power and hence not known explicitly as are the other two terms. The Doppler-reactivity contribution at the end of the next time interval, ρ_D^{k+1} , is obtained by a straightforward extrapolation using Eq. G.23, where the coefficients α_1 , β_1 , and γ_1 are obtained from the

values ρ_D^{k-2} , ρ_D^{k-1} , and ρ_D^k . The core-expansion reactivity, however, is based upon a knowledge of $d^2\rho_d/dt^2$ at any point in time; therefore, if Eq. G.24 is differentiated, one obtains

$$\gamma_2 = \frac{1}{2} \frac{d^2\rho_d}{dt^2}. \quad (G.25)$$

Thus, γ_2 is explicitly known as a function of time from the volume (and surface) integrals evaluated by Eq. G.22. At any point in time the coefficients in Eq. G.24 can be evaluated from the known values ρ_d^{k-1} , ρ_d^k , and $(d^2\rho_d/dt^2)_k^k$. The core expansion reactivity at the end of the next time step, ρ_d^{k+1} , is obtained by extrapolation using Eq. G.24. In the module the iterative scheme used in the point kinetics solution (described in Sect. E) to achieve compatibility between neutron level (power) and reactivity is no longer used, that is, the total reactivity ρ^{k+1} is known from Eqs. G.2, G.23, and G.24, and the new neutron density, n^{k+1} , is then calculated. The whole process outlined above is then repeated by updating the coefficients in Eqs. G.23 and G.24, and moving forward another time step. The time step is under program control and is either doubled or halved if the fractional change in power for a step is less than a specified minimum or greater than a specified maximum. In practice this method of solution has not given any problems with numerical stability, even on the down side of the power peak, as was experienced with the method used in the original MARS code. The calculation is continued until one of the following conditions is met:

1. The reactivity is less than a specified minimum,
2. The power falls outside specified minimum and maximum values, or
3. Real time exceeds a specified maximum value.

Termination of the Weak Explosion Module calculation ends the SAS1A problem.

III. CODE STRUCTURE

A. Schematic Diagram of Complete Code

Fig. 10. Overall Structure of SAS1A Code

In relating the actual code structure to the modular description of the code given in Sect. II, it should be recognized that each module may include a number of subroutines. For convenience and cross referencing the following list gives the subroutines which comprise the various modules:

Module	Subroutines
1. Heat Transfer	SSHTR and TSHTR
2. Coolant Dynamics	TSCOOL and SSCOOL
3. Fuel Deformation	DEFORM and BOUND
4. Fuel Dynamics	FULDYN
5. Point Kinetics	TSPK, SSPK, COOLFB and FUELFB
6. Weak Explosion	XPLODE, DKXPLO and PKXPLO

B. Input Driver

The READIN subroutine is called from MAIN; it differs from the TSDRIV and SSDRIV drivers in that it is a subroutine in the conventional sense and does perform data reading rather than just logical decisions. Both the INPOUT and HOLLER subroutines are called by READIN. The following is a listing of the subroutines which comprise the Input Driver and a brief description of their function.

1. READIN. Subroutine reads input data and stores it in the input common block; called from MAIN.
2. INPOUT. Subroutine edits input and makes consistency checks, i.e., range of integer values does not exceed maximum dimension or minimum permitted usage, fuel outer radius must be less than or equal to the clad inner radius, two values of density (liquid and solid) are input at fuel melting point, etc. It sets up the initial axial and radial mesh structure, calculates the axial material-worth curve and power profile for the fuel pin (from two-dimensional core-worth and power distributions, input for the weak-explosion calculation), and computes the internal energy table for fuel. The subroutine also normalizes power shapes, computes the slope of the Doppler coefficient as a function of coolant void fraction, and calculates the mass of each axial fuel node. It is called from READIN.
3. HOLLER. Subroutine is used to convert single-digit integers to hollerith characters for print-outs; called from INPOUT.

C. Steady-state Driver

A schematic diagram of the steady-state driver, SSDRIV, is presented in Fig. 11. As shown, there is an option available for making a search for the desired steady-state operating conditions for the reactor. If it is desired to operate the reactor fuel within a given range of power density and with a specific rise of coolant temperature, along with specified maximums for the fuel-centerline temperature and coolant inlet pressure, these quantities are input and the steady-state power search will determine the proper coolant flow rate and power density to obtain the desired conditions. If this option is selected, the flow is according to the schematic shown on the right-hand side of Fig. 11. If it is not selected, the call of the subroutines by SSDRIV is straightforward and in the sequence on the left-hand side. Subroutines SSCOOL and SSHTR are called twice to make a small correction in the axial mesh size which results from the expansion of the fuel between design-point temperature and the steady-state operating temperature. A brief description of the subroutines under control of SSDRIV follows.

Fig. 11. Steady-state Driver. ANL Neg. No. 113-2475 Rev. 1.

1. SSHTR: Steady-state Heat Transfer

This subroutine computes initial temperature distribution in the fuel, and calculates changes in the radial and axial meshes for fuel from these temperatures. If fuel melting occurs in the initial steady state, the latent heat of fusion is included in the temperature calculations. It requires the following input quantities:

<u>Data</u>	<u>From</u>
Coolant temperatures	SSCOOL
Power	SSPK, SHAPE
Input quantities specifying fuel-element configuration and material properties	User input

Two iterations are performed in calculating initial fuel temperatures. There is an inner iteration to achieve compatibility between temperatures and fuel properties (which are temperature-dependent), and an outer iteration to find the correct fuel-cladding bond-gap conductance consistent with the amount of fuel thermal expansion which has taken place.

2. SSCOOL: Steady-state Coolant Temperature

This subroutine computes coolant temperatures, pressures, saturation temperatures, and heat-transfer coefficients. It requires the following inputs:

<u>Data</u>	<u>From</u>
Axial mesh	User input initially and SSHTR later
Heat flux	SHAPE
Input quantities specifying cool- ant channel configuration	User input

3. SSPK: Steady-state Point Kinetics

This subroutine computes initial delayed-neutron precursor concentrations based on the normalized initial power of 1.0. It obtains all data from user input.

4. SSPRINT: Steady-state Printout

This subroutine provides an edit of the steady-state computed results.

D. Transient Driver

A flow diagram showing the operation of the transient driver (TSDRIV) is given in Fig. 12. The order of calling the subroutines TSPK, TSHTR, TSCOOOL, and DEFORM is quite straightforward until coolant boiling starts or the FULDYN subroutine is called. The calculation of coolant dynamics during boiling is handled within the TSCOOOL subroutine, and the calculations are initiated when the single-phase coolant temperature exceeds the calculated saturation temperature of the coolant. The FULDYN subroutine is normally called when the fuel-centerline temperature exceeds a maximum value (generally somewhat above the fuel melting point) which is specified by user input. When FULDYN is called it takes over essentially all the calculations which were being performed up to that time in the DEFORM and TSHTR subroutines. Calculations performed under control of the transient driver (TSDRIV) then continue in this mode until either the XPLODE driver or an exit termination is called. The following is a listing of the subroutines under the control of the TSDRIV with a brief description of the calculation performed in each.

1. TSPK: Transient Point Kinetics

This subroutine computes neutron flux (normalized power) level concentrations of delayed-neutron precursors, and feedback reactivities (via subroutines COOLFB and FUELFB) from steady state up to initiation of the weak-explosion calculations. There is an internal iterative scheme used to determine the local time step for most accurate flux calculations based on the difference between calculated results using the local time step and half the local time step. There is also an iterative scheme for calculating the reactivity-power compatibility (see Sect. G below). The following input quantities are required:

<u>Data</u>	<u>From</u>
Time and control parameters	TSDRIV
Major time step	TSCOOOL
Doppler and fuel-density reactivity changes	FUELFB
Structural and coolant-density reactivity changes	COOLFB
Other parameters	User input and SSPK

2. TSHTR: Transient Heat Transfer

This subroutine computes fuel temperature distributions, fraction of fuel melted (if and when melting occurs), and heat flux for each axial

Fig. 12. Transient Driver. ANL Neg. No. 113-2474 Rev. 1.

coolant node. It performs these calculations from steady state up until FULDYN is called. The subroutine receives the following input quantities:

Position of fuel nodes	DEFORM
Coolant temperatures, heat-transfer coefficients, and time step	TSCOOL
Control variables	TSDRIV
Power level	TSPK, SHAPE
Other parameters	User input and SSHTR

3. TSCOOL: Transient Coolant Dynamics

This subroutine computes basic coolant parameters from steady state through boiling and coolant ejection, until the weak-explosion calculation is initiated. It calculates coolant flow rates, pressures, temperatures, heat-transfer coefficients, void fraction, and quality. It also controls the major time step. The necessary input quantities are the following:

<u>Data</u>	<u>From</u>
Position of fuel nodes	DEFORM/FULDYN
Heat fluxes	TSHTTR/FULDYN
Control variables	TSDRIV
Other parameters	User input and SSCOOL

4. DEFORM: Fuel Deformation

This subroutine computes dimensional changes of fuel and cladding from steady state to the initiation of the fuel-dynamics calculations (FULDYN). It calculates the position of fuel nodes and stresses and strains in both the cladding and fuel. Both elastic and plastic flow of cladding are considered in the calculation. There is an internal iteration to obtain compatibility between the radial strains of adjacent axial fuel nodes. The necessary input quantities are the following:

<u>Data</u>	<u>From</u>
Fuel and clad temperature and fraction of fuel melted	TSHTTR
Control variables	TSDRIV
Other parameters	User input and SSHTR

5. BOUND: Radial Displacements for DEFORM

This subroutine obtains stresses and existing radial mesh from DEFORM, and calculates displacements to obtain the new radial node positions. It is called by DEFORM.

6. COOLFB: Coolant Reactivity Feedback

This subroutine calculates coolant and structural-expansion (radial, due to expansion of subassembly cans) reactivities from steady state up to the calling of the Weak Explosion Module. It calculates the coolant-reactivity feedbacks from main channel and up to three additional channels. It is called from TSPK. The input quantities required are the following:

<u>Data</u>	<u>From</u>
Coolant density	TSCOO L
Structure temperature	TSHT R
Boiling time and control parameters	TSPK
Other parameters	User input and steady-state calculations

7. FUELFB: Fuel-reactivity Feedback

This subroutine calculates Doppler and fuel-density reactivities from steady state up to initiation of the weak-explosion calculation. The Doppler reactivity depends upon the amount of sodium present and is called from TSPK. The input quantities used are the following:

<u>Data</u>	<u>From</u>
Position of axial fuel nodes	DEFORM/FULDYN
Fuel temperatures	TSHT R/FULDYN
Coolant density	COOLFB
Other parameters	User input and steady-state calculations

8. FULDYN: Fuel Dynamics

This subroutine is used to calculate the motion of molten fuel in the pin after a specified threshold temperature has been reached. The calculations terminate when the Weak Explosion Module is called. It

calculates axial fuel expansion, clad radii, volume-averaged temperature of the fuel, fuel surface temperature, fuel pressure, and clad temperature. FULDYN is called when either (a) fuel-centerline temperature exceeds a specified input value, (b) the clad temperature exceeds melting, or (c) the fuel surface temperature exceeds melting. In the latter two cases and after clad rupture in case (a), only the fuel-temperature calculation portion of FULDYN is used, since the model for fuel pressurization and motion does not apply once the clad has failed. The input quantities required are the following:

<u>Data</u>	<u>From</u>
Initial fuel and clad temperatures	TSHTTR
Initial position of fuel nodes	DEFORM
Power	TSPK, SHAPE
Coolant temperatures and heat-transfer coefficients and major time step	TSCOOOL
Control parameters	TSDRIV
Other parameters	User input and steady-state calculations

9. TSPRINT: Transient Printout

This subroutine provides an edit of calculated transient values.

E. Weak-explosion Driver

The XPLODE subroutine is called from MAIN; it differs from the TSDRIV and SSDRIV drivers in that it is a subroutine in the conventional sense and does perform calculational operations rather than just logical decisions. The DKXPLO and PKXPLO subprograms are called as needed by XPLODE. The following is a listing of these subprograms and a brief description of their function.

1. XPLODE: Weak-explosion Driver

This subroutine calculates power level, integrated power, and fuel temperature and pressure, as well as material motion and Doppler feedback reactivities during reactor disassembly. It is called from MAIN when either the radial-averaged fuel temperature exceeds a specified maximum value or the reactor period goes below a specified minimum (both criteria are user-input parameters). The required input data are the following:

<u>Data</u>	<u>From</u>
Normalized power level	PKXPLO
Total reactivity	DKXPLO
Other parameters	User input and transient calculations

2. DKXPLO: Net Reactivity, Weak Explosion

This function subprogram calculates all reactivities other than Doppler effect and material motion. It obtains all its input data from XPLODE.

3. PKXPLO: Point Kinetics, Weak Explosion

This subroutine is similar to TSPK; it calculates normalized power level during core disassembly. It obtains its input data from:

<u>Data</u>	<u>From</u>
Time and net reactivity	XPLODE
Other parameters	User input and transient calculations

F. General Function and Subroutine Subprograms

The following ancillary subprograms are called directly at various places in the program where needed:

1. K(T) is a function subprogram with multiple entries used to obtain a point in any of the tabular material properties which have been input or calculated. This method of multiple entry into one subprogram to obtain the material property data is used to avoid reproducing the logic and common blocks in subroutines where it would be used over and over. The actual table value is obtained by calling INTERP, and the particular table is determined by the entry point used. It is called primarily from SSHTR, TSHTR, and DEFORM.

2. INTERP is a subroutine subprogram used to interpolate linearly between entries in a table. It is called primarily from K(T), INPOUT, and XPLODE.

3. SHAPE is a subprogram which calculates the axial power distribution based on the maximum nodal power and the normalized axial power shape.

4. FITZ is a subroutine subprogram for fitting parabolically three values, such as reactivity versus time. The outputs are the coefficients of the parabolic fit. It is called from TSPK and PKXPLO.

5. PREA is a function subprogram which gives either the reactivity or power versus time input (depending on option chosen) for a power transient. This is an arbitrary function which is specified by the user.

G. Time-step Control

There are two places in the program where the major time step is under program control. These are in the Transient Coolant Dynamics subroutine (TSCOOL) immediately before and after boiling has started, and during the weak-explosion calculation. The initial time step at the start of the transient during single-phase coolant heating is input by the user and is unchanged until boiling is approached in the calculations. When the maximum coolant temperature is within 100°C of boiling, the time step is set equal to 0.10 sec (unless a smaller value has been selected by the user for this portion of the problem, in which case it does not change). It is further decreased to 0.01 sec within 50°C of boiling, so that the point where boiling begins in the channel may be located accurately. When boiling begins, the time step is adjusted in TSCOOL so that the interface between two-phase and single-phase coolant progresses through the spatial mesh a uniform distance each time step. In general, however, it is necessary for the point kinetics calculations to have a smaller time step than this major time step in order to obtain a stable solution to the kinetics equations. For this reason the Point Kinetics subroutine (TSPK) divides the major time step into smaller steps as required. Having traversed the major time step by a series of small steps (as required in TSPK), the net reactivity is recalculated (based on the power of the reactor at this time) and this value is compared with the extrapolated value which had been used to get the point kinetics solution to the end of this time step. If the new value of reactivity compares with the previous value within a certain error criterion, then the calculation is advanced one major time step and the point kinetics proceeds as before in moving across the major time step. If the value does not compare within the error criterion, then the calculation of reactor power at the end of the major time step is repeated using the new reactivity value. The reactivity is again evaluated based on the new power and compared with the most recent value. The process is repeated until either convergence or a maximum of thirty iterations.

When the slug-ejection model in TSCOOL is called into the calculation, the time step is then specified as 0.001 sec for this portion of the calculation. This becomes the major time step in the overall control scheme.

If the FULDYN subroutine is called, it operates in a manner similar to point kinetics in that it selects its own smaller time step to traverse the

major time step such that numerical stability in the FULDYN calculations is maintained. Since FULDYN replaces TSHTR and DEFORM when it is called, it is included in the loop for point kinetics described above wherein the power and reactivity are iterated to achieve compatibility.

When the program enters the Weak Explosion Module, the time step control is transferred to XPLODE. The control scheme is quite simple here in that the criterion for selecting the time step is merely a minimum and maximum percentage change (specified by input) for the power over a time step. The calculation starts with a user-input time step and then either halves or doubles this time step as needed if the percentage power change over the previous time step has fallen outside the specified limits. The doubling or halving of the step is permitted until a maximum specified reduction or increase in the time step has been achieved, at which point no further changes in that direction are permitted.

H. Common Blocks

The following is a brief description of the common block structure used in SAS1A. This structuring is set up as an aid in "bookkeeping." It helps simplify the work and reduces errors when program changes are made.

1. INPUT contains all input data plus initial conditions derived from input values (mass and internal energy).

2. FUBAR is a major array containing the following subarrays:

POWER, which contains variables used in the Point Kinetics Module and other power and reactivity variables needed for linkages.

MESH, which contains variables associated with position of the fuel, clad, and coolant nodes.

HEAT, which contains variables used in Heat Transfer Module and for linkages to it.

COOL, which contains variables used in Coolant Dynamics Module and for linkages to it.

In the weak-explosion calculation most of the variables in the above subarrays are not needed. Hence, to conserve space in the computer memory, the variables stored in FUBAR are equivalenced to the various dimensioned variables used in the Weak Explosion Module.

3. DEF initially contains those variables calculated and used in the Fuel Deformation Module, and later contains those variables calculated and used in the Fuel Dynamics Module. (This was done to conserve computer memory space as FULDYN and DEFORM are mutually exclusive subroutines, i.e., the flow of control always passes from DEFORM to FULDYN and never returns to DEFORM.)

4. TIME contains total time, time step, and time since scram initiation.

5. KON contains integers used to maintain program control.

I. Calculational Options Available

The major options available in running problems with SAS1A are the following:

1. Steady-state Power Search

The conditions for the reactor steady state may be specified in one of two ways. Either the following quantities are specified:

- (a) Power density in fuel
- (b) Coolant inlet temperature
- (c) Coolant exit pressure
- (d) Coolant mass flow rate,

in which case the steady state is determined; or the following quantities for the steady-state power search are specified:

- (a) Maximum power density in fuel
- (b) Minimum power density in fuel
- (c) Maximum fuel centerline temperature
- (d) Coolant inlet temperature
- (e) Coolant exit temperature
- (f) Maximum core inlet plenum pressure.

In this case, the steady-state calculation (SSDRIV) searches for the largest fuel power density between (a) and (b) such that (c) and (f) are not exceeded.

2. Power Transients

The user either specifies the power versus time function or requests that it be calculated using point kinetics. In the latter case the user supplies the driving reactivity as a function of time. In either case (power or reactivity) the driving function is formulated in equation form and placed in the PREA function subprogram.

3. Flow-coastdown Transients

In this type of calculation the channel net pressure head is assumed to decrease as an exponential function of time. The user specifies

the flow decay parameter as input to determine the desired decrease of flow rate in time. This parameter can be selected to produce either a rapid flow decrease to simulate a rather sudden blockage of flow, or a more gradual decrease representative of a loss of power-pump coastdown. The options for flow coastdown and power transient can be employed simultaneously, if desired.

4. Scram Feature

A negative reactivity insertion can be input starting at a time determined by occurrence of any one of the following computed events:

- (a) Reactor power exceeds a user-input value.
- (b) The reactor period is less than a minimum user-input value.
- (c) The coolant exit temperature exceeds a user-input value.
- (d) Coolant flow rate decreases below a user-input minimum.

If the scram reactivity is triggered by one of the above criteria (by tests made in TSDRIV), then the table values of scram reactivity versus time are called by selecting the proper entry point in $K(T)$.

If it is desired to have scram occur at a specific time rather than according to one of the above criteria, the scram reactivity can be input with the programmed reactivity (function subprogram PREA).

5. Fuel-dynamics Calculation

The SAS1A code can be run with or without the Fuel Dynamics Module. If this option is selected, a switch to the calculation takes place when a specified centerline temperature of the fuel is exceeded.

6. Weak-explosion Calculation

SAS1A can be run with or without the Weak Explosion Module. The two switch-over criteria for the weak-explosion calculation are:

- (a) Reactor period less than a minimum user input value;
- (b) The radially averaged fuel temperature at the hottest axial fuel node exceeds a user input value.

J. Plot Package

The plot package is used to graphically represent selected quantities output by the SAS1A code. It will produce the following graphs:

- 1) Power and net reactivity versus time;
- 2) Programmed, Doppler, density, scram, coolant + structure, and net reactivity versus time;
- 3) Structure and individual coolant channel reactivities and their sum versus time (after boiling and before weak explosion only);
- 4) Peak fuel node centerline temperature and fraction of fuel melted versus time;
- 5) Peak clad node midpoint temperature versus time.

At ANL the BCD version of the code uses a 580 Calcomp, and the EBCDIC (08-360) version used both the 580 and 780 Calcomp.

The following display routines must be supplied by the user:

- 1) Subroutine PLOT (X,Y,IC)

X,Y - Page locations in inches from a known 0.0, 0.0.

IC -

If IC ends in 2, the pen will be lowered before moving to point x,y.

If IC ends in 3, the pen will be raised before moving to point x,y.

If IC is negative, the appropriate action is taken and then the point x,y becomes 0.0, 0.0.

If IC equals 999 the plotting is finished and plot tape is closed.

(Routine is referenced only in HPLOT)

- 2) Subroutine PLOTS (BUFFER, NBUF, NTAPE)

BUFFER - the low-order core location of the area.

NBUF - the number of words in Buffer.

NTAPE - not used.

(Routine is referenced only in NPLOTS)

- 3) Subroutine SYMBOL (X,Y, HEIGHT, BCD, THETA, NS)

X,Y - Page location in inches.

HEIGHT - Height of character to be drawn in inches.

BCD - Location of first BYTE of alphanumeric characters to be drawn. The BCD version uses an 8-character-per-word transmission system while the EBCDIC uses a 4-character-per-word system. Changing the data statements should take care of any problem.

THETA - Angle at which characters are to be drawn.

NS - Number of characters to be drawn.

(Referenced only in SYMBOL)

4) Subroutine NUMBER (X1, Y1, HEIGHT, FTN, THETA, NA)

X1, Y1 - Page location in inches.

HEIGHT - Height of characters to be drawn in inches.

FTN - Floating-point number to be drawn.

THETA - Angle at which characters are to be drawn.

NN - Number of characters to be drawn,

If NN .GT. 0, NN places to right of decimal will be drawn.

If NN .LT. 0, (NN-1) places to the left of decimal will be deleted and the rest drawn as an integer.

If NN = 0, integral portion with a decimal.

In this routine, plot systems vary; two basic systems are programmed:

- (1) A right-justified plot using formats (NA = format specified).
- (2) A left-justified plot where the variable NN as defined above is used (NA = NN).

The BCD version assumes (1) and has (2) in comments while the EBCDIC version assumes (2) and has (1) in comments.

(Referenced only in SUMBER)

To use the plot package a disk or tape must have been saved from a normal SAS1A run. The input is as follows:

Cards 1 + 2, the two title cards from the run involved.

Card 3 (12I6), NPTS - number of data points in the transient.

NDIV - number of points to be plotted < 72. These points will be evenly distributed in time--not in time step.

Card 3 (12I6),
(Contd.)

NTAPE - the logical unit number of the device containing the data.

IPOWER $\left\{ \begin{array}{l} <0, \text{ reactivity as a function of time} \\ & \text{problem.} \\ >0, \text{ power as a function of time} \\ & \text{problem.} \end{array} \right.$

IPP = $\left\{ \begin{array}{l} 1, \text{ edit of results only.} \\ 2, \text{ plot of results only.} \\ 3, \text{ edit and plot of results.} \end{array} \right.$

Card 4 (5EI2.5),

TIEND - time (seconds) at the end of entire transient.

TIXPLO - time (seconds) at beginning of weak-explosion calculation (is $\leq$ TIEND).

TMF - melting temperature of the fuel.

Card 5 (12I6),

NWAVE - number of extra points to be plotted.

IEFFECT(J) $\left\{ \begin{array}{l} J=1, \text{ step number when scram} \\ & \text{initiated } (\geq 0). \\ J=2, \text{ step number when boiling} \\ & \text{initiated } (\geq 0). \\ J=3, \text{ step number when SLUG} \\ & \text{initiated } (\geq 0). \\ J=4, \text{ step number when fuel dynamics} \\ & \text{initiated } (\geq 0). \\ J=5, \text{ step number when wear explosion} \\ & \text{initiated } (\geq 0). \\ J=6,8 \text{ dummy (may be used as needed} \\ & \text{or set to 0).} \end{array} \right.$

If NWAVE = 0, then no more data for this edit.

Cards 6,7 (12I6), NWAVES(J)-J=1, NWAVE, extra points as needed must be in ascending order.

If SAS1A terminates normally, the print-out will give most of the above information; also edited will be those step numbers where the power went through a change in slope (peak or valley); these steps are normally input on cards 6 and 7.

Card 6 + NWAVE/12, I45 I45 = 0 No more data on logical unit NTAPE.

I45 $\neq$ 0 Another set of data follows title cards
and etc. will follow.

Some additional points are selected by the logic, they are:

- 1) The points when the additional channels start showing reactivity effects (seven additional points are found between boiling initiation and weak explosion).
- 2) Seven additional points during weak explosion.
- 3) The point at which centerline temperature exceeds melting.

IV. INPUT DESCRIPTION

The standard input format for SAS1A is 2I6 and 5E12.5 or 10I6, depending on whether decimal or integer variables are being input. The two integers in the 2I6 format are the location number of the first entry and number of entries on the card. If it is desired to rerun problems with only a few changes in input, it is only necessary to add cards at the end of the input data with the desired changes and their location numbers. The last value which is read in for a particular location is the one which is used in the computation. The input data must be preceded by two title cards. The integers are read first; the end of the integer input is marked by a card with -1 in the first I6 field. Next, the decimal numbers are read; the end of the input data for the problem is marked by a second -1 card. The following is a tabulation of the various input parameters and their locations.

As stated earlier, PREA is a function subprogram which gives either the reactivity or power versus time input. For the reactivity case, the input would be (for a \$1.5/sec ramp rate)

```
FUNCTION PREA (TIME)
  PREA = 1.5 * TIME
  RETURN
END
```

For the power versus time case, one would have

```
FUNCTION PREA (TIME)
  PREA = 1.0 + 0.5 * TIME
  RETURN
END
```

This would double the power in 2 sec (note that the value of PREA must equal 1.0 at time zero).

A. Integer Variables, Locations 1 to 30--Nodal and Tabular Options

Location	FORTAN Symbol	Definition/Comments
1	NT	Number of radial temperature points within the fuel. $4 \leq NT \leq 15$
2	MZ	Number of axial heat-transfer nodes in fuel pin. $1 \leq MZ \leq 20$

Location	FORTTRAN Symbol	Definition/Comments
3	MZC	Number of axial coolant nodes in coolant channel. $2 \leq \text{MZC} \leq 201$
4	MZUB	Number of axial heat-transfer nodes in upper blanket. $0 \leq \text{MZUB} \leq 20$
5	MZLB	Number of axial heat-transfer nodes in lower blanket. $0 \leq \text{MZLB} \leq 20$
6	N8	Number of fine coolant nodes in each coolant section for boiling calculations. (Suggested value of 8)
7	NDELAY	Number of delay groups $1 \leq \text{NDELAY} \leq 6$
8	MAXSTP	Maximum number of time steps
9	NOREG	Number of regions used to describe core. Not input if weak-explosion option is not specified. $1 \leq \text{NOREG} \leq 60$
10	NSRNO	Number of time steps between evaluations of volume and surface integrals. Not input if explosion option is not specified.
11	IPOWER	Greater than 0 use power as function of time in PREA subroutine. Less than or equal to 0 use reactivity as function of time in PREA subroutine.
12	ISSTS	Greater than 0 steady state only calculated. Less than or equal to 0 steady state and transient will be calculated.
13	ISSCAL	Greater than 0, will do steady-state power search. Less than or equal to 0, will specify power.
14	NOFULD	Greater than 0, the fuel-dynamics module will not be used. Less than or equal to 0, the fuel-dynamics module will be used.
15	NOMARS	Greater than 0, the weak-explosion module will not be used. Less than or equal to 0, the weak-explosion module will be used.
16	ICLCMP	Greater than 0, plotted output desired data will be placed on logical unit number (ICLCMP). Less than or equal to 0, no plots desired.
17	IPO	Number of time steps/printout before coolant boiling.

Location	FORTTRAN Symbol	Definition/Comments
18	IPOBOI	Number of time steps/printout after coolant boiling.
19	IPOPT	Number of time steps/printout of temperature and pressure distribution in all regions. Not input if weak-explosion option is not specified.
20	NKTB	Number of entries in fuel-conductivity table. $2 \leq \text{NKTB} \leq 20$.
21	NCPTB	Number of entries in fuel-specific-heat table. $2 \leq \text{NCPTB} \leq 20$.
22	NRHOTB	Number of entries in fuel-density table. $4 \leq \text{NRHOTB} \leq 20$.
23	NECTB	Number of entries in cladding Young's modulus table. $2 \leq \text{NECTB} \leq 20$.
24	NYLDTB	Number of entries in cladding-yield-point table. $2 \leq \text{NYLDTB} \leq 20$.
25	NSRMTB	Number of entries in scram-reactivity table. $2 \leq \text{NSRMTB} \leq 10$.
26	MZS	Number of entries in axial power shape. Not input if weak-explosion option is not specified. $2 \leq \text{MZS} \leq 20$.
27	NOPOWR	Number of entries in radial power shape. Not input if weak-explosion option is not specified. $2 \leq \text{NOPOWR} \leq 20$.
28	NOMR	Number of material-worth distribution curves to be used. Not input if weak-explosion option is not specified. $1 \leq \text{NOMR} \leq 20$.
29	NOMATR	Number of radial entries in material-worth distribution. Not input if weak-explosion option is not specified. $2 \leq \text{NOMATR} \leq 20$.
30	NGFLOW	Number of entries in coolant flow versus time table. $0 \leq \text{NGFLOW} \leq 20$.

B. Decimal Variables Locations Greater Than 301. Geometry and Design Configuration

Location	FORTTRAN Symbol	Definition/Comments	Units
31	RINFP	Fuel inner radius.	cm
32	ROUTFP	Fuel outer radius.	cm
33	RBR	Clad inner radius.	cm
34	RER	Clad outer radius.	cm
35	PLENL	Length of coolant in plenum to be considered.	cm
36-55	AXHI	Length of axial segment J, $1 \leq J \leq MZ$. All should be as near equal size as possible.	cm
56	TAUST	Equivalent thickness of structure (volume/surface area).	cm
57	LP	Pump leg (distance from pump to coolant inlet plenum).	cm
58	AR	Area ratio of pump leg. Flow area of pump leg/Total core flow area.	-
59	VFC	Volume fraction of coolant.	-
60	TR	Reference design-point temperature.	°C
61	T0	Coolant inlet temperature.	°C
62	PX	Coolant exit pressure.	atm
63	G0	Coolant mass flow rate.	gm/cm ² -sec
64	RST	Structure effective thermal resistance. (If 0 is input RST = TAUST/(3.0 · EK).)	°C-cm ² -W
65	GAM2	Structure-coolant surface area ratio. (If 0.0 is input, 1.0 is assumed.)	-
66	FR	Coolant friction factor. (0.1875 unless otherwise specified.)	-
67	VFS	Volume fraction of structure.	-

2. Material Properties

Location	FORTTRAN Symbol	Definition/Comments	Units
<u>Fuel</u>			
71	TMF	Fuel melting temperature.	°C
72	UMELT	Latent heat of melting.	J/gm
73	MOLWT	Molecular weight of the fuel.	gm/mole
74	AFS	Coefficient of linear thermal expansion of solid fuel. Base is design-point temperature.	°C ⁻¹
75	AFL	Coefficient of linear thermal expansion of liquid fuel. Base is melting point.	°C ⁻¹
76	AM	Fractional linear change due to melting. Base is melting point. (Note: AFS, AFL, AM will be computed if input equal to 0.0.)	-
77	NUS	Poisson's ratio of the fuel.	-
78	ES	Young's modulus of solid fuel.	dyne/cm ²
79	KLF	Bulk modulus of the liquid fuel.	dyne/cm ²
80-82	ACK1-3	Coefficients in Ackerman equation of state. (Should use -4.026, 59.45, -74590.0.) Not input if fuel-dynamics option is not selected. $P_{\text{sat}} = T_{\text{avg}}^{\text{ack1}} * e^{(\text{ack2} + \text{ack3}/T_{\text{avg}})}$ (T in °K)	-
83	SPRINK	Spring constant for fuel-retaining spring or equivalent spring constant for plenum gas.	dynes/cm
84	FF	Dynamic friction factor. Not input if fuel-dynamics option is not selected. (Suggested value of 100.0.)	-
85-104	FS	Stiction factor at axial node J, $1 \leq J \leq \text{MZ}$. Not input if fuel-dynamics option not selected.	dynes/cm ²
105	CC2	Coefficient in specific-volume equation. (Suggested value is 40000.0.) Not input if fuel dynamics not selected.	gm-°C/cm ³

Location	FORTTRAN Symbol	Definition/Comments	Units
<u>Fuel-Clad Interface</u>			
106	HBPAR	Coefficient in bond-conductance equation when a gap exists. (Bond conductance = HBPAR/gap.)	W/cm-°C
107	HBMAX	Maximum value of bond conductance when a gap exists, minimum value when gap does not exist.	W/cm ² -°C
108	HBGRAD	Gradient of fuel-clad conductance with pressure. No gap.	(W/cm ² -°C)/ (dynes/cm ²)
109	DEL	Stefan-Boltzmann constant	W/cm ² -°C ⁴
<u>Clad</u>			
110	TME	Clad melting temperature.	°C
111	AE	Coefficient of linear thermal expansion of the clad. Base is design-point temperature.	°C ⁻¹
112	CROE	Specific heat * density for clad. Average value over expected transient.	J/cm ³ -°C
113	EK	Thermal conductivity of the cladding. Average value over expected transient.	W/cm-°C
114	NUC	Poisson's ratio of the clad.	-
<u>Clad-Coolant Interface</u>			
115	HBURN	Heat-transfer conductance at clad burnout.	W/cm ² -°C
116-118	C1-3	Coefficients in film-conductance equation $h_c = K_c * (C_1 * [D_h * G * C_c / K_c]^{C_2} + C_3) / D_h$	-
<u>Coolant</u>			
119	CL	Coolant specific heat at design-point temperature.	J/gm-°C
120	DTS	Degrees of superheat.	°C
121	ABURN	Void fraction at clad burnout.	-

Location	FORTTRAN Symbol	Definition/Comments	Units
<u>Coolant (Contd.)</u>			
122	ASTR	Coefficient of linear thermal expansion of the structure. Base is design-point temperature.	$^{\circ}\text{C}^{-1}$
123	CRHOST	Specific heat * density for the structure. Average value over expected transients.	$\text{J}/\text{cm}^2\text{-}^{\circ}\text{C}$
124-130	-	Not currently used by SAS1A.	-

3. Power and Reactivity

Location	FORTTRAN Symbol	Definition/Comments	Units
131-150	PSHAPE	Normalized axial power at segment J, $1 \leq J \leq \text{MZ}$. Not input if weak-explosion option is specified.	W
151	POW	Steady-state power in the peak fuel rod node. Not input if power-search option is specified.	W
152	PZERO	Ratio of total reactor power to POW, not input if weak-explosion option is specified.	-
153	EL	Prompt neutron-generation time.	sec
154-159	BETA	Delayed-neutron fraction for group L, $1 \leq L \leq \text{NDELAY}$.	-
160-165	ALAM	Decay constant of precursors of group L, $1 \leq L \leq \text{NDELAY}$.	sec^{-1}
166-168	PFAC	Power factors for auxiliary phantom channel L, $1 \leq L \leq 3$.	-
169-188	AVGMAT	Total average material worth at segment J, $1 \leq J \leq \text{MZ}$. Not input if weak-explosion option is specified.	$\Delta k/k$
189	ANGPHI	Measurement of the core lower support plate's angular deflection from the horizontal (steady state). Not currently used by SAS1A.	radians

Location	FORTTRAN Symbol	Definition/Comments	Units
190	ADOP	Doppler coefficient when core is not voided.	$\Delta k/k$
191	BDOP	Doppler coefficient when core is fully voided.	$\Delta k/k$
192-211	WDOP	Doppler weighting factor at segment J, $1 \leq J \leq MZ$.	-
212-231	VOIREA	Reactivity for fully voiding section J, $1 \leq J \leq MZ$.	$\Delta k/k$
232	UMIN	Change in subassembly diameter/original diameter necessary for two subassemblies to come into contact.	-
233	UMAX	Change in core radius/original core radius necessary for the core to come into contact with the outer retaining structure.	-
234	STREA1	Slope of the reactivity when two subassemblies come into contact.	$(\Delta k/k)/(\Delta cm/cm)$
235	STREA2	Slope of the reactivity when the core comes into contact with the retaining structure.	$(\Delta k/k)/(\Delta cm/cm)$
236-255	WSTR	Weighting function for structural reactivity at section J, $1 \leq J \leq MZ$.	-
256-260		Currently not used by SAS1A.	-

4. Operational Controls

Location	FORTTRAN Symbol	Definition/Comments	Units
<u>Steady State</u>			
261	PMIN	Minimum allowable value of the peak nodal power. Not input if power-search option is not specified.	W
262	PMAX	Maximum allowable value of the peak nodal power. Not input if power-search option is not specified.	W

Location	FORTTRAN Symbol	Definition/Comments	Units
<u>Steady State (Contd.)</u>			
263	DLPMIN	Minimum power change allowable in search. Not input if power search option is not specified.	W
264	TCLM0	Maximum fuel-centerline temperature allowed in search. Not input if power-search option is not specified.	°C
265	P0	Maximum value of coolant inlet pressure allowed in search. Not input if power-search option not specified.	atm
266	TX	Desired coolant exit temperature in search. Not input if power search option not specified.	°C
267	EPSTEM	Steady-state temperature convergence delta. The steady-state temperatures of the fuel and clad must converge such that $ T' - T \leq \text{EPSTEM}$, where T' is the temperature at the last iteration. (Suggested value is 1.0.)	°C
268-281	-	Not input if transient-state option not selected.	-
268	DTO	Initial time step to be used.	sec
269	TIMAX	Maximum problem time allowed.	sec
270	PDEC	Pump head decay constant.	sec ⁻¹
271	AMAX	Maximum allowable void fraction ≤ 1.0 .	-
272	TCLMAX	Maximum centerline temperature for transient. If fuel-dynamics option is specified TCLMAX is the fuel-centerline temperature for switch to fuel dynamics.	°C
273	TMARS	Radial-averaged fuel temperature for switch to Weak Explosion Module. If not specified, program terminates.	°C

Location	FORTTRAN Symbol	Definition/Comments	Units
<u>Steady State (Contd.)</u>			
274	ALMARS	Inverse period for initiation of weak explosion. Not input if weak-explosion option is not specified.	sec ⁻¹
275	TSCRAM	Coolant exit temperature for scram initiation.	°C
276	ASCRAM	Inverse period for scram initiation.	sec ⁻¹
277	PSCRAM	Power level (normalized) for scram initiation.	W
278	GSCRAM	Inlet flowrate for scram initiation.	gm/cm ²
279	EPSCOL	Coolant-boiling convergence epsilon. Coolant quality converges such that $\left \frac{x' - x}{x} \right \leq \text{EPSCOL},$ where x' is the quality at the last iteration. (Suggested value is 0.001.)	-
280	EPSREA	Reactivity-iteration convergence epsilon. Net reactivity converges such that $\left \frac{\rho' - \rho}{\rho} \right \leq \text{EPSREA},$ where ρ' is the reactivity from the last power iteration. (Suggested value is 0.001.)	-
281	EPSPHI	Neutron-flux-iteration convergence epsilon. Flux must converge such that $(\phi^{1/2} - \phi)/\phi \leq \text{EPSPHI},$ where $\phi^{1/2}$ is the flux computed at 1/2 the time step used. (Suggested value is between 10 ⁻⁵ to 10 ⁻⁶ .)	-
282	EPSDEF	Deformation-iteration converges epsilon. Radii must converge such that $(R' - R)/R \leq \text{EPSDEF},$ where R' is the stressed radius at the last iteration.	-
283	EPSVAP	Not currently used by SAS1A.	-
284-290	-	Not currently used by SAS1A.	-

Location	FORTTRAN Symbol	Definition/Comments	Units
<u>Tables</u>			
291-310	KTAB	Fuel conductivity in table location L, $1 \leq L \leq \text{NKTB}$ versus	W/cm-°C
311-330	KTEM	Temperature	°C
331-350	CPTAB	Fuel specific heat in table loca- tion L, $1 \leq L \leq \text{NCPTB}$ versus	J/gm-°C
351-370	CPTEM	Temperature	°C
371-390	RHOTAB	Fuel density in table location L, $1 \leq L \leq \text{NRHOTB}$ versus	gm/cm ³
391-410	RHOTEM	Temperature (Two entries must be made at the melting point: first with the solid density, second with the liquid density.)	°C
411-430	ECTAB	Clad Young's modulus in table location L, $1 \leq L \leq \text{NECTB}$ versus	dynes/cm ²
431-450	ECTEM	Temperature	°C
451-470	YLDTAB	Clad yield point in table location L, $1 \leq L \leq \text{NYLDTB}$ versus	dynes/cm ²
471-490	YLDTEM	Temperature	°C
491-500	SCRTAB	Scram reactivity in table location L, $1 \leq L \leq \text{NSRMTB}$ versus	$\Delta k/k$
501-510	SCRTME	Time since initiation of scram	sec
511-519	-	Not currently used by SAS1A.	-
2635-2654	GFLOW	Coolant inlet flow ratio in the table location L. (Flow = GFLOW · GO, $1 \leq L \leq \text{NFLOW.}$)	-
2655-2674	TFLOW	Time since initiation of transient.	sec

5. Weak Explosion

Location	FORTTRAN Symbol	Definition/Comments	Units
520-2549	-	Not input if weak-explosion option not specified.	-
520	ZCENT	Distance from reactor base to core center.	cm
521-580	RINS	Inner radius of region K, $1 \leq K \leq \text{NOREG}$.	cm
581-640	ROUTS	Outer radius of region K, $1 \leq K \leq \text{NOREG}$.	cm
641-700	ZUPS	Upper boundary, relative to core center, of region K, $1 \leq K \leq \text{NOREG}$.	cm
701-760	ZDNS	Lower boundary, relative to core center, of region K, $1 \leq K \leq \text{NOREG}$.	cm
761-820	TH	Surface thickness of region K, $1 \leq K \leq \text{NOREG}$.	cm
821-880	REGRHO	Average density of region K, $1 \leq K \leq \text{NOREG}$.	gm/cm ³
881-940	CP0	First constant in specific heat equation for region K, $1 \leq K \leq \text{NOREG}$. $C_p = C_{p0} + C_{p1} * \text{Temp} + C_{p2} * \text{Temp}^2$.	J/gm-°K
941-1000	CP1	Second constant in specific heat equation for region K, $1 \leq K \leq \text{NOREG}$. $C_p = C_{p0} + C_{p1} * \text{Temp} + C_{p2} * \text{Temp}^2$.	J/gm-°K ²
1001-1060	CP2	Third constant in specific heat equation for region K, $1 \leq K \leq \text{NOREG}$. $C_p = C_{p0} + C_{p1} * \text{Temp} + C_{p2} * \text{Temp}^2$.	J/gm-°K ³
1061-1120	PRA	First constant in equation of state for region K, $1 \leq K \leq \text{NOREG}$. PRESSURE = PRA*EXP(-PRB/TEMP + PRC).	dyne/cm ²

Location	FORTTRAN Symbol	Definition/Comments	Units
1121-1180	PRB	Second constant in equation of state for region K, $1 \leq K \leq \text{NOREG}$. PRESSURE = $\text{PRA} * \text{EXP}(-\text{PRB} / \text{TEMP} + \text{PRC})$.	$^{\circ}\text{K}$
1181-1240	PRC	Third constant in equation of state for region K, $1 \leq K \leq \text{NOREG}$. PRESSURE = $\text{PRA} * \text{EXP}(-\text{PRB} / \text{TEMP} + \text{PRC})$.	-
1241-1300	DOPLA	First coefficient in Doppler reactivity equation for region K, $1 \leq K \leq \text{NOREG}$. $\Delta K_{\text{Dopp}} = -2 * \text{DOPLA} * \text{TEMP}^{-0.5} +$ $\text{DOPLB} * \text{LN}(\text{TEMP}) +$ $(\text{DOPLC} / \text{DOPLN} * \text{TEMP}) \text{DOPLN}$	-
1301-1360	DOPLB	Second coefficient in Doppler reactivity equation for region K, $1 \leq K \leq \text{NOREG}$. $\Delta K_{\text{Dopp}} = -2 * \text{DOPLA} * \text{TEMP}^{-0.5} +$ $\text{DOPLB} * \text{LN}(\text{TEMP}) +$ $(\text{DOPLC} / \text{DOPLN} * \text{TEMP}) \text{DOPLN}$	-
1361-1420	DOPLC	Third coefficient in Doppler reactivity equation for region K, $1 \leq K \leq \text{NOREG}$. $\Delta K_{\text{Dopp}} = -2 * \text{DOPLA} * \text{TEMP}^{-0.5} +$ $\text{DOPLB} * \text{LN}(\text{TEMP}) +$ $(\text{DOPLC} / \text{DOPLN} * \text{TEMP}) \text{DOPLN}$	-
1421-1480	DOPLN	Fourth coefficient in Doppler reactivity equation for region K, $1 \leq K \leq \text{NOREG}$. $\Delta K_{\text{Dopp}} = -2 * \text{DOPLA} * \text{TEMP}^{-0.5} +$ $\text{DOPLB} * \text{LN}(\text{TEMP}) +$ $(\text{DOPLC} / \text{DOPLN} * \text{TEMP}) \text{DOPLN}$	-
1481-1540	W	Ratio of the sonic velocity at region K to the sonic velocity at the base region. The base region is normally region 1. (The ratio should approximate 1.0, if 0.0 is input, 1.0 is assumed.)	-

Location	FORTTRAN Symbol	Definition/Comments	Units
1541-1780	SITG	<p>If SITG = 0.0 no surface integration. If SITG $\neq$ 0.0 surface integration.</p> <p>SITG(1,K) = inner surface (normally 0.0)</p> <p>SITG(2,K) = outer surface (normally 1.0)</p> <p>SITG(3,K) = upper surface (normally 1.0)</p> <p>SITG(4,K) = lower surface (normally 0.0)</p>	-
1781-2020	WCON	<p>If WCON = 0.0 a surface integration is carried out that approximates the effect to an outer surface in the reactor. If WCON $\neq$ 0.0 a surface integration is carried out that approximates the effect of two regions contacting. (In this latter case only one of the two surfaces should be input, the other is then taken care of.)</p> <p>WCON(1,K) = inner surface (normally 0.0)</p> <p>WCON(2,K) = outer surface (1.0 unless also reactor surface)</p> <p>WCON(3,K) = upper surface (1.0 unless also reactor surface)</p> <p>WCON(4,K) = lower surface (normally 0.0)</p>	-
2021	DTMARS	Initial time step in weak explosion.	sec
2022	DTMAX	Maximum time step allowed in weak explosion.	sec
2023	DTMIN	Minimum time step allowed in weak explosion.	sec
2024	XKLIM	Minimum k_{eff} allowed in weak explosion.	-
2025	PFINAL	Minimum normalized power allowed in weak explosion.	-
2026	PPSUP	Maximum normalized power which will detect divergence in the calculation. Must be larger than this. Should be greater than 1.0.	-

Location	FORTTRAN Symbol	Definition/Comments	Units
2027	ETA1	Time interval will be halved if the ratio of two successive powers is larger than this. Should be greater than 1.0.	-
2028	ETA2	Time interval will be doubled if the ratio of two powers is smaller than this. Should be greater than or equal to 1.0.	-
2029	ETA3	A power peak will be output if the power has decreased by more than this percentage. Should be less than or equal to 1.0.	-
2030-2049	PSHAPZ	Axial power profile at section L, $1 \leq L \leq MZS$.	cm^{-3}
2050-2069	POWZZ	Axial mesh corresponding to power profile at section L, $1 \leq L \leq MZS$.	cm
2070-2089	PSHAPR	Radial power profile at section L, $L \leq L \leq \text{NOPOWR}$.	cm^{-3}
2090-2109	POWRR	Radial mesh corresponding to power profile at section L, $1 \leq L \leq \text{NOPOWR}$.	cm
2110-2509	RMATW	Material worth reactivity distribution for each axial point J, $1 \leq J \leq \text{NOMR}$, the radial profile I, $1 \leq I \leq \text{NOMATR}$.	$(\Delta k/k)/\text{Vol}$
2510-2529	RMAT	Radial mesh corresponding to material worth at point I, $1 \leq I \leq \text{NOMATR}$.	cm
2530-2549	ZMAT	Axial mesh relative to core center (ZCENT) corresponding to the material worth radial profile at point J, $1 \leq J \leq \text{NOMR}$. If $\text{NOMR} = 1$, 0.0 is assumed.	cm
2550	-	Not currently used by SAS1A.	-

V. SAMPLE PROBLEM OUTPUT

A. Printed Output

Selected portions of the output of a typical SAS1A problem are presented in this section. The example problem is a \$2.5/sec ramp power transient for a 100-cm-high (with 30-cm upper and lower axial blankets) oxide-fueled LMFBR core. The standard output is ordered as follows:

1. Listing of input-data cards in input format.
2. Title cards and options specified in the calculation.
3. Input edit which contains the following headings:
 - a. Reactor regions (and map) specified for weak explosion
 - b. Integer data
 - c. Geometry and design configuration
 - d. Material properties
 - e. Power and reactivity
 - f. Point kinetics and feedbacks
 - g. Operational controls
 - h. Tabular properties
 - i. Weak-explosion data
4. Steady-state calculation output consisting of the major blocks:
 - a. Coolant profile
 - b. Point kinetics data
 - c. Heat transfer (fuel temperatures and radial fuel pin mesh)
5. Scram-criterion print-out. In the sample the scram-reactivity table values are set to zero so that there is actually no scram when a criterion is met.
6. Transient-calculation output (shown at a point just after flow reversal in the coolant channel) consisting of the major blocks:
 - a. Time, power, integrated power, and reactivity summary at each time step.
 - b. Point kinetics data and reactivity summary (when full print-out is requested--user option).

c. Coolant profile, temperatures, pressures, and void fractions (when full print-out is requested--user option).

d. Heat transfer, fuel temperatures, and percent of fuel molten (when full print-out is requested--user option).

e. Fuel- and clad-deformation parameters (when full print-out is requested--user option). The above format is somewhat different if the Fuel Dynamics Module is called; however, this has not been included in the sample presented here to save space.

7. Weak-explosion calculation output consisting of:

a. Message which states that the criterion for switch to weak-explosion calculation has been met; lists the two input criteria and current problem values for these parameters so that it is apparent which one triggered the switch (high fuel temperature in the sample).

b. Full print-out (listed under 6 above) just at the time the weak-explosion calculation is started (not at the option of the user).

c. Parameters for the Weak-explosion calculation.

d. Input data for the individual core regions (only region 1 shown in the sample, although this is given for all 20 core regions).

e. Initial pressure and temperature distribution in each region (only regions 1-4 shown in the sample, although this is given for all 20 core regions).

f. Time, power, and reactivity summary at each time step. The column labeled "Total Integral" is the value of the integral in Eq. G-22 plus contributions due to surface-integral correction terms, if included.

g. Full transient print-out (when requested--user option) which includes a power, energy, and reactivity summary plus the core transient pressure and temperature distribution.

h. Final full print-out on termination of the weak-explosion calculation due to tripping of one of the finishing criteria (low power in the sample).

i. Data for the plotting of results.

B. Plotted Output

The five plots for the \$2.5/sec ramp sample problem generated by the SAS1A Plot Package are included immediately following the printed output.

