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FORE II
A COMPUTATIONAL PROGRAM FOR THE ANALYSIS OF STEADY-STATE AND TRANSIENT REACTOR PERFORMANCE

J. N. FOX
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U.S. ATOMIC ENERGY COMMISSION
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GENERAL ELECTRIC
SUNNYVALE, CALIFORNIA

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SECTION I

SUMMARY

FORE II is a coupled thermal hydraulics - point kinetics digital computer code designed to calculate significant reactor parameters under steady-state conditions, or as functions of time during transients. The transients may result from a programmed reactivity insertion or a power change. Variable inlet coolant flow rate and temperature are considered. The code calculates the reactor power, the individual reactivity feedbacks, and the temperature of coolant, cladding, fuel, structure, and additional material for up to seven axial positions in three channel types which represent radial zones of the reactor. The heat of fusion accompanying fuel melting, the liquid metal voiding reactivity, and the spacial and the time variation of the fuel cladding gap coefficient due to changes in gap size are considered. FORE II is valid only while the core retains its initial geometry.

The significant material properties are specified in the input as functions of temperature or pressure, and the external effects as a function of time by tables. The feedback reactivity includes contributions due to the Doppler effect, density changes, dimensional changes (includes bowing and deformation), coolant voiding, and control rods. Any single-phase coolant may be used. Although the code is biased toward fast reactors, it can be used for a thermal spectrum reactor as a steady-state heat transfer code and as a transient point kinetics code.

The programming language is FORTRAN IV. A computer with a 32-K storage capacity is required for the operation of FORE II. This document contains a description of the physical model, required input, available options, curve plotting program, and programmed equations.

SECTION II

INTRODUCTION

FORE II was designed primarily to calculate the response of a reactor to a specified change of reactivity or power as a function of time for variable inlet coolant flow rate and temperature. Thus, accidents such as control rod withdrawal, coolant flow coast-down, or flow blockage can be readily analyzed. A study of the results from these analyses will (1) give insight into the temperature and thermal expansion effects expected of the core materials, (2) permit evaluation of potential reactivity feedback mechanisms, and (3) allow an evaluation of the effect of uncertainties in the kinetic parameters on the results. It is expected that the design of a reactor and its performance and safety characteristics will be intimately related. Ideally, the response of an initial design is analyzed; from this analysis, modifications and improvements are discovered which, in turn, refine the original design.

FORE II is a revision of the FORE I[1] code. In particular, FORE II offers the following major improvements over FORE I:

1. Increase in the allowable number of axial nodes from 5 to 7, and the number of radial fuel nodes from 8 to 10. The radial fuel nodes no longer must be equal volume cylinders.

2. Ability to calculate the heat transfer coefficient of fuel-cladding gap at any time step for all axial nodes as a function of surface roughness, type of gap gas, existing gap size, contact pressure (if any), and temperature, or the ability to set the coefficient equal to a constant.

3. Calculation of temperatures, heat fluxes, film coefficients, gap coefficients, and gap size for average, peak, and hot-spot channels.

4. Capability to input the inlet temperature and inlet coolant mass velocity as a function of time.

5. Consideration of heat transfer coefficient to or from the structure and additional material (such as BeO).

6. Specification of most material properties as a function of temperature by the use of tables that allow 20 property values corresponding to 20 temperature values. Many of these tables are built-in and need be considered only when an overlay of data is desired.

7. Calculation of film heat transfer coefficient for the cladding structure, and additional material at any time step as a function of conductivity of coolant, hydraulic diameter, Reynolds number, and Prandtl number.

8. More accurate projection of fuel temperatures over the core for Doppler calculations.

9. Ability to include a center void in the fuel pin.

10. Determination of the maximum time step size by the program, based on temperature stability requirements of the coolant, cladding, structure, additional material, or fuel.

11. Ability to include varying flux shapes within the fuel pin.

12. Capability to specify power as a function of time.

13. Plotting by computer of temperatures and power as a function of time, and of desired temperatures as a function of radial or axial position for any channel types.