C. Error Diagnostics

Most of the error messages printed out by SAS1A are self-explanatory; however, the following list is presented to give the user a better overview of the error-diagnostic structure. Basically, there are three main classes of diagnostics: 1) input-data consistency, 2) values of specific calculated parameters within reasonable ranges, and 3) iterations become excessive due to failure of calculations to converge. The following types of checks are made in the code:

<u>Location</u>	<u>No. of Checks</u>	<u>Type</u>
READIN	1	Input-data-card problem
INPOUT	17	Input-data consistency
SSHTR	4	Iteration count exceeded (3); fuel surface melting (1)
SSDRIV	3	Coolant boiling in steady state, desired starting conditions cannot be obtained in iteration of steady-state search option
TSPK	1	Reactivity-iteration count exceeded
TSHTTR	1	Machine error
DEFORM	2	Iteration count exceeded
FULDYN	1	Iteration count exceeded
XPLODE	1	Power level exceeds a specified value

D. Printout of Sample Problem*

*Due to some programming changes which have been made since this report was completed, the output for the sample problem will be slightly different with the current version of SAS1A.

100 CM CORE TEST PROBLEM
2.5 DOLLAR / SEC RAMP

FIXED POINT INPUT DATA

1 TO	10	10	16	81	3	3	8	6	1000	20	1
11 TO	20	-1	-1	10	10	-1	13	20	10	20	10
21 TO	29	10	10	10	10	2	19	18	7	15	
FLCATING POINT INPUT DATA											
31 TO	35	0.30000+000		2.80000+001		2.90000+001		3.25000+001		0.00000+000	
36 TO	40	1.00000+001		1.00000+001		1.00000+001		1.00000+001		1.00000+001	
41 TO	45	1.00000+001		1.00000+001		1.00000+001		1.00000+001		1.00000+001	
46 TO	50	1.00000+001		1.00000+001		1.00000+001		1.00000+001		1.00000+001	
51 TO	51	1.00000+001									
56 TO	60	3.00000+001		0.00000+000		1.00000+000		4.72000+001		2.70000+001	
61 TO	62	5.00000+002		3.00000+000							
64 TO	65	5.00000+001		1.00000+004							
67 TO	67	1.80000+001									
71 TO	73	2.80000+003		2.70000+002		2.70000+002					
76 TO	80	0.00000+000		3.00000+001		2.00000+008		1.00000+009		4.02600+000	
78 TO	78	1.00000+012									
79 TO	79	1.00000+012									
81 TO	84	5.94500+001		-7.45900+004		1.00000+001		5.00000+001			
85 TO	89	5.70000+007		4.00000+007		2.30000+007		6.50000+006		5.70000+006	
90 TO	94	4.90000+006		4.10000+006		2.00000+006		2.00000+006		4.10000+006	
95 TO	99	4.90000+006		5.70000+006		6.50000+006		2.30000+007		4.00000+007	
100 TO	100	5.70000+007									
105 TO	105	2.00000+004									
106 TO	110	8.00000+003		2.00000+000		0.00000+000		4.56800+012		1.50000+003	
111 TO	115	2.35000+005		4.60000+000		2.25000+001		2.50000+001		1.00000+002	
116 TO	120	1.05000+001		8.00000+001		2.09000+001		1.29070+000		0.00000+000	
116 TO	118	2.50000+002		8.00000+001		5.00000+000					
121 TO	123	9.00000+001		2.80800+005		4.60000+000					
122 TO	122	2.35000+005									
151 TO	155	-0.00000+000		1.70000+009		4.72800+007		7.62000+005		6.27000+004	
156 TO	160	5.61000+004		1.06000+003		4.80000+004		1.60000+004		1.30000+002	
161 TO	165	3.14000+002		1.36000+001		3.40000+001		1.32000+000		3.50000+000	
166 TO	168	9.80000+001		9.60000+001		9.40000+001					
190 TO	191	-5.80000+003		-2.90000+003							
195 TO	199	5.75000+002		7.69000+002		1.01400+001		1.26700+001		1.37600+001	
200 TO	204	1.37600+001		1.26700+001		1.01400+001		7.69000+002		5.75000+002	
212 TO	216	-1.14000+004		-2.40100+004		-5.53600+004		-5.06400+004		2.76000+004	
217 TO	221	1.10800+003		1.78300+003		2.15700+003		2.15700+003		1.78300+003	
222 TO	226	1.10800+003		2.76000+004		-5.06400+004		-5.53600+004		-2.40100+004	
227 TO	227	-1.14000+004									
232 TO	235	1.00000+002		4.60000+002		-1.22270+001		-1.00000+001			
239 TO	243	5.75000+002		7.69000+002		1.01400+001		1.26700+001		1.37600+001	
244 TO	248	1.37600+001		1.26700+001		1.01400+001		7.69000+002		5.75000+002	
261 TO	265	3.00000+003		5.00000+003		1.00000+001		2.00000+003		1.00000+001	
264 TO	264	2.40000+003									
266 TO	270	0.00000+000		1.00000+000		2.00000+002		5.00000+000		0.00000+000	
266 TO	266	6.30000+002									
271 TO	275	9.00000+001		4.00000+003		5.00000+003		2.00000+003		7.00000+002	
276 TO	280	2.00000+002		1.25000+000		3.00000+002		1.00000+003		1.00000+003	
281 TO	283	1.00000+005		1.00000+004		1.00000+003					
291 TO	295	5.62000+002		4.24000+002		2.93000+002		2.24000+002		1.81000+002	
296 TO	300	1.51000+002		1.65000+002		1.81000+002		2.93000+002		5.41000+002	
311 TO	315	1.00000+002		5.00000+002		1.00000+003		1.50000+003		2.00000+003	
316 TO	320	2.50000+003		2.80000+003		3.00000+003		4.00000+003		5.00000+003	
331 TO	335	1.98000+001		2.24000+001		3.12000+001		4.08000+001		5.06000+001	

336 TO	340	6.04000+001	6.62000+001	5.15000+001	5.15000+001	5.15000+001
351 TO	355	1.00000+002	5.00000+002	1.00000+003	1.50000+003	2.00000+003
356 TO	360	2.50000+003	2.80000+003	3.00000+003	4.00000+003	5.00000+003
371 TO	375	1.04200+001	1.03600+001	1.02400+001	1.00400+001	9.76600+000
376 TO	380	9.14100+000	8.74100+000	8.57100+000	7.65300+000	6.73500+000
391 TO	395	1.00000+002	5.00000+002	1.00000+003	1.50000+003	2.00000+003
396 TO	400	2.80000+003	2.80000+003	3.00000+003	4.00000+003	5.00000+003
411 TO	415	8.41800+011	8.41800+011	7.44800+011	6.81000+011	6.06000+011
416 TO	420	5.18400+011	4.16500+011	4.00000+011	4.00000+011	4.00000+011
431 TO	435	1.00000+002	5.00000+002	1.00000+003	1.10000+003	1.20000+003
436 TO	440	1.30000+003	1.40000+003	1.50000+003	2.00000+003	3.00000+003
451 TO	455	2.62000+009	2.07000+009	6.89000+008	5.51000+008	4.14000+008
456 TO	460	3.45000+008	2.76000+008	0.00000+000	0.00000+000	0.00000+000
471 TO	475	1.00000+002	5.00000+002	1.00000+003	1.10000+003	1.20000+003
476 TO	480	1.30000+003	1.40000+003	1.50000+003	2.00000+003	3.00000+003
491 TO	492	0.00000+000	0.00000+000			
501 TO	502	0.00000+000	1.00000+003			
520 TO	520	8.00000+001				
521 TO	525	0.00000+000	0.00000+000	0.00000+000	0.00000+000	5.00000+001
526 TO	530	5.00000+001	5.00000+001	5.00000+001	7.50000+001	7.50000+001
531 TO	535	7.50000+001	7.50000+001	9.00000+001	9.00000+001	9.00000+001
536 TO	540	9.00000+001	1.05000+002	1.05000+002	1.05000+002	1.05000+002
581 TO	585	5.00000+001	5.00000+001	5.00000+001	5.00000+001	7.50000+001
586 TO	590	7.50000+001	7.50000+001	7.50000+001	9.00000+001	9.00000+001
591 TO	595	9.00000+001	9.00000+001	1.05000+002	1.05000+002	1.05000+002
596 TO	600	1.05000+002	1.35000+002	1.35000+002	1.35000+002	1.35000+002
641 TO	644	2.50000+001	4.00000+001	5.00000+001	8.00000+001	
645 TO	648	2.50000+001	4.00000+001	5.00000+001	8.00000+001	
649 TO	652	2.50000+001	4.00000+001	5.00000+001	8.00000+001	
653 TO	656	2.50000+001	4.00000+001	5.00000+001	8.00000+001	
657 TO	660	2.50000+001	4.00000+001	5.00000+001	8.00000+001	
701 TO	704	0.00000+000	2.50000+001	4.00000+001	5.00000+001	
705 TO	708	0.00000+000	2.50000+001	4.00000+001	5.00000+001	
709 TO	712	0.00000+000	2.50000+001	4.00000+001	5.00000+001	
713 TO	716	0.00000+000	2.50000+001	4.00000+001	5.00000+001	
717 TO	720	0.00000+000	2.50000+001	4.00000+001	5.00000+001	
761 TO	765	1.00000+002	1.00000+002	1.00000+002	1.00000+002	1.00000+002
766 TO	770	1.00000+002	1.00000+002	1.00000+002	1.00000+002	1.00000+002
781 TO	785	1.00000+002	1.00000+002	1.00000+002	1.00000+002	1.00000+002
786 TO	790	1.00000+002	1.00000+002	1.00000+002	1.00000+002	1.00000+002
821 TO	824	4.00000+000	4.00000+000	4.00000+000	4.00000+000	
825 TO	828	4.00000+000	4.00000+000	4.00000+000	4.00000+000	
829 TO	832	4.00000+000	4.00000+000	4.00000+000	4.00000+000	
833 TO	836	4.00000+000	4.00000+000	4.00000+000	4.00000+000	
837 TO	840	5.00000+000	5.00000+000	5.00000+000	5.00000+000	
881 TO	885	4.50000+001	4.50000+001	4.50000+001	4.50000+001	4.50000+001
886 TO	890	4.50000+001	4.50000+001	4.50000+001	4.50000+001	4.50000+001
891 TO	895	4.50000+001	4.50000+001	4.50000+001	4.50000+001	4.50000+001
896 TO	900	4.50000+001	4.50000+001	4.50000+001	4.50000+001	4.50000+001
1061 TO	1063	7.60000+011	7.60000+011	7.60000+011	7.60000+011	
1065 TO	1067	7.60000+011	7.60000+011	7.60000+011	7.60000+011	
1069 TO	1071	7.60000+011	7.60000+011	7.60000+011	7.60000+011	
1073 TO	1075	7.60000+011	7.60000+011	7.60000+011	7.60000+011	
1121 TO	1123	5.55110+004	5.55110+004	5.55110+004	5.55110+004	
1125 TO	1127	5.55110+004	5.55110+004	5.55110+004	5.55110+004	
1129 TO	1131	5.55110+004	5.55110+004	5.55110+004	5.55110+004	
1133 TO	1135	5.55110+004	5.55110+004	5.55110+004	5.55110+004	
1301 TO	1303	-8.51000+004	-3.28000+004	-1.28000+004		
1305 TO	1307	-7.88000+004	-3.01000+004	-1.17000+004		
1309 TO	1311	-7.13000+004	-2.70000+004	-1.04000+004		
1313 TO	1315	-4.61000+004	-1.74000+004	-6.54000+005		
1541 TO	1544	0.00000+000	1.00000+000	1.00000+000	0.00000+000	

1545 TC	1548	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1549 TC	1552	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1553 TC	1556	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1557 TC	1560	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1561 TC	1564	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1565 TC	1568	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1569 TC	1572	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1573 TC	1576	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1577 TC	1580	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1581 TC	1584	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1585 TC	1588	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1589 TC	1592	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1593 TC	1596	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1597 TC	1600	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1601 TC	1604	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1605 TC	1608	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1609 TC	1612	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1613 TC	1616	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1617 TC	1620	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1781 TC	1784	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1785 TC	1788	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1789 TC	1792	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1793 TC	1796	0.00000+000	1.00000+000	0.00000+000	0.00000+000	
1797 TC	1800	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1801 TC	1804	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1805 TC	1808	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1809 TC	1812	0.00000+000	1.00000+000	0.00000+000	0.00000+000	
1813 TC	1816	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1817 TC	1820	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1821 TC	1824	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1825 TC	1828	0.00000+000	1.00000+000	0.00000+000	0.00000+000	
1829 TC	1832	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1833 TC	1836	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1837 TC	1840	0.00000+000	1.00000+000	1.00000+000	0.00000+000	
1841 TC	1844	0.00000+000	1.00000+000	0.00000+000	0.00000+000	
1845 TC	1848	0.00000+000	0.00000+000	1.00000+000	0.00000+000	
1849 TC	1852	0.00000+000	0.00000+000	1.00000+000	0.00000+000	
1853 TC	1856	0.00000+000	0.00000+000	1.00000+000	0.00000+000	
1857 TC	1860	0.00000+000	0.00000+000	0.00000+000	0.00000+000	
2021 TC	2025	2.00000-005	1.00000-003	1.00000-006	9.50000-001	9.50000-001
2026 TC	2029	1.00000+006	1.25000+000	1.05000+000	9.95000-001	
2030 TC	2034	5.00000-002	7.70000-002	1.16000+001	1.30000-001	5.95000-001
2035 TC	2039	6.70000-001	8.06000-001	9.11000-001	9.77000-001	1.00000+000
2040 TC	2044	9.77000-001	9.11000-001	8.06000-001	6.70000-001	5.95000-001
2045 TC	2048	1.30000-001	1.16000-001	7.70000-002	5.00000-002	
2050 TC	2054	0.00000+000	1.00000+001	2.00000-001	2.99990+001	3.00010+001
2055 TC	2059	4.00000+001	5.00000+001	6.00000+001	7.00000+001	8.00000+001
2060 TC	2064	9.00000+001	1.00000+002	1.10000+002	1.20000+002	1.29999+002
2065 TC	2068	1.30001+002	1.40000+002	1.50000+002	1.60000+002	
2070 TC	2074	1.02200+000	1.00000+000	9.22000-001	8.65000-001	8.37000-001
2075 TC	2079	8.05000-001	7.85000-001	1.02000+000	9.85000-001	9.27000-001
2080 TC	2084	8.15000-001	6.36000-001	5.18000-001	2.75000-001	2.31000-001
2085 TC	2087	6.50000-002	1.80000-002	1.00000-005		
2090 TC	2094	0.00000+000	2.00000+001	5.00000+001	6.25000+001	6.75000+001
2095 TC	2099	7.25000+001	7.49990+001	7.50010+001	7.75000+001	8.25000+001
2100 TC	2104	9.00000+001	1.00000+002	1.04999+002	1.05001+002	1.07500+002
2105 TC	2107	1.27500+002	1.47500+002	1.85000+002		
2110 TC	2114	2.02500-007	2.00500-007	1.93000-007	1.77400-007	1.67900-007
2115 TC	2119	1.57600-007	1.46800-007	2.96000-007	2.85000-007	2.63400-007
2120 TC	2122	2.35000-007	1.93000-007	1.67000-007		
2130 TC	2134	2.00000-007	1.98600-007	1.91000-007	1.77300-007	1.67700-007
2135 TC	2139	1.57500-007	1.47500-007	2.87000-007	2.76000-007	2.56400-007

2140 TO	2142	2.26800-007	1.85000-007	1.57000-007		
2150 TO	2154	1.95500-007	1.94300-007	1.87000-007	1.77000-007	1.67000-007
2155 TO	2159	1.57000-007	1.46000-007	2.69000-007	2.58100-007	2.41600-007
2160 TO	2162	2.10100-007	1.69900-007	1.37000-007		
2170 TO	2174	1.90000-007	1.87000-007	1.79000-007	1.70000-007	1.60000-007
2175 TO	2179	1.49000-007	1.39000-007	2.19000-007	2.17400-007	2.02400-007
2180 TO	2182	1.72100-007	1.36200-007	1.29000-007		
2190 TO	2194	1.85000-007	1.80000-007	1.72500-007	1.63000-007	1.54000-007
2195 TO	2199	1.43000-007	1.35000-007	1.92000-007	1.87200-007	1.72500-007
2200 TO	2202	1.37200-007	1.05000-007	8.40000-008		
2210 TO	2214	1.82500-007	1.76500-007	1.69000-007	1.59500-007	1.51000-007
2215 TO	2219	1.40000-007	1.33000-007	1.77000-007	1.72500-007	1.57000-007
2220 TO	2222	1.20200-007	9.00000-008	6.70000-008		
2510 TO	2514	0.00000+000	2.00000+001	5.00000+001	6.25000+001	6.75000+001
2515 TO	2519	7.25000+001	7.49990+001	7.50010+001	7.75000+001	8.25000+001
2520 TO	2524	9.00000+001	1.00000+002	1.04999+002	1.05001+002	1.85000+002
2530 TO	2534	0.00000+000	7.50000+000	2.25000+001	3.50000+001	4.50000+001
2535 TO	2536	5.00000+001	5.00010+001			

100 CM CORE TEST PROBLEM
2.5 DOLLAR / SEC RAMP

OPTIONS SPECIFIED --

STEADY STATE PLUS TRANSIENT

STEADY STATE POWER SEARCH

REACTIVITY INSERTION GIVEN AS FUNCTION OF TIME

FUEL DYNAMICS WILL NOT BE CALCULATED

WEAK EXPLOSION CALCULATION

THESE ARE THE REACTOR REGIONS THAT HAVE BEEN SPECIFIED FOR THE WEAK EXPLOSION MODULE

*** -- INTEGER DATA -- ***

NUMBER OF RADIAL TEMPERATURE NODES IN FUEL	10
NUMBER OF AXIAL SECTIONS IN FUEL	16
NUMBER OF AXIAL SECTIONS IN UPPER BLANKET	3
NUMBER OF AXIAL SECTIONS IN LOWER BLANKET	3
NUMBER OF AXIAL TEMPERATURE NODES IN COOLANT	81
NUMBER OF FINE COOLANT NODES PER COOLANT SECTION FOR BOILING CALCULATIONS	8
NUMBER OF REGIONS IN WEAK EXPLOSION CALCULATION	20
NUMBER OF TIME STEPS BETWEEN EVALUATION OF THE VOLUME AND SURFACE INTEGRALS	1
NUMBER OF TIME STEPS BETWEEN PRINTOUTS PRE-BOIL	20
NUMBER OF TIME STEPS BETWEEN PRINTOUTS AFTER THE COOLANT BEGINS BOILING	10
NUMBER OF TIME STEPS BETWEEN PRINTOUT OF PRESSURE AND TEMPERATURE DISTRIBUTION AFTER START OF WEAK EXPLOSION CODE	20
NUMBER OF ENTRIES IN AXIAL POWER SHAPE PROFILE	19
NUMBER OF ENTRIES IN RADIAL POWER SHAPE PROFILE	18
NUMBER OF MATERIAL WORTH DISTRIBUTION PROFILES	7
NUMBER OF ENTRIES IN EACH MATERIAL WORTH PROFILE	15
NUMBER OF ENTRIES IN FUEL CONDUCTIVITY TABLE	10
NUMBER OF ENTRIES IN FUEL SPECIFIC HEAT TABLE	10
NUMBER OF ENTRIES IN FUEL DENSITY TABLE	10
NUMBER OF ENTRIES IN CLAD YOUNGS MODULUS TABLE	10
NUMBER OF ENTRIES IN CLAD YIELD POINT TABLE	10
NUMBER OF ENTRIES IN SCRAM REACTIVITY TABLE	2

*** -- FLOATING POINT DATA -- ***

*** GEOMETRY AND DESIGN CONFIGURATION ***

FUEL INNER RADIUS	0.00000+000
FUEL OUTER RADIUS	2.80000-001
CLAD INNER RADIUS	2.90000-001
CLAD OUTER RADIUS	3.25000-001
LENGTH OF PLENUM COOLANT TO BE CONSIDERED	0.00000+000
STRUCTURAL THICKNESS	3.00000-001
STRUCTURE-COOLANT SURFACE AREA RATIO	1.00000+004
VOLUME FRACTION OF STRUCTURE	1.80000-001
PUMP LEG	0.00000+000
AREA RATIO	1.00000+000
VOLUME FRACTION OF COOLANT	4.72000-001
LENGTH OF FUEL IN PIN	1.60000+002
LENGTH OF COOLANT CONSIDERED	1.60000+002

REFERENCE DESIGN TEMPERATURE	2.70000+001
COOLANT INLET TEMPERATURE	5.00000+002
COOLANT EXIT PRESSURE	3.00000+000

FUEL NODES

NUMBER

HEIGHT OF CENTER

LENGTH

1	5.00000+000	1.00000+001
2	1.50000+001	1.00000+001
3	2.50000+001	1.00000+001
4	3.50000+001	1.00000+001
5	4.50000+001	1.00000+001
6	5.50000+001	1.00000+001
7	6.50000+001	1.00000+001
8	7.50000+001	1.00000+001
9	8.50000+001	1.00000+001
10	9.50000+001	1.00000+001
11	1.05000+002	1.00000+001
12	1.15000+002	1.00000+001
13	1.25000+002	1.00000+001
14	1.35000+002	1.00000+001
15	1.45000+002	1.00000+001
16	1.55000+002	1.00000+001

*** MATERIAL PROPERTIES ***

* FUEL *

MELTING TEMPERATURE	2.80000+003
LATENT HEAT OF MELTING	2.70000+002
MOLECULAR WEIGHT	2.70000+002
COEFFICIENT OF LINEAR EXPANSION OF SOLID	1.69632+005
COEFFICIENT OF LINEAR EXPANSION OF LIQUID	4.51283+005
FRACTIONAL LINEAR EXPANSION DUE TO MELTING	1.52538+002
POISSONS RATIO	3.00000+001
YOUNGS MODULUS	1.00000+012
LIQUID FUEL BULK MODULUS	1.00000+012
AXIAL RESTRAINT SPRING CONSTANT	1.00000+001

FUEL NODES

NUMBER	MASS
1	2.56915+001
2	2.56915+001
3	2.56915+001
4	2.56915+001
5	2.56915+001
6	2.56915+001
7	2.56915+001
8	2.56915+001
9	2.56915+001
10	2.56915+001
11	2.56915+001
12	2.56915+001
13	2.56915+001
14	2.56915+001
15	2.56915+001
16	2.56915+001

MATERIAL PROPERTIES CONTINUED.....

* FUEL CLAD INTERFACE *

BOND CONDUCTANCE PARAMETER	8.00000+003
MAXIMUM BOND CONDUCTANCE (NO PRESSURE)	2.00000+000
SLOPE OF BOND CONDUCTANCE VERSUS PRESSURE	0.00000+000
STEFAN BOLTZMANNS CONSTANT * EMMISIVITY	4.56800+012

* CLADDING *

MELTING TEMPERATURE	1.50000+003
COEFFICIENT OF LINEAR EXPANSION	2.35000+005
SPECIFIC HEAT * DENSITY	4.60000+000
THERMAL CONDUCTIVITY	2.25000+001
POISSONS RATIO	2.50000+001

* CLAD COOLANT INTERFACE *

HEAT TRANSFER CONDUCTANCE AT CLAD BURNOUT	1.00000+002
COEFFICIENTS IN FILM CONDUCTANCE EQUATION	2.50000+002
	8.00000+001
	5.00000+000

* COOLANT *

SPECIFIC HEAT	1.29070+000
FRICTION FACTOR	1.87500+001
DEGREES OF SUPERHEAT	0.00000+000
VOID FRACTION AT CLAD BURNOUT	9.00000+001

* STRUCTURE *

COEFFICIENT OF LINEAR EXPANSION	2.35000+005
EFFECTIVE THERMAL RESISTANCE	5.00000+001
SPECIFIC HEAT * DENSITY	4.60000+000

*** POWER AND REACTIVITY ***

FUEL NODES

NUMBER

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

POWER SHAPE

6.42387-002
9.76227-002
1.24432-001
6.39855-001
7.46586-001
8.68488-001
9.54982-001
1.00000+000
1.00000+000
9.54982-001
8.68488-001
7.46586-001
6.39855-001
1.24432-001
9.76227-002
6.42387-002

POWER FACTORS FOR AUXILIARY (PHANTOM) CHANNELS

CHANNEL

1
2
3

POWER FACTOR

9.80000-001
9.60000-001
9.40000-001

*** POINT KINETICS AND FEEDBACK ***

PROMPT NEUTRON GENERATION TIME

4.72800-007

BETA EFFECTIVE

2.96420-003

NUMBER OF DELAYED NEUTRON PRECURSORS

PRECURSOR

1
2
3
4
5
6

FRACTION

7.62000-005
6.27000-004
5.61000-004
1.06000-003
4.80000-004
1.60000-004

6

LAMBDA

1.30000-002
3.14000-002
1.36000-001
3.40000-001
1.32000+000
3.50000+000

DOPPLER COEFFICIENT (NO COOLANT VOIDING)

-5.80000-003

DOPPLER COEFFICIENT (FULL COOLANT VOIDING)

-2.90000-003

RATIO OF SUBASSEMBLY GAP TO DIAMETER OF
SUBASSEMBLY

1.00000-002

RATIO OF CORE RETAINING STRUCTURE GAP TO
CORE DIAMETER

4.60000-002

SLOPE OF REACTIVITY AFTER SUBASSEMBLYS ARE
IN CONTACT

-1.22270-001

SLOPE OF REACTIVITY AFTER CORE COMES IN CONTACT
WITH RETAINING STRUCTURE

-1.00000-001

AXIAL NODES

NUMBER

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

DOPPLER
WEIGHTING

0.00000+000
0.00000+000
0.00000+000
5.74885-002
7.68846-002
1.01380-001
1.26675-001
1.37572-001
1.37572-001
1.26675-001
1.01380-001
7.68846-002
5.74885-002
0.00000+000
0.00000+000
0.00000+000

STRUCTURAL
WEIGHTING

0.00000+000
0.00000+000
0.00000+000
5.74885-002
7.68846-002
1.01380-001
1.26675-001
1.37572-001
1.37572-001
1.26675-001
1.01380-001
7.68846-002
5.74885-002
0.00000+000
0.00000+000
0.00000+000

* REACTIVITY *

AXIAL NODES NUMBER	MATERIAL WORTH	COOLANT VOID
1	0.00000+000	-1.14000-004
2	0.00000+000	-2.40100-004
3	0.00000+000	-5.53600-004
4	1.21623-003	-5.06400-004
5	1.37080-003	2.76000-004
6	1.49580-003	1.10800-003
7	1.56258-003	1.78300-003
8	1.60978-003	2.15700-003
9	1.60978-003	2.15700-003
10	1.56258-003	1.78300-003
11	1.49580-003	1.10800-003
12	1.37080-003	2.76000-004
13	1.21623-003	-5.06400-004
14	0.00000+000	-5.53600-004
15	0.00000+000	-2.40100-004
16	0.00000+000	-1.14000-004

*** OPERATIONAL CONTROLS ***

* STEADY STATE *

MINIMUM POWER IN POWER SEARCH	3.00000+003
MAXIMUM POWER IN POWER SEARCH	5.00000+003
MINIMUM POWER CHANGE IN POWER SEARCH	1.00000+001
MAXIMUM FUEL CENTER LINE TEMPERATURE IN POWER SEARCH	2.40000+003
MAXIMUM ALLOWABLE VALUE FOR COOLANT INLET PRESSURE IN POWER SEARCH	1.00000+001
COOLANT EXIT TEMPERATURE IN POWER SEARCH	6.30000+002
TEMPERATURE CONVERGENCE DELTA	1.00000+000

* TRANSIENT STATE *

INITIAL TIME STEP	2.00000-002
MAXIMUM ALLOWABLE PROBLEM TIME	5.00000+000
PUMP HEAD DECAY INVERSE PERIOD	0.00000+000
MAXIMUM ALLOWABLE COOLANT VOID FRACTION	9.00000-001
MAXIMUM NUMBER OF TIME STEPS	1000
TEMPERATURE FOR SWITCH TO WEAK EXPLOSION	5.00000+003
INVERSE PERIOD FOR SWITCH TO WEAK EXPLOSION	2.00000+003
COOLANT EXIT TEMPERATURE FOR SCRAM INITIATION	7.00000+002
INVERSE PERIOD FOR SCRAM INITIATION	2.00000+002
NORMALIZED POWER FOR SCRAM INITIATION	1.25000+000
INLET FLOWRATE FOR SCRAM INITIATION	3.00000+002

CONVERGENCE EPSILONS

COOLANT BOILING	1.00000-003
FUEL DEFORMATION	1.00000-004
REACTIVITY	1.00000-003
NEUTRON FLUX	1.00000-005

*** TABULAR PROPERTIES ***

FUEL THERMAL CONDUCTIVITY

CONDUCTIVITY	TEMPERATURE
6.62000-002	1.00000+002
4.24000-002	5.00000+002
2.93000-002	1.00000+003
2.24000-002	1.50000+003
1.81000-002	2.00000+003
1.51000-002	2.50000+003
1.65000-002	2.80000+003
1.81000-002	3.00000+003
2.93000-002	4.00000+003
5.41000-002	5.00000+003

FUEL SPECIFIC HEAT

SPECIFIC HEAT	TEMPERATURE
1.98000-001	1.00000+002
2.24000-001	5.00000+002
3.12000-001	1.00000+003
4.08000-001	1.50000+003
5.06000-001	2.00000+003
6.04000-001	2.50000+003
6.62000-001	2.80000+003
5.15000-001	3.00000+003
5.15000-001	4.00000+003
5.15000-001	5.00000+003

FUEL INTERNAL ENERGY

INTERNAL ENERGY	TEMPERATURE
0.00000+000	1.00000+002
8.44000+001	5.00000+002
2.18400+002	1.00000+003
3.98400+002	1.50000+003
6.26900+002	2.00000+003
9.04400+002	2.50000+003
1.09430+003	2.80000+003
1.21200+003	3.00000+003
1.72700+003	4.00000+003
2.24200+003	5.00000+003

CLAD YOUNGS MODULUS

MODULUS	TEMPERATURE
8.41800+011	1.00000+002
8.41800+011	5.00000+002
7.44800+011	1.00000+003
6.81000+011	1.10000+003
6.06000+011	1.20000+003
5.18400+011	1.30000+003
4.16500+011	1.40000+003
4.00000+011	1.50000+003
4.00000+011	2.00000+003
4.00000+011	3.00000+003

CLAD YIELD POINT

YIELD POINT	TEMPERATURE
2.62000+009	1.00000+002
2.07000+009	5.00000+002
6.89000+008	1.00000+003
5.51000+008	1.10000+003
4.14000+008	1.20000+003
3.45000+008	1.30000+003
2.76000+008	1.40000+003
0.00000+000	1.50000+003
0.00000+000	2.00000+003
0.00000+000	3.00000+003

FUEL DENSITY

DENSITY	TEMPERATURE
1.04200+001	1.00000+002
1.03600+001	5.00000+002
1.02400+001	1.00000+003
1.00400+001	1.50000+003
9.76600+000	2.00000+003
9.14100+000	2.80000+003
8.74100+000	2.80000+003
8.57100+000	3.00000+003
7.65300+000	4.00000+003
6.73500+000	5.00000+003

SCRAM REACTIVITY

REACTIVITY	TIME
0.00000+000	0.00000+000
0.00000+000	1.00000+003

*** WEAK EXPLOSION DATA ***

DISTANCE FROM REACTOR BASE TO CORE CENTER	8.00000+001
INITIAL TIME STEP USED FOR CALCULATION	2.00000+005
MAXIMUM TIME STEP ALLOWED	1.00000+003
MINIMUM TIME STEP ALLOWED	1.00000+006
MINIMUM VALUE OF K-EFFECTIVE ALLOWED	9.50000+001
MINIMUM VALUE OF NORMALIZED POWER ALLOWED	9.50000+001
MAXIMUM VALUE OF NORMALIZED POWER ALLOWED	1.00000+006
TIME STEP HALVING POWER RATIO	1.25000+000
TIME STEP DOUBLING POWER RATIO	1.05000+000
POWER PEAK POWER RATIO	9.95000+001

POWER PROFILES

AXIAL NODE	AXIAL LOCATION	POWER SHAPE
1	0.00000+000	5.00000+002
2	1.00000+001	7.70000+002
3	2.00000+001	1.16000+001
4	2.99990+001	1.30000+001
5	3.00010+001	5.95000+001
6	4.00000+001	6.70000+001
7	5.00000+001	8.06000+001
8	6.00000+001	9.11000+001
9	7.00000+001	9.77000+001
10	8.00000+001	1.00000+000
11	9.00000+001	9.77000+001
12	1.00000+002	9.11000+001
13	1.10000+002	8.06000+001
14	1.20000+002	6.70000+001
15	1.29999+002	5.95000+001
16	1.30001+002	1.30000+001
17	1.40000+002	1.16000+001
18	1.50000+002	7.70000+002
19	1.60000+002	5.00000+002

RADIAL NODE	RADIAL LOCATION	POWER SHAPE
1	0.00000+000	1.00000+000
2	2.00000+001	9.78474+001
3	5.00000+001	9.02153+001
4	6.25000+001	8.46380+001
5	6.75000+001	8.18982+001
6	7.25000+001	7.87671+001
7	7.49990+001	7.68102+001
8	7.50010+001	9.98043+001
9	7.75000+001	9.63796+001
10	8.25000+001	9.07045+001
11	9.00000+001	7.97456+001
12	1.00000+002	6.22309+001
13	1.04999+002	5.06849+001
14	1.05001+002	2.69080+001
15	1.07500+002	2.26027+001
16	1.27500+002	6.36008+002
17	1.47500+002	1.76125+002
18	1.85000+002	9.78474+006

MATERIAL WORTH DISTRIBUTION

RADIAL LOCATION	AT 0.00 CM	AT 7.50 CM	AT 22.50 CM
0.00000+000	2.02500+007	2.00000+007	1.95500+007
2.00000+001	2.00500+007	1.98600+007	1.94300+007
5.00000+001	1.93000+007	1.91000+007	1.87000+007
6.25000+001	1.77400+007	1.77300+007	1.77000+007
6.75000+001	1.67900+007	1.67700+007	1.67000+007
7.25000+001	1.57600+007	1.57500+007	1.57000+007
7.49990+001	1.46800+007	1.47500+007	1.46000+007
7.50010+001	2.96000+007	2.87000+007	2.69000+007
7.75000+001	2.85000+007	2.76000+007	2.58100+007
8.25000+001	2.63400+007	2.56400+007	2.41600+007
9.00000+001	2.35000+007	2.26800+007	2.10100+007
1.00000+002	1.93000+007	1.85000+007	1.69900+007
1.04999+002	1.67000+007	1.57000+007	1.37000+007
1.05001+002	0.00000+000	0.00000+000	0.00000+000
1.85000+002	0.00000+000	0.00000+000	0.00000+000

MATERIAL WORTH DISTRIBUTION

RADIAL LOCATION	AT 35.00 CM	AT 45.00 CM	AT 50.00 CM
0.00000+000	1.90000-007	1.85000-007	1.82500-007
2.00000+001	1.87000-007	1.80000-007	1.76500-007
5.00000+001	1.79000-007	1.72500-007	1.69000-007
6.25000+001	1.70000-007	1.63000-007	1.59500-007
6.75000+001	1.60000-007	1.54000-007	1.51000-007
7.25000+001	1.49000-007	1.43000-007	1.40000-007
7.49990+001	1.39000-007	1.35000-007	1.33000-007
7.50010+001	2.19000-007	1.92000-007	1.77000-007
7.75000+001	2.17400-007	1.87200-007	1.72500-007
8.25000+001	2.02400-007	1.72500-007	1.57000-007
9.00000+001	1.72100-007	1.37200-007	1.20200-007
1.00000+002	1.36200-007	1.05000-007	9.00000-008
1.04999+002	1.29000-007	8.40000-008	6.70000-008
1.05001+002	0.00000+000	0.00000+000	0.00000+000
1.85000+002	0.00000+000	0.00000+000	0.00000+000

RADIAL LOCATION	AT 50.00 CM
0.00000+000	0.00000+000
2.00000+001	0.00000+000
5.00000+001	0.00000+000
6.25000+001	0.00000+000
6.75000+001	0.00000+000
7.25000+001	0.00000+000
7.49990+001	0.00000+000
7.50010+001	0.00000+000
7.75000+001	0.00000+000
8.25000+001	0.00000+000
9.00000+001	0.00000+000
1.00000+002	0.00000+000
1.04999+002	0.00000+000
1.05001+002	0.00000+000
1.85000+002	0.00000+000

STEADY STATE POWER SEARCH RESULTS

COOLANT MASS FLOW RATE
 STEADY STATE POWER IN THE PEAK NODE
 STEADY STATE TOTAL POWER IN THE PIN
 TOTAL REACTOR POWER

8.09714+002
 4.49200+003
 4.03939+004
 1.68384+009

*** STEADY STATE ***

COOLANT PROFILE

AXIAL LOCATION (CM)	COOLANT TEMPERATURE (C)	SATURATION TEMPERATURE (C)	PRESSURE (ATM)
INLET			
0.000	500.000	1099.419	5.321
2.000	500.184	1098.730	5.297
4.000	500.369	1098.039	5.274
6.000	500.558	1097.345	5.250
8.000	500.761	1096.649	5.226
10.000	500.983	1095.951	5.203
12.000	501.224	1095.249	5.179
14.000	501.483	1094.546	5.156
16.000	501.761	1093.839	5.132
18.000	502.056	1093.130	5.108
20.000	502.365	1092.418	5.085
22.000	502.690	1091.704	5.061
24.000	503.030	1090.987	5.038
26.000	503.436	1090.267	5.014
28.000	504.047	1089.543	4.990
30.000	504.946	1088.814	4.967
32.000	506.135	1088.080	4.943
34.000	507.612	1087.342	4.919
36.000	509.342	1086.599	4.895
38.000	511.211	1085.852	4.871
40.000	513.139	1085.102	4.847
42.000	515.126	1084.349	4.823
44.000	517.172	1083.592	4.799
46.000	519.278	1082.832	4.775
48.000	521.447	1082.068	4.751
50.000	523.683	1081.301	4.727
52.000	525.986	1080.530	4.703
54.000	528.356	1079.755	4.679
56.000	530.792	1078.977	4.655
58.000	533.284	1078.195	4.631
60.000	535.823	1077.410	4.607
62.000	538.409	1076.621	4.583
64.000	541.042	1075.828	4.559
66.000	543.722	1075.032	4.534
68.000	546.438	1074.231	4.510
70.000	549.178	1073.428	4.486
72.000	551.943	1072.620	4.462
74.000	554.732	1071.809	4.438
76.000	557.545	1070.994	4.413
78.000	560.372	1070.175	4.389
80.000	563.201	1069.352	4.365
82.000	566.029	1068.526	4.341
84.000	568.857	1067.696	4.317
86.000	571.685	1066.862	4.292
88.000	574.503	1066.025	4.268
90.000	577.300	1065.184	4.244
92.000	580.072	1064.339	4.220
94.000	582.819	1063.490	4.195
96.000	585.542	1062.637	4.171
98.000	588.233	1061.781	4.147
100.000	590.881	1060.921	4.123
102.000	593.482	1060.057	4.098
104.000	596.035	1059.190	4.074
106.000	598.541	1058.318	4.050
108.000	600.994	1057.443	4.026
110.000	603.386	1056.564	4.002
112.000	605.711	1055.682	3.977
114.000	607.969	1054.795	3.953
116.000	610.160	1053.905	3.929
118.000	612.286	1053.011	3.905
120.000	614.350	1052.112	3.881
122.000	616.356	1051.210	3.857
124.000	618.303	1050.304	3.833

126.000	620.192	1049.394	3.809
128.000	621.988	1048.480	3.784
130.000	623.578	1047.563	3.760
132.000	624.881	1046.644	3.736
134.000	625.896	1045.723	3.712
136.000	626.623	1044.800	3.689
138.000	627.092	1043.874	3.665
140.000	627.437	1042.945	3.641
142.000	627.768	1042.012	3.617
144.000	628.083	1041.073	3.594
146.000	628.383	1040.130	3.570
148.000	628.667	1039.182	3.546
150.000	628.935	1038.230	3.522
152.000	629.183	1037.272	3.499
154.000	629.413	1036.309	3.475
156.000	629.623	1035.342	3.451
158.000	629.816	1034.369	3.427
160.000	630.000	1033.391	3.404

OUTLET

POINT KINETICS

NORMALIZED POWER = 1.000000+000

PRECURSOR NUMBER	PRECURSOR CONCENTRATION
1	1.23975+004
2	4.22338+004
3	8.72462+003
4	6.59401+003
5	7.69112+002
6	9.66884+001

HEAT TRANSFER

AXIAL LOCATION (CM)	RADIAL TEMPERATURE MESH (C)									
	1	2	3	4	5	6	7	8	9	10
5.047	583.819	575.286	568.636	562.318	556.093	549.919	543.783	537.679	531.603	525.373
15.143	629.382	616.077	605.740	595.943	586.314	576.786	567.337	557.957	548.641	539.005
25.244	667.317	649.981	636.548	623.845	611.386	599.081	586.902	574.834	562.869	550.410
35.385	1520.065	1375.481	1268.704	1172.088	1081.009	994.226	912.652	836.390	764.513	696.472
45.573	1747.508	1562.281	1425.154	1303.594	1190.845	1084.821	984.328	890.921	804.263	723.452
55.782	2023.130	1785.686	1612.791	1458.039	1317.021	1186.822	1065.170	950.542	846.111	749.166
66.008	2238.954	1956.670	1754.188	1575.590	1411.071	1261.663	1123.750	995.005	876.959	768.657
76.248	2369.529	2062.655	1841.602	1648.553	1471.483	1310.360	1162.821	1025.904	899.612	784.593
86.495	2399.671	2089.887	1866.276	1671.363	1492.828	1329.866	1180.916	1042.874	914.864	798.574
96.742	2324.160	2034.429	1825.368	1641.852	1472.888	1318.569	1176.815	1044.961	922.157	810.274
106.982	2155.137	1904.520	1723.431	1562.283	1412.997	1276.323	1149.423	1030.431	919.280	817.061
117.209	1909.633	1712.662	1567.230	1435.766	1315.069	1202.464	1096.404	995.825	901.923	815.182
127.420	1705.852	1548.550	1431.236	1326.183	1227.976	1135.044	1046.505	961.751	882.804	808.759
137.584	803.304	784.160	769.318	755.301	741.573	728.038	714.662	701.429	688.330	674.745
147.707	765.056	750.478	739.168	728.464	717.956	707.571	697.284	687.084	676.963	666.527
157.826	718.745	709.422	702.162	695.270	688.485	681.762	675.084	668.445	661.841	655.085

AXIAL LOCATION (CM)	CLAD TEMPERATURES (C)			AVERAGE COOLANT TEMPERATURE (C)	AVERAGE STRUCTURE TEMPERATURE (C)	RADIAL LOCATION (CM)				FRACTION OF FUEL MELTED
	INNER	MIDPOINT	OUTER			INNER FUEL	OUTER FUEL	INNER CLAD	OUTER CLAD	
5.047	503.916	502.696	501.590	500.468	500.468	0.000	0.283	0.293	0.329	0.000
15.143	506.881	505.028	503.347	501.642	501.642	0.000	0.283	0.293	0.329	0.000
25.244	509.959	507.597	505.456	503.283	503.283	0.000	0.283	0.293	0.329	0.000
35.385	542.897	530.844	519.921	508.810	508.810	0.000	0.286	0.293	0.329	0.000
45.573	558.576	544.538	531.820	518.829	518.829	0.000	0.286	0.294	0.329	0.000
55.782	576.731	560.434	545.676	530.526	530.526	0.000	0.287	0.294	0.329	0.000
66.008	594.540	576.649	560.453	543.733	543.733	0.000	0.288	0.294	0.329	0.000
76.248	611.139	592.423	575.486	557.897	557.897	0.000	0.288	0.294	0.329	0.000
86.495	625.704	606.995	590.070	572.383	572.383	0.000	0.288	0.294	0.329	0.000
96.742	637.573	619.700	603.536	586.541	586.541	0.000	0.288	0.294	0.330	0.000
106.982	646.284	630.014	615.303	599.745	599.745	0.000	0.288	0.294	0.330	0.000
117.209	651.580	637.571	624.906	611.445	611.445	0.000	0.287	0.294	0.330	0.000
127.420	655.962	643.938	633.070	621.467	621.467	0.000	0.286	0.294	0.330	0.000
137.584	633.762	631.405	629.275	626.994	626.994	0.000	0.283	0.294	0.330	0.000
147.707	633.938	632.089	630.417	628.626	628.626	0.000	0.283	0.294	0.330	0.000
157.826	633.297	632.080	630.979	629.799	629.799	0.000	0.283	0.294	0.330	0.000

FUEL
NODE

RADIAL FUEL MESH (CM)

	1	2	3	4	5	6	7	8	9	10	11
1	0.0000	0.0666	0.1154	0.1490	0.1762	0.1998	0.2209	0.2401	0.2579	0.2746	0.2825
2	0.0000	0.0667	0.1155	0.1491	0.1764	0.2000	0.2210	0.2403	0.2581	0.2748	0.2827
3	0.0000	0.0667	0.1155	0.1491	0.1765	0.2001	0.2212	0.2404	0.2582	0.2749	0.2828
4	0.0000	0.0677	0.1171	0.1511	0.1786	0.2024	0.2236	0.2430	0.2609	0.2776	0.2856
5	0.0000	0.0679	0.1175	0.1515	0.1792	0.2030	0.2243	0.2437	0.2616	0.2783	0.2863
6	0.0000	0.0682	0.1180	0.1521	0.1798	0.2037	0.2250	0.2444	0.2624	0.2791	0.2871
7	0.0000	0.0685	0.1184	0.1526	0.1804	0.2043	0.2256	0.2450	0.2630	0.2797	0.2877
8	0.0000	0.0686	0.1186	0.1529	0.1807	0.2046	0.2260	0.2454	0.2634	0.2801	0.2881
9	0.0000	0.0687	0.1187	0.1530	0.1807	0.2047	0.2261	0.2455	0.2635	0.2802	0.2882
10	0.0000	0.0686	0.1185	0.1528	0.1806	0.2045	0.2259	0.2453	0.2633	0.2800	0.2880
11	0.0000	0.0684	0.1182	0.1525	0.1802	0.2041	0.2255	0.2449	0.2628	0.2796	0.2876
12	0.0000	0.0681	0.1178	0.1519	0.1796	0.2035	0.2248	0.2442	0.2622	0.2789	0.2869
13	0.0000	0.0679	0.1174	0.1515	0.1791	0.2030	0.2243	0.2437	0.2616	0.2783	0.2863
14	0.0000	0.0669	0.1158	0.1495	0.1769	0.2005	0.2217	0.2410	0.2588	0.2755	0.2835
15	0.0000	0.0668	0.1157	0.1494	0.1768	0.2004	0.2215	0.2408	0.2587	0.2754	0.2833
16	0.0000	0.0668	0.1156	0.1493	0.1766	0.2003	0.2214	0.2407	0.2585	0.2752	0.2832

*** TRANSIENT STATE ***

		REACTIVITIES (\$)												
TOTAL TIME (SEC)	TIME STEP (SEC)	NORMALIZED POWER	VALUES ENERGY	PROGRAM	DOPPLER	DENSITY	RADIAL EXPAN.	COOL 1	COOLANT CHANNELS COOL 2	COOL 3	COOL 4	SCRAM	NET	
0.0200	0.02000	1.052	0.021	0.050	-0.000	0.000	0.000	-0.000	0.000	0.000	0.000	0.000	0.050	
0.0400	0.02000	1.110	0.042	0.100	-0.001	-0.000	0.000	-0.000	0.000	0.000	0.000	0.000	0.099	
0.0600	0.02000	1.176	0.065	0.150	-0.002	-0.000	0.000	-0.000	0.000	0.000	0.000	0.000	0.147	
0.0800	0.02000	1.248	0.089	0.200	-0.004	-0.000	0.000	-0.000	0.000	0.000	0.000	0.000	0.195	

CRITERION FOR SCRAM INITIATION HAS BEEN MET

	CALCULATED VALUES	INPUT CRITEREON
INVERSE PERIOD	3.21206+000	2.00000+002
FLUX	1.33093+000	1.25000+000
COOLANT EXIT TEMPERATURE	6.29144+002	7.00000+002
COOLANT INLET FLOWRATE	8.09764+002	3.00000+002

* * * * * REACTIVITIES (\$) * * * * *													
TOTAL TIME (SEC)	TIME STEP (SEC)	NORMALIZED VALUES		PROGRAM	* * *			COOLANT CHANNELS				SCRAM	NET
		POWER	ENERGY		DOPPLER	DENSITY	RADIAL EXPAN.	COOL 1	COOL 2	COOL 3	COOL 4		
0.8941	0.00036	20.177	9.858	2.235	-1.418	-0.196	0.008	0.155	-0.015	0.000	0.000	0.000	0.762
0.8944	0.00031	19.943	9.865	2.236	-1.418	-0.196	0.008	0.154	-0.020	0.000	0.000	0.000	0.756
0.8948	0.00039	19.590	9.873	2.237	-1.418	-0.197	0.000	0.153	-0.023	0.000	0.000	0.000	0.753
0.8951	0.00031	19.371	9.879	2.238	-1.418	-0.197	0.000	0.152	-0.024	0.000	0.000	0.000	0.751
0.8955	0.00034	19.176	9.885	2.239	-1.419	-0.197	0.008	0.152	-0.026	0.000	0.000	0.000	0.749
0.8958	0.00034	18.996	9.892	2.240	-1.419	-0.197	0.008	0.152	-0.029	0.000	0.000	0.000	0.747
0.8961	0.00033	18.829	9.898	2.240	-1.419	-0.197	0.000	0.151	-0.030	0.000	0.000	0.000	0.745
0.8965	0.00030	18.703	9.904	2.241	-1.419	-0.197	0.000	0.151	-0.031	0.000	0.000	0.000	0.744
0.8968	0.00036	18.566	9.910	2.242	-1.419	-0.197	0.000	0.149	-0.033	0.000	0.000	0.000	0.742

THE NUMBER OF TIME STEPS IS 97

THE TIME IS 0.8972

THE TIME STEP IS 3.62059E-004

REACTOR POWER IS NOW 3.09666E+010 WATTS

ENERGY RELEASE IS 1.66985E+010 WATT-SEC

DELAYED NEUTRON PRECURSORS

PRECURSOR NUMBER	PRECURSOR CONCENTRATION
1	1.38523E+004
2	5.41577E+004
3	1.91605E+004
4	2.54967E+004
5	7.85195E+003
6	1.75383E+003

ERROR IN LAST FLUX CALCULATION WAS 1.80246E-006 MAXIMUM ALLOWABLE IS 8.00000E-005

LAST ITERATION COUNTS

REACTIVITY	FLUX
0	8

REACTIVITIES

TYPE	REACTIVITY (%)
PROGRAMMED	2.243
DCPPLER	-1.418
DENSITY	-0.198
RADIAL EXPANSION	0.000
COOLANT	

CHANNEL NUMBER

1	0.147
2	-0.036
3	0.000
4	0.000

BOILING TIME (SEC)

0.0141
0.0057
0.0000
0.0000

SCRAM

0.000

TIME IS 0.7972 SEC. SINCE INITIATION

NET REACTIVITY IS 0.738

K EFFECTIVE IS 1.0021917

INVERSE PERIOD -3.13369E+001

COOLANT PROFILE

THE AVERAGE MASS FLOW RATE IS 57.310 GM/(CMSQ SEC)
 THE INLET LIQUID SLUG IS 125.500 CM
 THE EXIT LIQUID SLUG IS -0.100 CM
 NUMBER OF TIME STEPS SINCE BOILING INITIATION
 LAST TWO PHASE ITERATION COUNT 5

51

AXIAL LOCATION (CM)	PRESSURE (ATM)	COOLANT TEMPERATURE (C)	SATURATION TEMPERATURE (C)	VAPOR QUALITY	VOID FRACTION	MASS FLOWRATE (GMS/SEC-CM**2)
INLET						
0.000	5.707	500.311	1100.331	0.000	0.000	-57.958
2.000	5.766	504.143	1099.694	0.000	0.000	-57.958
4.000	5.826	505.156	1099.027	0.000	0.000	-57.958
6.000	5.886	507.459	1098.386	0.000	0.000	-57.958
8.000	5.946	508.798	1097.743	0.000	0.000	-57.958
10.000	6.006	511.026	1097.069	0.000	0.000	-57.958
12.000	6.065	512.715	1096.421	0.000	0.000	-57.958
14.000	6.125	515.209	1095.772	0.000	0.000	-57.958
16.000	6.185	517.347	1095.091	0.000	0.000	-57.958
18.000	6.245	519.838	1094.437	0.000	0.000	-57.958
20.000	6.305	522.065	1093.752	0.000	0.000	-57.958
22.000	6.364	524.634	1093.094	0.000	0.000	-57.958
24.000	6.424	527.036	1092.404	0.000	0.000	-57.958
26.000	6.484	530.562	1091.740	0.000	0.000	-57.958
28.000	6.544	536.924	1091.046	0.000	0.000	-57.958
30.000	6.604	546.024	1090.319	0.000	0.000	-57.958
32.000	6.663	556.803	1089.619	0.000	0.000	-57.958
34.000	6.723	569.513	1088.886	0.000	0.000	-57.958
36.000	6.783	583.756	1088.121	0.000	0.000	-57.958
38.000	6.843	596.939	1087.382	0.000	0.000	-57.958
40.000	6.903	609.254	1086.610	0.000	0.000	-57.958
42.000	6.963	621.213	1085.864	0.000	0.000	-57.958
44.000	7.022	633.177	1085.085	0.000	0.000	-57.958
46.000	7.082	645.101	1084.333	0.000	0.000	-57.958
48.000	7.142	657.158	1083.546	0.000	0.000	-57.958
50.000	7.202	669.313	1082.756	0.000	0.000	-57.958
52.000	7.262	681.415	1081.992	0.000	0.000	-57.958
54.000	7.322	693.659	1081.194	0.000	0.000	-57.958
56.000	7.382	705.805	1080.392	0.000	0.000	-57.958
58.000	7.442	718.198	1079.585	0.000	0.000	-57.958
60.000	7.502	730.258	1078.774	0.000	0.000	-57.958
62.000	7.561	742.665	1077.959	0.000	0.000	-57.958
64.000	7.621	754.682	1077.139	0.000	0.000	-57.958
66.000	7.681	767.182	1076.315	0.000	0.000	-57.958
68.000	7.741	779.108	1075.486	0.000	0.000	-57.958
70.000	7.801	791.603	1074.652	0.000	0.000	-57.958
72.000	7.861	803.402	1073.845	0.000	0.000	-57.958
74.000	7.921	815.947	1073.002	0.000	0.000	-57.958
76.000	7.981	827.718	1072.153	0.000	0.000	-57.958

78.000	8,040	840.246	1071.300	0,000	0,000	-57.958
80.000	8,100	851.588	1070.441	0,000	0,000	-57.958
82.000	8,160	863.522	1069.577	0,000	0,000	-57.958
84.000	8,220	874.179	1068.707	0,000	0,000	-57.958
86.000	8,280	885.784	1067.832	0,000	0,000	-57.958
88.000	8,340	895.927	1066.952	0,000	0,000	-57.958
90.000	8,400	907.145	1066.066	0,000	0,000	-57.958
92.000	8,460	916.678	1065.174	0,000	0,000	-57.958
94.000	8,520	927.516	1064.277	0,000	0,000	-57.958
96.000	8,580	936.529	1063.408	0,000	0,000	-57.958
98.000	8,640	947.112	1062.499	0,000	0,000	-57.958
100.000	8,700	955.563	1061.585	0,000	0,000	-57.958
102.000	8,760	963.190	1060.699	0,000	0,000	-57.958
104.000	8,820	970.817	1059.772	0,000	0,000	-57.958
106.000	8,880	978.444	1058.875	0,000	0,000	-57.958
108.000	8,940	986.070	1057.937	0,000	0,000	-57.958
110.000	9,000	993.697	1057.027	0,000	0,000	-57.958
112.000	9,060	1001.324	1056.112	0,000	0,000	-57.958
114.000	9,120	1008.950	1055.156	0,000	0,000	-57.958
116.000	9,180	1016.577	1054.229	0,000	0,000	-57.958
118.000	9,240	1024.204	1053.296	0,000	0,000	-57.958
120.000	9,300	1031.831	1052.357	0,000	0,000	-57.958
122.000	9,360	1037.829	1051.449	0,000	0,000	-57.958
124.000	9,420	1044.151	1050.498	0,000	0,000	-57.958
126.000	9,480	1049.542	1049.542	4,685-003	4,507-001	239.977
128.000	9,221	1048.616	1048.616	2,139-002	6,891-001	311.964
130.000	8,995	1047.648	1047.648	3,718-002	7,560-001	352.329
132.000	8,726	1046.711	1046.711	5,189-002	7,912-001	381.716
134.000	8,420	1045.768	1045.768	6,386-002	8,118-001	405.186
136.000	8,102	1044.857	1044.857	7,186-002	8,235-001	425.322
138.000	7,780	1043.942	1043.942	7,643-002	8,303-001	443.304
140.000	7,468	1043.023	1043.023	7,791-002	8,335-001	460.046
142.000	7,181	1042.137	1042.137	7,647-002	8,336-001	476.345
144.000	6,910	1041.286	1041.286	7,344-002	8,319-001	492.686
146.000	6,626	1040.393	1040.393	7,019-002	8,300-001	509.090
148.000	6,329	1039.497	1039.497	6,673-002	8,279-001	525.870
150.000	6,023	1038.598	1038.598	6,305-002	8,253-001	543.732
152.000	5,425	1037.733	1037.733	5,950-002	8,251-001	545.038
154.000	5,317	1036.826	1036.826	5,672-002	8,220-001	564.586
156.000	4,974	1035.916	1035.916	5,215-002	8,179-001	589.532
158.000	4,617	1035.002	1035.002	4,713-002	8,127-001	616.462
160.000	4,294	1034.123	1034.123	4,191-002	8,058-001	647.996

OUTLET

HEAT TRANSFER

AXIAL
LOCATION
(CM)

RADIAL FUEL TEMPERATURE MESH (C)

	1	2	3	4	5	6	7	8	9	10
5.072	949.599	937.821	924.837	908.646	888.031	861.968	829.537	790.065	743.306	689.389
15.231	1146.312	1131.066	1114.298	1092.977	1064.997	1028.281	980.695	921.311	849.766	766.802
25.412	1291.830	1274.244	1255.117	1230.643	1198.050	1154.415	1096.612	1021.888	929.655	822.975
35.744	2916.868	2816.583	2800.000	2800.000	2800.000	2800.000	2645.881	2313.999	1832.888	1249.169
46.249	3530.788	3282.162	3240.346	3080.167	2943.950	2800.000	2800.000	2549.367	2020.750	1362.338
56.843	4085.282	3819.299	3665.347	3538.927	3423.976	3205.262	2872.669	2750.777	2211.931	1477.706
67.528	4606.974	4331.199	4105.963	3921.167	3741.175	3531.913	3252.098	2800.000	2341.879	1566.057
78.281	4886.936	4551.731	4326.825	4139.089	3947.712	3719.250	3397.406	2800.000	2411.399	1627.564
89.066	4888.596	4552.681	4326.930	4138.917	3947.517	3719.520	3398.481	2814.071	2440.079	1668.904
99.834	4694.872	4386.564	4219.823	4050.105	3842.952	3583.013	3270.775	2800.000	2427.780	1686.142
110.542	4216.279	3964.627	3810.010	3659.673	3501.210	3304.597	3009.656	2800.000	2370.199	1675.748
121.162	3659.639	3404.652	3266.841	3147.551	3054.922	2869.988	2800.000	2688.567	2239.605	1632.615
131.706	3085.318	2968.926	2838.872	2800.000	2800.000	2800.000	2773.307	2518.893	2110.317	1584.963
142.071	1386.793	1370.734	1356.209	1340.190	1321.498	1299.085	1271.777	1238.420	1198.181	1150.734
152.281	1246.696	1233.653	1221.950	1209.307	1194.993	1178.464	1159.169	1136.652	1110.807	1082.370
162.467	1058.337	1049.481	1041.997	1034.508	1026.810	1018.906	1010.876	1002.941	995.680	990.894

AXIAL
LOCATION
(CM)CLAD TEMPERATURES (C)
INNER MIDPOINT OUTERAVERAGE
COOLANT
TEMPERATURE
(C)AVERAGE
STRUCTURE
TEMPERATURE
(C)RADIAL LOCATION (CM)
INNER OUTER INNER OUTER
FUEL FUEL CLAD CLADFRACTION
OF FUEL
MELTED

5.072	532.432	523.283	516.558	506.149	501.063	0.000	0.284	0.293	0.329	0.000
15.231	555.041	541.791	532.205	517.435	504.067	0.000	0.285	0.294	0.329	0.000
25.412	577.021	560.884	549.622	533.036	508.058	0.000	0.285	0.294	0.329	0.000
35.744	780.073	713.429	664.023	583.253	521.536	0.000	0.297	0.297	0.333	0.398
46.249	855.707	784.893	733.194	645.192	543.632	0.000	0.302	0.302	0.337	0.620
56.843	936.266	861.876	808.289	712.000	567.675	0.000	0.307	0.307	0.341	0.722
67.528	1009.508	934.382	880.950	779.195	593.036	0.000	0.312	0.312	0.346	0.775
78.281	1072.233	997.745	945.083	839.804	618.513	0.000	0.315	0.315	0.348	0.828
89.066	1127.614	1055.273	1005.091	901.204	643.210	0.000	0.315	0.315	0.349	0.833
99.834	1170.721	1101.835	1055.023	954.642	666.010	0.000	0.313	0.313	0.347	0.797
110.542	1197.843	1133.426	1090.397	993.697	685.902	0.000	0.309	0.309	0.344	0.739
121.162	1208.706	1151.055	1113.733	1034.022	702.127	0.000	0.303	0.303	0.338	0.667
131.706	1208.319	1154.769	1114.526	1046.720	714.578	0.000	0.299	0.299	0.335	0.494
142.071	1038.938	1035.413	1036.936	1042.156	716.892	0.000	0.286	0.297	0.333	0.000
152.281	1015.832	1016.329	1023.524	1037.714	711.691	0.000	0.286	0.297	0.333	0.000
162.467	990.019	995.769	1010.241	1034.562	706.016	0.000	0.285	0.297	0.332	0.000

DEFORMATION PARAMETERS

AXIAL FUEL NODE	AXIAL FUEL LOCATION (CM)	*** FUEL ***			FUEL STRESSES (DYNES/CM**2)		
		STRESSED RADII (CM) INNER SOLID	OUTER SOLID	FREE RADIUS OF MELTED FUEL	NODE SLIPPAGE	INNER SOLID	OUTER SOLID
1	5.0724	0.00000+000	2.83972-001	0.00000+000	2.43553+005	-7.51270+008	2.43553+005
2	15.2306	0.00000+000	2.84752-001	0.00000+000	-6.58182+004	-9.93612+008	-6.58182+004
3	25.4125	0.00000+000	2.85340-001	0.00000+000	1.29110+006	-1.13150+009	1.29110+006
4	35.7435	2.34988-001	2.97309-001	2.39382-001	-1.52347+006	-7.61736+009	-1.77280+008
5	46.2493	2.59413-001	3.01906-001	2.64954-001	7.11405+005	-7.89696+009	-1.47505+008
6	56.8427	2.64615-001	3.06835-001	2.71742-001	-1.38722+006	-1.07015+010	-1.21507+008
7	67.5278	2.87901-001	3.12061-001	2.96172-001	9.49424+005	-7.89693+009	-9.40166+007
8	78.2815	2.90515-001	3.14580-001	2.99684-001	-1.97810+005	-8.69672+009	-7.50839+007
9	89.0658	2.90543-001	3.14631-001	2.99689-001	-1.21134+005	-8.61482+009	-6.62138+007
10	99.8343	2.88883-001	3.13059-001	2.97431-001	-2.09710+005	-8.02533+009	-6.01776+007
11	110.5417	2.84506+001	3.08889-001	2.91580-001	8.20917+005	-6.49991+009	-5.59261+007
12	121.1622	2.60452-001	3.03090-001	2.66180-001	-3.69660+005	-7.80299+009	-5.63010+007
13	131.7063	2.36121-001	2.98668-001	2.40689-001	-1.67726+006	-7.59188+009	-5.85975+007
14	142.0714	0.00000+000	2.86117-001	0.00000+000	1.41821+006	-2.73977+008	1.41821+006
15	152.2809	0.00000+000	2.85537-001	0.00000+000	-6.12384+004	-1.93057+008	-6.12384+004
16	162.4673	0.00000+000	2.84771-001	0.00000+000	2.31712+005	-2.60815+007	2.31712+005

DEFORMATION COUNT

NET CORE MOVEMENT

FUEL AXIAL STRESS

1

3.91988 CM.

4.66654+001 DYNES/CM**2

AXIAL
FUEL
NODE

RADIAL FUEL MESH (CM)

	1	2	3	4	5	6	7	8	9	10	11
1	0.0000	0.0670	0.1161	0.1498	0.1773	0.2010	0.2222	0.2415	0.2593	0.2760	0.2840
2	0.0000	0.0672	0.1164	0.1503	0.1778	0.2016	0.2228	0.2422	0.2601	0.2768	0.2848
3	0.0000	0.0674	0.1167	0.1507	0.1783	0.2021	0.2234	0.2428	0.2607	0.2774	0.2853
4	0.0000	0.0716	0.1237	0.1594	0.1883	0.2131	0.2350	0.2546	0.2727	0.2894	0.2973
5	0.0000	0.0736	0.1266	0.1632	0.1925	0.2176	0.2398	0.2594	0.2774	0.2941	0.3019
6	0.0000	0.0754	0.1296	0.1666	0.1965	0.2221	0.2447	0.2646	0.2825	0.2991	0.3068
7	0.0000	0.0773	0.1331	0.1709	0.2013	0.2272	0.2500	0.2703	0.2879	0.3043	0.3121
8	0.0000	0.0783	0.1345	0.1727	0.2033	0.2295	0.2524	0.2727	0.2905	0.3069	0.3146
9	0.0000	0.0783	0.1344	0.1726	0.2032	0.2294	0.2523	0.2727	0.2905	0.3069	0.3146
10	0.0000	0.0776	0.1333	0.1714	0.2021	0.2282	0.2509	0.2712	0.2889	0.3053	0.3131
11	0.0000	0.0759	0.1307	0.1681	0.1982	0.2240	0.2466	0.2668	0.2845	0.3011	0.3089
12	0.0000	0.0740	0.1272	0.1636	0.1930	0.2183	0.2406	0.2605	0.2785	0.2952	0.3031
13	0.0000	0.0720	0.1244	0.1602	0.1892	0.2141	0.2361	0.2558	0.2739	0.2907	0.2987
14	0.0000	0.0675	0.1169	0.1509	0.1786	0.2025	0.2238	0.2433	0.2613	0.2781	0.2861
15	0.0000	0.0674	0.1167	0.1506	0.1782	0.2020	0.2233	0.2427	0.2607	0.2775	0.2855
16	0.0000	0.0671	0.1163	0.1501	0.1776	0.2014	0.2227	0.2420	0.2600	0.2768	0.2848

*** CLADDING ***

AXIAL CLAD NODE	AXIAL CLAD LOCATION (CM)	STRESSED RADII (CM)		NODE SLIPPAGE	CLAD STRESSES (DYNES/CM**2)		HOOP STRESS
		INNER CLAD	OUTER CLAD		INNER CLAD	OUTER CLAD	
1	5.0724	2.93382-001	3.28790-001	1.63711+004	0.00000+000	1.63711+004	0.00000+000
2	15.2306	2.93508-001	3.28931-001	7.44000+002	0.00000+000	7.44000+002	0.00000+000
3	25.4125	2.93639-001	3.29078-001	3.98397+005	0.00000+000	3.98397+005	0.00000+000
4	35.7435	2.97309-001	3.32618-001	7.04529+004	-1.75757+008	7.04529+004	1.48635+009
5	46.2493	3.01906+001	3.36788-001	3.32604+004	-1.48217+008	3.32604+004	1.29769+009
6	56.8427	3.06835-001	3.41273-001	2.70580+004	-1.20120+008	2.70580+004	1.09192+009
7	67.5278	3.12061-001	3.46029-001	-2.39333+005	-9.49660+007	-2.39333+005	8.95362+008
8	78.2815	3.14580-001	3.48368-001	-2.13572+005	-7.48861+007	-2.13572+005	7.22282+008
9	89.0658	3.14631-001	3.48500-001	-1.35171+005	-6.60927+007	-1.35171+005	6.36598+008
10	99.8343	3.13059-001	3.47168-001	-2.08132+005	-5.99679+007	-2.08132+005	5.70697+008
11	110.5417	3.08889-001	3.43506-001	-1.29233+005	-5.67470+007	-1.29233+005	5.24161+008
12	121.1622	3.03090-001	3.38395-001	1.04242+005	-5.59313+007	1.04242+005	4.94653+008
13	131.7063	2.98668-001	3.34501-001	1.83572+005	-5.69202+007	1.83572+005	4.86394+008
14	142.0714	2.96876-001	3.32706-001	1.64500+005	0.00000+000	1.64500+005	0.00000+000
15	152.2809	2.96745-001	3.32559-001	-1.78891+003	0.00000+000	-1.78891+003	0.00000+000
16	162.4673	2.96605-001	3.32402-001	1.29570+004	0.00000+000	1.29570+004	0.00000+000

AXIAL CLAD NODE	STRENGTH (DYNES/CM**2)	ELASTICITY (DYNES/CM**2)	DEFORMATION CASE NUMBER	TOTAL PERMANENT DEFORMATION	
				INNER CLAD (CM)	OUTER CLAD (CM)
1	2.00569+009	8.37283+011	1	0.00000+000	0.00000+000
2	1.95457+009	8.33693+011	1	0.00000+000	0.00000+000
3	1.90184+009	8.29988+011	1	0.00000+000	0.00000+000
4	1.48051+009	8.00395+011	9	2.02857+003	1.79383+003
5	1.28312+009	7.86531+011	9	6.17629+003	5.45603+003
6	1.07050+009	7.71596+011	9	1.06143+002	9.38819+003
7	8.70237+008	7.57530+011	9	1.53654+002	1.36136+002
8	6.95227+008	7.45237+011	9	1.74852+002	1.55030+002
9	6.12723+008	7.09536+011	9	1.71532+002	1.52052+002
10	5.48486+008	6.79624+011	9	1.52905+002	1.35429+002
11	5.05206+008	6.55930+011	9	1.09625+002	9.69168+003
12	4.81055+008	6.42709+011	9	5.11991+003	4.51530+003
13	4.75966+008	6.39923+011	9	7.29584+004	6.43078+004
14	6.40130+008	7.22207+011	1	0.00000+000	0.00000+000
15	6.66466+008	7.34382+011	1	0.00000+000	0.00000+000
16	7.00686+008	7.45621+011	1	0.00000+000	0.00000+000

TOTAL TIME (SEC)	TIME STEP (SEC)	NORMALIZED POWER	VALUES ENERGY	PROGRAM	DOPPLER	DENSITY	RADIAL EXPAN.	COOLANT CHANNELS	COOL 1	COOL 2	COOL 3	COOL 4	SCRAM	NET
0.9470	0.00100	138.802	11.014	2.368	-1.296	-0.222	0.000	0.300	0.001	-0.063	-0.074	0.000	1.014	
0.9480	0.00100	199.851	11.180	2.370	-1.297	-0.226	0.000	0.324	0.006	-0.058	-0.074	0.000	1.045	
0.9490	0.00100	323.876	11.435	2.373	-1.308	-0.232	0.000	0.348	0.016	-0.057	-0.074	0.000	1.065	
0.9500	0.00100	496.313	11.847	2.375	-1.342	-0.241	0.000	0.348	0.022	-0.053	-0.074	0.000	1.035	
0.9510	0.00100	632.232	12.412	2.378	-1.379	-0.258	0.000	0.375	0.036	-0.052	-0.074	0.000	1.026	
0.9520	0.00100	694.713	13.091	2.380	-1.431	-0.276	0.000	0.375	0.058	-0.052	-0.074	0.000	0.981	
0.9530	0.00100	628.262	13.754	2.383	-1.461	-0.304	0.000	0.404	0.067	-0.042	-0.072	0.000	0.974	
0.9540	0.00100	558.510	14.348	2.385	-1.490	-0.332	0.000	0.432	0.082	-0.040	-0.072	0.000	0.964	

CRITERION FOR SWITCH TO WEAK EXPLOSION HAS BEEN MET

CALCULATED TEMP AT NODE 8 IS 5.0471+003 CALCULATED PERIOD IS 1.4568+002
 INPUT TEMPERATURE SWITCH IS 5.0000+003 INPUT PERIOD SWITCH 2.0000+003

THE NUMBER OF TIME STEPS IS 164

THE TIME IS 0.9540

THE TIME STEP IS 1.00000E-003

REACTOR POWER IS NOW 9.40442E+011 WATTS
ENERGY RELEASE IS 2.41605E+010 WATT-SEC

DELAYED NEUTRON PRECURSORS

PRECURSOR NUMBER	PRECURSOR CONCENTRATION
1	1.45619E+004
2	5.99835E+004
3	2.43073E+004
4	3.49952E+004
5	1.17699E+004
6	2.90649E+003

ERROR IN LAST FLUX CALCULATION WAS -2.62292E-006 MAXIMUM ALLOWABLE IS 8.00000E-005

LAST ITERATION COUNTS
REACTIVITY 0 FLUX 8

REACTIVITIES TYPE

	REACTIVITY (%)
PROGRAMMED	2.385
DOPPLER	-1.490
DENSITY	-0.332
RADIAL EXPANSION	0.000
COOLANT	

CHANNEL NUMBER

1	0.432
2	0.082
3	-0.040
4	-0.072

BOILING TIME (SEC)

0.0709
0.0626
0.0518
0.0380

SCRAM

0.000

TIME IS 0.8540 SEC. SINCE INITIATION

NET REACTIVITY IS 0.964
K EFFECTIVE IS 1.0028671
INVERSE PERIOD -1.45684E+002

COOLANT PROFILE

THE AVERAGE MASS FLOW RATE IS -919.273 GM/(CMSQ SEC)
 THE INLET LIQUID SLUG IS 85.873 CM
 THE EXIT LIQUID SLUG IS -20.498 CM
 NUMBER OF TIME STEPS SINCE BOILING INITIATION 119
 LAST TWO PHASE ITERATION COUNT 5

AXIAL LOCATION (CM)	PRESSURE (ATM)	COOLANT TEMPERATURE (C)	SATURATION TEMPERATURE (C)	VAPOR QUALITY	VOID FRACTION	MASS FLOWRATE (GMS/SEC-CM**2)
INLET						
0.000	6.252	619.852	1100.331	0.000	0.000	-919.273
2.000	0.000	635.868	1099.694	0.000	0.000	-919.273
4.000	0.000	644.575	1099.027	0.000	0.000	-919.273
6.000	0.000	660.198	1098.386	0.000	0.000	-919.273
8.000	0.000	669.117	1097.743	0.000	0.000	-919.273
10.000	0.000	684.681	1097.069	0.000	0.000	-919.273
12.000	0.000	694.126	1096.421	0.000	0.000	-919.273
14.000	0.000	709.268	1095.772	0.000	0.000	-919.273
16.000	0.000	719.431	1095.091	0.000	0.000	-919.273
18.000	0.000	733.835	1094.437	0.000	0.000	-919.273
20.000	0.000	745.009	1093.752	0.000	0.000	-919.273
22.000	0.000	757.850	1093.094	0.000	0.000	-919.273
24.000	0.000	770.638	1092.404	0.000	0.000	-919.273
26.000	0.000	781.523	1091.740	0.000	0.000	-919.273
28.000	0.000	796.624	1091.046	0.000	0.000	-919.273
30.000	0.000	804.853	1090.319	0.000	0.000	-919.273
32.000	0.000	822.568	1089.619	0.000	0.000	-919.273
34.000	0.000	827.825	1088.886	0.000	0.000	-919.273
36.000	0.000	848.382	1088.121	0.000	0.000	-919.273
38.000	0.000	851.100	1087.382	0.000	0.000	-919.273
40.000	0.000	873.514	1086.610	0.000	0.000	-919.273
42.000	0.000	874.249	1085.864	0.000	0.000	-919.273
44.000	0.000	895.882	1085.085	0.000	0.000	-919.273
46.000	0.000	897.555	1084.333	0.000	0.000	-919.273
48.000	0.000	915.465	1083.546	0.000	0.000	-919.273
50.000	0.000	922.035	1082.756	0.000	0.000	-919.273
52.000	0.000	932.099	1081.992	0.000	0.000	-919.273
54.000	0.000	947.183	1081.194	0.000	0.000	-919.273
56.000	0.000	947.231	1080.392	0.000	0.000	-919.273
58.000	0.000	970.112	1079.585	0.000	0.000	-919.273
60.000	0.000	966.318	1078.774	0.000	0.000	-919.273
62.000	0.000	974.082	1077.959	0.000	0.000	-919.273
64.000	0.000	981.847	1077.139	0.000	0.000	-919.273
66.000	0.000	989.611	1076.315	0.000	0.000	-919.273
68.000	0.000	997.376	1075.486	0.000	0.000	-919.273
70.000	0.000	1005.141	1074.652	0.000	0.000	-919.273
72.000	0.000	1012.905	1073.845	0.000	0.000	-919.273
74.000	0.000	1020.670	1073.002	0.000	0.000	-919.273
76.000	0.000	1028.435	1072.153	0.000	0.000	-919.273

78.000	0.000	1036.199	1071.300	0.000	0.000	-919.273
80.000	0.000	1043.964	1070.441	0.000	0.000	-919.273
82.000	0.000	1051.426	1069.577	0.000	0.000	-919.273
84.000	0.000	1051.426	1068.707	0.000	0.000	-919.273
86.000	8.140	1168.623	1168.623	0.000+000	5.178-001	0.000
88.000	0.000	1168.623	1168.623	0.000+000	7.731-001	0.000
90.000	0.000	1168.623	1168.623	0.000+000	8.273-001	0.000
92.000	0.000	1168.623	1168.623	0.000+000	8.564-001	0.000
94.000	0.000	1168.623	1168.623	0.000+000	8.752-001	0.000
96.000	0.000	1168.623	1168.623	0.000+000	8.871-001	0.000
98.000	0.000	1168.623	1168.623	0.000+000	8.940-001	0.000
100.000	0.000	1168.623	1168.623	0.000+000	8.975-001	0.000
102.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
104.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
106.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
108.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
110.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
112.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
114.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
116.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
118.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
120.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
122.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
124.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
126.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
128.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
130.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
132.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
134.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
136.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
138.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
140.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
142.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
144.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
146.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
148.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
150.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
152.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
154.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
156.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
158.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
160.000	0.000	1168.623	1168.623	0.000+000	9.000-001	0.000
OUTLET						

HEAT TRANSFER

RADIAL FUEL TEMPERATURE MESH (C)

AXIAL
LOCATION
(CM)

	1	2	3	4	5	6	7	8	9	10
5.085	1100.129	1087.947	1073.972	1056.171	1033.294	1004.535	969.687	929.332	883.805	823.931
15.271	1348.372	1333.280	1315.942	1293.285	1263.042	1223.273	1172.890	1113.006	1045.588	957.910
25.490	1528.921	1511.924	1492.586	1467.042	1432.256	1385.390	1324.550	1250.467	1166.679	1060.348
35.930	3853.040	3733.443	3645.173	3549.127	3438.523	3291.580	2900.315	2800.000	2515.294	1978.019
46.661	4622.424	4388.739	4312.078	4168.918	4017.968	3832.673	3388.103	2917.307	2747.917	2152.826
57.566	5358.137	5094.552	4937.447	4799.351	4643.005	4423.036	4119.726	3334.160	2800.000	2331.915
68.671	6009.767	5718.274	5501.376	5305.482	5100.519	4852.853	4500.995	3918.622	2800.000	2450.435
79.947	6350.695	6009.403	5785.257	5582.305	5362.369	5088.384	4721.471	4207.984	3186.510	2532.468
91.293	6353.769	6011.404	5785.671	5582.396	5362.595	5091.253	4732.287	4233.730	3187.509	2564.997
102.591	6095.052	5787.624	5603.375	5413.845	5187.836	4908.757	4546.504	4037.856	2955.161	2545.035
113.743	5491.903	5236.728	5072.818	4911.847	4734.690	4517.220	4217.013	3609.852	2800.000	2500.400
124.688	4748.870	4498.305	4357.293	4236.130	4112.362	3932.856	3619.205	3081.318	2800.000	2402.556
135.460	4025.219	3898.365	3761.321	3661.723	3544.987	3381.668	3173.368	2800.000	2764.381	2281.228
145.942	1613.636	1598.714	1584.926	1569.414	1550.963	1528.562	1501.295	1468.571	1429.505	1370.055
156.187	1438.897	1426.658	1415.490	1403.249	1389.220	1372.968	1354.288	1333.340	1309.923	1273.377
166.402	1200.246	1191.902	1184.868	1177.866	1170.759	1163.723	1157.212	1151.984	1148.410	1140.072

AXIAL
LOCATION
(CM)

CLAD TEMPERATURES (C)
INNER MIDPOINT OUTER

AVERAGE
COOLANT
TEMPERATURE
(C)

AVERAGE
STRUCTURE
TEMPERATURE
(C)

RADIAL LOCATION (CM)
INNER FUEL OUTER FUEL INNER CLAD OUTER CLAD

FRACTION
OF FUEL
MELTED

5.085	572.358	567.945	586.013	652.382	503.088	0.000	0.285	0.294	0.329	0.000
15.271	623.929	617.529	640.395	720.334	507.894	0.000	0.286	0.294	0.330	0.000
25.490	676.733	668.701	694.045	782.298	514.235	0.000	0.286	0.294	0.330	0.000
35.930	979.941	885.608	854.497	844.678	530.448	0.000	0.307	0.307	0.341	0.762
46.661	1069.148	966.471	928.490	901.037	554.676	0.000	0.314	0.314	0.348	0.833
57.566	1161.945	1051.031	1005.208	956.171	580.932	0.000	0.323	0.323	0.356	0.892
68.671	1237.856	1122.340	1069.448	1001.258	608.189	0.000	0.330	0.330	0.362	0.944
79.947	1296.173	1178.185	1121.886	1042.290	634.989	0.000	0.334	0.334	0.366	0.944
91.293	1348.016	1236.389	1199.811	1168.623	660.359	0.000	0.334	0.334	0.366	0.944
102.591	1399.342	1297.029	1267.294	1168.623	681.829	0.000	0.331	0.331	0.364	0.944
113.743	1444.560	1350.507	1325.123	1168.623	699.129	0.000	0.325	0.325	0.358	0.933
124.688	1464.203	1380.364	1358.290	1168.623	711.304	0.000	0.316	0.316	0.350	0.876
135.460	1439.715	1363.877	1344.096	1168.623	720.485	0.000	0.309	0.309	0.344	0.821
145.942	1079.486	1069.156	1066.610	1168.623	720.126	0.000	0.287	0.297	0.333	0.000
156.187	1057.756	1050.827	1049.216	1168.623	717.480	0.000	0.286	0.297	0.333	0.000
166.402	1032.399	1029.752	1029.280	~0.000	713.979	0.000	0.285	0.297	0.333	0.000

DEFORMATION PARAMETERS

AXIAL FUEL NODE	AXIAL FUEL LOCATION (CM)	*** FUEL ***			FUEL STRESSES (DYNES/CM**2)		
		STRESSED RADII (CM) INNER SOLID	OUTER SOLID	FREE RADIUS OF MELTED FUEL	NODE SLIPPAGE	INNER SOLID	OUTER SOLID
1	5.0845	0.00000+000	2.84651-001	0.00000+000	3.31874+005	-8.27504+008	3.31874+005
2	15.2715	0.00000+000	2.85680-001	0.00000+000	-9.32448+004	-1.05320+009	-9.32448+004
3	25.4896	0.00000+000	2.86444-001	0.00000+000	3.10423+005	-1.16729+009	3.10423+005
4	35.9303	2.82390-001	3.06933-001	2.89979-001	3.57097+004	-6.00734+009	-1.13279+008
5	46.6609	2.89676-001	3.13955-001	2.99959-001	-1.96671+006	-8.38838+009	-8.60011+007
6	57.5663	3.15061-001	3.22733-001	3.28207-001	1.57464+006	-3.65983+009	-6.18549+007
7	68.6705	3.22085-001	3.29642-001	3.38965-001	-8.07761+004	-4.44007+009	-5.14929+007
8	79.9472	3.26089-001	3.33579-001	3.45473-001	-1.05315+005	-4.88251+009	-4.31111+007
9	91.2928	3.26174-001	3.33671-001	3.45520-001	-7.49657+004	-4.85732+009	-3.77802+007
10	102.5908	3.23393-001	3.30947-001	3.40869-001	-9.71133+004	-4.51461+009	-3.44374+007
11	113.7426	3.16992-001	3.24668-001	3.30856-001	-5.44969+004	-3.74385+009	-3.19408+007
12	124.6880	3.08467-001	3.16288-001	3.18546-001	1.34666+006	-2.78251+009	-2.98999+007
13	135.4596	2.84314-001	3.08941-001	2.92420-001	-1.79290+006	-6.12271+009	-3.60703+007
14	145.9420	0.00000+000	2.87198-001	0.00000+000	4.53408+005	-2.51988+008	4.53408+005
15	156.1872	0.00000+000	2.86457-001	0.00000+000	-8.66401+004	-1.64076+008	-8.66401+004
16	166.4023	0.00000+000	2.85459-001	0.00000+000	3.16039+005	1.88240+007	3.16039+005

DEFORMATION COUNT

NET CORE MOVEMENT

FUEL AXIAL STRESS

1

7.47823 CM,

7.90561+001 DYNES/CM**2

RADIAL FUEL MESH (CM)

AXIAL
FUEL
NODE

	1	2	3	4	5	6	7	8	9	10	11
1	0.0000	0.0672	0.1164	0.1502	0.1777	0.2015	0.2227	0.2421	0.2600	0.2767	0.2847
2	0.0000	0.0675	0.1168	0.1508	0.1784	0.2023	0.2236	0.2430	0.2609	0.2777	0.2857
3	0.0000	0.0677	0.1172	0.1513	0.1790	0.2029	0.2242	0.2437	0.2617	0.2784	0.2864
4	0.0000	0.0748	0.1291	0.1662	0.1962	0.2219	0.2446	0.2645	0.2824	0.2991	0.3069
5	0.0000	0.0776	0.1333	0.1716	0.2024	0.2286	0.2517	0.2718	0.2897	0.3062	0.3140
6	0.0000	0.0808	0.1386	0.1781	0.2098	0.2369	0.2606	0.2815	0.2994	0.3151	0.3227
7	0.0000	0.0836	0.1433	0.1837	0.2161	0.2435	0.2674	0.2884	0.3068	0.3221	0.3296
8	0.0000	0.0851	0.1455	0.1865	0.2192	0.2469	0.2709	0.2920	0.3105	0.3261	0.3336
9	0.0000	0.0850	0.1455	0.1864	0.2191	0.2468	0.2709	0.2920	0.3106	0.3262	0.3337
10	0.0000	0.0838	0.1437	0.1844	0.2170	0.2445	0.2684	0.2895	0.3079	0.3234	0.3309
11	0.0000	0.0812	0.1395	0.1792	0.2110	0.2382	0.2619	0.2829	0.3012	0.3170	0.3247
12	0.0000	0.0783	0.1344	0.1728	0.2038	0.2303	0.2536	0.2742	0.2923	0.3085	0.3163
13	0.0000	0.0753	0.1300	0.1672	0.1973	0.2231	0.2458	0.2662	0.2843	0.3010	0.3089
14	0.0000	0.0678	0.1174	0.1515	0.1792	0.2032	0.2247	0.2442	0.2623	0.2791	0.2872
15	0.0000	0.0676	0.1170	0.1511	0.1787	0.2027	0.2240	0.2435	0.2616	0.2784	0.2865
16	0.0000	0.0673	0.1166	0.1505	0.1781	0.2019	0.2232	0.2426	0.2606	0.2774	0.2855

*** CLADDING ***

AXIAL CLAD NODE	AXIAL CLAD LOCATION (CM)	STRESSED RADII (CM)		NODE SLIPPAGE	CLAD STRESSES (DYNES/CM**2)		HOOP STRESS
		INNER CLAD	OUTER CLAD		INNER CLAD	OUTER CLAD	
1	5.0845	2.93686-001	3.29131-001	3.79208+004	0.00000+000	3.79208+004	0.00000+000
2	15.2715	2.94023-001	3.29509-001	1.42138+003	0.00000+000	1.42138+003	0.00000+000
3	25.4896	2.94375-001	3.29903-001	1.13672+006	0.00000+000	1.13672+006	0.00000+000
4	35.9303	3.06933-001	3.41402-001	-4.56519+005	-1.13315+008	-4.56519+005	3.29446+009
5	46.6609	3.13955-001	3.47773-001	1.54815+005	-8.40344+007	1.54815+005	3.71180+009
6	57.5663	3.22733-001	3.55753-001	-1.40138+005	-6.34295+007	-1.40138+005	3.02695+009
7	68.6705	3.29642-001	3.62074-001	-2.13977+005	-5.14121+007	-2.13977+005	3.08426+009
8	79.9472	3.33579-001	3.65706-001	-2.53941+005	-4.30057+007	-2.53941+005	3.05241+009
9	91.2928	3.33671-001	3.65873-001	-1.73965+005	-3.77053+007	-1.73965+005	2.85688+009
10	102.5908	3.30947-001	3.63502-001	-2.00914+005	-3.43403+007	-2.00914+005	2.57024+009
11	113.7426	3.24668-001	3.57932-001	-1.09878+005	-3.18863+007	-1.09878+005	2.16931+009
12	124.6880	3.16288-001	3.50477-001	5.25002+004	-3.12466+007	5.25002+004	1.78431+009
13	135.4596	3.08941-001	3.43915-001	-2.10898+005	-3.42774+007	-2.10898+005	1.84150+009
14	145.9420	2.97109-001	3.32967-001	9.15715+005	0.00000+000	9.15715+005	0.00000+000
15	156.1872	2.96981-001	3.32823-001	-2.49880+003	0.00000+000	-2.49880+003	0.00000+000
16	166.4023	2.96837-001	3.32662-001	1.29281+004	0.00000+000	1.29281+004	0.00000+000

AXIAL CLAD NODE	STRENGTH (DYNES/CM**2)	ELASTICITY (DYNES/CM**2)	DEFORMATION CASE NUMBER	TOTAL PERMANENT DEFORMATION	
				INNER CLAD (CM)	OUTER CLAD (CM)
1	1.88234+009	8.28619+011	1	0.00000+000	0.00000+000
2	1.74539+009	8.18999+011	1	0.00000+000	0.00000+000
3	1.60403+009	8.09072+011	1	0.00000+000	0.00000+000
4	1.00495+009	7.66992+011	9	1.05805+002	9.36630+003
5	7.81607+008	7.51305+011	9	1.70608+002	1.51330+002
6	6.18577+008	7.12242+011	9	2.51998+002	2.24156+002
7	5.20394+008	6.64245+011	9	3.15409+002	2.81191+002
8	4.43887+008	6.22361+011	9	3.50449+002	3.12801+002
9	3.88892+008	5.74123+011	9	3.47228+002	3.09871+002
10	3.47050+008	5.21003+011	9	3.16006+002	2.81673+002
11	3.10150+008	4.66933+011	9	2.50355+002	2.22594+002
12	2.89549+008	4.36509+011	9	1.65826+002	1.46942+002
13	3.00925+008	4.53309+011	9	9.47123+003	8.36771+003
14	5.93565+008	7.00679+011	1	0.00000+000	0.00000+000
15	6.18859+008	7.12373+011	1	0.00000+000	0.00000+000
16	6.47942+008	7.25818+011	1	0.00000+000	0.00000+000

TWO DIMENSIONAL WEAK EXPLOSION CALCULATION

NUMBER OF REGIONS 20

FORM OF NET REACTIVITY = DOPPLER REA + PROGRAMMED REA + MATERIAL WORTH REA + SCRAM REA IS

REA (TIME) = -1.27949-001 + (1.35369-001) * TIME

TOTAL REACTOR VOLUME 4.58044-006

TOTAL REACTOR POWER 1.68384-009

FRACTION OF TOTAL POWER

REGION	1	2	3	4	5	6
FRACTION	1.25733-001	6.10894-002	3.34845-002	1.49649-002	1.39512-001	6.77840-002
REGION	7	8	9	10	11	12
FRACTION	3.71540-002	1.66049-002	1.18400-001	5.75266-002	3.15317-002	1.40922-002
REGION	13	14	15	16	17	18
FRACTION	1.02559-001	4.98300-002	2.73130-002	1.22067-002	4.82116-002	2.34244-002
REGION	19	20				
FRACTION	1.28394-002	5.73821-003				

DATA FOR REGION 1

EQUATION OF STATE

PRESSURE = $7.6000+011 * \text{EXP} (-5.5511+004 / \text{TEMP} + 0.0000+000)$

SPECIFIC HEAT FUNCTION

CP (TEMP) = $4.50000-001 * (0.00000+000 * \text{TEMP}) + (0.0000+000 * \text{TEMP} **2)$

DOPPLER COEFFICIENT TERM

DOP REA (TEMP) = $-2.0 * 0.00000+000 * (\text{TEMP} ** -0.5) + -8.51000+004 * \text{LN}(\text{TEMP})$
 $+ 0.00000+000 / 1.00000+000 * (\text{TEMP} ** 1.00000+000)$

VOLUMETRIC AVERAGE TEMPERATURE 4.85709+003

DENSITY 4.00000+000

VOLUME 1.96349+005

TOTAL POWER 2.11715+008

LATTICE

AT A RADIUS OF FOR A HEIGHT OF 2,500		6,250	18,750	31,250	43,750
THE RELATIVE POWER IS		9.87562-001	9.73063-001	9.45093-001	9.12774-001
THE MATERIAL WORTH IS		2.01104-007	1.99855-007	1.97119-007	1.93903-007
AT A RADIUS OF FOR A HEIGHT OF 7,500		6,250	18,750	31,250	43,750
THE RELATIVE POWER IS		9.76015-001	9.61685-001	9.34043-001	9.02102-001
THE MATERIAL WORTH IS		1.99586-007	1.98498-007	1.95795-007	1.92570-007
AT A RADIUS OF FOR A HEIGHT OF 12,500		6,250	18,750	31,250	43,750
THE RELATIVE POWER IS		9.54039-001	9.40032-001	9.13012-001	8.81790-001
THE MATERIAL WORTH IS		1.98083-007	1.97109-007	1.94442-007	1.91229-007
AT A RADIUS OF FOR A HEIGHT OF 17,500		6,250	18,750	31,250	43,750
THE RELATIVE POWER IS		9.21633-001	9.08102-001	8.82000-001	8.51838-001
THE MATERIAL WORTH IS		1.96596-007	1.95688-007	1.93061-007	1.89879-007
AT A RADIUS OF FOR A HEIGHT OF 22,500		6,250	18,750	31,250	43,750
THE RELATIVE POWER IS		8.78798-001	8.65896-001	8.41007-001	8.12247-001
THE MATERIAL WORTH IS		1.95125-007	1.94234-007	1.91651-007	1.88521-007
SURFACE INTEGRAL EVALUATION		INNER	OUTER	UPPER	LOWER
0 = NO 1 = YES		0	1	1	0
CONTINUITY OF MATERIAL WORTH		INNER	OUTER	UPPER	LOWER
0 = DISCONTINUOUS 1 = CONTINUOUS		0	1	1	0

INITIAL PRESSURE AND TEMPERATURE DISTRIBUTION

REGION 1

PRESSURE (ATM)					TEMPERATURE (K)			
2.0203+001	1.7675+001	1.3525+001	9.7573+000	A	5.2691+003	5.2031+003	5.0757+003	4.9286+003
1.8168+001	1.5877+001	1.2122+001	8.7223+000	X	5.2165+003	5.1513+003	5.0254+003	4.8800+003
1.4755+001	1.2867+001	9.7815+000	7.0018+000	I	5.1165+003	5.0527+003	4.9297+003	4.7875+003
1.0691+001	9.2925+000	7.0181+000	4.9841+000	A	4.9689+003	4.9073+003	4.7885+003	4.6512+003
6.7740+000	5.8605+000	4.3858+000	3.0806+000	L	4.7739+003	4.7152+003	4.6019+003	4.4709+003

REGION 2

PRESSURE (ATM)					TEMPERATURE (K)			
4.1843+000	3.6028+000	2.6707+000	1.8547+000	A	4.5840+003	4.5280+003	4.4201+003	4.2954+003
2.7479+000	2.3564+000	1.7327+000	1.1916+000	X	4.4302+003	4.3765+003	4.2729+003	4.1532+003
1.6867+000	1.4396+000	1.0489+000	7.1341+001	I	4.2641+003	4.2128+003	4.1140+003	3.9997+003
9.5548+001	8.1122+001	5.8487+001	3.9285+001	A	4.0857+003	4.0371+003	3.9433+003	3.8349+003
4.9141+001	4.1471+001	2.9546+001	1.9565+001	L	3.8951+003	3.8492+003	3.7608+003	3.6587+003

REGION 3

PRESSURE (ATM)					TEMPERATURE (K)			
3.0497-001	2.5629-001	1.8108-001	1.1873-001	A	3.7689+003	3.7249+003	3.6401+003	3.5421+003
2.3282-001	1.9520-001	1.3728-001	8.9517-002	X	3.7011+003	3.6581+003	3.5752+003	3.4794+003
1.7595-001	1.4717-001	1.0302-001	6.6797-002	I	3.6332+003	3.5913+003	3.5103+003	3.4167+003
1.3157-001	1.0977-001	7.6471-002	4.9300-002	A	3.5654+003	3.5244+003	3.4453+003	3.3540+003
9.7277-002	8.0960-002	5.6120-002	3.5968-002	L	3.4976+003	3.4576+003	3.3804+003	3.2913+003

REGION 4

PRESSURE (ATM)				TEMPERATURE (K)				
0.0000+000	0.0000+000	0.0000+000	0.0000+000	A	1.3420+003	1.3337+003	1.3176+003	1.2989+003
0.0000+000	0.0000+000	0.0000+000	0.0000+000	X	1.2809+003	1.2735+003	1.2591+003	1.2425+003
0.0000+000	0.0000+000	0.0000+000	0.0000+000	I	1.2095+003	1.2031+003	1.1908+003	1.1765+003
0.0000+000	0.0000+000	0.0000+000	0.0000+000	A	1.1278+003	1.1226+003	1.1126+003	1.1010+003
0.0000+000	0.0000+000	0.0000+000	0.0000+000	L	1.0359+003	1.0320+003	1.0246+003	1.0160+003

REGION 5

PRESSURE (ATM)					TEMPERATURE (K)			
7.1038+000	5.1790+000	3.5786+000	2.2210+000	A	4.7935+003	4.6662+003	4.5256+003	4.3562+003
6.3340+000	4.6063+000	3.1737+000	1.9625+000	X	4.7465+003	4.6207+003	4.4817+003	4.3143+003
5.0595+000	3.6615+000	2.5086+000	1.5402+000	I	4.6970+003	4.5340+003	4.3982+003	4.2345+003
3.5743+000	2.5675+000	1.7441+000	1.0593+000	A	4.5251+003	4.4063+003	4.2751+003	4.1170+003
2.1860+000	1.5541+000	1.0432+000	6.2414+001	L	4.3507+003	4.2374+003	4.1123+003	3.9615+003

TIME (SEC)	TIME STEP (SEC)	NORMALIZED REACTOR POWER	NET REACTIVITY (\$)	PROGRAMMED REACTIVITY (\$)	SCRAM REACTIVITY (\$)	DOPPLER REACTIVITY (\$)	MAT. WORTH REACTIVITY (\$)	COOL + ETC REACTIVITY (\$)	TOTAL INTEGRAL
0.954020	2.00-005	5.569+002	0.9654500	2.385050	0.000000	-1.490449	-0.332385	0.403234	-1.594+002
0.954040	2.00-005	5.553+002	0.9633091	2.385100	0.000000	-1.492388	-0.333550	0.404148	-1.391+002

POWER REACHES ITS PEAK

TIME (SEC)	TIME STEP (SEC)	NORMALIZED REACTOR POWER	NET REACTIVITY (\$)	PROGRAMMED REACTIVITY (\$)	SCRAM REACTIVITY (\$)	DOPPLER REACTIVITY (\$)	MAT. WORTH REACTIVITY (\$)	COOL + ETC REACTIVITY (\$)	TOTAL INTEGRAL
0.954040	2.00-005	5.553+002	0.9633091	2.385100	0.000000	-1.492388	-0.333550	0.404148	-1.391+002

TOTAL ENERGY
(MEGAWATT - SEC)
2.41980+004

TOTAL POWER
(WATT)
9.35062+011

K - EFFECTIVE
1.00286+000

POWER REACHES ITS PEAK

TIME (SEC)	TIME STEP (SEC)	NORMALIZED REACTOR POWER	NET REACTIVITY (\$)	PROGRAMMED REACTIVITY (\$)	SCRAM REACTIVITY (\$)	DOPPLER REACTIVITY (\$)	MAT. WORTH REACTIVITY (\$)	COOL + ETC REACTIVITY (\$)	TOTAL INTEGRAL
0.967680	3.20-004	9.394-001	-6.7654145	2.419200	0.000000	-1.575541	-8.636131	1.027057	-2.726+002

TOTAL ENERGY
(MEGAWATT - SEC)
2.58704+004

TOTAL POWER
(WATT)
1.58178+009

K - EFFECTIVE
9.80340-001

FINAL OUTPUT

FINISHING CONDITIONS ARE NORMALIZED POWER OF 9.5000-001

TOTAL TIME OF 5.0000+000

K-EFFECTIVE OF 9.5000-001

PRESSURE AND TEMPERATURE DISTRIBUTION

REGION 1

VOLUMETRIC AVERAGE TEMPERATURE 5.1612+003

PRESSURE (ATM)

TEMPERATURE (K)

3.7906+001	3.3386+001	2.5888+001	1.8978+001	A	5.6038+003	5.5329+003	5.3961+003	5.2380+003
3.4270+001	3.0151+001	2.3329+001	1.7058+001	X	5.5473+003	5.4772+003	5.3420+003	5.1858+003
2.8121+001	2.4689+001	1.9023+001	1.3839+001	I	5.4398+003	5.3713+003	5.2391+003	5.0864+003
2.0702+001	1.8117+001	1.3870+001	1.0012+001	A	5.2813+003	5.2151+003	5.0874+003	4.9399+003
1.3410+001	1.1683+001	8.8641+000	6.3302+000	L	5.0718+003	5.0087+003	4.8869+003	4.7463+003

REGION 2

VOLUMETRIC AVERAGE TEMPERATURE 4.3265+003

PRESSURE (ATM)

TEMPERATURE (K)

8.4756+000	7.3492+000	5.5245+000	3.9014+000	A	4.8677+003	4.8076+003	4.6916+003	4.5576+003
5.6767+000	4.9025+000	3.6560+000	2.9572+000	X	4.7024+003	4.6448+003	4.5335+003	4.4049+003
3.5633+000	3.0633+000	2.2638+000	1.5662+000	I	4.5240+003	4.4689+003	4.3627+003	4.2399+003
2.0708+000	1.7709+000	1.2952+000	8.8502+001	A	4.3323+003	4.2801+003	4.1793+003	4.0628+003
1.0965+000	9.3210+001	6.7371+001	4.5389+001	L	4.1275+003	4.0783+003	3.9833+003	3.8735+003

REGION 3

VOLUMETRIC AVERAGE TEMPERATURE 3.6946+003

PRESSURE (ATM)

TEMPERATURE (K)

6.9447+001	5.8790+001	4.2143+001	2.8113+001	A	3.9920+003	3.9447+003	3.8535+003	3.7482+003
5.3621+001	4.5287+001	3.2315+001	2.1438+001	X	3.9191+003	3.8729+003	3.7838+003	3.6808+003
4.0998+001	3.4543+001	2.4532+001	1.6184+001	I	3.8462+003	3.8011+003	3.7140+003	3.6135+003
3.1024+001	2.6075+001	1.8429+001	1.2088+001	A	3.7733+003	3.7293+003	3.6443+003	3.5461+003
2.3219+001	1.9467+001	1.3690+001	8.9266+002	L	3.7004+003	3.6574+003	3.5745+003	3.4787+003

REGION 4

VOLUMETRIC AVERAGE TEMPERATURE 1.2084+003

PRESSURE (ATM)

TEMPERATURE (K)

0.0000+000	0.0000+000	0.0000+000	0.0000+000	A	1.3844+003	1.3754+003	1.3581+003	1.3381+003
0.0000+000	0.0000+000	0.0000+000	0.0000+000	X	1.3187+003	1.3107+003	1.2953+003	1.2774+003
0.0000+000	0.0000+000	0.0000+000	0.0000+000	I	1.2420+003	1.2351+003	1.2219+003	1.2065+003
0.0000+000	0.0000+000	0.0000+000	0.0000+000	A	1.1543+003	1.1487+003	1.1379+003	1.1254+003
0.0000+000	0.0000+000	0.0000+000	0.0000+000	L	1.0554+003	1.0513+003	1.0433+003	1.0341+003

DATA FOR PLOTTING
NUMBER OF STEPS = 240

NUMBER OF WAVES = 6
STEP FOR INITIATION OF.