14. Restart with changes in input from any of three wrapups at specified times.

15. Greatly increased edit flexibility.

16. Separation of power into prompt power and total power (includes decay heat).

17. Calculation of core average fuel temperatures and Doppler weighting factors.

18. Ability to include coolant reactivity effects as a function of time, with start of reactivity insertion based on specified bulk or coolant temperatures versus pressure or fuel center temperatures.

19. Capability to include specified film coefficients in axial sections where sodium voiding has started.

20. Inclusion of scram reactivity effects as a function of time, with start of reactivity insertion based on specified coolant temperature value or power level.

21. Ability to specify the location of the average nodal coolant temperature for axial nodes; that is, the average need not be the center of the node.

22. Inclusion of fuel bowing and core deformations due to axial pressure difference in radial feedback reactivity effect.

23. Capability to specify core radial power shape.

24. Calculation of inner surface average and outer surface cladding temperature.

25. Ability to handle correctly the variation of coolant flow rate in orificed and unorificed channels during a coastdown accident.

26. Capability to use any single-phase coolant.

27. Capability to use code for non-fast neutron spectra.

28. Expanded error messages.

The wrapup and restart capability extends the flexibility of FORE II more than may be apparent. The power shape, neutron lifetime, or reactivity coefficients, for example, are non-time-dependent inputs in FORE II However, time dependence for these types of inputs can be approximated to any degree of accuracy, using restarts and repeatedly running for a specified time step and taking a step change in value.

The voiding effect for liquid metal coolants is simulated by a voiding reactivity versus time curve, and by a decrease of the film coefficient to a low, specified number. The void propagation pattern must be determined separately and converted to a reactivity effect for input to FORE II.[2] Initiation of this feedback is based on a specific temperature and pressure.

SECTION III

PHYSICAL MODEL

3.1 FLOW CHART

This section contains an explanation of the physical model, with the aid of mathematical equations. The complete, detailed equations that are programmed are contained in Appendix D, omitting discussion on the merits of the formulation. The nomenclature used to describe the physical model and detailed equations is found in Appendix A.

Figure 3-1 is the flow chart for FORE II. The flow chart, physical model, and detailed equations are divided into the subroutines which compose the program.

3.2 NODAL REPRESENTATION

In the radial direction, the core is represented by three channel types: average, peak, and hot-spot. The radial power peaking factors for the peak and hot spot channels are input. In the normal operating procedure, the peak channel will represent the center region of the core and the average channel the region of the core at a radius near the mid-volume point. Because of additional and separate peaking factors (such as for the film coefficient, cladding thermal conductivity, gap coefficients, and fuel thermal conductivity) available for the hot-spot channel, the channel can be treated as a region of the core where statistically the worst combination of variables may occur beyond the normal axial and radial peaking factors. Another use of the hot-spot channel is to set the radial peaking factor at a value to provide a third data point for hand-plotting of core radial variables.

Within each channel, the basic heat transfer model involves one-dimensional radial conduction and convection. No axial heat transfer is considered other than the mass transport effect associated with the flowing coolant. A single fuel pin is divided into a maximum of seven axial nodes. Each axial node is divided into radial rings consisting of structure and additional material, coolant, cladding, gap, and fuel, with a maximum of ten fuel rings. The structure and additional material are effectively two separate heat sinks (or sources) in contact with the coolant but otherwise undefined in their exact physical location. Figure 3-2 indicates the nodal model for a typical channel type.

3.3 INPUT OF PROPERTY DATA

Several different techniques are used to input the required property data. The most widely-used technique is the table form. In this approach, 20 values of the dependent variable, corresponding to 20 values of the independent variable, can be supplied. The following tables are built into FORE II and need be considered only when an overlay of the data is desired:

Thermal conductivity of sodium
Coefficient of expansion of sodium
Dynamic viscosity of sodium
Specific heat of sodium
Density of sodium

—vs Temperature

The built-in values are listed in Appendix B of this report. These values can be overlayed by the appropriate input cards indicated in subsection 4.3.

The following tables are supplied by the user:

- Thermal conductivity of fuel (quadratic fit also available)
- Specific heat of fuel

—vs Temperature

- Coolant bulk boiling temperature
- Cladding burnout temperature

—vs Pressure

- Coolant mass velocity
- Coolant inlet temperature
- Effective multiplication factor or normalized power
- Δk due to sodium voiding
- Δk due to scram

—vs Time

Not all of these tables are required for every computer calculation.