SCRAM	BOILING	SLUG	FULDYN	XPL0DE	OTHERS				
5	47	114	0	164	0	0	0		

PEAK	STEPS FOR WAVES.		VALLEY	PEAK	VALLEY	PEAK	VALLEY	PEAK	VALLEY
42	44	46	135	162	166				

THE TRANSIENT HAS TERMINATED.

THE DATE IS 7/28/70
PLOT PROGRAM FOR SAS 1-A

100 CM CORE TEST PROBLEM

2.5 DOLLAR / SEC RAMP

REACTIVITY IN DOLLARS

- 1 = NET
- 2 = PROGRAMMED
- 3 = DOPPLER
- 4 = DENSITY
- 5 = SCRAM
- 6 = COOLANT + STRUCTURE

REACTIVITY IN DOLLARS

- 1 = COOLANT 1
- 2 = COOLANT 2
- 3 = COOLANT 3
- 4 = COOLANT 4
- 5 = STRUCTURE
- 6 = COOLANT + STRUCTURE

APPENDIXES

The following appendixes contain listings of the detailed equations actually programmed in the algorithms in the various SASIA subroutines. The variable names and nomenclature correspond to those in the FORTRAN listing of the code which are defined in the Dictionary (Appendix H).

The ordering of the appendixes parallels that used in the modular description of the various physical models in the main body of the report. This should aid the reader in making the transition from the partial differential equations and finite-difference schemes to the FORTRAN equations. Because of the great amount of detail which arises in a practical computing scheme, there is not a one-to-one correspondence between various finite-difference and algebraic equations developed in the main body of the report and the FORTRAN equations given in the appendixes.

However, sufficient explanations have been included with the descriptions given so that it should be relatively easy to follow the steps in the computing procedures and see their relationships to the equations given in the main body of the report. The numbers to the left of the equations in parentheses correspond to statement numbers in the FORTRAN listing of the code.

APPENDIX A

Detailed Equations for Heat Transfer Module

1. Subroutine SSHTR calculates initial fuel and clad temperatures based on input values of steady-state power or as part of the steady-state power search. The computing procedure is as follows:

a. Calculate and store constants for fuel, clad, and coolant subscripts.

$$NNN = NT - 2$$

$$NN = NT - 1$$

$$NR = NT + 1 \text{ (inner clad temp or outer fuel radius)}$$

$$NEPP = NR$$

$$NE = NEPP + 1 \text{ (mid clad temp or inner clad radius)}$$

$$NEP = NE + 1 \text{ (outer clad)}$$

$$NC = NEP + 1 \text{ (coolant)}$$

$$NS = NC + 1 \text{ (structure)}$$

b. Set up radial mesh at design point, based on equal volume nodes.

$$DELRSQ = \frac{ROUTFP^2 - RINFP^2}{NN}$$

$$RDES(1) = RINFP$$

$$RDES(2) = \sqrt{RDES(1)^2 + DELRSQ/2}$$

$$\text{Do to } 1, I = 3 \text{ to } NT$$

$$(1) \quad RDES(I) = \sqrt{RDES(I-1)^2 + DELRSQ}$$

$$RDES(NR) = \sqrt{RDES(NT)^2 + DELRSQ/2}$$

c. Put coolant temperatures and film coefficients on (coarser) heat-transfer axial mesh.

$$JJ = 1$$

$$\text{Do to } 4, \text{ for } J = 1 \text{ to } MZ$$

Call INTERP (interpolates coolant temperatures)

Call INTERP (interpolates film coefficients)

$$HSTR(J) = RST + 1.0/H2(J)$$

Set up initial structure temperatures.


```

TSTRSS(J) = T1(NC,J)
T1(NS,J) = T1(NC,J)
T2(NS,J) = T1(NC,J)
(4) MELT(J) = 1

      Initialize flags
      KTEST = KTEST2 = 1
      ITEST = 0

      Initialize counters
      IC = IC3 = 0
      DELU = 0.0

d. Set up initial radial mesh for steady state.

      Do for I = 1 to NR
      R(I,J) = RDES(I)

      Calculate power per radial mode.
      Do for I = 1 to NT
(6)  Q(I) =  $\frac{\text{PBAR}(J)}{\text{ZFI}(J+1) - \text{ZFI}(J)} \cdot \frac{\text{RDES}(I+1)^2 - \text{RDES}(1)^2}{[\text{RDES}(\text{NR})^2 - \text{RDES}(1)^2]} \pi$ 
      II = 0

e. Calculate clad midpoint temperature.

      T1(NE,J) = T1(NC,J) +  $\frac{Q(\text{NT})}{2} \left[ \frac{1}{\text{RER} \cdot \text{H2}(J)} + \frac{\text{RER} - \text{RBR}}{\text{EK} \cdot (1.5 \cdot \text{RER} + 0.5 \cdot \text{RBR})} \right]$ 

f. Iterate on clad midpoint temperature to account for clad
expansion.

(8)  TNE = T1(NC,J) +  $\frac{Q(\text{NT})}{2 + 2 \cdot \text{AE} \cdot [\text{T1}(\text{NE},J) - \text{TR}]}$ 
       $\cdot \left[ \frac{1}{\text{RER} \cdot \text{H2}(J)} + \frac{\text{RER} - \text{RBR}}{\text{EK} \cdot (1.5 \cdot \text{RER} + 0.5 \cdot \text{RBR})} \right]$ 
      IF  $|\text{TNE} - \text{T1}(\text{NE},J)| < \text{EPSTEM}$  then go to 9.
      T1(NE,J) = TNE
      II = II + 1
      If II > 10 then error

```

g. Set up clad radii and temperatures.

$$(9) \quad \begin{aligned} T1(NE,J) &= TNE \\ R(NEP,J) &= RER \{1 + AE[T1(NE,J) - TR]\} \\ R(NE,J) &= RBR \{1 + AE[T1(NE,T) - TR]\} \end{aligned}$$

h. Calculate clad surface temperature and store inner clad temperature.

$$\begin{aligned} TNE &= T1(NE,J) + \frac{Q(NT)}{2} \frac{R(NEP,J) - R(NE,J)}{2 \cdot R(NE,J) \cdot EK} \\ T1(NEPP,J) &= TNE \\ T1(NEP,J) &= T1(NC,J) + \frac{Q(NT)}{2R(NEP,J) \cdot H2(J)} \end{aligned}$$

i. Set up initial radial temperature distribution in fuel using parabolic curve with constant thermal conductivity of fuel.

$$\begin{aligned} T1(1,J) &= \frac{PBAR(J)}{4\pi K(TR) \cdot AXHI(J)} \\ T(NT,J) &= TNE + \frac{Q(NT)}{2 \cdot R(NE,J) \cdot HBMAX} \end{aligned}$$

j. Initialize radii for melting iteration

$$\begin{aligned} GA1 &= R(NE,J) \\ GA2 &= 0.0 \\ GC1 &= 0.0 \\ GC2 &= 0.0 \end{aligned}$$

Do for I = 2 to NN

$$\begin{aligned} T1(I,J) &= T1(1,J) \cdot \left\{ 1 - \frac{\left[\frac{R(I,J) + R(I+1,J)}{2} \right]^2}{R(NR,J)^2} \right\} + T1(NT,J) \\ T1(1,J) &= T1(1,J) + T1(NT,J) \end{aligned}$$

Set up fuel temperatures for outer iteration

(11) If IC > 4 go to 22

k. Set up fuel temperatures for inner iteration

(12) Do for I = 1 to NN
 $T2SS(I) = T1(I,J)$

(14) $IC = IC + 1$

If $IC > 10$ then error

1. Set up stress-free radial mesh.

$$R(1,J) = RINFP \{1 + AFS \cdot [T1(1,J) - TR]\}$$

Do to 20 for $I = 1$ to NT

$$DELR = RDES(I+1) - RDES(I)$$

$$DELRM = DELR \cdot [1 + AFS \cdot (TMF - TR)]$$

$$DELMR = DELRM \cdot (1 + AM)$$

$$DELM = DELMR - DELRM$$

Check for partial melting

If $I = ITEST$ then go to 15

If $T1(I,J) > TMF$ then go to 18

$$R(I+1,J) = R(I,J) + DELR \cdot \{1 + AFS \cdot [T1(I,J) - TR]\}$$

go to 20.

(15) $R(I+1,J) = R(I,J) + DELU \cdot DELM + DELRM$

go to 20.

(18) $R(I+1,J) = R(I,J) + DELMR \cdot \{1 + AFL[T1(I,J) - TMF]\}$

(20) continue loop

Calculate first fuel temperature from outer surface.

$$T1(NN,J) = T1(NT,J) + 0.25 \cdot Q(NN)$$

$$\frac{2R(NR,J) - R(NT,J) - R(NN,J)}{R(NT,J) \cdot K(T)}$$

where,

$$T = T1(NT,J) - \frac{2\{T1(NT,J) - T1(NN,J)\}\{R(NR,J) - R(NT,J)\}}{2R(NR,J) - R(NT,J) - R(NN,J)}$$

m. Calculate fuel-temperature distribution.

Do for $M = 2$ to NNN

$$I = NNN - M + 2$$

$$T1(I,J) = T1(I+1,J) + 0.25 \cdot Q(I) \cdot \frac{R(I+2,J) - R(I,J)}{R(I+1,J) K[\bar{T}(I)]}$$

where,

$$\bar{T}(I) = T1(I,J) + \frac{[T1(I+1,J) - T1(I,J)][R(I+1,J) - R(I,J)]}{R(I+2,J) - R(I,J)}$$

$$T1(1,J) = T1(2,J) + 0.25 \cdot Q(1) \cdot \frac{R(3,J) + R(2,J) - 2 \cdot R(1,J)}{R(2,J) \cdot K(\bar{T})}$$

where,

$$\bar{T} = T1(1,J) + 2 \frac{\{T1(2,J) - T1(1,J)\} \{R(2,J) - R(1,J)\}}{R(3,J) + R(2,J) - 2 \cdot R(1,J)}$$

Check for partial melting.

If KTEST = 1 then go to 28

If KTEST = 2 then go to 26

n. Inner iteration count exceeds 4, check for melting

(22) Do to 25 for I = 1 to NN

If T1(I,J) ≥ TMF then go to 24

If T2SS(I) < TMF then go to 25

(23) ITEST = 1

DELU = 0.0

KTEST = 2

KTEST2 = 2

go to 12

(24) If T2SS(I) < TMF then go to 23

(25) continue loop

go to 12

Check for partial melting nonconvergence

(26) If |T1(ITEST,J) - TMF| ≥ EPSTEM, go to 27

KTEST = 1

go to 12

Check for partially melted mode below TMF.

(27) If T1(ITEST,J) < TMF then go to 28

IC = 6

DELU = DELU + 0.1

If DELU ≤ 1.0 then go to 12

DELU = 1.0

KTEST = 1

go to 12

o. Check inner loop convergence

(28) Do for I = 1 to NN

If $|T1(I,J) - T2SS(I)| \geq EPSTEM$,

If KTEST2 = 1 then go to 11

If KTEST2 = 2 then go to 12

Set temperatures to last value.

Do for I = 1 to NN

T1(I,J) = T2SS(I)

IC = 0

p. Check outer fuel radius convergence at melting--uses previous and current values.

If IC3 < 1 then go to 301

If R(NR,J) = GA2 then go to 46

GC2 = R(NR,J)

If GC2 = GC1 or GA2 = GA1, go to 70

$$R(NR,J) = \frac{GC1 \cdot GA2 - GC2 \cdot GA1}{GA2 - GA1 - GC2 + GC1}$$

GA1 = GA2

GC1 = GC2

GA2 = R(NR,J)

go to 302

(301) GC1 = R(NR,J)

GA2 = R(NR,J)

Calculate new bond conductance and fuel surface temperature.

(302) TNTP = T1(NT,J)

TB = R(NE,J) - R(NR,J)

If TB > 0 then go to 32

(31) $T1(NT,J) = TNE + \frac{Q(NT)}{2R(NE,J) \cdot HBMAX}$

go to 36

$$(32) \quad HB = \frac{HBPAR}{TB}$$

If $HB \geq HBMAX$ go to 31

Iteration to find fuel surface temperature with radiative heat transfer.

II = 0

$$TN2 = \left[\frac{Q(NT)}{2R(NR,J) \cdot DEL} + TNE^4 \right]^{0.25}$$

$$TN1 = \frac{Q(NT)}{2R(NR,J) \cdot HB} + TNE$$

If $TN1 < TN2$ then go to 33

$$T1(NT,J) = TN2$$

go to 34

$$(33) \quad T1(NT,J) = TN1$$

$$(34) \quad II = II + 1$$

$$TNN = T1(NT,J) - \left[HB \cdot \{T1(NT,J) - TNE\} + DEL \cdot \{T1(NT,J)^4 - TNE^4\} - \frac{Q(NT)}{2R(NR,J)} \right] / [HB + 4 \cdot DEL \cdot T1(NT,J)^3]$$

If $|TNN - T1(NT,J)| < EPSTEM$ then go to 35

If $II > 10$ then go to 53

$$T1(NT,J) = TNN$$

go to 34

$$(35) \quad T1(NT,J) = TNN$$

$$(36) \quad \text{If } T1(NT,J) > TMF \text{ then print error message}$$

q. Check for convergence of outer loop.

If $|T1(NT,J) - TNTP| < EPSTEM$, go to 46

If $ITEST \leq 0$ then go to 39

$$T1(ITEST,J) = TMF$$

$$(39) \quad IC3 = IC3 + 1$$

$$KTEST2 = 1$$

$$KTEST = 1$$

$$ITEST = 0$$

```

      If IC3 > 10 then go to 70
      go to 12
(46)   If ITEST > 0, then T1(ITEST,J) = TMF

      r.   Calculate radius of fuel melting and latent heat of melting

            Do for I = 1 to NT
            If T1(I,J) < TMF, go to 48
            MELT(J) = NR
            go to 49
(48)   MELT(J) = I
            Latent-heat calculation
(49)   Do to 52, for I = 1 to NT
            If I = ITEST, go to 50
            If T1(I,J) ≥ TMF, go to 51
            U(I,J) = 0
            go to 52
(50)   U(I,J) = DELU · UMELT
            go to 52
(51)   U(I,J) = UMELT
(52)   continue loop
            go to 58
(53-57) print error messages if needed
(57)   IERROR = 1
(58)   continue J loop

            Check for melting with central hole
            If RINFP ≤ 0 then go to 68
            Do to 67, for J = 1 to MZ
            If MELT(J) ≤ 1 then go to 67
            Set up error flag
            IERROR = 1
(67)   continue loop
(68)   ZFI(1) = 0.0

```

s. Set up axial mesh

Do to 62 for J = 1 to MZ

DZ = AXHI(J)

ASI = 0.0

M1 = MELT(J)

Calculate $\int_{\text{inner solid}}^{\text{outer solid}} \alpha r T dr$, where α = linear expansion coefficient.

Do to 61, for I = M1 to NT

$$(61) \quad \text{ASI} = \text{ASI} + \text{AFS} \cdot \text{T1}(\text{I}, \text{J}) \cdot [\text{RDES}(\text{I} + 1)^2 - \text{RDES}(\text{I})^2]$$

$$(62) \quad \text{ZFI}(\text{J} + 1) = \text{ZFI}(\text{J}) + \text{DZ} \left[1 + \frac{\text{ASI}}{\text{RDES}(\text{NR})^2 - \text{RDES}(\text{M1})^2} \right]$$

ZFIO(1) = 0.0

Store steady-state axial mesh.

Do to 63, for J = 1 to MZ

ZFIO(J+1) = ZFI(J+1)

$$(63) \quad \text{ZFM}(\text{J}) = \frac{\text{ZFI}(\text{J}) + \text{ZFI}(\text{J} + 1)}{2}$$

Check for completion of steady-state calculations

If KHTSS = 1 then return to SSDRIV

t. Calculate volume-averaged fuel temperatures.

Do to 60, for J = 1 to MZ

TREF(J) = 0.0

Do to 59, for I = 1 to NT

$$(59) \quad \text{TREF}(\text{J}) = \text{TREF}(\text{J}) + \text{T1}(\text{I}, \text{J}) \cdot [\text{R}(\text{I} + 1, \text{J})^2 - \text{R}(\text{I}, \text{J})^2]$$

$$\text{TREF}(\text{J}) = \frac{\text{TREF}(\text{J})}{\text{R}(\text{NR}, \text{J})^2 - \text{R}(1, \text{J})^2}$$

$$(60) \quad \text{TBAR}(\text{J}) = \text{TREF}(\text{J})$$

u. Modify coefficients if linear expansion for shift in base temperature from design point to steady-state point. Change clad radii if in contact with fuel.

TCLAD = 0.0

TFUEL = 0.0

TSTRUC = 0.0

Do to 64, for J = 1 to MZ

TFUEL = TFUEL + TREF(J)

If R(NE,J) $\geq$ R(NR,J) then go to 69

XI = R(NEP,J)² - R(NE,J)²

R(NE,J) = R(NR,J)

R(NEP,J) = $\sqrt{\text{XI} + \text{R(NE,J)}^2}$

(69) TSTRUC = TSTRUC + TSTRSS(J)

(64) TCLAD = TCLAD + T1(NE,J)

TCLAD = TCLAD/MZ

TFUEL = TFUEL/MZ

TSTRUC = TSTRUC/MZ

$$\text{AFS} = \frac{\text{AFS}}{1 + \text{AFS} \cdot [\text{TFUEL} - \text{TR}]}$$

$$\text{AE} = \frac{\text{AE}}{1 + \text{AE} \cdot [\text{TCLAD} - \text{TR}]}$$

$$\text{ASTR} = \frac{\text{ASTR}}{1 + \text{ASTR} \cdot [\text{TSTRUC} - \text{TR}]}$$

v. Calculate mass fraction of fuel melted

Do to 65, for J = 1 to MZ

KZOT = MELT(J)

FRAC(J) = 0.0

If KZOT $\leq$ 2 then go to 65

Do to 66, for I = 2 to KZOT

(66) FRAC(J) = FRAC(J) + U(I - 1,J) · [RDES(I)² - RDES(I - 1)²]

$$\text{FRAC(J)} = \frac{\text{FRAC(J)}}{\text{UMELT} \cdot [\text{RDES(NR)}^2 - \text{RDES(1)}^2]}$$

(65) continue loop

Return to SSDRIV

End subroutine SSHTR.

2. Subroutine TSHTR calculates time-dependent fuel and clad temperatures and fraction of fuel melted. Uses initial values calculated by SSHTR as starting conditions. The computing procedure is as follows:

a. Check to see if this is the first time TSHTR has been entered.

If $KHT < 0$ then go to 2

If $KHT \geq 0$ then go to 1

Check for reactivity iteration

(1) If $KPOW < 0$ then go to 52

If $KPOW = 0$ then go to 4

If $KPOW > 0$ then go to 6

Store value of specific heat at the melting temperature and present amount of heat of melting absorbed.

(2) $CF = CPF(TMF)$

Do to 56, for $J = 1$ to MZ and $I = 1$ to NT

(56) $ULSTEP(I,J) = U(I,J)$

Store present value of coolant film conductance and fuel-pin temperature profile.

Do to 3 for $J = 1$ to MZ

$H1(J) = H2(J)$

Do to 3 for $I = 1$ to NS

(3) $T2(I,J) = T1(I,J)$

Halve time step first time through

$$DT = \frac{DT}{2}$$

Go to 13

Recalculate present time step and pick up previous projected temperature.

(4) Do for $J = 1$ to MZ and $I = 1$ to NEP

$T2(I,J) = T20(I,J)$

Go to 15

Calculate new time step and store last coolant and structure temperatures.

(6) Do to 53 for J = 1 to MZ

$T1(NC,J) = T2(NC,J)$

$T1(NS,J) = T2(NS,J)$

Store last coolant film conductance.

$H1(J) = H2(J)$

(53) continue loop

b. Put new coolant temperature and film conductance on heat-transfer axial mesh.

Do to 9, for J = 1 to MZ

Call INTERP[T2(NC,J)]

Call INTERP[H2(J)]

If JB < 1 then go to 9

Take average coolant temperature and film heat-transfer coefficient over fuel mesh.

HCBAR = 0.0

TCBAR = 0.0

NCOOL = 0

(7) If ZCOOL(JJ) > ZFI(J+1) then go to 8

TCBAR = TCBAR + TCOOL(JJ)

HCBAR = HCBAR + HCOOL(JJ)

NCOOL = NCOOL + 1

JJ = JJ + 1

If JJ ≤ MZC then go to 7

(8) $T2(NC,J) = TCBAR/NCOOL$

$H2(J) = HCBAR/NCOOL$

(9) continue loop

Store value of heat of melting absorbed

Do for J = 1 to MZ and I = 1 to NT

ULSTEP(I,J) = U(I,J)

c. Calculate structure temperature

Do to 10, for J = 1 to MZ

$$HSTR(J) = RST + \frac{1}{H2(J)}$$

$$TEMP = \frac{0.5DT}{CRHOST \cdot TAUST \cdot HSTR(J)}$$

$$T2(NS,J) = \frac{T1(NS,J) + TEMP[T2(NC,J) + T1(NC,J) - T1(NS,J)]}{1.0 + TEMP}$$

(10) continue loop

Check to see if this is the second time TSHTR has been entered.

If KHT < 0 then go to 52

If KHT = 0 then go to 13

If KHT > 0 then go to 11

Third time or later, then linearly project fuel-pin temperature to the middle of the time step and store last values.

(11) Do to 12, for J = 1 to MZ and I = 1 to NEP

$$TEM = T2(I,J)$$

$$T2(I,J) = \frac{[2DTP + DT] \cdot T2(I,J) - DT \cdot T1(I,J)}{2DTP}$$

$$T1(I,J) = TEM$$

(12) continue loop

Store projected temperatures for later recalculation

(13) Do to 14, for J = 1 to MZ and I = 1 to NEP

$$T20(I,J) = T2(I,J)$$

(14) continue loops

d. Calculate cladding thickness

(15) Do to 24, for J = 1 to MZ

$$DELRE = R(NEP,J) - R(NE,J)$$

e. Calculate linear power density

$$ZIT = \frac{PBAR(J)}{ZFI(J+1) - ZFI(J)}$$

f. Calculate fuel temperatures

Volumetric power densities

Do for I = 1 to NT

$$Q(I) = \frac{ZIT \cdot [RDES(I+1)^2 - RDES(I)^2]}{\pi \cdot [R(I+1,J)^2 - R(I,J)^2] \cdot RDES(NR)^2}$$

Set up α_i 's

Do for I = 1 to NT

$$ALPHA(I) = 2DT/[CRO(T2(I,J)) \cdot \{R(I+1,J) + R(I,J)\} \\ \cdot \{R(I+1,J) - R(I,J)\}]$$

$$ALPHA(NEPP) = 2DT/[CROE \cdot \{(R(NE,J) + DELRE/4)^2 - R(NE,J)^2\}]$$

$$ALPHA(NE) = 2DT/[CROE \cdot \{(R(NEP,J) - DELRE/4)^2 - (R(NE,J) \\ + DELRE/4)^2\}]$$

$$ALPHA(NEP) = 2DT/[CROE\{R(NEP,J)^2 - (R(NEP,J) - DELRE/4)^2\}]$$

Set up bond conductance

$$TB = R(NE,J) - R(NR,J)$$

If TB $\leq$ 0 go to 18

$$HB = HBPAR/TB$$

If HB > HBMAX go to 18

$$SYN = T2(NT,J)^4 - T2(NEP,J)^4$$

Go to 19

$$(18) \quad HB = HBMAX$$

$$\text{If } R(NR,J) = R(NE,J) \text{ then } HB = HBMAX + HBGRAD \\ \cdot (PFUEL(J) - 10^6 \cdot PX)$$

$$SYN = 0.0$$

Set up β_i 's.

$$\bar{T} = T2(1,J) + \frac{2 \cdot [T2(2,J) - T2(1,T)][R(2,J) - R(1,J)]}{R(3,J) + R(2,J) - 2R(1,J)}$$

$$(19) \quad BETA(2) = \frac{K(\bar{T})R(2,J)}{R(3,J) + R(2,J) - 2R(1,J)}$$

Do to 20, for I = 3 to NN

$$\bar{T} = T2(I-1,J) + \frac{[T2(I,J) - T2(I-1,J)][R(I,J) - R(I-1,J)]}{R(I+1,J) - R(I-1,J)}$$

$$BETA(I) = \frac{K(\bar{T})R(I,J)}{R(I+1,J) - R(I-1,J)}$$

$$(20) \quad \text{continue loop}$$

$$\bar{T} = T2(NT,J) - \frac{2 \cdot [T2(NT,J) - T2(NN,J)][R(NR,J) - R(NT,J)]}{2R(NR,J) - R(NT,J) - R(NN,J)}$$

$$BETA(NT) = \frac{K(\bar{T})R(NT,J)}{2R(NR,J) - R(NT,J) - R(NN,J)}$$

$$BETA(NEPP) = \frac{R(NR,J) \cdot HB}{2}$$

$$BETA(NE) = \frac{EK}{DELRE} \cdot [R(NE,J) + DELRE/4]$$

$$BETA(NEP) = \frac{EK}{DELRE} \cdot [R(NEP,J) - DELRE/4]$$

$$BETA(NC) = \frac{R(NEP,J)}{4} \cdot [H1(J) + H2(J)]$$

Gauss elimination for solution of the tridiagonal matrix system for fuel temperatures

Set up A_i 's.

$$A(1) = \frac{1}{ALPHA(1)} + BETA(2)$$

Do for I = 2 to NEP

$$A(I) = \frac{1}{ALPHA(I)} + BETA(I) + BETA(I+1) - \frac{BETA(I)^2}{A(I-1)}$$

Set up S_i 's

$$S(1) = T1(1,J) \cdot \left[\frac{1}{ALPHA(1)} - BETA(2) \right] + T1(2,J) \cdot BETA(2) \\ + \frac{Q(1) \cdot DT}{ALPHA(1)CRO(T2(1,J))}$$

Do to 22 for I = 2 to NEP

$$ZARF = 0.0$$

$$\text{If } I \leq NT \text{ then } ZARF = \frac{Q(I) \cdot DT}{ALPHA(I) \cdot CRO(T2(I,J))}$$

$$(22) \quad S(I) = T1(I-1,J) \cdot BETA(I) + T1(I,J) \cdot \left\{ \frac{1}{ALPHA(I)} - BETA(I) \right. \\ \left. - BETA(I+1) \right\} + T1(I+1,J) \cdot BETA(I+1) + ZARF \\ + \frac{BETA(I) \cdot S(I-1)}{A(I-1)}$$

$$S(NT) = S(NT) - DEL \cdot SYN \cdot R(NR,J)$$

$$S(NEPP) = S(NEPP) + DEL \cdot SYN \cdot R(NR,J)$$

Set up new temperature matrix

Do for M = 1 to NEP

I = NEP - M + 1 (backward loop)

$$T2(I,J) = \frac{S(I) + BETA(I+1) \cdot T2(I+1,J)}{A(I)}$$

(24) continue loop

g. Check for first entry into TSHTR

If KHT < 0 then go to 33

If KHT ≥ 0 then go to 34

First time, restore DT

(33) DT = 2DT

Go to 48

After first time

h. Calculate latent heat of melting

(34) Do to 43 for J = 1 to MZ

Do to 40 for I = 1 to NT

Check for fully melted mode

If U(I,J) ≥ UMELT then go to 38

Check for partial melting

If U(I,J) ≥ 0 then go to 36

Solid mode

If T2(I,J) ≤ TMF then go to 40

$$U(I,J) = ULSTEP(I,J) + CF \cdot [T2(I,J) - TMF]$$

If U(I,J) > UMELT then go to 35

$$T2(I,J) = TMF$$

Go to 40

Node has become fully melted this time step

(35)
$$T2(I,J) = TMF + \frac{U(I,J) - UMELT}{CF}$$

U(I,J) = UMELT

Go to 40

Partial melting

$$(36) \quad U(I,J) = ULSTEP(I,J) + CF \cdot [T2(I,J) - TMF]$$

If $U(I,J) \geq UMELT$ go then to 35

$$(37) \quad \text{If } U(I,J) \leq 0 \text{ go then to 39}$$

$$T2(I,J) = TMF$$

Go to 40

$$(38) \quad \text{If } T2(I,J) \geq TMF \text{ then go to 40}$$

$$U(I,J) = ULSTEP(I,J) + CF \cdot [T2(I,J) - TMF]$$

Go to 37

Node has become solid at this time step

$$(39) \quad T2(I,J) = TMF + \frac{U(I,J)}{CF}$$

$$U(I,J) = 0$$

(40) continue loop

i. Calculate subscript of radius of melting

Do to 41, for $I = 1$ to NT

If $T2(I,J) < TMF$ then go to 42

(41) continue loop

$I = NR$

$$(42) \quad MELT(J) = I$$

j. Calculate fraction of fuel melted

$$FRAC(J) = 0$$

If $MELT(J) < 2$ then go to 43

Do to 58 for $I = 2$ to $MELT(J)$

$$FRAC(J) = FRAC(J) + U(I-1,J) \cdot [RDES(I)^2 - RDES(I-1)^2]$$

(58) continue loop

$$FRAC(J) = \frac{FRAC(J)}{UMELT \cdot [RDES(NR)^2 - RDES(I)^2]}$$

If $FRAC(J) > 1.0$ then $FRAC(J) = 1.0$

(43) continue axial loop

k. Calculate volume-averaged fuel temperature

Do to 26, for J = 1 to MZ

TBAR(J) = 0

Do to 25, for I = 1 to NT

TBAR(J) = TBAR(J) + T2(I,J) · [R(I+1,J)² - R(I,J)²]

(25) continue loop

$$TBAR(J) = \frac{TBAR(J)}{R(NR,J)^2 - R(1,J)^2}$$

(26) continue loop

Set up KHT flag

(48) If KHT = 1 then go to 49

If KHT = 2 then go to 50

If KHT = 3 then go to 51

(49) KHT = 2

RETURN

(50) KHT = 3

(51) RETURN

(52) Print error message

Set error flag

IEERROR = 1

Return to TSDRIV

End Subroutine TSHTR

APPENDIX B

Detailed Equations for Coolant Dynamics Module

1. Subroutine SSCOOL calculates initial coolant temperatures and pressures based on input values of steady-state power and flow rate or as part of the steady-state power search. The computing procedure is as follows:

a. Calculate values for constants

$$DH = 2.0 \cdot RER \cdot VFC / (1.0 - VFC) \text{ (hydraulic diameter)}$$

$$FIBBER = PI \cdot DH \cdot RER \cdot GO$$

$$FIB = GO \cdot GO$$

$$K5 = 4/DH$$

$$DH = DH / (1 + GAM2)$$

$$HL2(1) = CL \cdot TO$$

b. Calculate power shape for coolant mesh

Do to 1 for J = 1 to MZ

$$(1) \quad A2(J) = PBAR(J) / [ZFI(J+1) - ZFI(J)]$$

J = 1

Do to 3, JJ = 1 to MZC

If ZCOOL(JJ) > ZFI(MZN) then go to 9

If ZCOOL(JJ) > ZFM(J) then J = J + 1

If J > MZ, then J = MZ

If J = 1 or ZCOOL(JJ) ≥ ZFM(MZ) then go to 2

$$QBAR(JJ) = A2(J - 1)$$

$$+ \frac{[A2(J) - A2(J - 1)] \cdot [ZCOOL(JJ) - ZFM(J - 1)]}{ZFM(J) - ZFM(J - 1)}$$

Go to 3

$$(2) \quad QBAR(JJ) = A2(J)$$

(3) continue loop

Go to 4

(9) Do to 10 for J = JJ to MZC

$$(10) \quad QBAR(J) = 0.0$$

(4) Do to 5 for J = 1 to MZC

If $J > 1$, then

$$HL2(J) = HL2(J - 1) + \frac{QBAR(J) + QBAR(J - 1) \cdot DZCOOL}{FIBBER}$$

$$TCOOL(J) = HL2(J)/CL$$

c. Calculate coolant properties

Liquid viscosity

$$VIL(J) = 0.01 \cdot \exp\left(\frac{756.9}{TCOOL(J) + 273} - 2.41\right)$$

Heat-transfer coefficient

$$KL = 4.185 \cdot [0.215 - 1.15 \times 10^{-4} \cdot TCOOL(J)]$$

$$HCOOL(J) = \frac{KL}{DH} \cdot \left\{ C1 \cdot \exp\left[C2 \cdot \text{alog}\left(\frac{DH \cdot GO \cdot CL}{KL}\right)\right] + C3 \right\}$$

Friction factors

$$FRL(J) = FR / \exp\left[0.20 \cdot \text{alog}\left(\frac{DH \cdot GO}{VIL(J)}\right)\right]$$

Density

$$DL2(J) = 0.9514 - 2.392 \times 10^{-4} \cdot TCOOL(J)$$

$$DAVSS(J) = DL2(J)$$

$$DAV2(J) = DL2(J)$$

d. Calculate steady-state pressure profile

$$FRGR(J) = \frac{FRL(J) \cdot FIB}{1961.4 \cdot DH \cdot DL2(J)} + DL2(J)$$

$$(5) \quad MO(J) = \frac{FIB}{980.7 \cdot DL2(J)}$$

$$PCOOL(MZC) = PX + \frac{GO^2}{2.028 \times 10^6 \cdot DL2(MZC)}$$

$$FI = 0.0$$

$$KMZ = MZC - 1$$

Do to 6 for $M = 1$ to KMZ

$$J = KMZ - M + 1$$

$$FI = FI + \frac{DZCOOL \cdot [FRGR(J+1) + FRGR(J)]}{2}$$

$$MI = MO(MZC) - MO(J)$$

$$MINT(J) = FI + MI$$

(6)
$$PCOOL = PCOOL(MZC) + \frac{MINT(J)}{1034.0}$$

$$PIN = PCOOL(1) + \frac{GO^2}{2.028 \times 10^6 \cdot DL2(1)}$$

e. Calculate saturation temperature

Do to 7 for J = 1 to MZC

$$TS(J) = \frac{12130.0}{10.51 - \text{alog}[PCOOL(J)]} - 273 + DTS$$

Initialize parameters

$$DELPO = PIN - PX$$

Do to 8 for J = 1 to MZC

$$A2(J) = 0.0$$

(8)
$$G2(J) = 0.0$$

Return to SSDRIV

End subroutine SSCOOL

2. Subroutine TSCOOL calculates basic coolant parameters from steady state through boiling and coolant ejection, until the weak-explosion calculation is initiated. It calculates coolant flow rates, pressures, temperatures, void fraction, and quality. It also controls the size of the major time step. The computing procedure is as follows:

i. Single-phase and Two-phase Calculations

a. Check for first entry into TSCOOL

If KCOOL = 1 then go to 1

If KCOOL = 2 then go to 3

b. Initialize various parameters

(1) $DEL T = DT$

$$NCHECK = 1$$

$$EBU = 0.0$$

$$UNB = 0.0$$

etc.

KCOOL = 2

Check to see if slug ejection is in operation

(3) If JSLUG $\neq$ 2, then go to 3000

Fully voided core

DT = DELT

DELT = 2.0 · DELT

If DELT > DTO then DELT = DTO

JB = JB + 1

Return to main

Check for flow reversal

(3000) If G2(1) < 0 then N7 = 1

Calculate heat flux at clad-coolant surface

Do to 304, for J = 1 to MZ

Insert proper clad temperature $T(\text{NEP}, J)$ for regular heat transfer
 $T(\text{NE}, J)$ for FULDYN

If KSANA = 2, then $T2(\text{NEP}, J) = T2(\text{NE}, J)$

NOTE: Clad and structure temperatures are linearly projected
to the middle of the time interval until coolant boiling.

If KBOIL = 1 then go to 302

$$A4(J) = H2(J) \cdot [T2(\text{NEP}, J) - T2(\text{NC}, J)] \\ + \frac{\text{GAM2}}{\text{HSTR}(J)} [T2(\text{NS}, J) - T2(\text{NC}, J)]$$

Go to 304

$$(302) \quad \text{TNSPRO} = T2(\text{NS}, J) + \frac{T2(\text{NS}, J) - T1(\text{NS}, J)}{2 \cdot \text{DT}} \cdot \text{DELT}$$

$$\text{TNEPRO} = T2(\text{NEP}, J) + \frac{T2(\text{NEP}, J) - T1(\text{NEP}, J)}{2 \cdot \text{DT}} \cdot \text{DELT}$$

$$A4(J) = H2(J) \cdot \text{TNEPRO} + \frac{\text{GAM2}}{\text{HSTR}(J)} \cdot \text{TNSPRO}$$

NOTE: A4 is different before and after boiling.

(304) continue loop

c. Put heat flux on coolant axial mesh

J = 2

Do to 320 for JJ = 1 to MZC

HCS(JJ) = 0

If ZCOOL(JJ) > ZFI(MZN) then go to 315

If ZCOOL(JJ) > ZFI(J), then J = J + 1

If J > MZ, then J = MZ

$$\text{PHI2(JJ)} = \frac{A4(J) - A4(J-1)}{ZFM(J) - ZFM(J-1)} \cdot [ZCOOL(JJ) - ZFM(J-1)] + A4(J-1)$$

Go to 320

(315) PHI2(JJ) = 0

(320) continue loop

Store quantities from last time step

$$\text{DADT} = (A2(\text{JEJ}) - A1(\text{JEJ}))/\text{DT}$$

Do to 4, for J = 1 to MZC

Adjust HCS if no boiling.

If KBOIL = 2 then go to 350

If PHI2(J) = 0 then go to 350

$$\text{HCS(J)} = \frac{\text{DELT} \cdot \text{K5}}{2\text{CL}} \left[\text{HCOOL(J)} + \frac{\text{GAM2}}{\text{RST} + \frac{1}{\text{HCOOL(J)}}} \right]$$

(350) G1(J) = G2(J)

$$\text{G2(J)} = \text{G1(J)} \frac{\text{GAV2}}{\text{GAV1}}$$

HVA1(J) = HVA2(J)

X1(J) = X2(J)

A1(J) = A2(J)

DL1(J) = DL2(J)

DAV1(J) = DAV2(J)

(4) DEP1(J) = DEP2(J)

JLAST = JE

NBL1 = NBL2

UNBO = UNB

If JSLUG > 0 then JE = J1

If JSLUG > 0 and GAVI ≤ 0 then go to 12

d. Calculate coolant enthalpy

Check for flow reversal

(5) If $G1(1) \geq 0$ then go to 10

Do to 6, for $J = 1$ to $J1$

$G2(J) = G1(J) + K3 \cdot DELT$

If $J6 \neq 0$ then go to 7

Enthalpy adjustment when liquid inlet, two-phase interface passes a coolant axial mesh point.

$J7 = J1 - 1$

$HL2(J7) = TS(J7) \cdot CL + 10.0$

$HL2(J7 - 1) = TS(J7 - 1) \cdot CL - 0.03$

$HL2(J7 - 2) = HL2(J7 - 1)$

(7) $U1 = G1(1) \frac{DEL T}{DZCOOL}$

$U2 = G2(1) \frac{DEL T}{DZCOOL}$

$U3 = \frac{DEL T}{DZCOOL}$

$SUSIG(1) = 0$

Do to 8, for $M = 1$ to $J1 - 4$

$J = J1 - 4 + M + 1$ (reverse loop)

$HL2(J) = \{HL1(J+1) \cdot [DL1(J+1) - U1 - HCS(J+1)] + HL1(J) \cdot [DL1(J) + U1 - HCS(J)] - HL2(J+1) \cdot [DL2(J+1) + U2 + HCS(J+1)] + DELT \cdot K5 \cdot [PHI2(J) + PHI2(J+1)]\} / \{DL1(J) - U2 + HCS(J)\}$

(8) continue loop

Enthalpy smoothing

Do to 9, for $M = J1 - 12$ to $J1 - 4$

$J = (J1 - 4) - M + (J1 - 12)$ (reverse loop)

$HL2(J) = HL2(J1 - 3) - \frac{J1 - 3 - J}{10} [HL2(J1 - 3) - HL2(J1 - 13)]$

(9) continue loop

Go to 12

$$(10) \quad G2(1) = G1(1) \frac{GAV2}{GAV1}$$

$$U1 = G1(1) \frac{DEL T}{DZCOOL}$$

$$U2 = G2(1) \frac{DEL T}{DZCOOL}$$

$$U3 = \frac{DEL T}{DZCOOL}$$

$$SUSIG(1) = 0$$

$$DHL2 = 0.0$$

Do to 11 for J = 2 to MZC

$$\begin{aligned} HL2(J) = & \{HL1(J) \cdot [DL1(J) - U1 - HCS(J)] + HL1(J-1) \cdot [DL1(J-1) \\ & + U1 - HCS(J-1)] - HL2(J-1) \cdot [DL1(J) + U2 + HCS(J+1)] \\ & + DELT \cdot K5 \cdot [PHI2(J) + PHI2(J-1)]\} / \{DL1(J) + U2 \\ & + HCS(J)\} \end{aligned}$$

If J > JIM4 then DHL2 = DHL2 + HL2(J) - HL1(J)

(11) continue loop

If JB < 1 then go to 12

$$DHL2 = DHL2/4.0$$

$$HL2(J1-1) = HL1(J1-1) + DHL2$$

e. Calculate coolant temperature and physical properties

$$HL2(J1) = HL1(J1) + DHL2$$

(12) Do to 13, for J = 1 to MZC

$$TCOOL(J) = HL2(J)/CL$$

Check for boiling

If TCOOL(J) > [TS(J) + TSCK] and JSLUG ≤ 0 then go to 15

$$DL2(J) = 0.9514 - 2.392 \times 10^{-4} \cdot TCOOL(J)$$

$$VIL(J) = 0.01 \cdot \exp \left[\frac{756.9}{TCOOL(J) + 273} - 2.41 \right]$$

If G2(J) = 0 then go to 125

$$FRL = FR \left[DH \cdot \frac{|G2(J)|}{VIL(J)} \right]^{-0.20}$$

$$(125) \quad FRGR = FRL \cdot G2(J) \cdot |G2(J)| / [1961.4 \cdot 4 \cdot DH \cdot DL2(J)] + DL2(J)$$


```

MO(J) = G2(J)2/[980.7 · DL2(J)]
SUSIG(J) = 0
DAV1(J) = DL1(J)
DAV2(J) = DL2(J)
If JSLUG > 0 then go to 13
X2(J) = 0
(13) A2(J) = 0.0
      If JSLUG > 0 then go to 37
      If J5 > 0 then go to 14
      NBL2 = DZCOOL(MZC - 1)
      Go to 37
(14) NBL2 = DZCOOL(J5 - 1)
      J = J5
      If [TS(J5) - TCOOL(J5)] > 0.005 then go to 15
      Go to 37
      Check for boiling initiation
(15) If JB > 0 then go to 17
      If J5 ≠ 0 then go to 156
      TSCK = 0.005
      JKK = J - 2
      JKL = J + 2
      BIG = HL1(J)
      Do to 155, for J2 = JKK to JKL
      If HL1(J2) < BIG then go to 155
      J = J2
      BIG = HL1(J2)
(155) Continue loop
(156) DELTP = DELT
      NBL2 = DZCOOL · (J5 - 1)
      If DELT ≤ 10-8 then go to 37
f. Adjust time step to achieve exact time of boiling initiation

```

$$\text{DELT} = \frac{\text{DELT} \cdot [\text{TS}(J) \cdot \text{CL} - \text{HL1}(J)]}{\text{HL2}(J) - \text{HL1}(J)}$$

If $\text{DELT} \leq 10^{-8}$ then $\text{DELT} = 10^{-8}$

$$\text{GAV2} = \text{GAV1} + \text{K9} \cdot \text{DELT}$$

$$\text{J5} = \text{J}$$

Do to 16, for $\text{J} = 2$ to MZC

$$\text{G2}(J) = \text{GAV2}$$

$$\text{HCS}(J) = \text{HCS}(J) \cdot \text{DELT} / \text{DELTP}$$

(16) Continue loop

Go to 10

(17) $\text{JB} = \text{JB} + 1$

$$\text{J6} = \text{J6} + 1$$

g. Calculate position of inlet liquid, two-phase interface

$$\text{EB} = \frac{\text{TS}(J-1) - \text{TCOOL}(J-1)}{\text{HL2}(J)/\text{CL} - \text{TCOOL}(J-1) + \text{TS}(J-1) - \text{TS}(J)} \cdot \text{DZCOOL}$$

$$\text{If } \text{N7} > 0, \text{ then } \text{EB} = \text{DZCOOL} \cdot \frac{\text{N8} - \text{J6}}{\text{N8}}$$

$$\text{NBL2} = (J-2) \cdot \text{DZCOOL} + \text{EB}$$

If $\text{J6} \neq \text{N8}$ then go to 18

Adjust NBL2 when interface crosses axial mesh point

If $\text{NBL2} \geq \text{DZCOOL} \cdot (\text{J1} - 2)$ then go to 18

$$\text{NBL2} = (\text{J1} - 2) \cdot \text{DZCOOL} + 0.01$$

$$\text{EB} = 0.01$$

$$\text{J} = \text{J} + 1$$

Calculate saturation temperature at interface

$$(18) \quad \text{TSB} = \frac{\text{EB} \cdot [\text{TS}(J) - \text{TS}(J-1)]}{\text{DZCOOL}} + \text{TS}(J-1)$$

$$\text{ENBL} = \text{ESTENBL}$$

$$\text{ESTNBL} = \text{NBL1} - \text{NBL2}$$

$$\text{J1} = \text{J}$$

$$\text{JIM4} = \text{J1} - 4$$

Check for first time step after boiling initiation

If $\text{JB} \neq 2$ then go to 19

```

JE = J1
JEP = J1
UNB = DZCOOL * [MZC - JE]
(19) HVA2(J1 - 1) = 1130.0 - 0.225 * TS(J)

h. Calculate physical properties in two-phase region

Do to 20, for J = J1 to JE
X2(J) = X1(J)
HVA2(J) = 1130.0 - 0.225 * TS(J)
DL2(J) = 0.9514 - 2.392 x 10-4 * TS(J)
VIL(J) = 0.01 * exp  $\left[ \frac{769.9}{TS(J) + 273} - 2.41 \right]$ 
VIG(J) = 1.18 x 10-7 * TS(J) + 1.22 x 10-4
B(J) = 2600/PCOOL(J)
DEP2(J) = DL2(J)  $\left[ \frac{1}{B(J)} + X2(J) \right]$ 
(20) Continue loop

      Adjust constants at inlet liquid, two-phase interface
G2F = G2(J1)
DEP2F = DEP2(J1)
DEP1(J1) = DEP2(J1)
ITER = 0

i. Two-phase void-fraction calculation

      Store quality at JEP for use in convergence check
(21) ESTX = X2(JEP)
SSIG = 0

      Check for inlet liquid, two-phase interface at an axial node
point.

If J6 = 1 then go to 22
A2F =  $\frac{A2F}{2.0} + \{ \text{DELT} \cdot K5 \cdot \text{PHI2}(J1) / \text{HVA2}(J1) - U3 \cdot G2F \cdot [X2F$ 
      +  $(TS(J1) - TS(J1 - 1) \cdot CL / \text{HVA2}(J1)) \} / [2 \cdot \text{DEP2F}]$ 
If A2F  $\geq$  0.99 then A2F = 0.99

```

If $A2F < 0.01$ then $A2F = 0.01$

$$A2(J1) = \frac{A2(J1) + A1(J1)}{2} + \{ \text{DELTA} \cdot K5 \cdot 2 \cdot \text{PHI2}(J1) / \text{HVA2}(J1) - \frac{U3 \cdot N8}{J6} \cdot [G1(J1) \cdot X1(J1) + G2(J1) \cdot (X2(J1) - X2F) + (G2(J1) + G1(J1)) \cdot (TS(J1) - TS(J1 - 1)) \cdot CL / \text{HVA2}(J1)] \} / \{ 2 \cdot [\text{DEP1}(J) + \text{DEP2}(J1)] \}$$

Go to 23

$$(22) \quad A2(J1) = \frac{A2(J1)}{2} + \{ \text{DELTA} \cdot K5 \cdot \text{PHI2}(J1) / \text{HVA2}(J1) - U3 \cdot [G2(J1) \cdot X2(J1) + G2(J1) \cdot (TS(J1) - TS(J1 - 1)) \cdot CL / \text{HVA2}(J1)] \} / [2 \cdot \text{DEP2}(J1)]$$

(23) If $A2(J1) \geq 0.99$ then $A2(J1) = 0.99$

If $A2(J1) < 0.01$ then $A2(J1) = 0.01$

Calculate void fractions for rest of two-phase region

Do to 24, for $J = J1 + 1$ to JE

If $J1 + 1 > JE$ then go to 24

$$A2(J) = \frac{A1(J) + A2(J)}{2} + \{ \text{DELTA} \cdot K5 \cdot [\text{PHI2}(J) + \text{PHI2}(J - 1)] / \text{HVA2}(J) - U3 \cdot [G1(J) \cdot (X1(J) - X1(J - 1)) + G2(J) \cdot (X2(J) - X2(J - 1)) + (G2(J) + G1(J)) \cdot (TS(J) - TS(J - 1)) \cdot CL / \text{HVA2}(J)] \} / [2 \cdot \text{DEP1}(J) + \text{DEP2}(J)]$$

If $A2(J) \geq 0.99$ then $A2(J) = 0.99$

If $A2(J) < 0.01$, then $A2(J) = 0.01$

(24) continue loop

Check for inlet liquid, two-phase interface at an axial node point.

If $J6 \leq 1$ then go to 25

Calculate two-phase parameters at the interface

$$\text{MPF} = 21.0 \cdot (1.0 - A2F)^2 / [1.0 - (1.0 - A2F)^2]$$

$$\text{CMF} = \frac{[\text{VIL}(J1) / \text{VIG}(J1)]^{0.111}}{\text{MPF}^{1.11} B(J1)^{0.555}}$$

$$X2F = \text{CMF} / (1.0 + \text{CMF})$$

$$\text{DEP2F} = \text{DL2(J1)} + [1/\text{B(J1)} + \text{X2F}]$$

$$\text{DAV2F} = \text{DL2(J1)} \cdot \text{A2F} \cdot [1/\text{B(J1)} - 1] + \text{DL2(J1)}$$

$$\text{SIGF} = [\text{DL1(J1)} - \text{DAV2F}]/(\text{U3} \cdot \text{N8})$$

$$\text{SUSIGF} = \text{SIGF} + \text{SUSIG(J1 - 1)}$$

go to 26

$$(25) \quad \text{SUSIGF} = 0$$

$$(26) \quad \text{Do to 28, for } J = \text{J1 to JE}$$

Calculate two-phase parameters at remainder of nodes.

$$\text{MP(J)} = 21.0 \cdot [1 - \text{A2(J)}]^2 / \{1 - [1 - \text{A2(J)}]^2\}$$

$$\text{C(J)} = \frac{[\text{VIL(J)}/\text{VIG(J)}]^{0.111}}{\text{MP(J)}^{1.11} \text{B(J)}^{0.555}}$$

$$\text{X2(J)} = \frac{\text{C(J)}}{1 - \text{C(J)}}$$

$$\text{DEP2(J)} = \text{DL2(J)} \left[\frac{1}{\text{B(J)}} + \text{X2(J)} \right]$$

$$\text{DAV2(J)} = \text{DL2(J)} \cdot \text{A2(J)} \left[\frac{1}{\text{B(J)}} - 1 \right] + \text{DL2(J)}$$

If J = J1 then go to 27

Spatial integration of time derivative of coolant density.

$$\text{SIG(J)} = \frac{\text{DAV1(J)} - \text{DAV2(J)}}{\text{U3}}$$

$$\text{SUSIG(J)} = \text{SIG(J)} + \text{SUSIG(J - 1)}$$

Go to 28

$$(27) \quad \text{SIG(J)} = \frac{\text{DAV1(J)} - \text{DAV2(J)}}{\text{U3}} \cdot \frac{\text{J6}}{\text{N8}}$$

$$\text{SUSIG(J)} = \text{SIG(J)} + \text{SUSIGF}$$

$$(28) \quad \text{SSIG} = \text{SSIG} + \text{SUSIG(J)} + \text{SUSIG(J - 1)}$$

$$(29) \quad \text{Do to 30 for } J = \text{J1 to JE}$$

Two-phase friction pressure gradient.

$$\text{PHISQ(J)} = 1 + \frac{20}{\text{MP(J)}} + \frac{1}{\text{MP(J)}^2}$$

$$\text{FRL(J)} = \text{FR} \cdot \left[\frac{\text{DH} \cdot |\text{G2(J)}|}{\text{VIL(J)}} \right]^{-0.2}$$

$$FRGRL(J) = \frac{FRL(J) \cdot G2(J) \cdot |G2(J)|}{1961.4 \cdot DH \cdot DL2(J)}$$

$$FRGR(J) = FRGRL(J) \cdot \{1 - X2(J)\}^{1.8} \cdot PHISQ(J) + DAV2(J)$$

Two-phase velocity head.

$$MO(J) = G2(J)^2 \left\{ \frac{B(J) \cdot X2(J)^2}{A2(J)} + \frac{[1 - X2(J)]^2}{1 - A2(J)} \right\} / [980.7 \cdot DL2(J)]$$

$$TCOOL(J) = TS(J)$$

(30) continue loop

j. Mass-flow-rate calculation

$$G2(1) = GAV2 - \frac{SSIG}{2(JE - 1)}$$

Do to 31, for J = 2 to JE

$$G2(J) = G2(1) + SUSIG(J)$$

(31) continue loop

$$G2F = G2(1) + SUSIGF$$

Check iteration count.

$$ITER = ITER + 1$$

If ITER $\leq$ 4 then go to 21

If ITER > 30 then go to 63

k. Test for convergence of iterations.

$$CO = |ESTX - X2(JEP)|$$

If X2(JEP) > 0 then CO = CO/X2(JEP)

If CO > EPSCOL then go to 21

Do to 315 for J = J1 to JE

If A2(J) $\geq$ AMAX then go to 63

(315) Continue loop

$$JDELTA = 0$$

If G2(JE) $\leq$ 0 then go to 63

Check for movement of upper liquid slug past an axial node.

If (MZC - 1 - JE) $\cdot$ DZCOOL $\leq$ UNB then go to 32

Extrapolated void fractions for next node

$$A2(JE + 1) = \frac{A2(JE)}{2}$$

$$X2(JE + 1) = \frac{X2(JE)}{2}$$

etc.

$$JE = JE + 1$$

$$JDEL T = 1$$

If $JE > MZC$ then $JE = MZC$

1. Check for existence of exit slug

(32) If $JE \geq MZC$ then go to 37

Exit slug mass flow rate

Do to 33, for $J = JE + 1$ to MZC

$$G2(J) = G2(JE)$$

(33) continue loop

Calculate movement of exit slug

$$EBU = DELT \cdot \frac{1}{2} \left[\frac{G2(JE)}{DAV2(JE)} + \frac{G1(JE)}{DAV1(JE)} \right]$$

Enthalpy of exit slug

$$HL2(JE + 1) = TS(JE + 1) \cdot CL$$

If $JE + 2 > MZC$ then go to 35

Do to 34 for $J = JE + 2$ to MZC

$$HL2(J) = HL1(J - JDEL T)$$

(34) continue loop

Physical properties of exit slug

Do to 36, for $J = JE + 1$ to MZC

$$TCOOL(J) = HL2(J)/CL$$

etc..

.

.

.

$$X2(J) = 0$$

(36) continue loop

m. Calculate momentum integral

(37) $FI = 0$
 Do to 38, for $J = 1$ to $MZC - 1$
 $JKK = (MZC - 1) - J + 1$ (backward loop)
 $FI = FI + DZCOOL \cdot \frac{FRGR(JKK + 1) + FRGR(JKK)}{2}$
 $MI = MO(MZC) - MO(JKK)$
 $MINT(JKK) = FI + MI$
 (38) continue loop

n. Calculate film heat-transfer coefficient

Do to 39, for $J = 1$ to MZC
 $KL = [0.215 - 1.15 \times 10^{-4} \cdot TCOOL(J)] \cdot 4.185$
 IF $G2(J) = 0$ then go to 385
 $HCOOL(J) = KL \frac{C1[DH|G2(J)| \cdot CL/KL]^{C2} + C3}{DH}$

Check to see if void fraction is greater than the burnout void fraction.

(385) If $A2(J) \geq ABURN$ then $HCOOL(J) = HBURN$
 If $G2(J) \neq 0$ then go to 39
 If $A2(J) < ABURN$ then $HCOOL(J) = \frac{KL \cdot C3}{DH}$

(39) Continue loop
 $GAV1 = GAV2$
 If $JSLUG > 0$ then go to 51
 $DT = DELT$
 $K3 = \frac{G2(1) - G1(1)}{DELT}$

Skip time step control after flow reversal

If $N7 > 0$ then go to 47

o. Check for boiling initiation

If $J5 \leq 0$ then go to 40

Time step at boiling initiation.

$$\text{DELT} = \frac{0.92 \cdot \text{DELT}}{\text{N8}} \cdot \frac{\text{TS}(\text{J5} - 1) \cdot \text{CL} - \text{HL2}(\text{J5} - 1)}{\text{HL2}(\text{J5} - 1) - \text{HL1}(\text{J5} - 1)}$$

JE = J5

JEP = J5

UNB = DZCOOL(MZC - JE)

J5 = 0

JB = 1

JES = JEP

NCHECK = 3

KBOIL = 2

If NGFLOW $\leq$ 1 then go to 47

$$\text{PIN} = \text{PCOOL}(1) + \frac{\text{G2}(1) \cdot |\text{G2}(1)|}{2.028 \times 10^6 \cdot \text{DAV2}(1)}$$

DELPO = PIN - PX

Go to 47

(40) If JB < 2 then go to 41

p. Main time-step control, after boiling initiation

$$\text{DELT} = \text{DELT} \cdot \left[\text{EB} - \frac{\text{DZCOOL} \cdot (\text{N8} - \text{J6} - 1)}{\text{N8}} \right] / \text{ESTNBL}$$

If J6 = N8 - 1 then DELT = 0.92 · DELT

If DELT $\leq$ 0 then DELT = DT

Go to 47

q. Main preboiling time-step control (reduces time step as boiling is approached)

(41) If NCHECK = $\begin{cases} 1 \text{ then go to 42} \\ 2 \text{ then go to 43} \\ 3 \text{ then go to 47} \end{cases}$

(42) TCHECK = 100.0

DTCHECK = 0.10

Go to 44

(43) TCHECK = 50.0

DTCHECK = 0.01

(44) Do to 46, for J = 1 to MZC

If $TS(J) - \left[TCOOL(J) + \frac{TCOOL(J) - HL1(J)/CL}{DT} \cdot DELT \right] > TCHECK$

then go to 46

If $DELT \leq DTCHECK$ then go to 45

$DELT = DTCHECK$

(45) $NCHECK = NCHECK + 1$

Go to 41

(46) continue loop

Check for inlet liquid, two-phase interface and an axial node

If $J6 = N8$ then $J6 = 0$

If $J6 \neq 0$ then go to 55

$ZIT = TIME + DT$

If $KBOIL = 1$ then $ZIT = ZIT - DT/2.0$

If $JB < 2$ then go to 48

$K4 = N8$

Go to 49

(48) $K4 = 1.0$

r. Calculation of coolant pressure and average mass flow rate

(49) $PCOOL(MZC) = PX + \frac{G2(MZC) \cdot |G2(MZC)|}{DAV2(MZC) \cdot 2.028 \times 10^6}$

Check for existence of exit slug

If $JE \geq MZC$ then go to 52

If $JE > MZC - 1$ then go to 51

Do to 50, for $JJ = JE$ to $MZC - 1$

$J = (MZC - 1) - JJ + JE$ (backward loop)

Pressure profile in exit slug

$PCOOL(J) = \frac{MINT(J) + \frac{[G2(MZC) - GJ6] \cdot (MZC - J) \cdot DZCOOL}{2 \cdot K4 \cdot DELT \cdot 980.7}}{1034.0} + PCOOL(MZC)$

If $PCOOL(J) < PCOOL(MZC)$ then $PCOOL(J) = PCOOL(MZC)$

(50) continue loop

$$(51) \quad K8 = 1034.0 \cdot \left[\text{DELPO} \cdot \exp(\text{ZIT} \cdot \text{PDEC}) + \text{PX} - \text{PCOOL}(\text{JE}) - \frac{\text{G2}(1) \cdot |\text{G2}(1)|}{\text{DAV2}(1) \cdot 2.028 \times 10^6} \right]$$

Go to 53

$$(52) \quad K8 = 1034.0 \cdot \left[\text{DELPO} \cdot \exp(\text{ZIT} \cdot \text{PDEC}) - \frac{\text{G2}(1) |\text{G2}(1)|}{\text{DAV2}(1) \cdot 2.028 \times 10^6} - \frac{\text{G2}(\text{MZC}) \cdot |\text{G2}(\text{MZC})|}{\text{DAV2}(\text{MZC}) \cdot 2.028 \times 10^6} \right]$$

$$(53) \quad \text{GAV2} = \text{GAV1} + 980.7 \cdot \text{DELT} \cdot K4 \cdot \frac{K8 - \text{MINT}(1) + \text{MINT}(\text{JE})}{\text{DZCOOL} \cdot (\text{JE} - 1) + \text{LP} \cdot \text{AR}}$$

If JSLUG > 0 then go to 671

If KBOIL = 2 then go to 539

Check to see if flow is specified as a function of time

If NGFLOW > 1 then go to 538

Correction for calculated average mass flow rate

AMINT1 = 0

Do to 536, for JJ = 1 to MZC

AMINT1 = AMINT1 + DL2(JJ)

(536) continue loop

AMINT1 = -AMINT1 · DZCOOL + 1034.0 · DELPO
· exp(ZIT · PDEC)

AMINT1 = AMINT1 · 980.7 · DELT /
[DZCOOL · (JE - 1) + LP · AR]

BG2SQ = GAV2 - GAV1

DELGP = $\frac{\text{BG2SQ}}{1 - \frac{\text{BS2SQ} - \text{AMINT1}}{\text{GAV1}}}$

GAV2 = GAV1 + DELGP

If JB = 0 and GAV2 < 0.10 · GO then GAV2 = 0.10 · GO

Go to 539

(538) Call INTERP(GFLOW, TFLOW, NGFLOW, ZIT, GAV2)

GAV2 = GAV2 · GO

$$PIN = DELPO \cdot \exp(ZIT \cdot PDEC) + PX$$

Pressure profile in inlet slug..

$$K9 = (GAV2 - GAV1) / (DEL T \cdot K4)$$

Do to 54 for JJ = 1 to JE - 1

J = (JE - 1) - JJ + 1 (backward loop)

$$PCOOL(J) = \frac{MINT(J) - MINT(JE) + \frac{(GAV2 - GAV1) \cdot (JE - J) DZCOOL}{K4 \cdot DEL T \cdot 980.7}}{1034.0} + PCOOL(JE)$$

(54) continue loop

$$GJ6 = G2(MZC)$$

(55) UNB = UNB - EBU

If UNB < -0.1 then UNB = -0.1

If KBOIL = 2 then return to TSDRIV

s. Calculate saturation temperature

Do to 57, for JJ = 1 to MZC

$$TS(JJ) = \frac{12130}{10.51 - \log [PCOOL(JJ)]} - 273.0 + DTS$$

Return to TSDRIV

ii. Slug-ejection Calculation

a. Initialize parameters for slug calculation

(63) J1SL = J1

JE = JLAST

ZIT = 0

Do to 64, for J = J1 to JE

If A1(J) ≤ ZIT then go to 64

ZIT = A1(J)

J1SL = J

(64) continue loop

JBOD = IFIX(1000 · TIME + 1)

$$DEL T = \frac{JBOD}{1000} - TIME$$

If DELT < 0.0001 then DELT = DELT + 0.001

JSLUG = 1

UNB = UNBO - 1×10^{-6}

NBL1 = NBL1 - 1×10^{-6}

K4 = 1.0

NBL2 = NBL1

J1 = IFIX(NBL2/DZCOOL+2.0)

KKK = IFIX(UNB/DZCOOL)

JE = MZC - KKK - 1

If J1SL < J1 then J1SL = J1

JESL = J1SL

JES = JESC

If DADT = 0 then DADT = 50.0

G2(1) = G1(1)

G2(MZC) = G1(MZC)

TSUM = 0

b. Calculate average temperatures and properties during slug ejection.

Do to 65, for J = 1 to J1

(65) TSUM = TSUM + TCOOL(J)

TSUM = TSUM/J1

DAVLSL = $0.9514 - 2.392 \times 10^{-4} \cdot \text{TSUM}$

VILSL = $0.01 \cdot \exp\left[\frac{756.9}{\text{TSUM} + 273} - 2.41\right]$

VLSSL = -G2(1)/DAVLSL

TSUM = 0.0

Do to 66, for J = JE to MZC

(66) TSUM = TSUM + TCOOL(J)

TSUM = TSUM/(MZC - JE + 1)

DAVUSL = $0.9514 - 2.392 \times 10^{-4} \cdot \text{TSUM}$

VIUSL = $0.01 \cdot \exp\left[\frac{756.9}{\text{TSUM} + 273} - 2.41\right]$

$$VUSL = G1(MZC)/DAVUSL$$

Do to 67, for J = 1 to MZC

$$A2(J) = A1(J)$$

$$X2(J) = 0.0$$

$$(67) \quad PCOOL(J) = 0$$

$$(671) \quad JE = JLAST$$

$$(68) \quad DELTHF = DELT/2$$

$$PCOOL(MZC) = PX + \frac{G2(MZC) \cdot |G2(MZC)|}{2.028 \times 10^6 \cdot DAVUSL}$$

$$PCOOL(1) = DELPO \cdot \exp[PDEC \cdot (TIME + DELTHF)] \\ + PX - \frac{G2(1) \cdot |G2(1)|}{2.028 \times 10^6 \cdot DAVLSL}$$

If $G2(1) \neq 0$ then

$$FRLLSL = \frac{FR}{\left[\frac{DH |G2(1)|}{VILSL} \right]^{0.2}}$$

$$\text{If } G2(MZC) \neq 0 \text{ then } FRLUSL = \frac{FR}{\left[\frac{DH \cdot |G2(MZC)|}{VIUSL} \right]^{0.2}}$$

$$TMAX1 = TCOOL(J1 - 1)$$

If $J1 \leq 0$ then $TMAX1 = 0.0$

Do to 93, for J = 1 to MZ

If $KSANA = 2$ then $T2(NEP, J) = T2(NEP, J)$

$$(93) \quad C(J) = T2(NEP, J)$$

c. Calculate driving pressures for upper and lower slug.

Call INTERP[C, ZFM, MZ, ZCOOL(J1), TNE]

If $TNE > TMAX1$ then $TMAX1 = TNE$

If $JE < MZC$ and $TCOOL(JEH) > TMAX1$ then $TMAX1$
 $= TCOOL(JEH)$

$$(687) \quad TNE = TMAX1$$

$$DPLSL = 1.014 \times 10^6 \left[\exp \left(10.51 - \frac{12130}{TNE + 273} \right) - PCOOL(1) \right]$$

Call INTERP[C,ZFM,MZ,ZCOOL(JE),TNE]

$$DPUSL = 1.014 \times 10^6 \cdot \left[\exp\left(10.51 - \frac{12130}{TNE + 273}\right) - PCOOL(MZC) \right]$$

UNBO = UNB

If JESL $\geq$ MZC then go to 73

If JE $\geq$ MZC then go to 69

d. Perform Runge-Kutta solution for motion of upper slug.

$$ZOT = \frac{1}{UNB - VUSL \cdot DELTHF}$$

If ZOT $\leq$ 0, then go to 90

$$ZIT = \frac{FRLUSL}{2 \cdot DH}$$

$$C5 = DELT \cdot \left[\frac{DPSUL \cdot ZOT}{DAVUSL} - ZIT \cdot VUSL \cdot |VUSL| \right]$$

$$ZOT = \frac{1}{UNB - \left(VUSL + \frac{C5}{2}\right) \cdot DELTHF}$$

If ZOT $\leq$ 0, then go to 90

$$C6 = DELT \cdot \left[\frac{DPSUL \cdot ZOT}{DAVUSL} - ZIT \cdot \left(VUSL + \frac{C5}{2}\right) \cdot \left|VUSL + \frac{C5}{2}\right| \right]$$

$$ZOT = \frac{1}{UNB - \left(VUSL + \frac{C6}{2}\right) \cdot DELTHF}$$

If ZOT $\leq$ 0 then go to 90

$$C7 = DELT \cdot \left[\frac{DPSUL \cdot ZOT}{DAVUSL} - ZIT \cdot \left(VUSL + \frac{C6}{2}\right) \cdot \left|VUSL + \frac{C6}{2}\right| \right]$$

$$ZOT = \frac{1}{UNB - \left(VUSL + \frac{C7}{2}\right) \cdot DELTHF}$$

If ZOT $\leq$ 0, then go to 90

$$C8 = DELT \cdot \left[\frac{DPSUL \cdot ZOT}{DAVUSL} - ZIT \cdot (VUSL + C7) \cdot |VUSL + C7| \right]$$

$$ZIT = VUSL + \frac{C5 + 2 \cdot C6 + 2 \cdot C7 + C8}{6}$$

$$UNB = UNBO - (ZIT + VUSL) \cdot DELTHF$$

If $ZIT + VUSL < 2 \cdot VELUSL$, then $UNB = UNBO - VELUSL \cdot DELT$

$$VUSL = ZIT$$

$$ZIT = VUSL \cdot DAVUSL$$

Go to 70

(90) $UNB = 0$

Go to 70

(69) $UNB = UNB - VUSL \cdot DELT$

If $VUSL < VELUSL$, then $UNB = UNBO - VELUSL \cdot DELT$

(70) If $UNB > UNBO$, then $UNB = UNBO$

e. Move the upper slug coolant properties to correspond with slug movement through the mesh.

$$KKK = \text{INTEGER}(UNB/DZCOOL)$$

$$JEP = MZC - KKK$$

If $UNB > 0$ then $JEP = JEP - 1$

$$JDEL T = JEP - JE$$

$$JE = JEP$$

$$JESL = JESL + JDEL T$$

$$KKK = JE + 1$$

$$ZIT = VUSL \cdot DAVUSL$$

Do to 71, for $J = KKK$ to MZC

$$JJ = MZC - J + KKK$$

If $KKK > MZC$ then go to 71

$$G2(JJ) = ZIT$$

$$TCOOL(JJ) = TCOOL(JJ - DELT)$$

$$X2(JJ) = 0.0$$

$$A2(JJ) = 0.0$$

(71) Continue loop.

$$KKK = JESL + 1$$

If $KKK > JE$, then go to 73


```

Do to 72 for J = KKK, JE
JJ = JE - J + KKK
If JJ > MZC, then go to 72
A2(JJ) = A2(JJ - JDELT)
TS(JJ) = TMAX1
TCOOL(JJ) = TS(JJ)
G2(JJ) = 0
PCOOL(JJ) = 0
(72) Continue loop.
(73) If J1SL < 1, then go to 80
      NBL1 = NBL2

f. Use computed average mass flow rate for inlet interface motion.

   If J1SL < 1 then go to 8
   ZIT = -GAV1
   
$$NBL2 = NBL1 - \frac{ZIT \cdot DELT}{DAVL SL}$$

   If GAV1  $\geq$  0.0 then NBL2 = NBL1

g. Move the lower slug coolant properties to correspond with slug
movement through the mesh. This involves essentially the same steps as
in e above.

h. Adjust void in vapor region

   Do to 79, for J = J1SL to JESL
   If J < 1 or J > MZC then go to 79
   A2(J) = A1(JES) + DADT  $\cdot$  DELT
   If A2(J) > AMAX then A2(J) = AMAX
   G2(J) = 0.0
   PCOOL(J) = 0.0
   TS(J) = TMAX1
   TCOOL(J) = TS(J)
(79) Continue loop.

      Reset interfaces.

```

JESL = JES

J1SL = JES

- i. Calculate heat-transfer coefficient of coolant

(80) Do to 82, for J = 1 to MZC.

DENL = $0.9514 - 2.392 \times 10^{-4} \cdot \text{TCOOL}(J)$

DAV2(J) = DENL · [1.0 - A2(J)]

KL = $0.215 - 1.15 \times 10^{-4} \cdot \text{TCOOL}(J)$

If G2(J) = 0, then go to 81

$$\text{HCOOL}(J) = \frac{\text{KL}}{\text{DH}} \cdot \left\{ \text{C1} \cdot \left[\frac{\text{DH} \cdot |\text{G2}(J)| \cdot \text{CL}}{\text{KL}} \right]^{\text{C2}} + \text{C3} \right\}$$

Go to 82

Check to see if burnout criterion has been exceeded.

(81) If A2(J) ≥ ABURN, then HCOOL(J) = HBURN

If A2(J) = AMAX and J1SL > J, then J1SL = J

If A2(J) = AMAX and JESL < J, then JESL = J

If A2(J) < ABURN, then $\text{HCOOL}(J) = \frac{\text{KL} \cdot \text{C3}}{\text{DH}}$

(82) Continue loop.

If J1 > 1 then

$$\text{PCOOL}(J1) = \frac{\text{DPLSL}}{1.014 \times 10^6} + \text{PCOOL}(1)$$

If JE < MZC then

$$\text{PCOOL}(JE) = \frac{\text{DPSUL}}{1.014 \times 10^6} + \text{PCOOL}(\text{MZC})$$

JB = JB + 1

- j. Time-step control for slug ejection

DT = DELT

If DELT ≠ 0.001, then DELT = 0.001

If A2(1) ≥ AMAX, then VUSL = 0

If A2(MZC) ≥ AMAX, then VUSL = 0

If J1SL ≤ 1 and JESL ≥ MZC then go to 84

Return to TSDRIV

(84) DELT = 2.0 · DELT

JSLUG = 2

PRINT 185, DELT

Return to TSDRIV

(185) Message = coolant channel fully voided, further calculations are
meaningless with the current model--the new time step is ...

End Subroutine TSCOOL.

APPENDIX C

Detailed Equations for Fuel Deformation Module

1. Subroutine DEFORM calculates dimensional changes of fuel and cladding as well as stresses and strains in both the cladding and fuel.

If KDEF = 2 then go to 4

a. Initialization

(1) $FZF = FZC = 0$

$$KS = \frac{ES}{3(1-2 \cdot NUS)}$$

Initialize clad case number to 1 and store steady-state axial and radial mesh. Store steady-state temperatures and densities.

(4) $FZF = SPRINIK \cdot [ZFK(MZN) - ZFIO(MZN)]$

Set up temperature-dependent elasticity and yield point. Calculate temperature rise from steady state.

(5) $T(I,J) = T2(I,J) - TFO(I,J)$

(6) $T(NE,J) = T2(NE,J) - TFO(NE,J)$

b. Density and Compressibility Calculation

Do to 10, for J = 1 to MZC

$BL(J) = 0$

$K(J) = 0$

$KMELT = MELT(J) - 1$

If KMELT < 1 then go to 65

Do to 7 for I = 1 to NT

Calculate reciprocal of average density.

$$RHOBAR = \frac{U(I,J)}{UMELT \cdot RHOL[T2(I,J)]} + \frac{1 - \frac{U(I,J)}{UMELT}}{RHOS[T2(I,J)]}$$

Calculate reciprocal of average bulk modulus.

$$KBAR = \frac{\frac{U(I,J)}{UMELT \cdot RHOL[T2(I,J)]} \cdot KLF}{RHOBAR} + \frac{1 - \frac{U(I,J)}{UMELT}}{RHOS[T2(I,J)] \cdot KS}$$

Compute terms in equation for liquid radial mesh.

$$R\text{BAR}(I,J) = \text{RHO}(I,J) : \text{RHOBAR}(I,J) \cdot [\text{RO}(I+1,J)^2 - \text{RO}(I,J)^2]$$

Compute free radius of melting; liquid properties calculated.

$$\text{BL}(J) = \left[\sum_{I=1}^{k_J} R\text{BAR}(I,J) \right]^{1/2}$$

Compute $1/K_J$

$$K(J) = \left[\sum_{I=1}^{k_J} R\text{BAR}(I,J) \cdot K\text{BAR}(I,J) \right] / \text{BL}(J)$$

c. Calculation of Linear-expansion Integrals

$$\text{ASSI}(J) = 0$$

$$\text{ASI}[\text{MELT}(J),J] = 0$$

$$\text{M1} = \text{MELT}(J) + 1$$

Do to 9 for $I = \text{M1}$ to NR

$$\text{ASI}(I,J) = \text{ASI}(I-1,J) + \text{AFS} \cdot \text{T}(I-1,J)$$

$$\cdot [\text{RO}(I,J)^2 - \text{RO}(I-1,J)^2] / 2$$

$$(9) \quad \text{ASSI}(J) = \text{ASSI}(J) + \text{AFS} \cdot \text{T}(I-1,J)$$

$$\cdot [\text{RO}(I,J)^3 - \text{RO}(I-1,J)^3] / 3$$

$$\text{ACI}(J) = \text{AE} \cdot \text{T}(\text{NE},J) \cdot \text{ABCSQ}(J) / 2$$

Do to 14, for $J = 1$ to MZ

Set up inner solid fuel radius and associated constants

$$\text{AS}(J) = \text{RO}[\text{MELT}(J),J]$$

$$\text{ASSQ}(J) = \text{AS}(J)^2$$

$$\text{ABSSQ}(J) = \text{BSSQ}(J) - \text{ASSQ}(J)$$

Set up outer fuel and clad radii for convergence check

$$\text{XBS1}(J) = \text{BS}(J)$$

$$\text{XBC}(1) = \text{BC}(J)$$

Set up initial case numbers for fuel

If $RO(1,J) > 0$ then $NFUEL(J) = 3$

If $RO(1,J) \leq 0$ and $MELT(J) > 1$ then $NFUEL(J) = 6$

If $RO(1,J) \leq 0$ and $MELT(J) = 1$ then $NFUEL(J) = 0$

Initialize node slippage stresses to zero

$$(14) \quad SS(J) = SC(J) = 0$$

d. Set Up Total Case Number

Case number = $NFUEL(J) + NCLAD(J)$

$NFUEL(J) = 0$, No central hole and no melting

$NFUEL(J) = 3$, Central hole

$NFUEL(J) = 6$, No central hole and melting

$NCLAD(J) = 1$, Gap between fuel and clad

$NCLAD(J) = 2$, No gap between fuel and clad

$NCLAD(J) = 3$, Plastic flow in clad

e. Force on Solid Fuel

Do to 40, for $J = 1$ to MZ

$$FZS = FZF + \pi \cdot BL(J)^2 \cdot PFUEL(J)$$

$$D1 = \frac{AC(J)}{EC(J) \cdot ABCSQ(I)} \cdot \{BCSQ(J) \cdot [1 + NUC] + ACSQ(J) \cdot [1 - NUC]\} + \frac{BS(J)}{ES \cdot ABSSQ(J)} \cdot \{BSSQ(J) \cdot [1 - NUS] + ASSQ(J)[1 + NUS]\}$$

$$D2 = \frac{BL(J) \cdot K(J)}{2} + \frac{BL(J) \cdot \{BL(J)^2 - 2NUS \cdot ASSQ(J)\}}{2ES \cdot ABSSQ(J)} + \frac{AS(J) \cdot \{BSSQ(J) \cdot [1 + NUS] + ASSQ(J)[1 - NUS] - NUS \cdot BL(J)^2\}}{ES \cdot ABSSQ(J)}$$

$$D3 = \frac{BSSQ(J) \cdot [2AS(J) - NUS \cdot BL(J)]}{ES \cdot ABSSQ(J)}$$

$$D4 = \frac{BS(J) \cdot [2ASSQ(J) - NUS \cdot BL(J)^2]}{ES \cdot ABSSQ(J)}$$

$$D5 = AS(J) - BL(J) + \frac{[2AS(J) + BL(J)] \cdot ASI(NR,J)}{ABSSQ(J)} + \frac{FZF \cdot [BL(J) - 2NUS \cdot AS(J)]}{2ES \cdot \pi \cdot ABSSQ(J)}$$

$$D6 = AC(J) \left\{ 1 + \left[\frac{-NUC \cdot FZC}{EC(J) \cdot \pi} + 2ACI(J) + \frac{2BCSQ(J) \cdot SC(J)}{EC(J)} \right. \right. \\ \left. \left. + SS(J) \cdot \frac{BCSQ(J)(1+NUC) + ACSQ(J)(1-NUC)}{EC(J)} \right] / ABCSQ(J) \right\} \\ + BS(J) \cdot \left\{ -1 + \left[\frac{NUS \cdot FZF}{ES \cdot \pi} - 2ASI(NR,J) \right] / ABSSQ(J) \right\}$$

$$(16) \quad NCASE(J) = NFUEL(J) + NCLAD(J)$$

If total case number is 1 2 3 4 5 6 7 8 9
then go to 34 38 26 37 32 27 24 21 17

f. Case No. 9

Calculate stresses at elastic verge

$$(17) \quad \begin{aligned} SRR(4,J) &= SC(J) \\ SRR(3,J) &= -SOC(J) \cdot DC(J) / AC(J) + SRR(4,J) \\ SRR(2,J) &= SRR(3,J) + SS(J) \\ PFUEL(J) &= -\frac{D5}{D2} - \frac{D3}{D2} [SS(J) + SRR(3,J)] \\ SRR(1,J) &= PFUEL(J) \end{aligned}$$

Set up elastic-verge deformations

$$\begin{aligned} CALL \text{ BOUND}(J) \\ UAC &= XAC(J) - AC(J) \\ UDC &= XBC(J) - XAC(J) - DC(J) \end{aligned}$$

Perform plastic-flow iteration

$$(18) \quad \begin{aligned} URAC &= UAC \\ SRR(3,J) &= \frac{-SOC(J)[AC(J) + UAC][DC(J) + UDC]}{XBS(J)^2} + SC(J) \\ SRR(2,J) &= SRR(3,J) + SS(J) \\ PFUEL(J) &= -\frac{D5}{D2} - \frac{D3}{D2} [SS(J) + SRR(3,J)] \\ SRR(1,J) &= -PFUEL(J) \end{aligned}$$

Calculate $a_c + \nu_r(a_c)$ plastic

$$CALL \text{ BOUND}(J)$$

XBS(J) from BOUND is equal to $a_c + V_r(a_c)$ plastic

If $\left| 1 - \frac{URAC}{XBS(J) - AC(J)} \right| < EPSDEF$ then go to 19

$$URAC = XBS(J) - AC(J)$$

go to 18

Set clad case number down for next calculation

$$(19) \quad NCLAD(J) = 2$$

$$XBC(J) = XBS(J) + \frac{[AC(J) + UAC][DC(J) + UDC]}{XBS(J)}$$

Check for inner solid under compression

If $SRR(1,J) \leq 0$ then go to 40

$$NFUEL(J) = 3$$

go to 40

g. Case No. 8

Set up surface and loop stresses

$$(21) \quad SRR(4,J) = SC(J)$$

$$PFUEL(J) = - \frac{D1 \cdot D5 + D3 \cdot D6}{D1 \cdot D2 + D3 \cdot D4}$$

$$SRR(1,J) = - PFUEL(J)$$

$$SRR(2,J) = \frac{D4 \cdot D5 + D2 \cdot D6}{D1 \cdot D2 + D3 \cdot D4}$$

$$SRR(3,J) = SRR(2,J) - SS(J)$$

$$SRR(5,J) = \frac{AC(J)}{DC(J)} \cdot [SRR(4,J) - SRR(3,J)]$$

Check for plastic clad

If $SRR(5,J) > SOC(J)$ then go to 36

Check for inner solid under compression.

If $SRR(1,J) \leq 0$ then go to 22

$$NFUEL(J) = 3$$

Check for inner clad under compression.

$$(22) \quad \text{If } SRR(3,J) \leq 0 \text{ then go to 39}$$

$$NCLAD(J) = 1$$

go to 39

h. Case No. 7

Set up surface stresses.

$$\begin{aligned}
 (24) \quad & \text{SRR}(4,J) = \text{SC}(J) \\
 & \text{SRR}(3,J) = 0 \\
 & \text{SRR}(2,J) = \text{SS}(J) \\
 & \text{PFUEL}(J) = -\frac{D5}{D2} - \frac{D3}{D2} \cdot \text{SS}(J) \\
 & \text{SRR}(1,J) = -\text{PFUEL}(J)
 \end{aligned}$$

Check for inner solid fuel under compression.

If $\text{SRR}(1,J) \leq 0$ then go to 25

$\text{NFUEL}(J) = 3$

$$\begin{aligned}
 (25) \quad & \text{CALL BOUND} \\
 & \text{go to 35}
 \end{aligned}$$

i. Case No. 3

$$\begin{aligned}
 (26) \quad & \text{ICASE} = 2 \\
 & \text{go to 28}
 \end{aligned}$$

j. Case No. 6

$$(27) \quad \text{ICASE} = 0$$

Set up surface stresses at elastic verge

$$\begin{aligned}
 (28) \quad & \text{SRR}(4,J) = \text{SC}(J) \\
 & \text{SRR}(3,J) = -\frac{\text{SOC}(J) \cdot \text{DC}(J)}{\text{AC}(J)} + \text{SRR}(4,J) \\
 & \text{SRR}(2,J) = \text{SRR}(3,J) + \text{SS}(J) \\
 & \text{SRR}(1,J) = 0 \\
 & \text{If ICASE} > 1 \text{ then } \text{SRR}(1,J) = \text{SRR}(2,J) + \frac{\text{ES}}{1 - \text{NUS}} \\
 & \quad \cdot \left[-\frac{\text{AFS}}{2} \cdot \text{T}(1,J) + \frac{\text{ASI}(\text{NR},J)}{\text{BSSQ}(J)} \right]
 \end{aligned}$$

Calculate $U_r(\text{ac})$ and U_{sc} at elastic verge

$$\begin{aligned}
 & \text{CALL BOUND}(J) \\
 & \text{UAC} = \text{XAC}(J) - \text{AC}(J) \\
 & \text{UDC} = \text{XBC}(J) - \text{XAC}(J) - \text{DC}(J)
 \end{aligned}$$

Perform plastic iteration

$$URAC = UAC$$

$$(29) \quad SRR(3,J) = -\frac{SOC(J)[AC(J)+UAC] \cdot [DC(J)+UDC]}{XBS(J)^2} + SC(J)$$

$$SRR(2,J) = SRR(3,J) + SS(J)$$

$$SRR(1,J) = 0$$

$$\text{If ICASE} > 1 \text{ then } SRR(1,J) = SRR(2,J) + \frac{ES}{1 - NUS} \cdot \left[-\frac{AFS}{2} \cdot T(1,J) + \frac{ASI(NR,J)}{BSSQ(J)} \right]$$

CALL BOUND(J)

$$\text{If } \left| 1 - \frac{URAC}{XBS(J) - AC(J)} \right| < EPSDEF \text{ then go to 30}$$

$$URAC = XBS(J) - AC(J)$$

Go to 29

Set clad case number for next step.

$$(30) \quad NCLAD(J) = 2$$

$$XBC(J) = XBS(J) + \frac{[AC(J)+UAC][DC(J)+UDC]}{XBS(J)}$$

If ICASE > 1 then go to 40

Check for liquid under compression.

$$\text{If } BL(J) \leq XAS(J) \cdot \left\{ 1 + \left[\frac{FZS}{\pi} + 2 \cdot ES \cdot ASI(NR,J) - 2 \cdot NUS \right. \right.$$

$$\left. \cdot (SRR(2,J) \cdot BSSQ(J) - SRR(1,J) \cdot ASSQ(J)) \right] / [ES \cdot ABSSQ(J)] \left. \right\}^{1/2}$$

then go to 40

$$NFUEL(J) = 6$$

go to 16

k. Case No. 5

Set up surface and loop stresses.

$$(32) \quad SRR(1,J) = 0.0$$

$$SRR(4,J) = SC(J)$$

$$\begin{aligned}
SRR(3,J) = & \left\{ AC(J) - BS(J) + \frac{AC(J)}{ABCSQ(J)} \left[\frac{-FZC \cdot NUC}{EC(J) \cdot \pi} \right. \right. \\
& + 2 \cdot ACI(J) + 2 \frac{BCSQ(J) \cdot SC(J)}{EC(J)} \left. \right] \\
& + \frac{BS(J)}{ABSSQ(J)} \left[\frac{FZS \cdot NUS}{ES \cdot \pi} - 2 \cdot ASI(NR,J) \right. \\
& \left. \left. - \frac{SS(J)}{ES} (BSSQ(J)\{1 - NUS\} + ASSQ(J)\{1 + NUS\}) \right] \right\} / D1
\end{aligned}$$

$$SRR(2,J) = SRR(3,J) + SS(J)$$

$$SRR(5,J) = \frac{AC(J)}{DC(J)} \cdot [SRR(4,J) - SRR(3,J)]$$

Check for plastic cladding

If $SRR(5,J) > SOC(J)$ then go to 36

Check for liquid fuel under compression

CALL BOUND(J)

$$\begin{aligned}
\text{If } BL(J) \leq XAS(J) \cdot \left\{ 1 + \left[\frac{FZS}{\pi} + 2 \cdot ES \cdot ASI(NR,J) - 2 \right. \right. \\
\left. \left. \cdot NUS(SRR(2,J) \cdot BSSQ(J) - SRR(1,J) \cdot ASSQ(J)) \right] \right\} / \\
\left[ES \cdot ABSSQ(J) \right]^{1/2} \text{ then go to 33}
\end{aligned}$$

$$NFUEL(J) = 6$$

go to 16

Check for inner clad under compression

(33) If $SRR(3,J) \leq 0$ then go to 40

$$NCLAD(J) = 1$$

go to 40

1. Case No. 1

Set up surface stresses

$$(34) \quad SRR(2,J) = SS(J)$$

$$SRR(3,J) = 0$$

$$SRR(4,J) = SC(J)$$

$$\begin{aligned}
SRR(1,J) = & \frac{ES}{2 \cdot (1 - NUS)} \cdot AFS \cdot T(1,J) + SRR(2,J) \\
& + \frac{ES \cdot ASI(NR,J)}{BSSQ(J)[1 - NUS]}
\end{aligned}$$

CALL BOUND(J)

Check for fuel and clad in contact

(35) If $XBS(J) \leq XAC(J)$ then go to 40

NCLAD(J) = 2

go to 16

(36) NCLAD(J) = 3

go to 16

m. Case No. 4

Set up surface stresses

(37) SRR(1,J) = 0

SRR(2,J) = SS(J)

SRR(3,J) = 0

SRR(4,J) = SC(J)

CALL BOUND(J)

Check for molten fuel under compression

If $BL(J) \leq XAS(J) \cdot \left\{ 1 + \left[\frac{FZS}{\pi} + 2 \cdot ES \cdot ASI(NR,J) \right. \right.$
 $\left. \left. - 2 \cdot NUS \cdot (SRR(2,J) \cdot BSSQ(J) - SRR(1,J) \cdot ASSQ(J)) \right] \right\}^{1/2}$

$\left[ES \cdot ABSSQ(J) \right] \}$ then go to 35

NFUEL(J) = 6

go to 16

n. Case No. 2

Set up surface and hoop stresses.

(38)
$$SRR(3,J) = \left\{ AC(J) - BS(J) + \frac{AC(J)}{ABCSQ(J)} \cdot \left[- \frac{FZC \cdot NUC}{EC(J) \cdot \pi} \right. \right.$$

$$+ 2 \cdot ACI(J) + 2 \cdot \frac{BCSQ(J) \cdot SC(J)}{EC(J)} \left. \right] + \frac{FZS \cdot NUS}{BS(J) \cdot ES \cdot \pi}$$

$$- 2 \cdot \frac{ASI(NR,J)}{BS(J)} - \frac{BS(J) \cdot SS(J) \cdot (1 - NUS)}{ES} \left. \right\} / D1$$

SRR(2,J) = SRR(3,J) + SS(J)

$$SRR(1,J) = \frac{-ES}{2(1-NUS)} AFS \cdot J(1,J) + SRR(2,J) + \frac{ES \cdot ASI(NR,J)}{BSSQ(J) \cdot (1-NUS)}$$

$$SRR(4,J) = SC(J)$$

$$SRR(5,J) = \frac{AC(J)}{DC(J)} [SRR(4,J) - SRR(3,J)]$$

Check for plastic cladding

If $SRR(5,J) > SOC(J)$ then go to 36

Check for inner clad under compression

If $SRR(3,J) \leq 0$ then go to 39

$$NCLAD(J) = 1$$

(39) CALL BOUND(J)

(40) continue loop

Check for node slippage iteration convergence for all
J from 1 to MZ

If $\left| 1 - \frac{XBS1(J)}{XBS(J)} \right| \geq EPSDEF$ then go to 54

If $\left| 1 - \frac{XBC1(J)}{XBC(J)} \right| \geq EPSDEF$ then go to 54

o. Calculate Fuel and Cladding Axial and Radial Mesh

Do to 49, for J = 1 to MZ

$$FZS = FZF + \pi \cdot BL(J)^2 \cdot PFUEL(J)$$

$$ZOT = SRR(3,J)$$

For plastic clad use elastic-verge stress

$$\text{If } IPLAS(J) > 0 \text{ then } ZOT = -\frac{SOC(J) \cdot DC(J)}{AC(J)} + SRR(4,J)$$

Set up constants needed in fuel axial mesh calculation

$$X1 = \left\{ \frac{-FZS \cdot NUS}{\pi} + \frac{[1 - 3 \cdot NUS] \cdot ES}{1 - NUS} ASI(NR,J) + [1 - NUS][SRR(2,J) \cdot BSSQ(J) - SRR(1,J) \cdot ASSQ(J)] \right\} / [ES \cdot ABSSQ(J)]$$

$$X2 = \left\{ \frac{BSSQ(J)}{ES} \cdot [SRR(2,J) - SRR(1,J)] + \frac{ASI(NR,J)}{1 - NUS} \right\} / ABSSQ(J)$$

Calculate axial mesh

$$\begin{aligned} ZFI(J+1) = & ZFI(J) + [ZFIO(J+1) - ZFIO(J)] \cdot \left\{ 1 + \left[\frac{FZS}{\pi} \right. \right. \\ & + 2 \cdot ES \cdot ASI(NR,J) - 2 \cdot NUS \cdot (SRR(2,J) \cdot BSSQ(J) \\ & \left. \left. - SRR(1,J) \cdot ASSQ(J)) \right] / [ES \cdot ABSSQ(J)] \right\} \end{aligned}$$

$$\begin{aligned} ZEI(J+1) = & ZEI(J) + [ZFIO(J+1) - ZFIO(J)] \cdot \left\{ 1 + \left[\frac{FZC}{\pi} \right. \right. \\ & + 2 \cdot EC(J) \cdot ACI(J) - 2 \cdot NUC \cdot (SRR(4,J) \\ & \left. \left. \cdot BCSQ(J) - ZOT \cdot ACSQ(J)) \right] / [EC(J) \cdot ABCSQ(J)] \right\} \end{aligned}$$

$$ZFM(J) = \frac{ZFI(J) + ZFI(J+1)}{2}$$

Set up constants for radial mesh calculation

$$ZFAC = \frac{ZFIO(J+1) - ZFIO(J)}{ZFI(J+1) - ZFI(J)}$$

$$KMELT = MELT(J)$$

Calculate radial mesh in solid fuel

Do to 44, for I = MELT(J) to NR

If RO(I,J) = 0 then go to 43

$$\begin{aligned} R(I,J) = & RO(I,J) + \frac{1 + NUS}{1 - NUS} \cdot RO(I,J) \cdot ASI(I,J) \\ & + RO(I,J) \cdot X1 + \frac{[1 + NUS] \cdot X2 \cdot ASSQ(J)}{RO(I,J)} \end{aligned}$$

go to 44

$$(43) \quad R(I,J) = RO(I,J)$$

(44) continue loop

$$KMELT = MELT(J) - 1$$

$$SUMXR = 0$$

$$SUMXK = 0$$

If KMELT(J) ≤ 0, then go to 49

Calculate liquid fuel radial mesh

Go to 48 for II = 1 to MELT(J) - 1

$$I = MELT(J) - II$$

If NCASE(J) > 6 then go to 45

- SUMXR = SUMXR + ZFAC · RBAR(I,J)
- $R(I,J) = \sqrt{XAS(J)^2 - SUMXR}$
- go to 48
- (45) If $II \leq 1$ then go to 46
- $R(II,J) = \sqrt{SUMXR} \cdot \left\{ 1 - \frac{1}{2} \left[\frac{PFUEL(J)}{SUMXR} \cdot SUMXK + \frac{1}{ZFAC} - 1 \right] \right\}$
- go to 47
- (46) $R(II,J) = 0$
- (47) SUMXR = SUMXR + RBAR(II,J)
- SUMXK = SUMXK + RBAR(II,J) · KBAR(II,J)
- (48) continue loop
- (49) continue loop

p. Plastic-flow Calculation

Set up clad radii and permanent deformation

Do to 50 for J = 1 to MZ

If IPLAS(J) ≤ 0 then go to 52

Store final clad-thickness change

UDC = XBC(J) - XBS(J) - DC(J)

Calculate clad elastic final values

CALL BOUND(J)

Calculate new base radii with permanent deformation

AC(J) = AC(J) + XBS(J) - XAC(J)

BC(J) = BC(J) + UDC - [XBC(J) - XAC(J) - DC(J)]
+ XBS(J) - XAC(J)

XAC(J) = XBS(J)

XBC(J) = XAC(J) + DC(J) + UDC

DC(J) = BC(J) - AC(J)

ACSQ(J) = AC(J)²

BCSQ(J) = BC(J)²

ABCSQ(J) = BS(J)² - AC(J)²

$$(52) \quad R(NEP,J) = XBC(J)$$

$$R(NE,J) = XAC(J)$$

(50) continue loop

q. Calculate Fuel Outer-surface Pressure

Do to 66, for J = 1 to MZ

$$(66) \quad PFUEL(J) = -SRR(2,J) + PX \cdot 1.014 \times 10^6$$

Store permanent plastic deformation for print-out.

Do to 53, for J = 1 to MZ

$$XBS1(J) = AC(J) - ACO(J)$$

$$XBC1(J) = BC(J) - BCO(J)$$

(53) continue loop

Return to TSDRIV

r. Calculate Node-slippage Stresses

(54) Do to 55, for J = 1 to MZ

$$FZS = FZF + \pi \cdot BL(J)^2 \cdot PFUEL(J)$$

$$\begin{aligned} UIS = & \frac{BSSQ(J) + AS(J) \cdot BS(J) + ASSQ(J)}{3[BS(J) + AS(J)]ES} \cdot \left\{ - \frac{FZS \cdot NUS}{\pi} \right. \\ & + \frac{4 \cdot ES}{1 - NUS} \cdot ASI(NR,J) + (1 - NUS) \cdot [BSSQ(J) \cdot SRR(2,J) \\ & \left. - ASSQ(J) \cdot SRR(1,J)] \right\} - \frac{1 + NUS}{1 - NUS} \cdot ASSI(J) \\ & + \frac{(1 + NUS) \cdot ASSQ(J) \cdot BSSQ(J)}{ES \cdot [BS(J) + AS(J)]} \cdot [SRR(2,J) - SRR(1,J)] \end{aligned}$$

$$UIC = AC(J) \cdot DC(J) \cdot XAC(J)$$

$$XBS1(J) = XBS(J)$$

$$(55) \quad XBC1(J) = XBC(J)$$

Do to 64, for J = 1 to MZ

If J = 1 then go to 56

$$SSI2 = \frac{UIS(J) - UIS(J-1)}{ZFIO(J+1) - ZFIO(J-1)}$$

go to 57

- (56) SSI2 = 0
- (57) If J = MZ, then go to 58
- $$SSI1 = \frac{UIS(J+1) - UIS(J)}{ZFIO(J+2) - ZFIO(J)}$$
- go to 59
- (58) SSI1 = 0
- (59) $SS(J) = \frac{ES \cdot (SSI1 - SSI2)}{BS(J) \cdot [ZFIO(J+1) - ZFIO(J)] \cdot (1 + NUS)}$
- If J = 1 then go to 60
- $$SCI2 = \frac{UIC(J) - UIC(J-1)}{ZFIO(J+1) - ZFIO(J-1)}$$
- go to 61
- (60) SCI2 = 0
- (61) If J = MZ then go to 62
- $$SCI1 = \frac{UIC(J+1) - UIC(J)}{ZFIO(J+2) - ZFIO(J)}$$
- go to 63
- (62) SCI1 = 0
- (63) $SC(J) = \frac{EC(J) \cdot [SCI1 - SCI2]}{BC(J) \cdot [ZFIO(J+1) - ZFIO(J)](1 + NUC)}$
- (64) continue loop
- go to 15

End subroutine DEFORM

2. Subroutine BOUND(J)

Given the surface stresses for axial section J, BOUND calculates new radial node displacements, i.e., $a_s + u_r(a_s)$, $b_s + u_r(b_s)$, $a_c + u_r(a_c)$, $b_c + u_r(b_c)$.

$$FZC = FZF + PI \cdot BL(J)^2 \cdot PFUEL(J)$$

a. Calculate $a_c + u_r(a_c)$

$$\begin{aligned} XAC(J) = AC(J) + AC(J) \cdot \left\{ \frac{-NUC \cdot FZC}{EC(J) \cdot \pi \cdot ABCSQ(J)} \right. \\ + AE \cdot T(NE, J) + [2 \cdot BCSQ(J) \cdot SRR(4, J) \\ - \{BCSQ(J)(1 + NUC) + ACSQ(J)(1 - NUC)\} SRR(3, J)] / \\ \left. [EC(J) \cdot ABCSQ(J)] \right\} \end{aligned}$$

b. Calculate $b_s + u_r(b_s)$

$$\begin{aligned} XBS(J) = BS(J) + \frac{BS(J)}{ES \cdot ABSSQ(J)} & \left\{ \frac{-FZS \cdot NUS}{\pi} + 2 \cdot ES \right. \\ & \cdot ASI(NR,J) + SRR(2,J) \cdot [BSSQ(J)(1 - NUS) \\ & \left. + ASSQ(J)(1 + NUS)] - 2 \cdot SRR(1,J) \cdot ASSQ(J) \right\} \end{aligned}$$

c. Calculate $a_s + u_r(a_s)$

$$\begin{aligned} XAS(J) = AS(J) + \frac{AS(J)}{ES \cdot ABSSQ(J)} & \left\{ \frac{-FZF \cdot NUS}{\pi} + 2 \cdot ES \right. \\ & \cdot ASI(NR,J) + 2 \cdot BSSQ(J) \cdot SRR(2,J) - SRR(1,J)[BSSQ(J) \\ & \left. \cdot (1 + NUS) + ASSQ(J) \cdot (1 - NUS)] \right\} \end{aligned}$$

d. Calculate $b_c + u_r(b_c)$

$$\begin{aligned} XBC(J) = BC(J) + BC(J) \cdot & \left\{ \frac{-NUC \cdot FZC}{EC(J) \cdot \pi \cdot ABCSQ(J)} \right. \\ & + AE \cdot T(NE,J) + [SRR(4,J) \cdot \{BCSQ(J)(1 - NUC) \\ & + ACSQ(J)(1 + NUC)\} - 2 \cdot ACSQ(J) \cdot SRR(3,J)] / \\ & \left. [EC(J) \cdot ABCSQ(J)] \right\} \end{aligned}$$

Return to DEFORM

End subroutine BOUND(J)

APPENDIX D

Detailed Equations for Fuel Dynamics Module

Subroutine FULDYN replaces TSHTR and DEFORM subroutines when the centerline temperature reaches an input value or when either the clad or fuel surface temperature reaches melting. FULDYN uses an internal time step of $50 \mu\text{sec}$. The subroutine is slightly unstable and will be replaced in the near future. The user is cautioned not to rely on the results.

a. Change pressure units from dynes/cm² to gm/cm² (for this subroutine only)

Do to 100, for J = 1 to MZ

$$(100) \quad \text{PFUEL}(J) = \frac{\text{PFUEL}(J)}{980.0}$$

$$\text{DTI} = 5 \times 10^{-5}$$

If KPOW = 1 then go to 300 (initialization)

If KPOW = 2 then go to 400 (restart calculation)

If KPOW = 3 then go to 200 (standard first calculation)

b. First calculation, set up restart values

$$(200) \quad \text{ISTPRS} = \text{ISTOP}$$

Do to 220, for J = 1 to MZ

$$\text{RSH1}(J) = \text{H1}(J)$$

$$\text{RSH2}(J) = \text{H2}(J)$$

$$\text{RSH3}(J) = \text{H3}(J)$$

$$\text{RSZ2}(J) = \text{Z2}(J)$$

$$\text{RSDQ}(J) = \text{DQ}(J)$$

$$\text{RSA}(J) = \text{A}(J)$$

$$\text{RSR}(J) = \text{R}(\text{NR}, J)$$

$$\text{T20}(1, J) = \text{TBAR}(J)$$

$$\text{T20}(\text{NT}, J) = \text{T}(\text{NT}, J)$$

$$\text{T20}(\text{NE}, J) = \text{T}(\text{NE}, J)$$

$$\text{RSPF}(J) = \text{PFUEL}(J)$$

$$\text{MOTRS}(J) = \text{MOTION}(J)$$

$$\text{RSSIG}(J) = \text{SIGRR}(J)$$

Pick up coolant temperatures and heat-transfer coefficients

CALL INTERP (TCOOL,ZCOOL,MZC,Z2(J),T(NC,J))

CALL INTERP (HCOOL,ZCOOL,MZC,Z2(J),H(J))

(220) continue loop

DT3 = DT1

RSPINT = PINTG2

go to 430

c. Initialization entrance

Initialize counters, error stops, and base pressure

(300) PINTG2 = PINTGO

IQUIK = 0

ISTOP = 0

ISTPRS = 0

DTBASE = DT1

$PO = \frac{PX}{980.0} \cdot 10^6$

MZ10 = MZ - MZUB

MZ11 = MZ10 + 1

MZ1 = MZLB + 1

MZ2 = MZ1 + 1

Compute mass of upper blanket

FUELM = 0.0

Do to 310, for J = MZ11 to MZ

FUELM = FUELM + FUELMS(J)

(310) continue loop

Initialize mesh and movement variables

Do to 320, for J = 1 to MZ

A(J) = 0.0

MZ12(J) = 0

MOTION(J) = -1

RO(J) = AC(J)

```

      DQ(J) = 0.0
      FS(J) = FS(J) / 980.0
      Z2(J) = ZFM(J)
      H1(J) = ZFI(J+1)
      H0(J) = ZFIO(J+1)
      H2(J) = H1(J)
      H3(J) = H1(J)
      ZP3(J) = (H1(J))
      DCO(J) = DC(J)
(320)  continue loop

      Initialize core movement and averaging variables
      THETA1 = 0.5
      THETA2 = 1.0 - THETA1
      IPASS = 1
      ZZTO = ZFI(MZN) - ZFIO(MZN)
      PFUEL(MZ11) = PO +  $\frac{ZZTO \cdot SPRINK}{\pi RO(MZ)^2}$ 
      DELHT = HZ(MZ10) - HO(MZ10)
      ZZT = ZFI(MZ11)
      Do to 340, for J = 1 to MZ

      Initialize strength, elasticity, pressure radius, and density
      STRENT(J) =  $\frac{YELDPT(T(NE,J))}{980.0}$ 
      ELAST(J) = YOUNG(T(NE,J)) *  $\frac{DC(J)}{980.0}$ 
      DELROR =  $\frac{[PFUEL(J) - PO] \cdot RO(J) \cdot [1 - NUC/2.0]}{ELAST(J)}$ 
               + AE * [T(NE,J) - TFO(NE,J)]
      R(NR,J) = RO(J) * (1 + DELROR)
      V(J) =  $\pi \cdot R(NR,J)^2 \cdot [H1(J) - ZFI(J)]$ 
      RHOAVG = FUELMS(J)/V(J)

```

Initialize energy, temperature volume, clad thickness,
and stress

$$CC1(J) = \frac{CC2}{RHOAVG(J)} - TBAR(J)$$

$$UO(J) = ULQTAB(TBAR(J))$$

$$DC(J) = \frac{RO(J) \cdot DCO(J)}{R(NR,J)}$$

$$SIGRR(J) = [PFUEL(J) \cdot PO] \cdot \frac{R(NR,J)}{DC(J)}$$

Check on rupture

If $SIGRR(J) \leq STRENT(J)$ and $T(NE,J) \leq TME$ and $T(NT,J) \leq TMF$
then go to 340

Rupture

ISTOP = 1

DC(J) = 0.0

(340) continue loop

DT3 = DT1

If ISTOP = 1 then go to 2550

go to 1840

Restart calculation, reset mesh, temperatures, and counters

(400) ICOUNT = 1

PINTG2 = RSPINT

ISTOP = ISTPRS

Do to 420, for J = 1 to MZ

H1(J) = RSH1(J)

H2(J) = RSH2(J)

H3(J) = RSH3(J)

Z2(J) = RSZ2(J)

DQ(J) = RSDQ(J)

A(J) = RSA(J)

R(NR,J) = RSR(J)

TBAR(J) = T20(1,J)

T(NE,J) = T20(NE,J)

$T(NT,J) = T20(NT,J)$

$PFUEL(J) = RSPF(J)$

$MOTION(J) = MOTRS(J)$

$SIGRR(J) = RSSIG(J)$

$ELAST(J) = \frac{YOUNG(T(NE,J))}{980.0} \cdot DCO(J) \cdot \frac{RO(J)}{R(NR,J)}$

Compute shock-loading strength

$STRENT(J) = \frac{VELDPT(T(NE,J))}{980.0} \cdot 2.0$

(420) continue loop

(430) If ISTOP = 1, then go to 2250

Set up loops for energy over the time step

$DT3 = DT1$

Break time step into milliseconds

$DTA = DT \cdot 1000.0$

Break into sets of 250 μ sec

$IDTA = DTA \cdot 4$

If $DTA \leq 0.5$ then $IDTA = 1$

Compute actual size of sets

$DTB = DT/IDTA$

Compute average energy release per set

$PINTGA = \frac{PINTG - PINTGO}{IDTA}$

Set up 250- μ sec loop

$PINTG = PINTGO$

Do to 2500, for JABC = 1 to 2 $\cdot$ IDTA for each odd integer

$PINTG = PINTG + \frac{JABC \cdot PINTGA}{IDTA}$

Associated energy with each set with energy addition increasing through the time step

$DT1 = DTBASE$

(500) IPASS = 1

Set up inner 50- μ sec loop

$$\text{NUMDT} = \frac{\text{DTB}}{\text{DT1}}$$

ICOUNT = 1

Compute size of last time step

DT2 = DTB - NUMDT · DT1

If DT2 > 10⁻⁸ then go to 520

DT2 = DT1

If NUMDT = 0. then go to 2550

NUMDT = NUMDT - 1

(520) continue

Set up average energy per inner step

PINTG1 = PINTG2

$$\text{DQ3} = (\text{PINTG} - \text{PINTG1}) \frac{\text{DTB}}{\text{DT1}}$$

$$\text{DQ4} = (\text{PINTG} - \text{PINTG1}) \frac{\text{DTB}}{\text{DT2}}$$

PINTG2 = PINTG

Check on rupture

If ISTOP = 1 then go to 2240

d. Start of Calculations and Inner Loop

(600) If NUMDT + 1 - ICOUNT < 0 then go to 2300

If NUMDT + 1 - ICOUNT = 0 then go to 620

If NUMDT + 1 - ICOUNT > 0 then go to 640

Last inner loop

(620) JCHECK = 0

Go to 660

Normal loop

(640) JCHECK = 1

(660) continue loop

Reset height matrix

H2(MZ1) = H3(MZ1)

$$Z2(MZ1) = \frac{H3(MZ1) + ZFI(MZ1)}{2.0}$$

Do to 720, for J = MZ2 to MZ10

$$H2(J) = H3(J)$$

$$Z2(J) = \frac{H3(J) + H3(J - 1)}{2.0}$$

(720) continue loop

$$ZGAS1 = H2(MZ10) - ZZT + ZZTO$$

If IPASS = 2, then go to 1300

e. Update axial height matrix

Do to 920 for J = MZ1 to MZ10

$$H1(J) = ZP3(J)$$

$$ZP3(J) = H3(J)$$

Check on rupture

If SIGRR(J) ≤ STRENT(J) and T(NE,J) ≤ TME
and T(NT,J) < TMF then go to 920

Rupture

$$ISTOP = 1$$

$$DC(J) = 0.0$$

(920) continue loop

(940) If ISTOP = 1 then go to 2200

f. Add HEAT to fuel, neglecting transfer to coolant

If JCHECK = 1 then go to 1120

$$(1100) \quad DT1 = DT2$$

$$(1120) \quad ICOUNT = ICOUNT + 1$$

(1200) Do to 1280, for J = 1 to MZ

If NUMDT + 1 = ICOUNT then DQ3 = DQ4

$$DQ1 = DQ(J)$$

$$DQ(J) = DQ(J) + \frac{DQ3 \cdot PSHAPE(J) \cdot POW}{FUELMS(J)}$$

$$UZ = DQ(J) + UO(J)$$

$$TBAR(J) = TLIQ(UZ)$$

$$T(NT,J) = T(NT,J) + \frac{DQ(J) - DQ1}{CPF(T(NT,J))}$$

$$DC(J) = \frac{RO(J) \cdot DCO(J)}{R(NR,J)}$$

g. Compute bond conductance

$$\text{If } R(NR,J) < R(NE,J) \text{ then HBOND} = \frac{HBPAR}{R(NE,J) - R(NR,J)}$$

$$\text{If HBOND} > HBMAX \text{ then HBOND} = HBMAX$$

$$\text{If } R(NR,J) = R(NE,J) \text{ then HBOND} = HBMAX + HBGRAD \cdot (PFUEL - PO)$$

Calculate clad temperature

$$T(NE \cdot J) = T(NE,J) + DT3 \cdot \{HBOND \cdot [T(NT,J) - T(NE,J)] - H(J) \cdot [T(NE,J) - T(NC,J)]\} / (DC(J) \cdot CROE)$$

Calculate modified elasticity

$$ELAST(J) = \frac{YOUNG(T(NE,J)) \cdot DC(J)}{980.0}$$

(1280) continue loop

Calculate plenum pressure

$$(1300) \quad PLENP = \frac{ZGAS1 \cdot SPRINK}{\pi RO(J)^2} + PO$$

$$PFUEL(MZ11) = PLENP$$

Do to 1575, for J = MZ1 to MZ10

Set up pressure and radius for new temperature

Actual volume

$$VREAL = \frac{TBAR(J) + CC1(J)}{CC2(J)} \cdot FUELMS(J)$$

If IPASS = 2 then go to 1320

h. Set up projections for pressure and radius

$$RP(J) = \left\{ \frac{VREAL}{2\pi [H2(J) - Z2(J)]} \right\}^{1/2}$$

$$XI = RO(J) \cdot \{1.0 + AE \cdot [T(NE,J) - TFO(NE,J)]\}$$

If $RP(J) < XI$ then $RP(J) = XI$

$$DELOR = \frac{RP(J)}{RO(J)} - 1.0$$

$$PP3(J) = \frac{\{DELOR - AE \cdot [T(NE,J) - TFO(NE,3)]\} \cdot ELAST(J)}{RO(J) \cdot (1 - NUC/2)} + PO$$

If $PP3(J) \leq PO$ then $PP3(J) = PO$

$$PFUEL(J) = PP3(J)$$

$$R(NR,J) = RP(J)$$

go to 1575

Set up actual pressure and radius

$$(1320) \quad RREAL = \frac{VREAL}{2\pi[H2(J) - Z2(J)]}$$

$$ISET = 0$$

$$XI = RO(J) \cdot \{1.0 + AE \cdot [T(NE,J) - TFO(NE,J)]\}$$

If $RREAL \geq XI$ then go to 1340

Set up for fuel collapse

$$ISET = 1$$

$$RREAL = XI$$

(1340) continue

$$R(NR,J) = RREAL$$

$$DELOR = \frac{R(NR,J)}{RO(J)} - 1.0$$

Compute pressure

$$PFUEL(J) = \frac{\{DELOR - AE \cdot [T(NE,J) - TFO(NE,J)]\} \cdot ELAST(J)}{RO(J) \cdot (1 - NUC/2)} + PO$$

If $PFUEL(J) \leq PO$ then $PFUEL(J) = PO$

Compute fuel vapor pressure

$$PSAT(J) = [TBAR(J) + 273.16]^{ACK1} \cdot \exp \left[ACK2 + \frac{ACK3}{TBAR(J) + 273.16} \right]$$

If $PSAT(J) \leq PFUEL(J)$ then go to 1475

Vaporization

$$MZ12(J) = 1$$

```

Print ERROR
go to 2100
(1475) If ISET = 0 then go to 1575
      i. Adjust heights to maintain fuel-clad contact at constant height
           Reset flag
           ISET = 0
           If J  $\neq$  1 then go to 1500
            $Z21 = ZFI(J) + \frac{VREAL}{\pi R(NR,J)^2}$ 
           go to 1520
(1500)  $Z21 = H2(J - 1) + \frac{VREAL}{\pi R(NR,J)^2}$ 
(1520) continue
           Compute difference between actual height and computer value
            $DELTA1 = H2(J) - Z21$ 
            $KL = J$ 
           If  $KL > 1$  then go to 1530
            $H2(J) = Z21$ 
            $Z2(J) = \frac{ZFI(J) + H2(J)}{2}$ 
            $KL = J + 1$ 
(1530) Do to 1540, for L = KL to MZ10
            $H2(L) = H2(L) - DELTA1$ 
            $Z2(L) = \frac{H2(L) + H2(L - 1)}{2.0}$ 
(1540) continue loop
(1575) continue loop
           If IPASS = 1 then go to 1840
           Compute stress and strength
           Do to 1700, for J = MZ1 to MZ10
            $DC(J) = DCO(J) \cdot \frac{RO(J)}{R(NR,J)}$ 

```

$$\text{SIGRR}(J) = [\text{PFUEL}(J) - \text{PO}] \cdot \frac{\text{R}(\text{NR}, J)}{\text{DC}(J)}$$

$$\text{STRENT}(J) = \frac{\text{YELDPT}(\text{T}(\text{NE}, J))}{980.0} \cdot 2.0$$

(1700) continue loop

j. Average pressure and radius with projection to decrease instability

Do to 1820, for J = MZ1 to MZ10

$$\text{PFUEL}(J) = \text{THETA1} \cdot \text{PFUEL}(J) + \text{THETA2} \cdot \text{PP3}(J)$$

$$\text{R}(\text{NR}, J) = \text{THETA1} \cdot \text{R}(\text{NR}, J) + \text{THETA2} \cdot \text{RP}(J)$$

(1820) continue loop

(1840) Do to 1880, for J = MZ1 to MZ10

Compute clad radius, dynamic friction, and mass per unit area

$$\text{R}(\text{NE}, J) = \text{R}(\text{NR}, J)$$

If J = MZ10 then go to 1860

$$\text{DELZL}(J) = \frac{\text{FUELMS}(J)}{\pi \text{R}(\text{NR}, J)^2}$$

$$\text{PFRIK}(J) = \text{FF} \cdot \frac{\text{H1}(J) + \text{H1}(J+1) - \text{H3}(J) - \text{H3}(J+1)}{2.0 \cdot (\text{DT3} + \text{DT1})}$$

go to 1880

(1860)
$$\text{DELZL}(J) = \frac{\text{FUELM} + \text{FUELMS}(J)}{\pi \text{R}(\text{NR}, J)^2}$$

$$\text{PFRIK}(J) = \text{FF} \cdot \frac{\text{H1}(J) - \text{H3}(J)}{\text{DT3} + \text{DT1}}$$

(1880) continue loop

Acceleration and movement

Do to 1960, for J = MZ1 to MZ10

If MOTION(J) $\neq$ -1 then go to 1900

Check on pressure exceeding stiction

If $|\text{PFUEL}(J) + \text{PFRIK}(J) - \text{PFUEL}(J+1)| \leq \text{FS}(J)$ then go to 1960

(1900) If J = MZ10 then go to 1920

Compute acceleration

$$A(J) = \frac{PFUEL(J) + PFRIK(J) - PFUEL(J+1)}{DELZL(J) + DELZL(J+1)} \cdot 2.0 \cdot 980.0$$

go to 1940

$$(1920) \quad A(J) = \frac{P(FUEL(J) + PFRIK(J) - PFUEL(J+1))}{DELZL(J)} \cdot 980.0$$

Update motion counter

(1940) If IPASS = 2 then MOTION(J) = MOTION(J) + 1

(1960) continue loop

Compute axial mesh

Do to 2060, for J = MZ1 to MZ10

If MOTION(J) < 0 then go to 2000

If MOTION(J) = 0 then go to 2020

If MOTION(J) > 0 then go to 2040

No movement

(2000) H3(J) = ZP3(J)

Go to 2060

Initial movement

(2020) H3(J) = ZP3(J) + $\frac{1}{2}A(J) \cdot DT1^2$

Go to 2060

Full movement

(2040) $H3(J) = ZP3(J) + DT3 \cdot \left[A(J) \cdot \frac{DT1 + DT3}{2.0} + \frac{ZP3 - H1(J)}{DT1} \right]$

(2060) Continue loop

If KPOW = 1 then go to 2550

Set up pass counter

IPASS = 3 - IPASS

If IPASS = 2 then go to 660

Go to 600

k. End of main-loop calculations

(2100) Set error stop

IERROR = 1

Go to 2550

(2200) Determine time of clad rupture
 If ICOUNT $\neq$ NUMDT + 1 then go to 2220
 End of innermost loop
 Go to 2300
 Rupture before end of innermost loop
 Determine energy and time left in step

(2220) $TIMEL = (NUMDT - ICOUNT) \cdot DT1 + DT2$
 $DELQ = (PINTG - PINTG1) \cdot \frac{TIMEL}{DTB}$
 $DT3 = TIMEL$
 Go to 2260

(2240) Rupture in previous internal time step, not done with outer loop
 $DT3 = DTB$
 $IQUIK = 1$
 $DELQ = PINTG - PINTG1$
 Go to 2260

(2250) Rupture in previous outer time step
 $DT3 = DT$
 $IQUIK = 2$
 $DELQ = PINTG - PINTGO$
 Add energy

(2260) Do to 2290, for J = 1 to MZ
 $DELQ1 = DELQ \cdot POW \cdot \frac{DSHAPE(J)}{FUELMS(J)}$
 $TBAR(J) = TBAR(J) + \frac{DELQ1}{CPF(TBAR(J))}$
 $T(NT,J) = T(NT,J) + \frac{DELQ1}{CPF(T(NT,J))}$
 Check for nodal rupture
 If $DC(J) = 0.0$ then go to 2290
 Compute bond conductance
 If $R(NR,J) < R(NE,J)$ then $HBOND = \frac{HBPAR}{R(NE,J) - R(NR,J)}$

If HBOND > HBMAX then HBOND = HBMAX

If R(NR,J) = R(NE,J) then HBOND = HBMAX + HBGRAD
 · [PFUEL(J) - PO]

Compute clad temperature

T(NE,J) = T(NE,J) + DT3

$$\left\{ \frac{\text{HBOND} \cdot [T(\text{NT},J) - T(\text{NE},J)] + H(J) \cdot [T(\text{NC},J) - T(\text{NE},J)]}{\text{DC}(J) \cdot \text{CROE}} \right\}$$

(2290) Continue loop

(2300) Continue loop

If IQUIK > 1 then go to 2550

1. Heating for upper and lower blankets (if any)

(2320) If MZUB = 0 then go to 2410

Do to 2400, for J = MZ11 to MZ

ZFI(J+1) = ZFI(J+1) + H2(MZ10) - ZFI(MZ10 + 1)

(2400) $ZFM(J) = \frac{ZFI(J) + ZFI(J+1)}{2}$

(2410) Do to 2420, for J = MZ1 to MZ10

ZFM(J) = Z2(J)

(2420) ZFI(J+1) = H2(J)

(2500) Continue loop

(2550) Do to 2600, for J = 1 to MZ

PFUEL(J) = PFUEL(J) + 980.0

(2600) Continue loop

Return to TSDRIV

End subroutine FULDYN

APPENDIX E

Detailed Equations for Point Kinetics Module

1. Subroutine SSPK calculates initial delayed-neutron-precursor concentrations based on the normalized initial power of 1.0.

PHI = 1

If POWER > 0, then return to SSDRIV

EPSI = 0.1 · EPSPHI

Do to 1, for I = 1 to 5

XI = I

$$(1) \quad AO(I) = \frac{1}{XI}$$

Do to 2, for I = 1 to NDELAY

$$BETA(I) = \frac{BETA(I)}{EL}$$

$$C(I) = \frac{BETA(I)}{ALAM(I)}$$

$$(2) \quad CO(I) = C(I)$$

PHIP = PHI

Return to SSDRIV

End subroutine SSPK

2. Subroutine TSPK calculates neutron-flux level, delayed-neutron-precursor concentrations, and feedback reactivities (via subroutines COOLFB and FUELFB) from steady state up to the initiation of the weak-explosion calculations.

a. Check to see if power versus time option is specified.

If IPOWER > 0, then go to 42

If DTP = DT and TIME ≠ 0 then go to 35

b. Calculation of internal time steps and other constants over an external time step (e.g., powers of functions of $\lambda_l \cdot DT$ such as

$\left(\frac{\lambda_l \cdot DT}{2^n}\right)^m$ needed in the Kaganove point kinetics solution).

TEX = 0.125 · DT

Do to 9, for J = 1 to 8

```

      T(J,1) = TEX
      Do to 1, for I = 2 to 5
(1)      T(J,I) = T(J,J - 1) · TEX
      Do to 8, for K = 1 to NDELAY
      Do to 2, for I = 1 to 5
(2)      O(J,K,I) = 0
      X = ALAM(K) · T(J,1)
      If |X| < 1, then go to 4
      
$$RX = \frac{1}{ALAM(K)}$$

      O(J,K,1) = 1.0 - RX · e-X
      Do to 3, for JJ = 2 to 5
      XI = JJ
(3)      O(J,K,JJ) = RX · {[T(J,JJ - 1) - XI - 1.0]} · O(J,K,JJ - 1)}
      Go to 8
(4)      SUM = AO(5) · T(J,5)
      EPS3 = SUM · 1 x 10-20
      FJ2 = 6
      TERM = SUM
(5)      TERM = -X · TERM/FJ2
      If |TERM| ≤ EPS3 then go to 6
      SUM = SUM + TERM
      FJ2 = FJ2 + 1.0
      Go to 5
(6)      O(J,K,5) = SUM
      Do to 7, for JJ = 2 to 5
      I2 = 6 - JJ
(7)      O(J,K,I2) = [T(J,I2) - ALAM(K) · O(J,K,I2 + 1)] · AO(I2)
(8)      continue loop
(9)      TEX = 0.5 · TEX
(35)     If KPOW = 1, then go to 10
      If KPOW = 2, then go to 28
      If KPOW = 3, then go to 40

```

c. Initialization of parameters (first time TSPK is entered).

```

(10)  PINTG = 0
      PINTGO = 0
      REABOI = 0
      KI8 = 1
      IBOIL = 0
      IREAS = 1
      IREA = 0
      READOP = 0
      READPP = 0
      READEN = 0
      READNP = 0
      REASTR = 0
      REASCM = 0
      Do to 11, for J = 1 to 4
      REACOL(J) = 0
(11)  BOILTI(J) = 0
      DTP = DT
      KI1 = 1
      BETAS =  $\frac{\text{BETAS}}{\text{EL}}$ 
      REAPRG = PREA(TIME+DT) * BETAS
          Reactivity change assumed linear for first time step.
      VREAT(3) = REAPRG
      VREAT(2) = 0
(13)  VREAT(1) = -VREAT(3)
(14)  J3 = 1
      SUMN = 0
      ERROR = 0
      DTIME = 0
      J4 = 0
      IPHI = 0

```

Parabolic fitting of reactivity

Call FITZ(REAT,VREAT,DT,DTP)

REAJ = REAT(1)

d. Main routine

(15) SUMCD = 0

IPHI = IPHI + 1

Subtime step

DT2 = T(J3,1)

Do to 16, for I = 1 to NDELAY

$C_i \lambda_i$ product:

CLAM(I) = C(I) · ALAM(I)

$\dot{C}_i$ calculation

CDOT(I) = BETA(I) · PHI - CLAM(I)

$\Sigma \dot{C}_i$ calculation

(16) SUMCD = SUMCD + CDOT(I)

Do to 19, for J5 = 1 to 3

J2 = J3 - 1 + J5

SUMCI = 0

e. Kaganove solution.

Do to 17, for I = 1 to 3

SUMREA(I) = AO(I) · T(J2,I) · REAJ + AO(I+1) · T(J2,I+1)
 · [REAT(2) + 2 · REAT(3) · DTIME] + AO(I+2)
 · T(J2,I+2) · REAT(3)

(17) SUMB(J5,I) = 0

Do to 18, for I = 1 to NDELAY

CBURN(J4,I) = CLAM(I) · O(J2,I,1)

SUMCI = SUMCI + CBURN(J5,I)

Do to 18, for I1 to 3

BINT(J5,I1,I) = BETA(I) · O(J2,I,I1)

SUMB(J5,I1) = SUMB(J5,I1) + BINT(J5,I1,I)

```

(18)      continue loop
           AQQ(J5,1) + T(J2,1) - SUMREA(2) + SUMB(J5,2)
           AQQ(J5,2) = T(J2,2) - SUMREA(3) + SUMB(J5,3)
           AQQ(J5,3) = PHI * [SUMREA(1) - SUMB(J5,1)] + SUMCI

(19)      continue loop
           Do to 20, for J5 = 2,3
           J2 = J5 - 1
           DEQ(1) = AQQ(J2,3) * AQQ(J5,2) - AQQ(J2,2) * AQQ(J5,3)
           DEQ(2) = AQQ(J2,1) * AQQ(J5,3) - AQQ(J2,3) * AQQ(J5,1)
           DEQ(3) = AQQ(J2,1) * AQQ(J5,2) - AQQ(J2,2) * AQQ(J5,1)

           EN(J2,1) =  $\frac{DEQ(1)}{DEQ(3)}$ 
           EN(J2,2) =  $\frac{DEQ(2)}{DEQ(3)}$ 
           EN(J2,3) = PHI * DT2 * [EN(J2,1) + DT2 * EN(J2,2)]
                     (n at end of subtime step)

(20)      continue loop

f.      Flux convergence

           EPSILN =  $1 - \frac{EN(1,3)}{EN(2,3)}$ 

           If |EPSILN| > EPSPHI then go to 21
           J4 = J4 + 2(6-J3) (integer subtime step counter, avoids round
                           off in adding subtime steps)

           If |EPSILN| - EPSI < 0 then go to 22
           If |EPSILN| - EPSI = 0 then go to 23
           If |EPSILN| - EPSI > 0 then go to 23

(21)      Halve time step and recalculate

           J3 = J3 + 1
           If J3 < 6 then go to 15
           J3 = 6
           J4 = J4 + 1
           go to 23

           Double time step (no recalculation)

```

(22) J3 = J3 - 1

If J3 > 0 then go to 23

J3 = 1

Bring precursors and reactivity up to end of subtime step

(23) DTIME = DTIME + DT2

ERROR = ERROR + EPSILN

REAJ = REAT(1) + DTIME · [REAT(2) + DTIME · REAT(3)]

Evaluation of the integral of PHI

$$\text{SUMN} = \text{SUMN} + \text{DT2} \cdot \left\{ \text{PHI} + \text{DT2} \cdot \left[\frac{\text{EN}(1,1)}{2} + \text{DT2} \cdot \frac{\text{EN}(1,2)}{3} \right] \right\}$$

PHI = EN(1,3)

Do to 24, for I = 1 to NDELAY

(24) C(I) = C(I) - CBURN(1,I) + PHI · BINT(1,1,I) + EN(1,1) · BINT(1,2,I) + EN(1,2) · BINT(1,3,I)

Check for end of full time step (DT)

(25) PRINT 1006

IERROR = 1

Return to TSDRIV

New subtime step, check so that new subtime will exceed DT.

(26) DT2 = T(J3,1)

If $2^{(6-J3)} - 256 \leq 0$ then go to 15

J3 = J3 + 1

If J3 ≤ 6 then go to 26

J3 = J3 - 1

Average PHI

(27)
$$\text{QMULT} = \frac{\text{SUMN}}{\text{DT}}$$

Reactivity not yet converged

KPOW = 2

Call SHAPE(QMULT)

Total integral of PHI since time zero

PINTG = PINTGO + SUMN

Return to TSDRIV

End of main routine

g. Reactivity interaction

(28) If TIME = 0 call COOLFB(REACOL)

Call FUELFB

REAPRG = PREA(TIME + DT) · BETAS

If KSCRAM > 1, then

REASCM = $\frac{\text{SCRAM}(\text{SCRTIM} + \text{DT})}{\text{EL}}$

Reactivity at end of DT from last iteration

If |READOP| ≤ 1 × 10⁻¹⁰ then READOP = 0

If |READIN| ≤ 1 × 10⁻¹⁰ then READIN = 0

VREAT(3) = REAPRG + READEN + READOP + REASTR
+ REASCM + REACOL(1) + REACOL(2)
+ REACOL(3) + REACOL(4)

Reactivity convergence

EPSLON = XI - VREAT(3)

If XI ≠ 0 then EPSLON = $\frac{\text{EPSLON}}{\text{XI}}$

If |EPSLON| < EPSREA then go to 31

Check on reactivity-iteration count.

IREA = IREA + 1

If IREA > 30 then go to 30

Reset PHI and C_i's for iteration

PHI = PHIP

Do to 29, for I = 1 to NDELAY

(29) C(I) = CO(I)

Check for first time step

If KI1 < 0 then go to 13

If KI1 = 0 then go to 14

(30) Print VREAT(3), XI

IERROR = 1

Return to TSDRIV

Reactivity converged, check for coolant boiling

(31) If KBOIL = 0 then go to 33

Do to 32, for I = 1 to IBOIL

Time since boiling for three secondary channels.

(32) BOILTI(I) = BOILTI(I) + DT

Time since first channel boiled, shift reactivity values for next time step.

(33) STIME(IREAS) = BOILTI(1)

PINTGO = PINTGO + SUMN

IREA = 0

If KBOIL < 0 then go to 39

If KBOIL = 0 then go to 36

(36) If K18 < 0, then go to 37

If K18 = 0, then go to 38

Store integral of PHI from boiling initiation.

(37) PHIBOI = PINTGO

IBOIL = 1

K18 = 2

(38) If IBOIL ≥ 4 then go to 39

If $PINTGO < \frac{PHIBOI}{PFAC(IBOIL)}$ then go to 39

Trigger secondary channels

IBOIL = IBOIL + 1

go to 38

Parabolic extrapolation of PHI for next time step

(39) DEQ(1) = PHIP

DEQ(2) = QMULT

DEQ(3) = PHI

$XI = \frac{DT}{2}$

Call FITZ(CDOT,DEQ,XI,XI)

QMULT = CDOT(1) + DT * [CDOT(2) + DT * CDOT(3)]

Reactivity has converged, new time step

KPOW = 3

DTP = DT

Call SHAPE(QMULT)

PINTG = PINTGO + QMULT * DT

Return to TSDRIV

New time step

(40) Call COOLFB(REACOL)

Shift reactivity values for next time step

VREAT(1) = VREAT(2)

VREAT(2) = VREAT(3)

READPP = READOP

READNP = READEN

Call FUELFB

REAPRG = PREA(TIME + DT) * BETAS

If KSCRAM > 1 then

REASCM = $\frac{\text{SCRAM}(\text{SCRTIM} + \text{DT})}{\text{EL}}$

If $|\text{READOP}| \leq 1 \times 10^{-10}$, then READOP = 0

If $|\text{READEN}| \leq 1 \times 10^{-10}$, then READEN = 0

Total reactivity resulting from extrapolation (below statement 39 above).

VREAT(3) = REAPRG + READEN + READOP + REASTR
+ REASCM + REACOL(1) + REACOL(2)
+ REACOL(3) + REACOL(4)

Store PHI and C_i for reactivity iteration.

PHIP = PHI

Do to 41, for I = 1 to NDELAY

(41) CO(I) = C(I)

KI1 = 2

go to 14

h. Power specified as a function of time option.

(42) If KPOW = 1, then go to 43

If KPOW = 2, then go to 44

If KPOW = 3, then go to 45

(43) PINTG = 0

PINTGO = 0

go to 45

(44) If DTP $\neq$ DT then go to 45

KPOW = 3

DTP = DT

Return to TSDRIV

(45) PHI = PREA(TIME+DT)

Use beginning, middle and end of DT.

$$QMULT = \frac{PREA(TIME) + PREA\left(TIME + \frac{DT}{2}\right) + PHI}{3}$$

If KPOW = 3, then PINTGO = PINTG

PINTG = PINTGO + QMULT · DT

KPOW = 2

Call SHAPE(QMULT)

Return to TDRIV

End subroutine TSPK

APPENDIX F

Detailed Equations for Feedback Reactivity

1. Subroutine COOLFB calculates coolant and structural-expansion (radial, due to expansion of subassembly cans) reactivities during the transient solution up to calling the Weak Explosion Module.

a. Structural Reactivity

Do to 15, for J = 1 to MZ

Fractional expansion of structure

$$UBAR = ASTR \cdot [T2(NS, J) - TSTRESS(J)]$$

Check expansion relative to UMIN and UMAX.

If $UBAR \leq UMIN$, then REABAR = 0

If $UBAR > UMIN$ and $UBAR \leq UMAX$, then REABAR = STREA1 $\cdot$ (UBAR - UMIN)

If $UBAR > UMAX$ then REABAR = STREA1 $\cdot$ (UMAX - UMIN) + STREA2 $\cdot$ (UBAR - UMAX)

Multiply by weighing function

$$(15) \quad REASTR = REASTR + WSTR(J) \cdot REABAR$$

Divide by lifetime

$$REASTR = REASTR / EL$$

$$JCHECK = 0$$

$$REA = 0$$

$$JJ = 1$$

$$Z = 0$$

b. Coolant Reactivity

Calculate void fractions, put on axial heat-transfer mesh, and calculate void reactivity.

Do to 3, for J = 1 to MZ

$$ABAR = 0$$

$$NCOOL = 0$$

$$Z = Z + AXPFI(J)$$

If $JJ > MZC$, then go to 16

(2) If ZCOOL(JJ) > Z, then go to 1
 ABAR = ABAR + 1 - DAV2(JJ)/DAVSS(JJ)
 NCOOL = NCOOL + 1
 JJ = JJ + 1
 If JJ ≤ MZC, then go to 2
 SA(J) used to modify Doppler reactivity.

$$(1) \quad SA(J) = \frac{ABAR}{NCOOL}$$

(3) REA = REA + SA(J) · VOIREA(J)
 go to 17

(16) Do to 18, for JJ = J to MZ

(18) SA(JJ) = 0

$$(17) \quad REA = \frac{REA}{EL}$$

If $|REA| \leq 1 \times 10^{-10}$ then REA = 0

Return void reactivity for channel No. 1

REAC(1) = REA

Check for boiling

If KBOIL ≤ 1 then return to TSPK

Check for boiling initiation

If IREAS > 1 then go to 5

Store coolant-density reactivity at time of boiling initiation.

REABOI = REA

Store void reactivity at time of boiling initiation.

Do to 4, for J = 1 to MZ

(4) SABOIL(J) = SA(J)

Store two-phase reactivity as a function of time.

$$(5) \quad SREA(IREAS) = \frac{REA - REABOI}{4}$$

Return coolant reactivity for channel No. 1

REAC(1) = SREA(IREAS) · REABOI

If $|REAC(1)| \leq 1 \times 10^{-10}$ then REAC(1) = 0

Store coolant void as function of time

Do to 6, for J = 1 to MZ

$$SVOID(J, IREAS) = \frac{SA(J) - SABOIL(J)}{4}$$

(6) $SA(J) = SVOID(J, IREAS) + SABOIL(J)$

$$ICHECK = 2$$

Check for reactivity versus time storage having more than one value stored

If IREAS $\leq$ 1 then go to 11

- c. Linear interpolation for delayed boiling channels (gives reactivity and void fraction)

Do to 10, for JJ = 2 to IREAS

$$J = IREAS - JJ + 2$$

(7) If ICHECK > IBOIL then go to 11

If STIME(J - 1) $\leq$ BOILTI(ICHECK) and

STIME(J) $\geq$ BOILTI(ICHECK) then go to 8
go to 10

Return reactivity for channels Nos. 2, 3, 4

(8) REAC(ICHECK) =

$$\frac{[SREA(J) - SREA(J - 1)][BOILTI(ICHECK) - STIME(J - 1)]}{STIME(J) - STIME(J - 1)}$$

$$+ SREA(J - 1)$$

Do to 9, for J1 = 1 to MZ

(9) SA(J1) =

$$\frac{[SVOID(J1, J) - SVOID(J1, J - 1)] \cdot [BOILTI(ICHECK) - STIME(J - 1)]}{STIME(J) - STIME(J - 1)}$$

$$+ SA(J1)$$

$$ICHECK = ICHECK + 1$$

Check for all 4 channels boiling

If ICHECK > 5, then JCHECK = J - 1

go to 7

(10) continue

(11) IREAS = IREAS + 1

If all 4 channels are boiling, stored values for times earlier than the boiling time of channel No. 4 are no longer needed.

If JCHECK $\leq$ 0, then go to 13
 IREAS = IREAS - JCHECK
 Do to 12, for J = 1 to IREAS
 STIME(J) = STIME(J + JCHECK)
 Do to 14, for JJ = 1 to MZ
 SVOID(JJ, J) = SVOID(JJ, J + JCHECK)
 (14) continue loop
 (12) SREA(J) = SREA(J + JCHECK)
 Check for storage overflow
 (13) If IREAS $\leq$ 400 then RETURN to TSPK
 IERROR = 1
 Return to TSPK
 End Subroutine COOLFB

2. Subroutine FUELFB calculates Doppler and fuel-density reactivities from steady state up to the time the Weak Explosion Module is called.

a. Fuel-density Reactivity

 Reactivity due to linear change in fuel density
 Do to 1, for J = 1 to MZ

$$\text{READEN} = \frac{\text{READEN} - \text{AVGMAT}(J) \cdot [1 - \text{ZFIO}(J+1) + \text{ZFIO}(J)]}{\text{ZFI}(J+1) - \text{ZFI}(J)}$$

b. Doppler Reactivity

$$\text{READOP} = \text{READOP} + [1 - \text{BDOP} \cdot \text{SA}(J)] \cdot \text{WDOP}(J) \left[\frac{\text{TBAR}(J) + 273.16}{\text{TREF}(J) + 273.16} \right]$$

 (1) continue

$$\text{READEN} = \frac{\text{READEN}}{\text{EL}}$$

$$\text{READOP} = \frac{\text{READOP} \cdot \text{ADOP}}{\text{EL}}$$

 Return to TSPK
 End Subroutine FUELFB

APPENDIX G

Detailed Equations for Weak Explosion Module

1. Subroutine XPLODE (Weak-explosion Driver) calculates power level, integrated power, fuel temperature, and pressure, as well as material motion and Doppler-feedback reactivities during reactor disassembly.

a. Set up axial and radial space mesh

```

Do to 5, for L = 1 to 9
(5)  PRNTRE(L) = 0.0
      NPASS = 1
      Do to 330, for N = 1 to NOREG
      RDIF = ROUTS(N) - RINS(N)
      RDIF1 =  $\frac{RDIF}{3}$ 
      ZDIF1 =  $\frac{ZUPS(N) - ZDNS(N)}{2}$ 
      RIN(1) = RINS(N) +  $\frac{RDIF}{8}$ 
      RIN(2) = RINS(N) + RDIF1
      RIN(3) = RINS(N) + 2 * RDIF1
      RIN(4) = ROUTS(N) -  $\frac{RDIF}{8}$ 
      ZIN(3) = ZDNS(N) +  $\frac{ZDIF1}{5}$ 
      ZIN(2) = ZDNS(N) + ZDIF1
      ZIN(1) = ZUPS(N) -  $\frac{ZDIF1}{5}$ 
      ZUP = ZUPS(N)
      ZDN = ZDNS(N)
      RINB = RINS(N)
      ROUT = ROUTS(N)
      DELZS(N) =  $\frac{ZUP - ZDN}{5}$ 
      DELRS(N) =  $\frac{ROUT - RINB}{4}$ 

```

Do to 10, for I = 1 to 5

XI = I

$$(10) \quad ZZ(I) = ZUP - (XI - 0.5) \cdot DELZS(N)$$

Do to 20, for J = 1 to 4

$$(20) \quad RR(J) = RINB + (XJ - 0.5) \cdot DELRS(N)$$

b. Power and material-worth distributions are set up in each region on a fixed-code-specified radial and axial mesh using linear interpolations of the input power and worth shapes. Since the calculation assumes axial and radial symmetry, only values for one quadrant are stored.

Do to 40, for I = 1 to 3

ZI = ZIN(I) + ZCENT

Call INTERP(PSHAPZ,POWZZ,MZS,ZI,PZI)

Do to 30, for J = 1 to 4

Call INTERP(PSHAPR,POWRR,NOPOWER,RIN(J),PRN)

Relative power at a node within a region

PWRA(I,J) = PZI + PRN

(30) continue loop

(40) continue loop

Calculation of the first fit of the axial values on a regional basis

(50) I = 1

Do to 60, for J = 1 to 4

$$PWRAC(I,J) = \frac{PWRA(I,J) - PWRA(I+2,J) - [PWRA(I,J) - PWRA(I+1,J)] \cdot [ZIN(I) - ZIN(I+2)]}{[ZIN(I) - ZIN(I+1)] \cdot [ZIN(I) - ZIN(I+2)] \cdot [ZIN(I+2) - ZIN(I+1)]}$$

$$PWRAB(I,J) = \frac{PWRA(I,J) - PWRA(I+1,J)}{ZIN(I) - ZIN(I+1)} - PWRAC(I,J) \cdot [ZIN(I) + ZIN(I+1)]$$

$$PWRAA(I,J) = PWRA(I,J) - [PWRAB(I,J) + ZIN(I) \cdot PWRAC(I,J)] \cdot ZIN(I)$$

(60) continue loop

K = 1

Calculate profiles for the region on new finer axial (ZZ) mesh

Do to 80, for I = 1 to 5


```

Do to 70, for J = 1 to 4
  PWRB(I,J) = PWRAA(K,J) + [PWRAB(K,J) + PWRAC(K,J) · ZZ(I)]
    · ZZ(I)
(70)   continue loop
(80)   continue loop

      Recalculate the radial profiles at the new axial points
Do to 90, for I = 1 to 5
  Do to 90, for J = 1 to 2
    PWRBC(I,J) =
      
$$\frac{PWRB(I,J) - PWRB(I,J+2) - [PWRB(I,J) - PWRB(I,J+1)]}{[RIN(J) - RIN(J+2)] \cdot [RIN(J+2) - RIN(J+1)]}$$

      
$$\cdot \frac{RIN(J) - RIN(J+2)}{RIN(J) - RIN(J+1)}$$

    PWRBB(I,J) = 
$$\frac{PWRB(I,J) - PWRB(I,J+1)}{RIN(J) - RIN(J+1)}$$

      - PWRBC(I,J) · [RIN(J) - RIN(J+1)]
    PWRBA(I,J) = PWRB(I,J) - [PWRBB(I,J) + PWRBC(I,J)
      · RIN(J)] · RIN(J)
(90)   continue

Do to 130, for J = 1 to 4
Do to 100, for K = 1 to 2
If RIN(K+2) > RR(J) then go to 110
(100)  continue

      K = 2

      Recalculate the radial profiles on the new radial (RR) mesh.
Do to 120, for I = 1 to 5
  PWR(I,J) = PWRBA(I,K) + [PWRBB(I,K) + RR(J) · PWRBC(I,K)
    · RR(J)]

      Calculate radial derivative of power shape
  DPOR(I,J) = PWRBB(I,K) + 2 · PWRBC(I,K) · RR(J)
(120)  continue loop

```

(130) continue loop

Recalculate the axial profiles on the ZZ axial mesh at the RR radial nodes.

Do to 140, for I = 1 to 3

Do to 140, for J = 1 to 4

PWRCC(I,J) = PWR(I,J) - PWR(I+2,J)

$$- \frac{[PWR(I,J) - PWR(I+1,J)] \cdot [ZZ(I) - ZZ(I+2)]}{[ZZ(I) - ZZ(I+2)] \cdot [ZZ(I+2) - ZZ(I+1)] \cdot [ZZ(I) - ZZ(I+1)]}$$

$$PWRCB(I,J) = \frac{PWR(I,J) - PWR(I+1,J)}{ZZ(I) - ZZ(I+1)} - PWRCC(I,J)$$

$$\cdot [ZZ(I) + ZZ(I+1)]$$

$$PWRCA(I,J) = PWR(I,J) - [PWRCB(I,J) + PWRCC(I,J) \cdot ZZ(I)] \cdot ZZ(I)$$

(140) continue loop

Do to 170, for I = 1 to 5

Do to 150, for K = 1 to 3

If ZZ(I) > ZZ(K+2) then go to 160

(150) continue

K = 3

Calculate axial derivative of power shape.

(160) Do to 170, for J = 1 to 4

$$DPDZ(I,J) = PWRCB(K,J) + 2 \cdot PWRCC(K,J) \cdot ZZ(I)$$

(170) continue

At this point we have all the power and/or material-worth shapes as well as the power gradient on the ZZ and RR mesh.

$$NPASSD = MOD(NPASS, 2)$$

Check for material worth or power calculation

If NPASSD = 0, then go to 200

Calculate radial power shape on upper surface of region N

Do to 180, for J = 1 to 4

$$PSUPS(J,N) = PWRCA(1,J) + [PWRCB(1,J) + PWRCC(1,J) \cdot ZUP] \cdot ZUP$$

Calculate radial power shape on lower surface of region N

$$\text{PSDNS}(J,N) = \text{PWRCA}(3,J) + [\text{PWRCB}(3,J) + \text{PWRCC}(3,J) \cdot \text{ZDN}] \cdot \text{ZDN}$$

(180) $\text{RRS}(J,N) = \text{RR}(J)$

Calculate axial power shape on inner surface of region N

Do to 190, for I = 1 to 5

$$\text{PSINS}(I,N) = \text{PWRBA}(I,1) + [\text{PWRBB}(I,1) + \text{PWRBC}(I,1) \cdot \text{RINB}] \cdot \text{RINB}$$

$$\text{PSOUTS}(I,N) = \text{PWRBA}(I,2) + [\text{PWRBB}(I,2) + \text{PWRBC}(I,2) \cdot \text{ROUT}] \cdot \text{ROUT}$$

(190) $\text{ZZS}(I,N) = \text{ZZ}(I)$

go to 230

(200) Do to 210, for J = 1 to 4

Calculate material-worth profile on upper surface of region N

$$\text{DSUPS}(J,N) = \text{PWRCB}(1,J) + \text{PWRCC}(1,J) \cdot [2 \cdot \text{ZUP} - \text{TH}(N)]$$

Calculate material-worth profile on lower surface of region N

(210) $\text{DSDNS}(J,N) = -\text{PWRCB}(3,J) - \text{PWRCC}(3,J) \cdot [2 \cdot \text{ZDN} + \text{TH}(N)]$

Do to 220, for I = 1 to 5

Calculate material-worth profile on inner surface of region N

$$\text{DSINS}(I,N) = -\text{PWRBB}(I,1) - \text{PWRBC}(I,1) \cdot [2 \cdot \text{RINB} + \text{TH}(N)]$$

Calculate material-worth profile on outer surface of region N

(220) $\text{DSOUTS}(I,N) = \text{PWRBB}(I,2) + \text{PWRBC}(I,2) \cdot [2 \cdot \text{ROUT} - \text{TH}(N)]$

go to 310

(230) continue

Do to 240, for I = 1 to 5

Do to 240, for J = 1 to 4

Store calculated values of power shape and power-shape gradients for region N.

$$\text{PWRS}(I,J,N) = \text{PWR}(I,J)$$

$$\text{DPDRS}(I,J,N) = \text{DPDR}(I,J)$$

$$\text{DPDZS}(I,J,N) = \text{DPDZ}(I,J)$$

(240) continue loop

$$\text{NPASS} = \text{NPASS} + 1$$

c. Set up material-worth distributions on code internal mesh by linear interpolation from input mesh. Use this as starting point for second pass through the foregoing loop to obtain material-worth curves on the ZZ, RR mesh.

```

      Do to 300, for L = 1 to 3
      If NOMR = 1 then go to 260
      Do to 250, for J = 1 to NOMR
      If ZIN(L) ≥ ZMAT(NOMR) then go to 260
      If ZIN(L) ≥ ZMAT(J) and ZIN(L) < ZMAT(J+1) then go to 270
(250)  continue loop
(260)  J = NOMR
(270)  continue loop
      Do to 290, for J1 = 1 to 4
      Do to 280, for LL = 1 to NOMATR
(280)  RMW(LL) = RMAT(LL,J)
      Call INTERP(RMW,RMAT,NOMATR,RIN(J1),PWRA(L,J1))
      If RIN(J1) ≥ RMAT(NDMATR) then PWRA(L,J1) = RMW(NOMATR)
      If NOMR = 1 then go to 290
      If ZIN(L) ≥ ZMAT(NOMR) then go to 290
      Do to 285, for LL = 1 to NOMATR
(285)  RMW(LL) = RMATW(LL,J+1)
      Call INTERP(RMW,RMAT,NOMATR,RIN(J1),PWRA2)
      If RIN(J1) ≥ RMAT(NOMATR) then PWRA2 = RMW(NOMATR)
      PWRA(L,J1) = 
$$\frac{[PWRA2 - PWRA(L,J1)] \cdot [ZIN(L) - ZMAT(J)]}{ZMAT(J+1) - ZMAT(J)}$$

      + PWRA(L,J1)
(290)  continue loop
(300)  continue loop
      go to 50

```

Store calculated values of material worth and material-worth gradients for region N

```

(310)  Do to 320, for I = 1 to 5
      Do to 320, for J = 1 to 4

```

```

DPWRS(I,J,N) = PWR(I,J)
DDDZ(I,J,N) = DPDZ(I,J)
(320)  DDDR(I,J,N) = DPDR(I,J)
NPASS = NPASS + 1
(330)  continue loop (return and do next region)

```

d. Integration of initial power and temperature profiles to obtain regional averages. Initial temperature profile is assumed proportional to normalized power shape with the peak fuel temperature occurring at the peak in the reactor power distribution.

```

Do to 350, for K = 1 to NOREG
POWER(K) = 0
(350)  VOL(K) = 0
      JL = 4
      IL = 5
      Do to 370, for K = 1 to NOREG
      Do to 360, for J = 1 to JL
      Do to 360, for I = 1 to IL
(360)  POWER(K) = POWER(K) + PWRS(I,J,K) · RRS(J,K)
      Volume of region
VOL(K) =  $\pi \cdot [ZUPS(K) - ZDNS(K)] \cdot [ROUTS(K)^2 - RINS(K)^2]$ 
      Power in region
POWER(K) =  $2\pi \cdot POWER(K) \cdot DELRS(K) \cdot DELZ(K)$ 
(370)  continue
      TOTV = 0
      TOTP = 0
      Total volume and power (initial)
      Do to 380, for K = 1 to NOREG
      TOTV = TOTV + VOL(K)
(380)  TOTP = TOTP + POWER(K)

```

e. Calculate temperatures at the region surfaces

```

Do to 400, for K = 1 to NOREG
THES = 0

```

Do to 390, for I = 1 to IL

Inner surface

THIN(I,K) = PSINS(I,K) · TMAX + TO

Outer surface

THOUT(I,K) = PSOUT(I,K) · TMAX + TO

Temperature distribution in a region

Do to 390, for J = 1 to JL

THETA(I,J,K) = PWRS(I,J,K) · TMAX + TO

THET1(I,J,K) = THETA(I,J,K)

Volume-averaged temperature

THES = THES + THETA(I,J,K) · RRS(J,K) · DELRS(K) · DELZS(K)

Pressure distribution

$$PR(I,J,K) = PRA(K) \cdot \exp \left[-\frac{PRB(K)}{THETA(I,J,K)} + PRC(K) \right]$$

(390)

continue loop

Volume-averaged temperature for Doppler coefficient

$$THETO(K) = \frac{2\pi \cdot THES}{VOL(K)}$$

Do to 400, for J = 1 to JL

Upper surface temperature

THUP(J,K) = PSUPS(J,K) · TMAX + TO

Lower surface temperature

THDN(J,K) = PSDNS(J,K) · TMAX + TO

(400)

continue loop

Set up initial reactivities based on last time steps

REASCR = 0

REASRP = 0

If KSCRAM ≤ 1 then go to 410

REASCR = SCRAM(SCRTIM)/EL

REASRP = SCRAM(SCRTIM - DT)/EL

(410)

REAPP = PREA(TIME - DT) · BETAS

REAP = PREA(TIME) · BETAS

REARM = VREAT(3) - REAP - READOP - READEN - REASCR
 REARMP = VREAT(2) - REAPP - READPP - READNP - REASRP

Extrapolation of reactivity from previous part of calculation

$$AK = \frac{(REARM - REARMP) \cdot EL}{DT}$$

Initial Δk due to coolant and radial (structure) expansion

$$DELKO = REARMP \cdot EL - AK \cdot (TIME - DT)$$

Do to 420, for K = 1 to NOREG

$$TEMPR = THETO(K)$$

If DOPLN(K) = 0, then DOPLN(K) = 1.0

$$BEKI = DOPLN(K)$$

$$(420) \quad DOPPO(K) = - \frac{2 \cdot DOPLA(K)}{TEMPR^{0.5}} + DOPLB(K) \cdot ALOG(TEMPR) \\ + \frac{DOPLC(K) \cdot TEMPR^{BEKI}}{DOPLN(K)}$$

$$SMBETA = BETAS \cdot EL$$

f. Output of initial values; this portion omitted here, see code listing for details

g. Normalize values such that $\sum POWER(I,J,K) = 1.0$

Do to 540, for K = 1 to NOREG

Do to 530, for I = 1 to IL

$$PSINS(I,K) = \frac{PSINS(I,K)}{TOTP}$$

$$PSOUTS(I,K) = \frac{PSOUTS(I,K)}{TOTP}$$

(530) continue loop

Do to 540, for J = 1 to JL

$$PSUPS(J,K) = \frac{PSUPS(J,K)}{TOTP}$$

$$PSDNS(J,K) = \frac{PSDNS(J,K)}{TOTP}$$

Do to 540, for I = 1 to IL

$$PWRS(I,J,K) = \frac{PWRS(I,J,K)}{TOTP}$$

$$DPDRS(I,J,K) = \frac{DPDRS(I,J,K)}{TOTP}$$

$$DPDZS(I,J,K) = \frac{DPDZS(I,J,K)}{TOTP}$$

(540) continue loop

h. Set up initial conditions for reactor kinetics calculations

Flux

PTEMP = PHI

Energy

QTEMP = PINTGO

Initial excess reactivity

$$XK = \frac{1}{1 - VREAT(3) \cdot EL}$$

IDBLE = 0

NSRN = 0

ASSIGN 750 to ISRN

Previous values

FN(2) = READNP · EL

READEN = READEN · EL

Set up density extrapolation

FN(3) = READEN

TM(2) = 0

TM(3) = DT

Coefficients in the fit of density reactivity

CF(1) = 0

$$CF(2) = \frac{READEN - FN(2)}{DT}$$

CF(3) = FN(2)

Set up Doppler reactivity

DFN(2) = READOP · EL (previous value)

DFN(3) = READOP (current value)

Coefficients in fit of Doppler reactivity

CFD(1) = 0

CFD(2) = $\frac{\text{READOP} - \text{DFN}(2)}{\text{DT}}$

CFD(3) = DFN(2)

Initialize times

X(1) = TIME

X(2) = DTMARS (initial Weak Explosion time step)

X(3) = TIMAX (dummy, not to be exceeded)

Y(1) = 0 (dummy)

Y(2) = FN(3) (density)

Y(3) = PHI (flux)

XPASS = 0

KPOW = 1 (first pass)

Y(4) = PINTGO (energy)

DTP = DT

i. Main integration routine

IDERIV = 1

go to 880 (evaluate volume and surface integrals)

(570) continue loop

Initialize values for the next time step

Do to 580, for K = 1 to NOREG

XKDOPL = READOP

(580) DOPP(K) = DOPPO(K)

ASSIGN 690 to ISELEC

INIZN = 1

PROTIM = X(1) + X(2)

DK = DKXPLO(PROTIM, SCRTIM, Y(2), SMBETA, XKDOPL,
DELKO, AK, Y4, Y5, Y6, Y7, Y8, Y9)

(590) $\text{XK} = \frac{1}{1 - \text{DK}}$

If KPOW = 3, then DTP = TOUT2

CALL PKXPLO(X(2), DELQ, DK)

KPOW = 3

XPASS = X(1)

X(1) = X(1) + X(2)

Y(4) = Y(4) + DELQ

X(3) = PHI

If X(1) < TIMAX then go to 670

go to 840

Reevaluate time-step size

(600) X(1) = XPASS

Y(4) = Y(4) - DELQ

KPOW = 2

(610) PROTIM = X(1) + X(2)

REATIM = PROTIM - TIME + DT

IDBL = 0

XKPOPL = [CFD(1) · REATIM + CFD(2)] · REATIM + CFD(3)

Y(2) = [CF(1) · REATIM + CF(2)] · REATIM + CF(3)

DK = DKXPLO(PROTIM, SCRTIM, Y(2), SMBETA, XKDOPL,
DELKO, AK, Y4, Y5, Y6, Y7, Y8, Y9)

go to 590

j. Short and full print-out.

k. Output of the power peak.

l. Check on limiting values for k_{eff} and normalized power.

m. Check on power divergence for doubling or halving time step.

n. Check for prompt critical to see if volume and surface integrals should be calculated every time step.

o. Material-worth reactivity fit in time (necessary if volume and surface integrals are not recomputed each time step--user option)

FN(1) = FN(2)

FN(2) = FN(3)

FN(3) = CF(3) + REAX · [CF(2) + REAX · CF(1)]

```

      TM(1) = TM(2)
      TM(2) = TM(3)
      TM(3) = REAX
      CF(1) =  $\frac{FF1}{2}$ 
      CF(2) =  $\frac{FN(3) - FN(2)}{TM(3) - TM(2)} - CF(1) \cdot [TM(3) + TM(2)]$ 
      CF(3) = FN(3) - CF(1) · TM(3)2 - CF(2) · TM(3)
      Do to 790, for K = 1 to NOREG
      THES = 0
      Do to 780, for I = 1 to IL
      Do to 780, for J = 1 to JL
      THES = THES + THETA(I,J,K) · RRS(J,K) · DELRS(K) · DELZS(K)
(780)  continue loop
      THBAR(K) =  $\frac{2\pi \cdot THES}{VOL(K)}$ 
(790)  continue loop
      Do to 800, for K = 1 to NOREG
      TEMPR = THBAR(K)
      BEKI = DOPLN(K)
(800)  DOPP(K) = -  $\frac{2 \cdot DOPLA(K)}{(TEMPR)^{0.5}} + DOPLB(K) \cdot LOG(TEMPR)$ 
           +  $\frac{DOPLC(K) \cdot (TEMPR)^{BEKI}}{DOPLN(K)}$ 
      XKDOPL = READOP
      Do to 810, for K = 1 to NOREG
(810)  XKDOPL = XKDOPL + DOPP(K) - DOPPO(K)

```

p. Doppler reactivity fit in time (necessary if Doppler reactivity is not recomputed each time step--user option)

```

      DFN(1) = DFN(2)
      DFN(2) = DFN(3)
      DFN(3) = XKDOPL

```

$$CFD(1) = \frac{DFN(1) - DFN(2)}{[TM(1) - TM(3)] \cdot [TM(3) - TM(2)]} - \frac{[DFN(1) - DFN(2)] \cdot [TM(1) - TM(3)]}{[TM(1) - TM(2)] \cdot [TM(1) - TM(3)] \cdot [TM(3) - TM(2)]}$$

$$CFD(2) = \frac{DFN(1) - DFN(2)}{TM(1) - TM(2)} - CFD(1) \cdot [TM(1) + TM(2)]$$

$$CFD(3) = DFN(1) - [CFD(2) + CFD(1)] \cdot TM(1)^2$$

$$QTEMP = Y(4)$$

$$NSRN = NSRNO$$

$$(820) \quad NSRN = NSRN - 1$$

$$QOUT = Y(4)$$

$$TOUT1 = X(1)$$

$$TOUT2 = X(2)$$

$$XKOUT1 = Y4$$

$$XKOUT2 = Y5$$

$$XKOUT3 = Y6$$

$$XKOUT4 = Y7$$

$$XKOUT5 = Y8$$

$$XKOUT6 = Y9$$

$$PTEMP = Y(3)$$

$$INIZN = 0$$

If IDBLE = 1, then $X(2) = 2 \cdot X(2)$.

go to 610 (next interval)

(830) If $X(1) < TIMAX$, then go to 720

p. Final output procedure (at end of transient)

q. Evaluation of volume integrals

$$(880) \quad QQ1 = \frac{Y(4) \cdot PZERO}{2}$$

$$QQ0 = \frac{QTEMP \cdot PZERO}{2}$$

Do to 900, for $K = 1$ to NOREG

IL = 5

JL = 4

Do to 890, for I = 1 to IL

Do to 890, for J = 1 to JL

XNUM = (QQ1 - QQ0) · PWRS(I,J,K)

New temperatures

$$\text{DELTH} = \frac{\text{XNUM}}{\text{REGRHO}(K) \cdot \{ \text{CPO}(K) + [\text{CPI}(K) + \text{CP2}(K) \cdot \text{THETA}(I,J,K)] \cdot \text{THETA}(I,J,K) \}}$$

THETA(I,J,K) = THETA(I,J,K) + DELTH

(890) continue loop

Do to 900, for I = 1 to IL

Do to 900, for J = 1 to JL

New pressures

$$\text{PR}(I,J,K) = \text{PRA}(K) \cdot \exp \left[- \frac{\text{PRB}(K)}{\text{THETA}(I,J,K)} + \text{PRC}(K) \right]$$

(900) continue

SUMV = 0

Do to 910, for K = 1 to NOREG

SUMA(K) = 0

Do to 910, for I = 1 to IL

Do to 910, for J = 1 to JL

$$\text{SUMA}(K) = \text{SUMA}(K) + \frac{\text{PRB}(K) \cdot \text{PR}(I,J,K)}{\text{THETA}(I,J,K)^2}$$

$$\cdot \frac{2\pi\text{RRS}(J,K) \cdot \text{DELRS}(K) \cdot \text{DELZS}(K)}{\text{REGRHO}(K)}$$

$$\cdot \left\{ \left[\frac{(\text{THETA}(I,J,K) - \text{THETA1}(I,J,K)) \cdot \text{DPDRS}(I,J,K)}{\text{PWRS}(I,J,K)} \right. \right.$$

$$+ \text{DPDRS}(I,J,K) \cdot \text{TOTP} \cdot \text{TMAX} \left. \right] \cdot \text{DDDR}(I,J,K)$$

$$+ \left[\frac{(\text{THETA}(I,J,K) - \text{THETA1}(I,J,K)) \cdot \text{DPDZS}(I,J,K)}{\text{PWRS}(I,J,K)} \right.$$

$$+ \text{DPDZS}(I,J,K) \cdot \text{TOTP} \cdot \text{TMAX} \left. \right] \cdot \text{DDDZ}(I,J,K) \left. \right\}$$

(910) continue loop

r. Evaluation of surface integrals.

SUMS = 0

Do to 1050, for K = 1 to NOREG

If W(K) = 0, then W(K) = 1

SUMB(K) = 0

Do to 920, for I = 1 to IL

Inner surface temperature

XNUM = [QQ1 - QQ0] · PSINS(I,K)

$$\text{DELTH} = \frac{\text{XNUM}}{\text{REGRHO}(K) \cdot [\text{CPO}(K) + \text{CP1}(K) \cdot \text{THIN}(I,K) + \text{CP2}(K) \cdot \text{THIN}(I,K)^2]}$$

THIN(I,K) = THIN(I,K) + DELTH

Outer surface temperature

XNUM = (QQ1 - QQ0) · PSOUTS(I,K)

$$\text{DELTH} = \frac{\text{XNUM}}{\text{REGRHO}(K) \cdot [\text{COP}(K) + \text{CP1}(K) \cdot \text{THOUT}(I,K) + \text{CP2}(K) \cdot \text{THOUT}(I,K)^2]}$$

THOUT(I,K) = THOUT(I,K) + DELTH

(920)

continue loop

If SITG(I,K) = 0 then go to 950

Do to 940, for I = 1 to IL

Sum of inner surfaces

$$\text{PRTEMP} = \text{PRA}(K) \cdot \exp \left[-\frac{\text{PRB}(K)}{\text{THIN}(I,K)} + \text{PRO}(K) \right]$$

If WCON(I,K) ≠ 0 then go to 930

SUMB(K) = SUMB(K)

$$+ \frac{2\pi \cdot \text{RINS}(K) \cdot \text{DELZS}(K) \cdot \text{PRTEMP} \cdot \text{DSINS}(I,K)}{\text{REGRHO}(K)}$$

go to 940

(930)

$$\text{P1} = \text{PRA}(K - \text{NXN}) \cdot \exp \left[-\frac{\text{PRB}(K - \text{NXN})}{\text{THOUT}(I,K - \text{NXN})} + \text{PRC}(K - \text{NXN}) \right]$$

PRTEMP = PRTEMP - P1

SUMB(K) = SUMB(K) + 2π · RINS(K) · DELZS(K) · PRTEMP

$$\frac{[\text{DSINS}(I,K) \cdot \text{W}(K) - \text{DSOUTS}(I,K - \text{NXN}) \cdot \text{W}(K - \text{NXN})]}{\text{REGRHO}(K - \text{KXN}) \cdot \text{W}(K - \text{KXN}) + \text{REGRHO}(K) \cdot \text{W}(K)}$$

(940) continue loop

(950) If SITG(2,K) = 0 then go to 980

Do to 970, for I = 1 to IL

Sum of outer surfaces

$$PRTEMP = PRA(K) \cdot \exp \left[-\frac{PRB(K)}{THOUT(I,K)} + PRC(K) \right]$$

If WCON(2,K) $\neq$ 0 then go to 960

$$SUMB(K) = SUMB(K) + \frac{2\pi \cdot ROUTS(K) \cdot DELZS(K) \cdot DSOUTS(I,K)}{REGRHO(K)}$$

go to 970

(960)
$$P1 = PRA(K+NXN) \cdot \exp \left[-\frac{PRB(K+NXN)}{THIN(I,K+NXN)} + PRC(K+NXN) \right]$$

$$PRTEMP = PRTEMP - P1$$

$$SUMB(K) = SUMB(K) + 2\pi \cdot ROUTS(K) \cdot DELZS(K) \cdot PRTEMP \cdot \frac{[DSOUTS(I,K) \cdot W(K) - DSINS(I,K+NXN) \cdot W(K+NXN)]}{REGRHO(K+NXN) \cdot W(K+NXN) + REGRHO(K) \cdot W(K)}$$

(970) continue loop

(980) Do to 990, for J = 1 to JL

Upper surface temperature

$$XNUM = [QQ1 - QQ0] \cdot PSUPS(J,K)$$

$$DELTH = \frac{XNUM}{REGRHO(K) \cdot [CPO(K) + CP1(K) \cdot THUP(J,K) + CP2(K) \cdot THUP(J,K)^2]}$$

$$THUP(J,K) = THUP(J,K) + DELTH$$

Lower surface temperature

$$XNUM = [QQ1 - QQ0] \cdot PSDNS(J,K)$$

$$DELTH = \frac{XNUM}{REGRHO(K) \cdot [CPO(K) + CP1(K) \cdot THDN(J,K) + CP2(K) \cdot THDN(J,K)^2]}$$

$$THDN(J,K) = THDN(J,K) + DELTH$$

(990) continue loop

If SITG(3,K) = 0, then go to 1020

Do to 1010, for J = 1 to JL

Sum of upper surfaces

$$PRTEMP = PRA(K) \cdot \exp \left[-\frac{PRB(K)}{THUP(J,K)} + PRC(K) \right]$$

If WCON(3,K) $\neq$ 0 then go to 1000

SUMB(K) = SUMB(K)

$$+ \frac{2\pi \cdot \text{RRS}(J,K) \cdot \text{DELRS}(K) \cdot \text{PRTEMP} \cdot \text{DSUPS}(J,K)}{\text{REGRHO}(K)}$$

go to 1010

(1000)
$$P1 = \text{PRA}(K+1) \cdot \exp \left[- \frac{\text{PRB}(K+1)}{\text{THUP}(J,K+1)} + \text{PRC}(K+1) \right]$$

PRTEMP = PRTEMP - P1

$$\text{SUMB}(K) = \text{SUMB}(K) + 2\pi \cdot \text{RRS}(J,K) \cdot \text{DELRS}(K) \cdot \text{PRTEMP} \\ + \frac{[\text{DSUPS}(J,K) \cdot W(K) - \text{DSDNS}(J,K+1) \cdot W(K+1)]}{\text{REGRHO}(K+1) \cdot W(K+1) + \text{REGRHO}(K) \cdot W(K)}$$

(1010) continue loop

If SITG(4,K) = 0 then go to 1050

Do to 1040, for J = 1 to JL

Sum of lower surfaces

$$\text{PRTEMP} = \text{PRA}(K) \cdot \exp \left[- \frac{\text{PRB}(K)}{\text{THDN}(J,K)} + \text{PRC}(K) \right]$$

If WCON(4,K) $\neq$ 0 then go to 1030

SUMB(K) = SUMB(K)

$$= \frac{2\pi \cdot \text{RRS}(J,K) \cdot \text{DELRS}(K) \cdot \text{PRTEMP} \cdot \text{DSDNS}(J,K)}{\text{REGRHO}(K)}$$

go to 1040

(1030)
$$P1 = \text{PRA}(K-1) \cdot \exp \left[- \frac{\text{PRB}(K-1)}{\text{THDN}(J,K-1)} + \text{PRC}(K-1) \right]$$

PRTEMP = PRTEMP - P1

$$\text{SUMB}(K) = \text{SUMB}(K) + 2\pi \cdot \text{RRS}(J,K) \cdot \text{DELRS}(K) \cdot \text{PRTEMP} \\ + \frac{[\text{DSDNS}(J,K) \cdot W(K) - \text{DSUPS}(J,K-1) \cdot W(K-1)]}{\text{REGRHO}(K-1) \cdot W(K-1) + \text{REGRHO}(K) \cdot W(K)}$$

(1040) continue loop

(1050) continue loop

Final sums

Do to 1060, for K = 1 to NOREG

SUMV = SUMA(K) + SUMV


```

(1060)   SUMS = SUMB(K) + SUMS
         FFOUT = FF1
         FF1 = SUMV + SUMS
         If IDERIV < 0 then go to 570
         If IDERIV = 0 then go to 770
         End Subroutine XPLODE

```

2. Subroutine DKXPLO calculates all reactivities other than Doppler effect and material motion. It is called from XPLODE.

Computation of the Δk for XPLODE

```

         Y6 = 0
         Y5 = PREA(PROTIM)
         If SCRTIM ≤ 0 then go to 5
         Y6 =  $\frac{\text{SCRAM}(\text{SCRTIM})}{\text{BETAS}}$ 
(5)      Y7 =  $\frac{\text{XKDOPL}}{\text{BETAS}}$ 
         Y8 =  $\frac{Y}{\text{BETAS}}$ 
         Y9 =  $\frac{\text{DELKO} + \text{AK} \cdot \text{PROTIM}}{\text{BETAS}}$ 
         Y4 = Y5 + Y6 + Y7 + Y8 + Y9
         DKXPLO = Y4 · BETAS
         Return to EXPLODE
         End Subroutine DKXPLO

```

3. Subroutine PKXPLO calculates normalized power level during core disassembly. The calculations are essentially the same as in subroutine TSPK (see Appendix E). There are different statement numbers, but the variables are identical.

APPENDIX H

Dictionary

This dictionary consists of an alphabetical list of the variables used in the actual programming of the detailed equations. Each variable is listed with a definition, units, array dimensions, approximate statement numbers in the subroutines where it is calculated, and additional comments as appropriate.

Part 1 lists the variables that are in common and, therefore, can be computed outside the subroutine where they are used. Part 2 lists variables that are only computed and used in one subroutine, and, accordingly, they are grouped by subroutine.

A second set of common variables appear under the listing for FULDYN in Part 2. Actually, these variables are calculated and used only by FULDYN (except for editing), and were put in the DEFORM common block to conserve space, since the FULDYN subroutine replaces DEFORM once it has been called. In a similar manner XPLODE uses the entire FUBAR common area for its arrays when the calculation enters weak explosion.

1. Common Variables

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
A0(L)	POWER(35) SSPK--1	Reciprocal matrix, $A0(L) = 1/L$	Dim = 5
A2(J)	COOL(2234) SSCOOL--1+,7+ TSCOO--1+,13,21+,22 23+,31+,35+,66+,71+, 76+,78+	Coolant void fraction at time	Dim = 201
A2F	COOL(1626) TSCOO--1+,21+	Estimate of void fraction at liquid 2-phase interface	
ABCSQ(J)	DEF(381) DEFORM--1+,49+	Stores differences of clad radius squared i.e., $R_{outer}^2 - R_{inner}^2$ (cm ²)	Dim = 20
ABSSQ(J)	DEF(361) DEFORM--10+	Stores differences of solid radius squared i.e., $R_{outer}^2 - R_{inner}^2$ (cm ²)	Dim = 20
ABURN	INPUT(121)	Void fraction for clad burnout < AMAX	
AC(J)	DEF(221) DEFORM--1+,49+	Cladding inner radius at operating conditions with plastic flow. (cm)	Dim = 20
AC0(J)	DEF(1583) DEFORM--1+	Cladding inner radius at operating conditions with no plastic flow. (cm)	Dim = 20
ACK1	INPUT(80)	Coefficients in Ackerman equation of state for fuel. Saturated vapor pressure $P_{SAT} = TEMP^{ACK1} * e^{(ACK2 + ACK3/TEMP)}$	-4.026
ACK2	INPUT(81)		59.0
ACK3	INPUT(82)		-74590.0

Variable	Location in Common and Where Calculated	Definition and Units :	Miscellaneous
ACSQ(J)	DEF(321) DEFORM--1+,49	Square of clad inner radius, AC. (cm ²) (See AC(J))	Dim = 20
ADOP	INPUT(190)	Doppler coefficient for zero void. ($\Delta k/k$)	
AE	INPUT(111) SSHTR--64+	Coefficient of linear thermal expansion of the cladding. ($^{\circ}\text{C}^{-1}$) (See KHTSS) (Input at reference temperature, TR)	
AFL	INPUT(75) INPOUT--820+	Coefficient of linear thermal expansion of liquid fuel. ($^{\circ}\text{C}^{-1}$) (Input at fuel melting temperature, TMF) (If 0.0 is input, AFL will be computed from the density tables)	
AFS	INPUT(74) INPOUT--810+ SSHTR--64+	Coefficient of linear thermal expansion of solid fuel. ($^{\circ}\text{C}^{-1}$) (See KHTSS) (Input at reference temperature, TR) (If 0.0 is input, AFS will be computed from the density tables)	
ALAM(L)	INPUT(160)	Decay constant of precursors of type L, $1 \leq L \leq \text{NDELAY}$	Dim = 6
ALMARS	INPUT(274)	Inverse period for weak-explosion initiation. (sec^{-1})	
AM	INPUT(76) INPOUT--830	Percent change in fuel due to melting. (If 0.0 is input, AM will be computed from the density table)	
AMAX	INPUT(271)	Maximum allowable void fraction	
ANGPHI	INPUT(189)	The present value of the angle between the plane of the earth's orbit and the plane formed by the earth's axis of rotation and the center of the sun. (steradians)	
AR	INPUT(58)	Area ratio for pump leg, LP. (Diameter of pump leg) ² /(Diameter of coolant channel) ²	
AS(J)	DEF(181) DEFORM--10+	Inner radius of solid fuel at operating conditions, with melting. (cm)	Dim = 20
ASCRAM	INPUT(276)	Inverse period for scram initiation. (sec^{-1})	
ASI(I,J)	DEF(441) DEFORM--8+	Integral of the coefficient of linear expansion across the fuel. (cm ²)	Dim = 17,20
ASSQ(J)	DEF(281) DEFORM--10+	Square of inner solid fuel radius, As. (cm ²) (See AS(J)).	Dim = 20
ASTR	INPUT(122) SSHTR--64+	Coefficient of linear thermal expansion of the structure. (See KHTSS) (Input at reference temperature, TR)	
AVGMAT(J)	INPUT(169) INPOUT--490+,500, 550,580	Average material reactivity in axial direction. If weak-explosion code is specified AVGMAT(J) is computed from RMATW(I,J), weighted with the radial power profile. (See RMATW(I,J))	Dim = 20
AXHI(J)	INPUT(36)	Length of fuel axial segment. (cm) (All should be as near equal size as possible)	Dim = 20

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
BC(J)	DEF(241) DEFORM--1+,49+	Clad outer radius at node J and operating conditions, with plastic flow. (cm)	Dim = 20
BC0(J)	DEF(1603) DEFORM--1+	Clad outer radius at node J. At operating conditions, no plastic flow. (cm)	Dim = 20
BCSQ(J)	DEF(341) DEFORM--1+,49+	Square of clad outer radius, BC. (cm ²) (See BC(J))	Dim = 20
BDOP	INPUT(191) INPOUT--880+	Doppler coefficient for fully voided core. (No sodium) (Modified in INPOUT to represent slope of the Doppler from no void to full void	
BETA(L)	INPUT(154) SSPK--1+	Delayed-neutron fraction of group L. (For computational reasons BETA(L) is divided by the half-life in the steady state) (In TSHTR BETA(L) is represented by the variable QBETA(L))	Dim = 6
BETAS	POWER(45) INPOUT--80+ TSPK--11+	Summation of BETA(L)	
BL(J)	DEF(261) DEFORM--1+,7+,8+	Free radius of melted fuel at node J. (cm)	Dim = 20
BOILTI(L)	POWER(47) TSPK--11,32	Time since boiling initiation in coolant channels. (sec) 1 = MAIN 2, 3, 4 = PHANTOM CHANNELS	Dim = 4
BS(J)	DEF(201) DEFORM--2+	Solid-fuel outer radius at operating conditions. (cm)	Dim = 20
BSSQ(J)	DEF(301) DEFORM--2+	Square of solid-fuel outer radius, BS. (cm ²) (See BS(J))	Dim = 20
C(L)	POWER(23) SSPK--1+ TSPK--24,29	Precursor concentration of group L, at time	Dim = 6
CO(L)	POWER(29) SSPK--2 TSPK--41	Precursor concentration at previous time step	Dim = 6
C1 C2 C3	INPUT(116) INPUT(117) INPUT(118)	Clad-coolant film heat-transfer con- ductance. Equation coefficients: $h_c = K_c \left(C_1 \left[\frac{D_n G C_c}{K_c} \right]^{C_2} + C_3 \right) / D_n$	
CC2	INPUT(105)	Constant in specific volume equation; specific volume = (TEMP+CC1)/CC2	40000.0
CF	HEAT(1189) TSHTR--2	Fuel specific heat at the melting point. (J/gm-°C)	
CL	INPUT(119)	Specific heat of the coolant at the reference temperature, TR. (J/gm-°C)	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
CP0(K)	INPUT(881)	Constants in the specific heat	Dim = 60
CP1(K)	INPUT(941)	equation for each region K used in	Dim = 60
CP2(K)	INPUT(1001)	the weak-explosion module $C_p = C_{p0} + C_{p1} * T + C_{p2} * T^2$ (C_p in J/gm-°C)	Dim = 60
CPTAB(L)	INPUT(331)	Fuel specific heat table as a function of temperature, CPTTEM. (J/gm-°C)	Dim = 20
CPTTEM(L)	INPUT(351)	Temperature table for fuel specific heat. (°C) (See CPTAB(L))	Dim = 20
CRHOST	INPUT(123) INPOUT--880+	Specific heat * density for the structure. (J/cm ³ -°C)	
CROE	INPUT(112)	Specific heat * density for the cladding. (J/cm ³ -°C)	
DAV2(J)	COOL(1413) SSCOOL--4+ TSCOOL--1+,12+,26+ 31+,35+,80	Average coolant density of node J at time. (gm/cm ³)	Dim = 201
DAVLSL	COOL(2651) TSCOOL--65+	Average density of the lower slug. (gm/cm ³)	
DAVSS(J)	COOL(1212) SSCOOL--4+	Average steady-state coolant density at node J. (gm/cm ³)	Dim = 201
DAVUSL	COOL(2650) TSCOOL--65+	Average density of the upper slug. (gm/cm ³)	
DC(J)	DEF(421) DEFORM--1+,49+, FULDYN--320+,800+, 1260+,1575+	Thickness of the cladding at node J. (cm)	Dim = 20
DEL	INPUT(109)	Stefan-Boltzmann's * emissivity for fuel clad radiant heat transfer. (W/cm ² -°C ⁴)	
DELMR	HEAT(42) SSHTR--1	Radial mesh with melting. (cm) (DELRM*(1.0+% expansion in fuel at melting)) (See DELRM)	
DELPO	COOL(1209) SSCOOL--7+ TSCOOL--39+	Pressure drop across the coolant channel. (dynes/cm ²)	
DELR	HEAT(41) SSHTR--1	Smoothed size of the radial fuel mesh at steady state. (cm)	
DELRM	HEAT(43) SSHTR--1	Size of radial mesh at melting. (cm) $DELRM = DELR * (1.0 +$ $\alpha_{FUEL}(T_{MELT} - T_{REF}))$	
DELTA	COOL(1615) TSCOOL--1,15+,44+ 64+,40+,39+,82+,3+	Time step used by the coolant code for the following step. (sec)	
DEP2(J)	COOL(2435) TSCOOL--1+,20,26+ 31+	Density of the liquid * quality plus the density of the gas for each coolant node. (gm/cm ³)	Dim = 201
DH	COOL(1207) SSCOOL--1	Hydraulic diameter of the coolant channel. (cm)	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
DL2(J)	COOL(1006) SSCOOL--4+ TSCOO--12+,19+,35+	Present coolant liquid density at node J. (gm/cm ³)	Dim = 201
DOPLA(K)	INPUT(1241)	Coefficients for Doppler equation used by weak-explosion module for each region K. $\Delta K_{DOPP} =$ $-2.0 * DOPLA * T^{-0.5} + DOPLB * LN(T) +$ $(DOPLC / DOPLN * TEMP)^{DOPLN}$	Dim = 60
DOPLB(K)	INPUT(1301)		Dim = 60
DOPLC(K)	INPUT(1361)		Dim = 60
DOPLN(K)	INPUT(1421)		Dim = 60
DT	TIME(2) INPOUT--10 TSCOO--39,82,3 TSHTR--3+,33	Current time step. (sec)	
DTO	INPUT(268)	Initial time step. (sec)	
DTMAX	INPUT(2022)	Maximum time step allowed in the weak-explosion module. (sec)	
DTMIN	INPUT(2023)	Minimum time step allowed in the weak-explosion module. (sec)	
DTMARS	INPUT(2021)	Initial time step in weak-explosion module. (sec)	
DTP	POWER(40) TSPK--11+,44+ TSHTR--34+	Previous time step. (sec)	
DTS	INPUT(120)	Degrees of coolant superheat. (°C)	
DZCOOL	MESH(1064) INPOUT--10+	Size of coolant mesh spacing. (cm)	
DLPMIN	INPUT(263)	Minimum power change for steady- state power-search iteration	
EBU	COOL(1630) TSCOO--1+,33+	Average movement of coolant in time interval. (cm)	
EC(J)	DEF(1563) DEFORM--4+	Clad Young's modulus at node J. (dynes/cm ²)	Dim = 20
ECTAB(L)	INPUT(411)	Cladding Young's modulus table as a function of temperature, ECTEM. (dynes/cm ²)	Dim = 20
ECTEM(L)	INPUT(431)	Temperature table for cladding Young's modulus. (See ECTAB(L)) (°C)	
EK	INPUT(113)	Thermal conductivity of the cladding. (W/cm-°C)	
EL	INPUT(153)	Prompt neutron-generation time. (sec)	
EPS1	POWER(8895) SSPK--1	If local error in neutron flux is less than EPS1 then time step is doubled. (EPS1 = 0.10*EPSPHI) (See EPSPHI)	
EPSCOL	INPUT(279)	Acceptable percent error in coolant iteration	~0.001
EPSDEF	INPUT(282)	Acceptable percent error in defor- mation iteration	~10 ⁻⁴

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
EPSPHI	INPUT(281)	Acceptable percent error in neutron-flux iteration	$\sim 10^{-5}$ to 10^{-6}
EPSREA	INPUT(280)	Acceptable percent error in reactivity iteration	~ 0.001
EPSTEM	INPUT(267)	Maximum allowable error in steady-state temperature iteration. ($^{\circ}\text{C}$)	~ 1.0
EPSVAP	INPUT(283)	Acceptable percent error in energy balance of fuel-vaporization iteration	~ 0.001
ERROR	POWER(8908) TSPK--14+,23+	Current neutron-flux error as approximated by the extrapolation of the half-time interval	
ES	INPUT(78)	Young's modulus of the solid fuel. (dynes/cm ²)	
ESTNBL	DUMCOL(3) TSCOOL--1+,18+	Last value of movement of lower (inlet) interface	
ETA1	INPUT(2027)	Ratio of successive powers greater than which the time step is halved in the weak-explosion module	~ 1.275
ETA2	INPUT(2028)	Ratio of successive powers less than which the time step is doubled in the weak-explosion module	~ 1.05
ETA3	INPUT(2029)	Ratio of successive powers less than which the power peak is determined	~ 1.0
FDELT	DUMTSP(3)	Ratio of fraction melted to average temperature for plots	
FF	INPUT(84)	Dynamic friction factor in Fuel Dynamics Module. ($P_{\text{FRIC}} = \text{FF} \cdot \text{VELOCITY}$) (dyne-sec/cm ³)	~ 50 to 500
FR	INPUT(60) INPOUT--880+	Single-phase coolant friction coefficient (if 0.0 input 0.1875 is used)	
FRAC(J)	HEAT(764) SSHTR--64+ TSHTR--43	Fraction of fuel melted at node J	Dim = 20
FS(J)	INPUT(85)	Static friction factor at node J. (dynes/cm ²)	Dim = 20 $\sim 10^6$ to 10^{10}
FUELMS(J)	INPUT(2555) INPOUT--880	Mass of the fuel at node J. (gm)	Dim = 20
FZC	DEF(1162) DEFORM--1+	Axial restraining force on the cladding	0.0
FZF	DEF(1161) DEFORM--1+,4	Axial restraining force on the fuel	
GO	INPUT(63)	Initial coolant mass flowrate. (gm/sec-cm ²)	
G2(J)	COOL(1631) SSCOOL--8 TSCOOL--1,20+,3+,6, 10,16,30+,31,33,64+, 70+,71+,75+,76+,78+	Mass flowrate at coolant node J. (gm/sec-cm ²)	Dim = 201

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
G2F	COOL(1628) TSCOOL--1+,31+,20	Estimate of the mass flowrate at inlet 2-phase interface. (gm/sec-cm ²)	
GAM2	INPUT(65) INPOUT--880+	Ratio of surface area of structure to surface area of cladding (if 0.0 is input 1.0 is used)	$\sim 10^{-4}$ to 2.0
GAV1	COOL(1623) TSCOOL--1+,39	Average mass flowrate at time. (gm/sec-cm ²)	
GAV2	COOL(1624) TSCOOL--1+,15+,53, 536,538	Average mass flowrate at end of time step. (gm/sec-cm ²)	
GFLOW(L)	INPUT(2635)	Normalized inlet flow table as a function of time. (G2(1) = GO · GFLOW(L)) (See TFLOW(L))	Dim = 20
GJ6	COOL(1622) TSCOOL--1+,54+	Average mass flowrate at last pressure calculation. (gm/sec-cm ²)	
GSCRAM	INPUT(278)	Inlet mass flowrate for scram initiation. (gm/sec-cm ²)	
H2(J)	HEAT(1791) SSHTR--4 TSHTR--9	Coolant film heat-transfer coefficient. (W/°C-cm ²)	Dim = 20
H2(J)		Used in Fuel Dynamics Module; see FULDYN subsection (in FULDYN H(J) is equivalent to H2(J) and H2(J) is axial mesh)	
HBGRAD	INPUT(108)	Gradient of fuel-clad conductance with pressure. No ((W/cm ² -°C)/(dyne/cm ²))	
HBMAX	INPUT(107)	Maximum value of the bond conductance when a gap exists. Minimum value of conductance at no gap. (W/cm ² -°C)	
HBPAP	INPUT(106)	Coefficient in bond-conductance equation when a gap exists. (Conductance = HBPAP/gap) (W/cm ² -°C)	
HBURN	INPUT(115)	Fuel coolant heat-transfer conductance at clad burnout. (W/cm ² -°C)	
HCOOL(J)	COOL(202) SSCOOL--4+ TSCOOL--38,39,80+, 81	Heat-transfer coefficient at coolant node J. (W/cm ² -°C)	Dim = 201
HL2(J)	COOL(403) SSCOOL--1,4 TSCOOL--6+,8+,9,11+, 33+,34+,73+	Enthalpy of the coolant liquid at node J at time. (W/gm)	Dim = 201
HSTR(J)	HEAT(1811) SSHT--1+ TSHT--57+	Structure heat-transfer coefficient. (RST+1.0/H2(J)) (°C-cm ² /W)	Dim = 20
HVA2	COOL(1832) TSCOOL--2,19	Enthalpy of the coolant vapor at node J at time. (W/gm)	Dim = 201

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
IBOIL	POWER(53) TSPK--10+,37+,38+	Number of channels currently boiling	
ICLCMP	INPUT(16)	If ICLCMP > 0 calcomp output desired on unit ICLCMP. If ICLCMP ≤ 0 no calcomp output desired.	
ICOUNT	DEF(1683) DEFORM--10+,54	Number of outer iterations performed in deform	
IERROR	KON(7) READIN--3+,7+ SSCOOL--13 SSHTR--57+ INPOUT--730+,740+,750+, 760+,770+,790+,800+,840+, 850+,860+,765+,862+,864+, 865+,866+,867+,868 TSPK--25+,30+ TSHTR--52+ DEFORM--10+,31+,51 FULDYN--2100+ SSDRIV--6+,7+,2+ SAS1A--0(main)	If IERROR = 0 no errors. If IERROR = 1 terminal error.	
IHEAD	DUMTSP(4) TSPR--0,4,12	If IHEAD = 0 skip print heading	
IMELT	INPUT(2553) INPOUT--880	Location in density table where melting point is found	
IPO	INPUT(17)	Full printout every IPO steps before boiling	
IPOBOI	INPUT(18)	Full printout every IPOBOI steps after boiling	
IPOPT	INPUT(19)	Full printout of pressure and temperature distribution every IPOPT steps in Weak Explosion Module	
IPOWER	INPUT(11)	If IPOWER > 0 normalized power is specified as a function of time in PREA function. If IPOWER ≤ 0 reactivity (\$) is specified as a function of time in PREA function.	
IPHI	POWER(8910) TSPK--14+,15+	Number of neutron-flux iterations	
IREA	POWER(8909) TSPK--10+,28+,32+	Number of reactivity iterations	
IREAS	POWER(8894) COOLFB--11+	Number of coolant reactivity versus time points being stored for computation of phantom channel reactivity	
ISSCAL	INPUT(13)	If ISSCAL > 0 steady-state power search is computed. If ISSCAL ≤ 0 power will be specified.	
ISSTS	INPUT(12)	If ISSTS > 0 steady-state computation only. If ISSTS ≤ 0 steady state plus transient.	
ISTEP	TIME(4) TSDRIV--1+,22	Number of time steps calculated	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
ISTEP1	IPLOT4(1) SSPR--8 TSPR--920 XPLO--480	Number of steps on plot tape. (ICLCMP)	
ITER	COOL(2638) TSCOO--1+,20+,31+	Iteration count in 2-phase coolant iteration	
J1	COOL(2640) TSCOO--1+,18+,75+,64	Node number of inlet interface between liquid and 2 phase	
JIM4	DUMCOL(5)	J1-4	
J1SL	COOL(2644) TSCOO--63+,64+,75+	Node number of inlet interface between vapor and 2 phase	
J5	COOL(1211) TSCOO--1+,15+,39+	Node number where coolant tem- perature exceeds saturation	
J6	COOL(2642) TSCOO--1+,17+,39+	Fine mesh counter in boiling loop. (see N8)	
JB	COOL(2636) TSCOO--1+,17+,39+, 82±	Number of time steps plus 1 since boiling initiation	
JDIREC	IPLOT4(5) SSPRNT--8 TSPRNT--1300	If JDIREC = 1 power is increasing. If JDIREC = 2 power is decreasing.	
JE	COOL(2641) TSCOO--1+,18+,31+, 39+,70+,4	Node number of exit interface between liquid and 2 phase	
JES	DUMCOL(4) TSCOO--1+,39+,64+	Node number of peak void fraction	
JESL	COOL(2645) TSCOO--64+,70+	Node number of exit interface between vapor and 2 phase	
JEP	COOL(2639) TSCOO--1+,18+,39+, 70+	Node number of boiling initiation	
JSETCL	IPLOT4(2) SSPRNT--1148	Axial node number of plotted fuel temperature	
JSETNE	IPLOT(3) SSPRNT--1148	Axial node number of plotted clad temperature	
JSLUG	COOL(2643) TSCOO--1+,64	If JSLUG > 0 slug-ejection model is in use. If JSLUG ≤ 0 normal computation.	
K3	COOL(1619) TSCOO--1+,39+	Time derivative of the mass flow rate at the inlet. (gm/cm ² - sec ²)	REAL
K5	COOL(1208)	Conversion factor for coolant channel from W/cm ² to W/cm ³ . (K5 = 4.0/DH) (See DH) (cm ⁻¹)	REAL
K8	COOL(1620) TSCOO--51,52	Effective driving pressure. (gm-wt/cm ²)	REAL
K9	COOL(1621) TSCOO--1+,53+	Time derivative of the average mass flow rate. (gm/cm ² -sec ²)	REAL
KBOIL	KON(6) TSCOO--1+,39+	If KBOIL = 1 no boiling. If KBOIL = 2 boiling.	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
KCOOL	KON(2) TSDRIV--1 TSCOO--2	If KCOOL = 1 first time step. If KCOOL = 2 subsequent time steps.	
KDEF	KON(4) TSDRIV--1 DEFORM--3	If KDEF = 1 first time step. If KDEF = 2 subsequent time steps.	
KHT	KON(1) TSDRIV--1 TSHTR--49,50	KHT = 1 first half time step. KHT = 2 first full time steps. KHT = 3 subsequent time steps.	
KHTSS	KON(8) SSDRIV--1-,1+	If KHTSS = 1 bypass adjustment of coefficient of expansion in SSHTR. If KHTSS = 2 adjust coefficient of expansion in SSHTR.	
KII	POWER(44) TSPK--11+,41+	If KII = 1 first time step. If KII = 2 subsequent time steps.	
KLF	INPUT(79)	Bulk modulus of the fuel. (dyne/cm ²)	REAL
KPOW	KON(3) TSDRIV--1,15 TSPK--27+,39+,44+,45+ XPLODE--540+,600+,590	If KPOW = 1 first time step. If KPOW = 2 any recalculation of last time step. If KPOW = 3 calculation of subsequent time steps.	
KSANA	KON(9) TSDRIV--1,15	If KSANA = 1 no fuel-dynamics com- putation. If KSANA = 2 fuel- dynamics computation.	
KSCRAM	KON(5) TSDRIV--1,5	If KSCRAM = 1 no scram as yet. If KSCRAM = 2 scram has been initiated.	
KTAB(L)	INPUT(291)	Table of thermal conductivity of the fuel as a function of temperature, KTEM. (W/cm-°C)	Dim = 20 REAL
KTEM(L)	INPUT(311)	Table of temperatures for thermal conductivity of the fuel, KTAB. (°C) (See KTAB(L))	Dim = 20 REAL
LP	INPUT(57)	Pump leg, distance from pump to coolant channel inlet. (cm)	REAL
MAXSTP	INPUT(8)	Maximum number of time steps allowed	
MELT(J)	HEAT(1851) SSHTR--47+,48 TSHTR--41+,42	The radial fuel node where the liquid-solid interface is located, for each axial node J	Dim = 20
MOLWT	INPUT(73)	Molecular weight of the fuel. (gm/mole)	REAL
MZ	INPUT(2)	Number of axial fuel nodes	
MZC	INPUT(3)	Number of axial coolant nodes	
MZLB	INPUT(5)	Number of axial fuel nodes located in the lower blanket	
MZN	INPUT(2552) INPOUT--10 DEFORM--1	Number of axial fuel interfaces. (MZ + 1)	
MZUB	INPUT(4)	Number of axial fuel nodes located in the upper blanket.	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
MZS	INPUT(26)	Number of entries in the axial power shape. If weak explosion option is specified. (When NOMARS > 0 then MZ is the number of input values for the axial power shape.)	
N7	COOL(1614) TSCOOL--1+,3	If N7 = 1 negative inlet mass flow rate. If N7 = -1 positive inlet mass flow rate.	
N8	INPUT(6)	Number of time steps for the inlet two-phase interface to traverse 1 coolant mesh interval	
NBL2	COOL(1617) TSCOOL--1+,13+,14,17+, 64+,73+,74,75,91	Length of the inlet liquid segment at time. (cm)	REAL
NC	HEAT(1188) SSHTR--1	Node number of the average coolant temperature in radial mesh. (NC = NEP + 1) (see NEP)	
NCHECK	COOL(1616) TSCOOL--1+,39+,45	A flag to shorten the time step when boiling is approached. If NCHECK = 1 check if temperature projection is within 100° of boil. If NCHECK = 2 check if temperature projection is within 50° of boil. If NCHECK = 3 minimum preboiling time step has been reached.	
NCLAD(J)	DEF(801) DEFORM--1+,19,22+, 30,33,35+,38+,36	A flag on the current clad condition of node J. If NCLAD = 1 no fuel-clad contact. If NCLAD = 2 fuel-clad contact. If NCLAD = 3 plastic flow.	Dim = 20
NCPTB	INPUT(21)	Number of entries in the fuel specific heat table	
NCASE(J)	DEF(1684) DEFORM--16	Case number for fuel-clad condition at node J. (NCASE = NFUEL + NCLAD) (see NCLAD(J) and NFUEL(J))	Dim = 20
NDELAY	INPUT(7)	Number of delayed-neutron precursors	
NE	HEAT(1186) SSHTR--1	Node number of the mid-clad temperature in the radial mesh. (NE = NR + 1) (see NR)	
NECTB	INPUT(23)	Number of entries in the cladding Young's modulus table	
NEFECT(L)	IPLOT4(6)	Time step of initiation of NEFECT(J)	Dim = 8
NEP	HEAT(1187) SSPRNT--1147 TSPRNT--1	Node number of the outer clad temperature in the radial mesh. (NEP = NE + 1) (see NE)	
NFUEL(J)	DEF(781) DEFORM--10+,11+,19+, 21+,23,24+,30+,32+,37+	A flag on the current fuel condition node J. If NFUEL = 0 no central hole and no melting. If NFUEL = 3 central hole, can be either melt or no melt. If NFUEL = 6 no central hole and melting.	Dim = 20

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
NGFLOW	INPUT(30)	Number of entries in coolant flow table	
NKTB	INPUT(20)	Number of entries in fuel thermal-conductivity table	
NN	HEAT(1184) SSHTR--1-	Node number of the first inner fuel temperature just inside the clad in the radial mesh. (NN = NT - 1) (see NT)	
NOFULD	INPUT(14)	If NOFULD > 0 no fuel-dynamics calculation. If NOFULD ≤ 0 fuel dynamics will be calculated.	
NOMARS	INPUT(15)	If NOMARS > 0 no weak-explosion calculation. If NOMARS ≤ 0 weak explosion will be calculated.	
NOMATR	INPUT(29)	Number of entries in each material worth radial profile	
NOMR	INPUT(28)	Number of material-worth radial profiles	
NOPOWR	INPUT(27)	Number of entries in radial power shape	
NOREG	INPUT(9)	Number of regions to be used in Weak Explosion Module	
NR	HEAT(1185) SSHTR--1	Node number of the inner clad temperature in the radial mesh. (NR = NT + 1) (see NT)	
NRHOTB	INPUT(22)	Number of entries in the density table	
NS	COOL(2637) SSHTR--1	Node number of the structure temperature	
NSRMTB	INPUT(25)	Number of entries in the scram reactivity table	
NSRNO	INPUT(10)	Frequency of evaluation of volume and surface integrals and calculation of temperatures. (Used only if system is not prompt critical.)	
NT	INPUT(1)	Number of radial fuel temperature points. (see Fig. 2)	
NUC	INPUT(114)	Poisson's ratio for the cladding	REAL
NUS	INPUT(77)	Poisson's ratio for the fuel	REAL
NWAVE	IPL0T4(4) SSPRNT--8,920 TSPRNT--1300+,1307+ XPLODE--680	Number of entries in NWAVES	
NWAVES	IPL0T4(4) TSPRNT--1305,920 EXPLODE--680	Time step of either a power peak or a power valley	Dim = 30
NXN	INPUT(2554) INPOUT--490+	Number of axial regions in weak-explosion calculation	
NYLDTB	INPUT(24)	Number of entries in the cladding yield point table	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
P0	INPUT(265)	Maximum value of the inlet coolant pressure in the steady state. (atm)	
PBAR(J)	POWER(1) SHAPE--1	Value of the power at axial node J. (W)	Dim = 20
PCOOL(J)	COOL(604) SSCOOL--5+,6 TSCOOL--49+,54+,67+, 71+,76,78+,82+	Coolant pressure at axial node J. (atm)	Dim = 201
PDEC	INPUT(270)	Pump heat decay constant. (sec ⁻¹)	
PFAC(L)	INPUT(166)	Power factors in the phantom pins for coherent boiling. (PFAC(L) ≤ 1.0)	Dim = 3
PFINAL	INPUT(2025)	Minimum allowable normalized power in the Weak Explosion Module	
PFUEL(J)	DEF(401) DEFORM--18+,21+,24+, 17+,8,66	Relative pressure (above ambient) of the fuel at node J. (dyne/cm ²)	Dim = 20
PHI	POWER(21) TSPK--23+,28+,45 SSPK--1	Normalized power level at time	
PHI2(J)	HEAT(1190) TSHTR--31,54,55+	Heat flux between outer clad and coolant at node J. (W/cm ²)	Dim = 201
PHIBOI	POWER(52) TSPK--37	Power level at boiling	
PHIP	POWER(22) SSPK--2+ TSPK--40+	Power level at previous time step	
PHIPP	DUNTSP(1) TSPRNT--1,1309	Power level at 2 time steps previous	
PI	INPUT(2551) INPOUT--10	3.14159	
PIN	COOL(1210) SSCOOL--6 TSCOOL--39+,539	Inlet plenum pressure. (atm)	
PINTG0	POWER(8896) TSPK--10,43+,32+,45+	Integrated power at last time step. (J)	
PINTG	POWER(51) TSPK--10,27+,39+,43,45+	Integrated power at time. (J)	
PLENL	INPUT(35)	Length of plenum to be considered. (cm)	
PMAX	INPUT(262)	Maximum value of the peak nodal power in the steady-state power search. (W)	
PMIN	INPUT(261)	Minimum value of the peak nodal power in the steady-state power search. (W)	
POW	INPUT(151)	Value of the peak nodal power when steady-state power search is not done. (W)	
POWRR(I)	INPUT(2090)	Mesh for radial power shape. (cm) (see PSHAPR(J))	Dim = 20

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
POWZZ(J)	INPUT(2050)	Mesh for axial power shape. (cm) (see PSHAPZ(J))	Dim = 20
PPSUP	INPUT(2026)	Maximum normalized power allowed in weak-explosion calculation. (Normally used as a divergence check.)	
PRA(K)	INPUT(1061) (dyne/cm ²)	Coefficients of the equation of state of region K.	Dim = 60
PRB(K)	INPUT(1121) (°K)	Used by weak-explosion code	Dim = 60
PRC(K)	INPUT(1181) (-)	Pressure = $PRA * e^{(-PRB/TEMP + PRC)}$	Dim = 60
PSCRAM	INPUT(277)	Power level for scram initiation	
PSHAPE(J)	INPUT(131) INPOUT--645+,650,660,710	Axial power shape at node J, $1 \leq J \leq MZ$. (Not input if weak- explosion option is specified.) (Code will normalize.)	Dim = 20
PSHAPR	INPUT(2070) INPOUT--680+	Radial power shape at node I, $1 \leq I \leq NOPOWER$. (Code will normalize.) (cm ⁻³)	Dim = 20
PSHAPZ(J)	INPUT(2030) INPOUT--680+	Axial power shape at node J, $1 \leq J \leq MZS$. (Code will normalize.) (cm ⁻³)	Dim = 20
PX	INPUT(62)	Coolant exit pressure. (atm)	
PZERO	INPUT(152) INPOUT--685+,720 SSDRIV--19+	Total reactor power. (W)	
R(I,J)	MESH(285) SSHTR--5,9+,14+,15+,18+, 60+ DEFORM--42+,43,44+,45+, 46,49	Radial matrix in the pin for each node J. (cm)	Dim = 19,20
R0(I,J)	MESH(655) DEFORM--1+,2+	Steady-state radial matrix. (cm)	Dim = 19,20
RBR	INPUT(33)	Inner radius of the cladding. (cm)	
RDES(I)	MESH(1045) SSHTR--1	Radial equal volume spacing at design point for all axial nodes. (cm)	Dim = 19
REABOI	POWER(46) TSPK--10+ COOLFB--17+	Coolant reactivity at initiation of boiling. ($\Delta k/k$)	
REACOL(L)	POWER(8903) TSPK--10+,40	Coolant reactivity at time for main channel and 3 phantom channels. ($\Delta k/k$)	Dim = 4
READEN	POWER(8899) TSPK--10+ FUELFB--1 XPLODE--540+	Density reactivity at time. ($\Delta k/k$)	
READNP	POWER(8898) TSPK--10+,40+	Density reactivity at previous time step. ($\Delta k/k$)	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
READOP	POWER(8900) TSPK--10+ FUELF--1 XPLODE--420+	Doppler reactivity at time. ($\Delta k/k$)	
READPP	POWER(8897) TSPK--10+,40+	Doppler reactivity at previous time step. ($\Delta k/k$)	
REAPRG	POWER(8901) TSPK--11+,40+,28+	Programmed reactivity at time. ($\Delta k/k$)	
REASCM	POWER(8907) TSPK--10+,40+,28+	Scram reactivity at time. ($\Delta k/k$)	
REASTR	POWER(8902) TSPK--10+ COOLFB--1,15+	Structural reactivity at time. ($\Delta k/k$)	
REGRHO(K)	INPUT(821)	Density of region K in Weak Explosion Module. (gm/cm^3)	Dim = 60
RER	INPUT(34)	Outer radius of cladding at design point. (cm)	
RHO(I,J)	DEF(821) DEFORM--1+	Density matrix for radial nodes at each axial node J, steady-state conditions	Dim = 17, 20
RHOTAB(L)	INPUT(371)	Fuel density table as a function of temperature, RHOTEM. (gm/cm^3)	Dim = 20
RHOTEM(L)	INPUT(391)	Temperatures for fuel density table RHOTAB. (see RHOTAB(L)) ($^{\circ}\text{C}$)	Dim = 20
RINFP	INPUT(31)	Fuel-pin inner radius. (cm)	
RINS(K)	INPUT(521)	Inner radius of each region K used by Weak Explosion Module. (cm)	Dim = 60
RMAT(I)	INPUT(2510)	Radial entries for material-worth shapes. (see RMATW) (cm)	Dim = 20
RMATW(I,J)	INPUT(2110)	Radial material-worth distribution entries for each axial location, ZMAT. (see ZMAT(J)) ($\Delta k/k/\text{cm}^3$)	Dim = 20, 20
ROUTFP	INPUT(32)	Fuel-pin inner radius. (cm)	
ROUTS(K)	INPUT(581)	Outer radius of each region K used by Weak Explosion Module. (cm)	Dim = 60
RST	INPUT(64)	Thermal resistance of the structure. ($^{\circ}\text{C}\text{-cm}/\text{W}$) (see HSTR)	
SA(J)	POWER(54) COOLFB--6,9,16+	Void fraction at each axial node J	Dim = 20
SABOIL(J)	POWER(74) COOLFB--4	Void fraction at boiling initiation at each axial node J	Dim = 20
SC(J)	DEF(1724) DEFORM--13+,63	Relative slippage stress between clad nodes. (dynes/cm^2)	Dim = 20
SCRTAB(L)	INPUT(491)	Entries for scram reactivity table as a function of time, SCRTME. ($\Delta k/k$)	Dim = 10
SCRTIM	TIME(3) TSDRIV--4,1	Time since scram initiation. (sec)	
SCRTME(L)	INPUT(501)	Entries for time table as a function of scram reactivity, SCRTAB. (see SCRTAB(L)) (sec)	Dim = 10

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
SITG(L,K)	INPUT(541)	If SITG = 0.0 no surface effects. If SITG $\neq$ 0.0 surface effects will be computed. SITG(1, K) = inner surface of region K. SITG(2, K) = outer surface of region K. SITG(3, K) = upper surface of region K. SITG(4, K) = lower surface of region K.	Dim = 4, 60
SOC(J)	DEF(1623) DEFORM--4+	Clad yield stress at node J. (dynes/cm ²)	Dim = 20
SPRINK	INPUT(83)	Equivalent plenum spring constant. (dynes/cm)	
SREA(L)	POWER(8494) COOLFB--5,12	Coolant reactivity entries as a function of time for boiling coherence. (see STIME(L))	Dim = 400
SRR(L,J)	DEF(81) DEFORM--17+,18+,21+, 24+,28+,29+,32+,34+,37+, 38+,49	Stress matrix for each axial node J. SRR(1, J) = inner solid fuel stress. (dynes/cm ²). SRR(2, J) = outer solid fuel stress. SRR(3, J) = inner clad stress. SRR(4, J) = outer clad stress. SRR(5, J) = hoop stress of the clad. (A positive stress indicates tension.) (A negative stress indicates compression.) (See write-up for a further explanation of the stress meanings.)	Dim = 5, 20
SS(J)	DEF(1704) DEFORM--13,59	Relative node slippage stress in the solid fuel. (dynes/cm ²).	Dim = 20
STIME(L)	POWER(8094) COOLFB--11	Times entries for the coolant reactivity tables, SREA, and the average sodium-void table, SVOID. (sec) (see SREA(L) and SVOID(J, L))	Dim = 400
STREA1	INPUT(234)	Initial structural reactivity slope for fractional expansion past subassembly contact. (($\Delta k/k$)/($\Delta cm/cm$)) (see UMIN)	
STREA2	INPUT(235)	Final structural reactivity slope for fractional expansion beyond retaining ring. (($\Delta k/k$)/($\Delta cm/cm$)) (see UMAX)	
SVOID(J,L)	POWER(94) COOLFB--5,11	Average sodium void at each axial node J since boiling, for void table as a function of time. (see STIME)	Dim = 20, 400
T(I,J)	DEF(1163) DEFORM--5,6	Temperature rise since steady state. (°C)	Dim = 20, 20
T0	INPUT(61)	Coolant inlet temperature. (°C)	
T1(I,J)	HEAT(44) SSHTR--3,7+,8+,9+,10,20+, 21+,30,31,32+,34+,33,35,38, 41,44,46,50 TSHTR--6+,11+	Temperature at the last time step at each radial node, I, and for all axial nodes, J. (°C)	Dim = 20, 20
T2(I,J)	HEAT(784) TSHTR--3,5,8,11+,22+,23+, 34+,35,37+,39	Temperature at time at each radial node, I, and for all axial nodes, J. (°C) (Same as T(I, J) in Fuel Dynamics Module.)	Dim = 20, 20

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
T20(I,J)	HEAT(1391) TSHTR--14	Projected value of temperature, T2, used if a reevaluation is necessary. (°C)	Dim = 20, 20
TAUST	INPUT(56) INPOUT--880+	Equivalent thickness of the structure. (Volume of structure/surface area of structure) (cm)	
TBAR(J)	HEAT(1) SSHTR--60 TSHTR--24,25,26	Volumetric average fuel temperature at each axial node J. (°C)	Dim = 20
TCLM0	INPUT(264)	Maximum fuel centerline tempera- ture, T2(1, J), allowed in steady-state power search. (°C)	
TCLMAX	INPUT(272)	Maximum allowable centerline tem- perature, T2(1, J), allowed in pro- gram if no fuel dynamics or MARS is to be computed. If fuel-dynamics option is selected, TCLMAX is the centerline temperature for switching to it. (°C)	
TCOOL(J)	COOL(1) SSCOOL--4 TSCOO--12+,30,35+,70, 71,76+,78	Temperature of the coolant at axial node J. (°C)	Dim = 20
TDELT	DUMTSP(2) TSPRNT--950	Ratio of temperature changes for plots	
TF0(I,J)	HEAT(1871) DEFORM--1+,2+	Temperature at steady state for each radial node, I, for all axial nodes, J. (°C)	Dim = 18, 20
TFLOW(L)	INPUT(2655)	Time table as a function of nor- malized inlet flow. (see GFLOW(L)) (sec)	Dim = 10
TH(K)	INPUT(761)	Surface thickness of region K in Weak Explosion Module. (cm)	Dim = 60
TIMAX	INPUT(269)	Maximum allowable time in transient. (sec)	
TIME	TIME(1) SSPK--1 SSPRNT--8 TSDRIV--1,3	Total time in transient. (sec)	
TITLE(L)	INPUT(2575)	Neumonic run identification. (Hollerith)	Dim = 40
TMARS	INPUT(273)	Volumetric average temperature, TBAR(J), for weak-explosion ini- tiation. If weak-explosion option not specified, TMARS is the tem- perature for fuel-dynamics termination. (°C)	
TME	INPUT(110)	Melting temperature of the cladding. (°C)	
TMF	INPUT(71)	Melting temperature of the fuel. (°C)	
TR	INPUT(60)	Design-point reference temperature. (°C)	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
TREF(J)	HEAT(21) SSHTR--59+,63+	Volumetric average temperature at each axial node, J, at steady state. (°C)	Dim = 20
TS(J)	COOL(805) SSCOOL--7	Saturation temperature of the coolant at node J. (°C)	Dim = 201
TSB	COOL(1625) TSCOO--1+,18	Saturation temperature at the inlet liquid node nearest the 2-phase interface. (°C) (see EB in TSCOO subsection)	
TSCRAM	INPUT(275)	Coolant exit temperature for scram initiation. (°C)	
TSTRSS(J)	HEAT(1831) SSHTR--6+	Structure temperature at node J, at steady state. (°C)	Dim = 20
TX	INPUT(266)	Coolant exit temperature desired during steady-state power search. (°C)	
U(I,J)	HEAT(444) SSHTR--49+,50,51 TSHTR--34+,35+,36,38+,39+	Latent heat absorbed at each radial node, I, for all axial nodes, J. (J/gm)	Dim = 16,20
ULQTAB(L)	INPUT(2615) INPOUT--690+	Internal energy table as a function of temperature, CPTEM(L). Computed from specific heat table, CPTEM. (J/gm)	Dim = 20
UMAX	INPUT(233)	Fractional change in core radius for core to touch retaining ring	
UMELT	INPUT(72)	Latent heat of melting for the fuel. (J/gm)	
UMIN	INPUT(232)	Fractional change in subassembly diameter for subassemblies to come into contact	
UNB	COOL(1629) TSCOO--1+,18+,39+,55,69,70,90,93	Length of exit liquid slug. (cm)	
VELLSL	DUMCOL(2) TSCOO--64+	Initial velocity of lower (inlet) slug. (cm/sec)	
VELUSL	DUMCOL(1) TSCOO--64+	Initial velocity of upper (exit) slug. (cm/sec)	
VFC	INPUT(59)	Volume fraction of coolant. (Volume of coolant/volume of reactor)	
VFS	INPUT(67)	Volume fraction of additional material	
VILSL	COOL(2647) TSCOO--65+	Viscosity of inlet slug. (poises)	
VIUSL	COOL(2646) TSCOO--66+	Viscosity of exit slug. (poises)	
VLSL	COOL(2649) TSCOO--65+,73+,82+	Velocity of inlet slug. (cm/sec)	
VOIREA(J)	INPUT(212)	Reactivity for total voiding of axial node, J. ($\Delta k/k$)	Dim = 20

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
VREAT(L)	POWER(41) TSPK--12+,13,28+,32,39,40	Values of net reactivity at time. ($\Delta k/k/\text{sec}$). VREAT(3) = @ time + DT. VREAT(2) = @ time. VREAT(1) = @ time - DTP.	Dim = 3
VUSL	COOL(2648) TSCOO--66+,82,93	Velocity of the exit (upper) slug. (cm/sec)	
W(K)	INPUT(1481)	Ratio of the sonic velocity at region K to the sonic velocity at the base re- gion. The base region is normally region 1. (The ratio should approxi- mate 1.0, if 0.0 is input, 1.0 is assumed.)	Dim = 60 ~1.0
WCON(L,K)	INPUT(1781)	If WCON = 0.0 a surface integration is carried out that approximates the effect to an outer surface in the re- actor. If WCON $\neq$ 0.0 a surface in- tegration is carried out that approximates the effect of 2 regions contacting. (In this latter case only one of the 2 surfaces should be in- put, the other is then taken care of.) (Setup is same as SITG, see SITG(L, K).)	Dim = 4, 60
WDOP(J)	INPUT(192) INPOUT--710	Doppler weighting factor at axial node J. (Code will normalize.)	Dim = 20
WSTR(J)	INPUT(236) INPOUT--720	Structural-reactivity weighting fac- tor at axial node J. (Code will normalize.)	Dim = 20
X2(J)	COOL(2033) TSCOO--1+,12+,19+,26+, 31+,36,66+	Coolant quality at axial node, J	Dim = 201
X2F	COOL(1627) TSCOO--1+,24+	Coolant quality at 2-phase interface, inlet side	
XAC(J)	DEF(41) BOUND--1+ DEFORM--18,20,30,49	Clad inner radius including stresses. (cm)	Dim = 20
XAS(J)	DEF(1) BOUND--1+	Solid-fuel inner radius, including stresses. (cm)	Dim = 20
XBC(J)	DEF(61) BOUND--1+ DEFORM--49,30	Clad outer radius, including stresses. (cm)	Dim = 20
XBC1(J)	DEF(1663) DEFORM--10+,66,55	Clad outer radius, XBC; at last iteration. (cm) (see XBC(J))	Dim = 20
XBS(J)	DEF(21) BOUND--1+	Outer solid-fuel radius, including stresses. (cm)	Dim = 20
XBS1(J)	DEF(1643) DEFORM--10+,54,66	Outer solid-fuel radius, XBS, at last iteration. (cm) (see XBS(J))	Dim = 20
XKLIM	INPUT(2024)	Minimum value of effective multipli- cation factor in Weak Explosion Module	21.0

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
YLDTAB(L)	INPUT(451)	Clad yield point table as a function of temperature, YLDTEM. (dynes/cm ²)	Dim = 20
YLDTEM(L)	INPUT(471)	Temperature table for clad yield point, YLDTAB. (°C) (see YLDTAB(L))	Dim = 20
ZCENT	INPUT(520)	Distance from reactor base (point where ZFI(1) = 0.0) to core center. (cm) (see ZFI(J))	
ZCOOL(J)	MESH(42) INPOUT--10+,20	Axial matrix in the coolant channel. (cm)	Dim = 201
ZDNS(K)	INPUT(701)	Location of lower edge of region K, relative to the core center, ZCENT, used by Weak Explosion Module. (cm) (Input in ascending order.)	Dim = 60
ZEI(J)	MESH(264) DEFORM--42+	Height of cladding interface at segment J. (cm) (ZEI(1) = 0.0) (ZEI(MZ + 1) = top of clad considered.)	Dim = 21
ZFI(J)	MESH(21) INPOUT--10+ SSHTR--62 DEFORM--42+	Height of fuel interface at segment J. (cm) (ZFI(1) = 0.0) (ZFI(MZ + 1) = top of fuel considered.)	Dim = 21
ZFIO(J)	MESH(243) DEFORM--1	Steady-state value of fuel interfaces, ZFI. (cm) (see ZFI(J))	Dim = 21
ZFM(J)	MESH(1) INPOUT--1 SSHTR--63 DEFORM--42+	Height of center of mass at segment J. $ZFM(J) = [ZFI(J) + ZFI(J+1)]/2.0$ (cm)	Dim = 20
ZMAT(J)	INPUT(2530)	Axial location, relative to the core center (ZCENT), of the Jth radial material-worth profile. (cm) (see ZCENT and RMATW(I, J))	Dim = 20
ZUPS(K)	INPUT(641)	Location of the upper edge of region K, relative to the core center, ZCENT, used by the Weak Explosion Module. (cm) (Input in ascending order.)	Dim = 60

2. Local (Subroutine) Variables

a. SSHTR

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
ASI	SSHTR--68	Integral of linear thermal expansion: (cm ²) ($\int \alpha_{TR} dR$ from Ac to Bc)	
DELM	SSHTR--1-	Change in radial mesh due to melting. (cm)	
DELU	SSHTR--23+,27+	Increment of the latent heat. (J/gm)	
DZ	SSHTR--68+	Difference between ZFI's. (cm)	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
GA1	SSHTR--9,30	Assumed value of fuel outer radius in last iteration	
GA2	SSHTR--9,30	Assumed value of fuel outer radius in this iteration	
GC1	SSHTR--9,30	Calculated value of fuel outer radius in last iteration	
GC2	SSHTR--9,30	Calculated value of fuel outer radius in this iteration	
HB	SSHTR--32	Bond conductance. ($W/cm^2-^{\circ}C$)	
KTEST	SSHTR--4+,23+,27+,45+	Set of convergence criterion for use with steady-state melting. Converges by incrementing the latent heat.	
KTEST2	SSHTR--4+,25+,26+,27+,45		
KTEST3	SSHTR--4+,42,45+		
KTEST4	SSHTR--4+,36+		
KTEST5	SSHTR--4+,43		
NEPP	SSHTR--1-	Subscript of the inner clad temperature	
NNN	SSHTR--1-	Subscript of the second temperature in fuel. ($NT - 2$)	
Q(I)	SSHTR--6	Volumetric power-density * area to that point $Q = \int Pwr R * dR / \text{volume}$. (W/cm)	Dim = 20
T2SS(I)	SSHTR--13,40	Previous value of temperature at Ith node for the thermal-conductivity iteration. ($^{\circ}C$)	Dim = 20
T3SS(I)	SSHTR--7,39+	Previous value of temperature at Ith node for bond-gap iteration. ($^{\circ}C$)	Dim = 20
TB	SSHTR--30+	Bond-gap thickness. (cm)	
TCCLAD	SSHTR--63+,64+	Average value of clad temperature for adjustment of the coefficient of expansion. ($^{\circ}C$)	
TFUEL	SSHTR--63+,64+	Average value of fuel temperature for adjustment of the coefficient of expansion. ($^{\circ}C$)	
TN1	SSHTR--32+	Conductance temperature change, used to find fuel surface temperature. ($^{\circ}K$)	
TN2	SSHTR--32+	Radiation temperature change, used with TN1. ($^{\circ}K$)	
TNE	SSHTR--8,9+	Temporary storage of temperature in clad-temperature iteration. ($^{\circ}K$)	
TNN	SSHTR--34+	Temporary storage of temperature in fuel-surface-temperature iteration. ($^{\circ}K$)	
TNTP	SSHTR--30+	Previous temperature in bond-gap iteration. ($^{\circ}K$)	
XI	SSHTR--63+	Used to hold cross-sectional area when adjusting clad radius. (cm^2) ($R_{out}^2 - R_{in}^2$)	

b. TSHTR

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
A(I)	TSHTR--21,21+,55	Used in the Gauss elimination in the tridiagonal matrix; A is related to the coefficient of the solution. (see S)	Dim = 20
ALPHA(I)	TSHTR--1+,17+	Coefficient for the solution to the heat-transfer equations	Dim = 20
BETA(I)	TSHTR--19,20,20+,21+		Dim = 20
CON1	TSHTR--20+,21+	Constant from fuel-rod centerline boundary conditions	
GAME	TSHTR--20+	Average value of coolant heat-transfer coefficient over time step. ($W/cm^2-^{\circ}C$)	
GAMN	TSHTR--20+	Temporary storage of bond conductance * radius _{fuel} . ($W/cm-^{\circ}C$)	
H1(J)	TSHTR--2+,53+	Previous value of average coolant heat-transfer coefficient. ($W/cm^2-^{\circ}C$)	Dim = 20
HB	TSHTR--17+,18	Bond conductance at time and mode. ($W/cm^2-^{\circ}C$)	
HCBAR	TSHTR--53+,7+	Temporary storage for film heat-transfer coefficient. ($W/cm^2-^{\circ}C$)	
NCOOL	TSHTR--53+,7+	Number of coolant nodes per fuel node	
NCPP	TSHTR--1-	Subscript of temperature at inner clad radius	
Q(I)	TSHTR--16	Volumetric power density * area to that point $Q(I) = \int P * R * dR$. (W/cm)	Dim = 20
S(I)	TSHTR--21+,22,22+	S is related to the constants on right side of equation. (see A and theory)	Dim = 20
SYN	TSHTR--17+,18+	Radial heat transfer = $SYN * K * E$. $SYN = T_{fuel}^4 - T_{clad}^4$ ($^{\circ}C^4$)	
TB	TSHTR--17+	Bond thickness. (cm)	
TCBAR	TSHTR--53+,7+	Temporary storage of coolant temperature. ($^{\circ}C$)	
TEM	TSHTR--11+	Temporary storage of projected fuel temperature. ($^{\circ}C$) (usually equal to T2)	
TEP	TSHTR--23+	Temporary storage of outer clad ratio for fuel-surface-temperature calculation. ($^{\circ}C/sec$) ($2. * T_{clad outer} / \text{time step}$)	
TEPP	TSHTR--23+	Same as TEP but for clad inner ratio. ($^{\circ}C/sec$)	
THETE	TSHTR--20+	Temporary storage of conductivity ratio for fuel surface temperature calculation. ($W/cm-^{\circ}C$) ($2.0 * \text{thermal conductivity of clad} / \text{thickness}$)	
THETN	TSHTR--20+	THETE * Radius of outer clad. ($W/cm-^{\circ}C$) (see THETE and RER)	

c. SSCOOL

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
FI	SSCOOL--5+	Integral of coolant friction gradient	
FIB	SSCOOL--1	Temporary storage of mass flow rate squared	
FIBBER	SSCOOL--1	FIBBER = π *Hydraulic Diameter* Radius outer Clad*Mass Flow Rate	
FRGR	SSCOOL--4+	Friction gradient of coolant	
FRL	SSCOOL--4	Coolant liquid friction factor	
MO(J)	SSCOOL--5	Friction pressure gradient. (dynes/cm ²)	Dim = 201
QBAR(J)	SSCOOL--1,2,10	Linear power in coolant. (cm)	Dim = 201
V1L	SSCOOL--4+	Liquid viscosity of coolant. (poises)	

d. TSCOOL

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
A1(J)	TSCOOL--350	Coolant void fraction in previous time step	Dim = 201
A4(J)	TSCOOL--3	Heat flux (clad-coolant) on fuel mesh before boiling extrapolated heat-transfer flux after boiling	
B(J)	TSCOOL--19+	Liquid-vapor density ratio	Dim = 201
C(J)	TSCOOL--26+,93+	Coefficient from Martinelli flow parameters	Dim = 201
CMF	TSCOOL--24+	Coefficient at inlet liquid 2-phase interface. (see C(J))	
C ϕ	TSCOOL--1+,31+	Percent error in void-fraction iteration	
DAV1(J)	TSCOOL--350,12+,35+	Density at previous time step. (gm/cm ³)	Dim = 201
DAV2F	TSCOOL--24+	Value of average density at inlet 2-phase interface. (gm/cm ³)	
DELTHF	TSCOOL--68	Time step 2.0. (sec)	
DEP1(J)	TSCOOL--4,20+	Coefficient in void equation at last time step. (gm/cm ³)	Dim = 201
DEP2F	TSCOOL--20+,24+	Coefficient in void equation. (gm/cm ³)	
DL1(J)	TSCOOL--350	Liquid density at last time step. (gm/cm ³)	Dim = 201
DPLSL	TSCOOL--93	Driving pressure on inlet slug. (dynes/cm ²)	
DPUSL	TSCOOL--93	Driving pressure on exit slug. (dynes/cm ²)	
DTCHEK	TSCOOL--42+,43+	Time step as boiling is approached. (sec) At boil - 100°C DTCHEK = 0.1 sec. At boil - 50°C DTCHEK = 0.01 sec.	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
EB	TSCOO--17+	Movement of inlet interface at time. (cm)	
ESTX	TSCOO--21	Quality from last iteration at initial boiling point	
FI	TSCOO--37	Integral of coolant friction gradient in space	
FRGR(J)	TSCOO--12+,29+,35+	Total friction gradient in the coolant	Dim = 201
FRGRL(J)	TSCOO--29+	Liquid friction gradient in the coolant	Dim = 201
FRL(J)	TSCOO--12+,29+,35+	Liquid friction factor in the coolant	Dim = 201
FRLLSL	TSCOO--68+	Liquid fraction factor in lower (inlet) slug	
FRLUSL	TSCOO--68+	Liquid friction factor in upper (exit) slug	
G1(J)	TSCOO--350	Mass flow rate at last time step (gm/cm ² -sec)	Dim = 201
HL1(J)	TSCOO--350	Coolant enthalpy at last time step. (W/gm)	Dim = 201
HVA1(J)	TSCOO--350	Coolant enthalpy of vaporization at last time step. (W/gm)	Dim = 201
JDELT	TSCOO--1+,31+,70+,75	Number of 2-phase vapor nodes passed in motion	
KL	TSCOO--38+,80+	Thermal conductivity of the coolant. (W/cm-°C)	
MO(J)	TSCOO--12+,29+,35+	Two-phase velocity head	Dim = 201
NBL1	TSCOO--4,73	Inlet liquid slug length at last time step. (cm)	
SIG(J)	TSCOO--26+,27	Time rate of change of average den- sity in space. ((gm/cm ³)cm/sec)	Dim = 201
SIGF	TSCOO--24	SIG(J) at the inlet 2-phase interface. ((gm/cm ³)cm/sec) (see SIG(J))	
SSIG	TSCOO--21+,28	Change in average mass flow rate slug length/mesh size. (gm/cm ² -sec)	
SUSIG(J)	TSCOO--7+,10+,12+,26, 27,35	Average mass flow rate minus G2(J). (gm/cm ² -sec)	Dim = 201
SUSIGF	TSCOO--24,25	Average mass flow rate minus G2F at inlet liquid 2-phase interface. (gm/cm ² -sec)	
TCHECK	TSCOO--42,43	Temperature for time step change near boiling. (°K) (see DTCHEK)	
U1	TSCOO--7+,10+,33+	Temporary storage of last time- step value of time rate of change of mass flow rate. ((gm/cm ² -sec)sec/cm)	
U2	TSCOO--7+,10+,33+	Temporary storage of present value of time rate of change of mass flow rate. ((gm/cm ² -sec)sec/cm)	
U3	TSCOO--7+,10+	Temporary storage of time step/ mesh space. (sec/cm)	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
VIG(J)	TSCOOL--19+	Viscosity of coolant vapor. (poises)	Dim = 201
VIL(J)	TSCOOL--12+,19+,35	Viscosity of coolant liquid. (poises)	Dim = 201
X1(J)	TSCOOL--350	Vapor quality at last time step	Dim = 201

e. DEFORM

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
ACI(J)	DEFORM--9+	Integral of αTR dr across the clad at node J. (cm^2)	Dim = 20
ASSI(J)	DEFORM--8+,9+	Integral of αTR dr across the solid fuel at node J. (cm^2)	Dim = 20
D1 D2 D3 D4 D5 D6	DEFORM--16+	Constants used to determine fuel stresses after melting. (see writeup)	
FZS	DEFORM--16+,42+,54	Axial force on solid portion of fuel. (dynes)	
ICASE	DEFORM--26,27	If ICASE = 0 central hole with melting. If ICASE = 2 no melting.	
IMAX	DEFORM--10+	Maximum number of iterations allowed	IMAX = 30
IPLAS(J)	DEFORM--16+,18+,29+	Number of iterations of plastic flow	Dim = 20
K(J)	DEFORM--7,7+,8	Reciprocal of average compressibility of the molten axial fuel nodes. (gm^2/dyne)	REAL Dim = 20
KBAR(I,J)	DEFORM--6+	Reciprocal of average compressibility of each radial and axial nodes. (cm^2/dyne)	REAL Dim = 20,20
KMELT	DEFORM--7+,42,44	Internal storage for node number of radial melt	
RBAR(I,J)	DEFORM--6+	Radial mesh = $\frac{\text{Unstressed volume of a node}}{2.0\pi\Delta Z}$	Dim = 20,20
RHOBAR(I,J)	DEFORM--6+	Reciprocal of average fuel density. (cm^3/gm)	Dim = 20,20
SCI1	DEFORM--61+,62	(Upper) (see SCI2)	
SCI2	DEFORM--59+,60	(Lower) Force on consecutive nodes for slippage-stress calculation on the clad. (cm^2)	
SSI1	DEFORM--58,57+	(Upper) Force on consecutive nodes for slippage-stress calculation on the solid fuel. (cm^2)	
SSI2	DEFORM--55+,56	(Lower) (see SSI1)	
SUMXK	DEFORM--44+,47	Integral of compressibility with radius. (dynes/cm)	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
SUMXR	DEFORM--44+,47	Temporary storage of unstressed radius of a node. (cm)	
UAC	DEFORM--49+,17+,28+	Permanent change in inner clad radius. (cm)	
UDC	DEFORM--49+,17+,28+	Permanent change in clad thickness. (cm)	
UIC(J)	DEFORM--54+	Integral of percent change across the cladding $\int UR \, dR$. (cm ³)	Dim = 20
UIS(J)	DEFORM--54+	Integral of percent change across the solid fuel $\int UR \, dR$. (cm ³)	Dim = 20
URAC	DEFORM--17+,18+,28+,29+	Change in clad inner radius during plastic flow. (cm)	
X1	DEFORM--42+	Storage for solution of arbitrary constant C1S in surface equations	
X2	DEFORM--42+	Storage for solution of arbitrary constant C2S in surface equations	
ZFAC	DEFORM--42+	Axial expansion ratio at time (i.e., $\Delta Z(\text{INITIAL})/\Delta Z(\text{TIME})$)	

f. FULDYN

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
A(J)	DEF(381) FULDYN--310+,400+, 1900+,1920+	Acceleration of the upper interface of node J. (cm/sec ²)	Dim = 20
CC1(J)	DEF(601) FULDYN--320	Additive constant at node J to retain consistency in specific-volume equation when FULDYN is initiated. (°C)	Dim = 20
DC0(J)	DEF(441) FULDYN--320	Initial value of clad thickness at node J. (cm)	Dim = 20
DELZL(J)	DEF(681) FULDYN--1800+,1840	Average mass/area at interface J. (gm/cm ²)	Dim = 20
DQ(J)	DEF(361) FULDYN--310,400,1200+, 2290	Energy at node J in time. (J/gm)	Dim = 20
ELAST(J)	DEF(521) FULDYN--320,400,1200	Modules of elasticity*clad thickness at node J. (gm/cm)	Dim = 20
H(J)	HEAT--(1791) FULDYN--200	Average value of coolant heat-transfer coefficient. (W/cm ² -°C)	Dim = 20
HO(J)	DEF(321) FULDYN--310	Initial values of height matrix. (cm)	Dim = 20
H1(J)	DEF(201) FULDYN--310+,400+,720+	Past value of height matrix. (cm)	Dim = 20
H2(J)	DEF(241) FULDYN--310+,400,660	Future value of height matrix in iteration. (cm)	Dim = 20
H3(J)	DEF(261) FULDYN--310-,400,2000, 2020,2040	Future value of height matrix. (cm)	Dim = 20

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
MOTION(J)	DEF(701) FULDYN--400+,1940+	Steps of motion at node J. MOTION(J) = -1 no motion. MOTION(J) = 0 start of motion. MOTION(J) > 0 total steps of motion.	Dim = 20
PFRIK(J)	DEF(481) FULDYN--1840+,1860	Dynamic friction factor at node J. (gm-wt/cm ²)	Dim = 20
PFUEL(J)	DEF(401) FULDYN--320+,400+, 1300+,1340+,1800+,2360+	Pressure at node J. (gm-wt/cm ²)	Dim = 20
PP3(J)	DEF(641) FULDYN--1300+	Pressure estimate at node J. (gm-wt/cm ²) (from IPASS = 1)	Dim = 20
RO(J)	MESH(665) FULDYN--310	Initial value of the fuel-clad interface radius. (cm) (Includes plastic flow if any.)	Dim = 20
R(NR,J)	MESH(285) FULDYN--320+,400+, 1300+,1340+,1800+	Radial mesh at interface at time. (cm)	Dim = 19,20
RP(J)	DEF(661) FULDYN--1300	Estimate of R(NR,J) at node J. (cm) (from IPASS = 1)	Dim = 20
SIGRR(J)	DEF(401) FULDYN--340+,400+,1575	Stress on the cladding at node J. (gm-wt/cm ²)	Dim = 20
STRENT(J)	DEF--541 FULDYN--320+,400+,1575+	Yield point of the cladding. (gm-wt/cm ²)	Dim = 20
TBAR(J)	HEAT(1) FULDYN--320+,400+, 1300+,1400+,1410,1200 2280+,2430+,2450	Volumetric average temperature of the fuel. (°C)	Dim = 20
T(NE,J)	HEAT(784) FULDYN--400+,1200+, 2280+	Clad average temperature. (°C) (Same as T2(NE,J) in transient.)	Dim = 19,20
T(NT,J)	HEAT(784) FULDYN--400+,1200+, 2280+	Fuel surface temperature. (°C) (Same as T2(NT,J) in transient.)	Dim = 19,20
UO(J)	DEF(301) FULDYN--320+	Initial energy of the fuel. (J/gm)	Dim = 20
V(J)	DEF(341) FULDYN--320+	Volume of fuel at node J. (cm ³)	Dim = 20
Z2(J)	DEF(281) FULDYN--320+,400+,600+, 1520+	Midpoint of axial node J. (cm)	Dim = 20
ZP3	DEF(621) FULDYN--720	Last value of the interface at node J. (cm)	Dim = 20

g. FULDYN 2

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
DELHT	FULDYN--320	Change in total height of core. (cm)	
DELQ	FULDYN--2220+,2240,2250	Total normalized heat added after clad rupture. (sec)	

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
DELQ1	FULDYN--2260	Normalized heat to be added at node J. (J/gm)	
DELROR	FULDYN--320+,1300+, 1340+,1360	Change in radius/initial radius of fuel	
DELTA1	FULDYN--1520+	Change in axial node height necessary to conserve mass. (cm)	
DQ3	FULDYN--520+,1260	Normalized heat added in time interval DT1. (sec)	
DQ4	FULDYN--520+	Normalized heat added in time interval DT2. (sec)	
DT1	FULDYN--100,430,1100+	Present time step. (sec)	
DT10	FULDYN--2420	Time left in step after rupture. (sec)	
DT2	FULDYN--500+	Remainder of time left if total step not a multiple of DT1. (sec)	
DT3	FULDYN--340+,420+	DT1 of last step. (sec)	
FUELM	FULDYN--300	Mass of fuel in upper blanket. (gm)	
HBOND	FULDYN--1200,2280+	Bond conductance. (W/cm-°C)	
IPASS	FULDYN--320,500,2060+	If IPASS = 1 heat is added. If IPASS = 2 recalculate last amount of heat added.	
ISTOP	FULDYN--300+,320+,400+, 720	If ISTOP = 1 clad rupture. If ISTOP = 0 no rupture.	
MZ10	FULDYN--300+	Upper blanket-core interface node	
MZ1	FULDYN--300+	Lower blanket-core interface node	
NUMDT	FULDYN--500+	Number of time steps in inner loop	
PINTG1	FULDYN--520	Value of normalized heat added at last step. (sec)	
PINTG2	FULDYN--520	Value of normalized heat added at time. (sec)	

h. TSPK

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
AQQ(L,L1)	TSPK--18+	Coefficients (L1) for algebraic equation (L) solving the kinetics differentials	Dim = 3, 3
BINT(L,L1,L2)	TSPK--17+	BETA*0 integral for equation (L), coefficient L1, and delay group L2. (See BETA(L) in common dictionary and 0(M, L2, N).)	Dim = 3, 3, 6
CBURN(L,L2)	TSPK--17+	Precursor delay for equation (L) and delay group L2	Dim = 3, 6
CDOT(L2)	TSPK--15+	Time derivate of precursor concentration of group L2	Dim = 6
CLAM(L2)	TSPK--15+	C(L2)*ALAM(L2) for group L2. (see C1L), ALAM(L) in common dictionary.)	Dim = 6

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
DEQ(L1)	TSPK--19+,39+	Determinant value for coefficient L1, uses Kramer's rule	Dim = 3
DT2	TSPK--15+,26	Local time step. (sec)	
DTIME	TSPK--14+,23+	Total time within TSPK (at end will equal total time step). (sec)	
EN(L4,L1)	TSPK--19+	Coefficient L1 flux in time parabola. L4 = 1 full-interval fit. L4 = 2 half- interval fit.	Dim = 2, 3
EPSILN	TSPK--20+,28	Error between using results of full- interval fit and extrapolation of half- interval fit.	
QMULT	TSPK--27,39+,45+	Average value of flux across time step DT	
REAT(L1)	TSPK--14+	Computed in FLTZ. Coefficients of parabolic fit of reactivity (VREAT) in time	
REAJ	TSPK--14+,23+	Current value of reactivity at time = DTIME	
SUMN	TSPK--14+,23+	Integral of power (flux) in time. (sec)	
T(L1,L2)	TSPK--1+	Temporary storage of partitioned time steps. (sec)	Dim = 8, 5

XPLODE

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
AK	XPLODE--410+	Coefficient in reactivity-insertion fit of previous values. ($\Delta k/k/\text{sec}$) ($\text{REA} = \text{DELKO} + \text{AK} * \text{TIME}.$) (see DELKO)	
CF(L)	XPLODE--540+,770+	Coefficients in parabolic fit of material-worth reactivity in time. ($\text{REAM} = \text{CF}(3) + \text{TIME} * (\text{CF}(2) +$ $\text{CF}(1) * \text{TIME}).$)	Dim = 3
CFD(L)	XPLODE--540+,810+	Coefficients in parabolic fit of Doppler reactivity in time. ($\text{READ} = \text{CFD}(3) + \text{TIME} * (\text{CFD}(2) +$ $\text{CFD}(1) * \text{TIME}).$)	Dim = 3
DDDR(I,J,K)	XPLODE--320	Radial gradient of material worth by point and region. ($\Delta k/k/\text{Vol}/\text{cm}$)	Dim = 5, 4, 60
DDDZ(I,J,K)	XPLODE--310+	Axial gradient of material worth by point and region. ($\Delta k/k/\text{Vol}/\text{cm}$)	Dim = 5, 4, 60
DELK0	XPLODE--410+	Reactivity insertion at time = 0.0 as projected from last values. ($\Delta k/k$) ($\text{REA} = \text{DELKO} + \text{AK} * \text{TIME}.$) (see AK)	
DELQ	XPLODE--590+	Change in energy over the time step. (J)	
DELRS(K)	XPLODE--10	Radial mesh space in region K. (cm) ($\text{ROUT} - \text{RIN})/4.0$	Dim = 60

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
DELZS(K)	XPLODE	Axial mesh space in region K. (cm) (ZUP - ZDN/5.0)	Dim = 60
DFN(L)	XPLODE--540+,810+	Last 3 values of Doppler reactivity at time. ($\Delta k/k$)	Dim = 3
DK	XPLODE--580+,610+	Net reactivity at time. ($\Delta k/k$)	
DOPP0(K)	XPLODE--4204	Initial value of Doppler reactivity at region K. ($\Delta k/k$)	Dim = 60
DOPP(K)	XPLODE--580+,800+	Current value of Doppler reactivity at time at region K. ($\Delta k/k$)	Dim = 60
DPDRS(I,J,K)	XPLODE--230+,530+	Radial gradient of the power shape by point and region. (PWR(I, J, K)/cm) (see PWR(I, J, K))	Dim = 5, 4, 60
DPDZS(I,J,K)	XPLODE--230+,530+	Axial gradient of the power shape by point and region. (PWR(I, J, K)/cm) (see PWR(I, J, K))	
DPWRS(I,J,K)	XPLODE--310+	Material-worth reactivity by point and region. ($\Delta k/k/\text{Vol}$)	Dim = 5, 4, 60
DSDNS(J,K)	XPLODE--210+	Gradient of material worth across lower surface of region K. ($\Delta k/k/\text{Vol}/\text{cm}$)	Dim = 4, 60
DSINS(I,K)	XPLODE--210+	Gradient of material worth across inner surface of region K. ($\Delta k/k/\text{Vol}/\text{cm}$)	Dim = 5, 60
DSOUTS(I,K)	XPLODE--220	Gradient of material worth across outer surface of region K. ($\Delta k/k/\text{Vol}/\text{cm}$)	Dim = 5, 60
DSUPS(J,K)	XPLODE-200+	Gradient of material worth across upper surface of region K. ($\Delta k/k/\text{Vol}/\text{cm}$)	Dim = 4, 60
FF1	XPLODE--1060+	Value of second derivative of the material-worth feedback at calculation	
FFOUT	XPLODE--1060+	Value of FF1 at the last calculation. (see FF1)	
FN(L)	XPLODE--540+,770+	Last three (3) values of the material- worth reactivity in time	Dim = 3
IDBLE	XPLODE--610+,720	If IDBLE = 0 no change in time step. If IDBLE = 1 time step will be doubled.	
POWER(K)	XPLODE--340+,360+,440+, 450+	Power at region K. (W)	Dim = 60
PR(I,J,K)	XPLODE--380+,890+	Pressure by mesh point (I, J) and region K. (dynes/cm ²)	Dim = 5, 4, 60
PROTIM	XPLODE--580+,610	Time since steady state. (sec)	
PRTEMP	XPLODE--920,930,950, 960,990,1000,1020,1030	Temporary storage for pressure. (dynes/cm ²)	
PSDNS(J,K)	XPLODE--170+,530+	Normalized power gradient across the lower surface of region K	Dim = 4, 60
PSINS(I,K)	XPLODE--180+,520+	Normalized power gradient across the inner surface of region K	Dim = 5, 60

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
PSOUTS(L,K)	XPLODE--180+,520+	Normalized power gradient across the outer surface of region K	Dim = 5, 60
PSUPS(J,K)	XPLODE--170+,530+	Normalized power gradient across the upper surface of region K	Dim = 4, 60
PTEMP	XPLODE--540+,820+	Last value of the normalized power	
PWRS(I,J,K)	XPLODE--230+,530+	Normalized value of the power by mesh point and region	Dim = 5, 4, 60
QOUT	XPLODE--820+	Previous value of normalized energy, used for output. (sec)	
QQ0	XPLODE--880	Previous value of total energy. (J)	
QQ1	XPLODE--880+	Present value of total energy. (J)	
QTEMP	XPLODE--540+,810+	Previous value of normalized energy. (sec)	
RATIO	XPLODE--700+,710+	Ratio of successive values of power ratio. (≥ 1.0)	
REAP	XPLODE--410+	Programmed reactivity at time. ($\Delta k/k$)	
REAPP	XPLODE--410+	Programmed reactivity at last time step. ($\Delta k/k$)	
REARM	XPLODE--410+	Net reactivity (Doppler + Density + Programmed + Scram) at time. ($\Delta k/k$)	
REARMP	XPLODE--410+	REARM at previous time step. ($\Delta k/k$) (see REARM)	
REATIM	XPLODE--610+	Time since weak-explosion initiation. (sec)	
RIN(J)	XPLODE--10-	Radial mesh points in a region used with input to parabolic fits of power and worth. (cm)	Dim = 4
RINB	XPLODE--10-	Inner boundary of a region. (cm)	
ROUT	XPLODE--10-	Outer boundary of a region. (cm)	
RR(J)	XPLODE--20	Smoothed radial mesh points in a region used with output or parabolic fits. (cm)	Dim = 4
RRS(J,K)	XPLODE--180+	RR(I) for region K. (cm)(see RR(I))	Dim = 4, 60
SMBETA	XPLODE--420+	Summation of the precursor fractions	
SUMA(K)	XPLODE--900+	Second derivative of density reactivity in time due to volume effects for region K. ($\partial^2 k / \partial t^2$)	Dim = 60
SUMB(K)	XPLODE--910+,920+,930+,950+,960+,1000+,1020+,1030	Same as SUMA(K) only for surface effects. ($\partial^2 k / \partial t^2$) (see SUMA(K))	Dim = 60
SUMS	XPLODE--910+,1060+	Summation of SUMB(K) for all regions. ($\partial^2 k / \partial t^2$) (see SUMB(K))	
SUMV	XPLODE--910+,1050+	Summation of SUMA(K) for all regions. ($\partial^2 k / \partial t^2$)	
THBAR(K)	XPLODE--780+	Volumetric average temperature at region K at time. ($^{\circ}\text{K}$)	Dim = 60

Variable	Location in Common and Where Calculated	Definition and Units	Miscellaneous
THDN(J,K)	XPLODE--390+,980+	Temperature distribution across lower boundary of region K at time. (°K)	Dim = (4, 60)
THETO(K)	XPLODE--390+	Volumetric average temperature at region K at initiation of weak explosion. (°K)	Dim = 60
THETA(I,J,K)	XPLODE--380+,880	Temperature distribution by point and region at time. (°K)	Dim = 5, 4, 60
THET1(I,J,K)	XPLODE--380	Temperature distribution at weak- explosion initiation. (°K)	Dim = 5, 4, 60
THIN(I,K)	XPLODE--380+,910	Temperature distribution across inner boundary of region K at time. (°K)	Dim = 5, 60
THOUT(I,K)	XPLODE--380+,910	Same as THIN(K) only for outer boundary. (°K) (see THIN(K))	Dim = 5, 60
THUP(J,K)	XPLODE--390+,980	Same as THPN(K) only for upper boundary. (°K) (see THDN(K))	Dim = 4, 60
TM(L)	XPLODE--540+,770+	Values of time used in parabolic fits. (sec)	Dim = 3
TMAX	XPLODE--330+,340+	Maximum value of volumetric tem- perature in the fuel pin when MARS is initiated. (°C)	
TOTP	XPLODE--370+,380+	Total normalized reactor power	
VOL(K)	XPLODE--350+,360+	Volume of region K. (cm ³)	Dim = 60
X(L)	XPLODE--540+,590+,600+, 730+,820	X(1) = current time since steady state. (sec) X(2) = current time step. (sec) X(3) = maximum allow- able time allowed. (sec)	Dim = 3
XKDOPL	XPLODE--570+,610+,810	Doppler reactivity. ($\Delta k/k$)	
Y(L)	XPLODE--540+,590+,600+, 610+	Y(1) = 0.0. Y(2) = net reactivity at time + DT. Y(3) = normalized power at time. Y(4) = normalized energy at time.	Dim = 10
ZDN	XPLODE--10	Lower boundary of a region. (cm)	
ZIN(I)	XPLODE--10+	Axial mesh points in a region used with input for parabolic fits of power and worth. (cm)	Dim = 3
ZUP	XPLODE--10	Upper boundary of a region. (cm)	
ZZS(I,K)	XPLODE--190	Smoothed axial mesh points used with output of parabolic fits in a region. (cm)	Dim = 5

REFERENCES

1. B. J. Toppel *et al.*, *The Argonne Reactor Computation (ARC) System*, ANL-7332 (Nov 1967).
2. D. F. Schoeberle, J. Heestand, and L. B. Miller, *A Method of Calculating Transient Temperatures in a Multiregion, Axisymmetric, Cylindrical Configuration. The ARGUS Program, 1089/RE 248, Written in Fortran II*, ANL-6654 (Nov 1963).
3. J. N. Fox *et al.*, *FORE-II, A Computational Program for the Analysis of Steady State and Transient Reactor Performance*, GEAP-5273 (Sept 1966).
4. M. Lees, "An Extrapolated Crank-Nicholson Difference Scheme for Quasi-linear Parabolic Equations," *Proceedings of the Symposium on Non-Linear Partial Differential Equations*, edited by W. F. Ames, Academic Press (1966).
5. L. H. Back, *Technical Brief, Numerical Approximation of the Convective Boundary Condition*, Trans. ASME J. of Heat Transfer, p. 82 (Feb 1962).
6. J. E. Meyer, *Hydrodynamic Models for the Treatment of Reactor Thermal Transients*, Nucl. Sci. Eng. 10(3) (1961).
7. P. A. Lottes, *Nuclear Reactor Heat Transfer*, ANL-6469 (Dec 1961).
8. R. W. Lockhart and R. C. Martinelli, *Proposed Correlation of Data for Isothermal Two-phase Two-component Flow in Pipes*, Chem. Engr. Prog. 45, No. 1 (1949).
9. G. Birkhoff and T. F. Kimes, *CHIC Programs for Thermal Transients*, WAPD-TM-245 (1962).
10. J. E. Meyer and R. P. Rose, *Application of Momentum Integral Model to Study of Parallel Channel Boiling Flow Oscillations*, ASME J. Heat Transfer (Feb 1963).
11. S. Timoshenko, *Theory of Plates and Shells*, McGraw-Hill Book Co., New York (1940).
12. R. O. Brittan, *Some Problems in the Safety of Fast Reactors*, ANL-5577, p. 7 (1956).
13. J. J. Kaganove, *Numerical Solution of the One-group Space-independent Reactor Kinetics Equations for Neutron Density Given the Excess Reactivity*, ANL-6132 (Feb 1960).
14. N. Hirakawa, *MARS, A Two-Dimensional Excursion Code*, APDA-198 (June 1967).
15. R. B. Nicholson, *Methods for Determining the Energy Release in Hypothetical Reactor Meltdown Accidents*, APDA-150 (Dec 1962).
16. W. T. Sha and R. B. Nicholson, "Maximum Accident of Zoned Fast Reactors," *Reactor Physics Division Annual Report, July 1, 1967 to June 30, 1968*, ANL-7410, pp. 286-290 (Jan 1969).
17. E. P. Hicks and D. C. Menzies, "Theoretical Studies on the Fast Reactor Maximum Accident," *Proceedings of the Conference on Safety, Fuels, and Core Design in Large Fast Power Reactors, October 11-14, 1965*, ANL-7120, pp. 654-670.
18. W. T. Sha and T. H. Hughes, *VENUS, A Two-dimensional Coupled Neutronics-Hydrodynamics Fast Reactor Power Excursion Computer Program*, ANL-7701 (Oct 1970).