The remaining property data are supplied by a quadratic fit equation or as single values. Linear interpolation is used for all the tables to find property data at intermediate values.

3.4 STEADY-STATE CALCULATIONS (INIT Subroutine)

Finite difference techniques are used to calculate the temperature profile in the cladding and the fuel for steady state, even though exact solutions are available. For the transient temperature calculations, the only method available is finite difference By using the finite difference approach in steady state, a discontinuity in temperature between steady state and the first time step is avoided.

Consider the case of a steady-state transient where the effective multiplication constant, k, is set equal to 1.0 at 0 and 10 seconds. When this problem is calculated with FORE II, all the temperatures, heat transfer data, and feedbacks remain at their steady-state value, which is physically correct. If exact temperature solutions are used for steady state, the discontinuity in temperature will introduce feedback reactivity which, in turn, causes the power and then the temperature to change further. The net result is a numerically unstable solution. For typical ramp reactivity insertion, the danger of using exact heat transfer equations for steady state is that the true solutions could be overpowered by a growing temperature error.

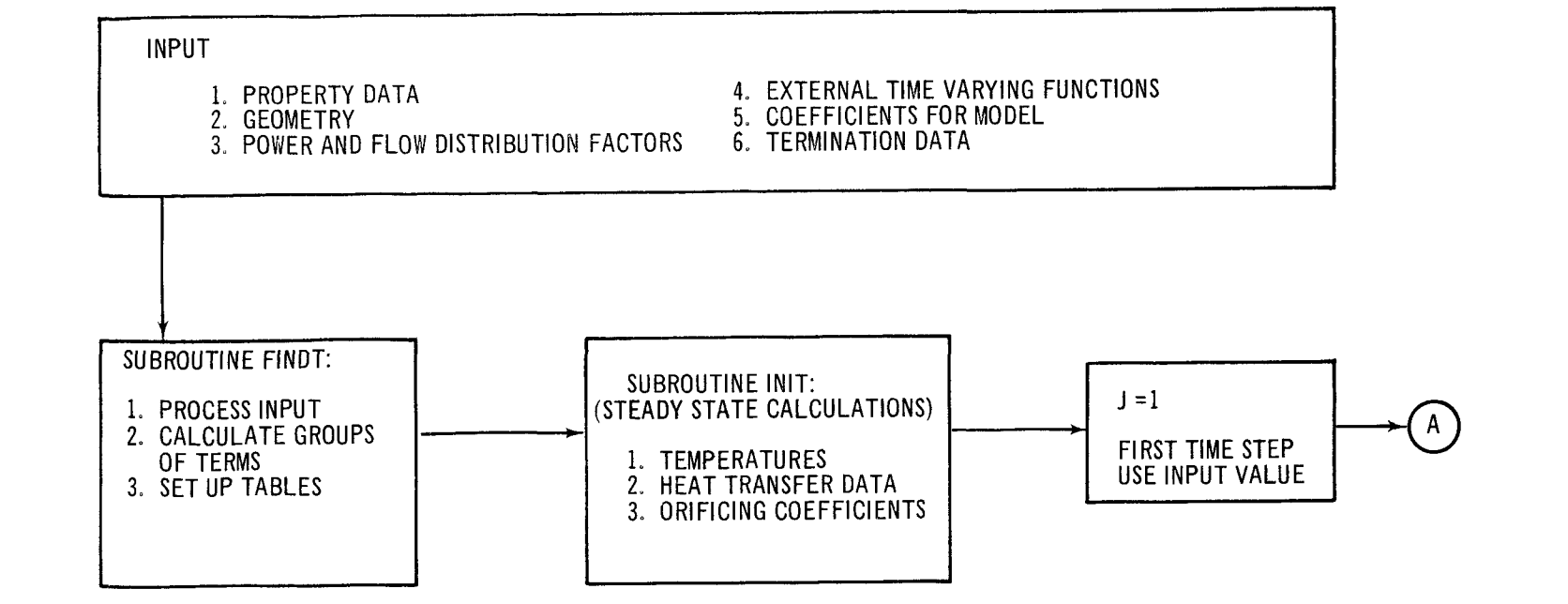


FIGURE 3-1. FLOW CHART OF FORE II

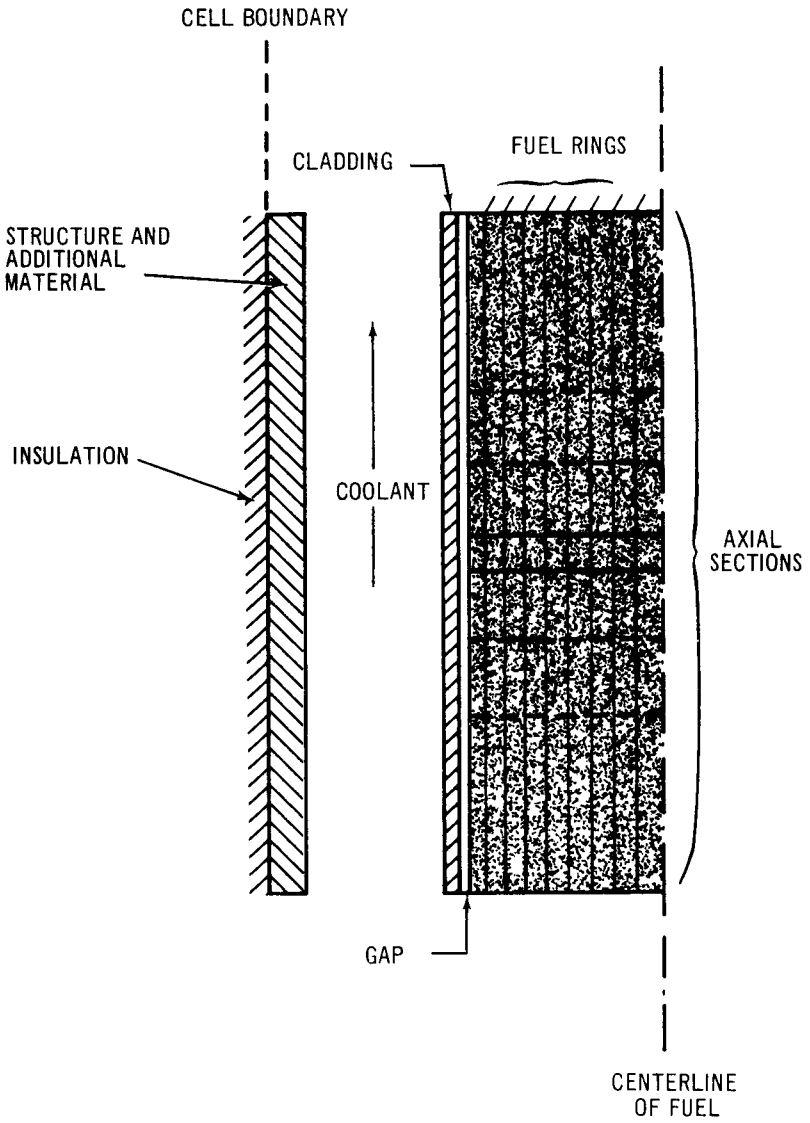


FIGURE 3-2 CROSS SECTION OF A CHANNEL

As an example, the exact solution for the temperature difference between the inner surface of the cladding (T_e at R_e) and the outer surface (T_E at R_E) is

$$T_e - T_E = \frac{\ln \frac{R_E}{R_e}}{2\pi K_e} \left[Q_f A_f - Q_e \pi R_e^2 \right] + \frac{Q_e}{4K_e} \left(R_E^2 - R_e^2 \right) . \quad (1)$$

In the finite difference approximation, all the heat generated in the cladding is assumed to be generated at the volumetric average radius, R_a. The resulting finite difference equation is

$$T_e - T_E = \frac{\ln \frac{R_E}{R_e}}{2\pi K_e} Q_f A_f + \frac{\ln \frac{R_E}{R_a}}{2\pi K_e} Q_e A_e , \quad (2)$$

where

$$R_a = \left(\frac{R_E^2 + R_e^2}{2} \right)^{\frac{1}{2}} . \quad (3)$$

For typical values of radii and gamma-neutron heating in the cladding, the error in the finite difference approximation is on the order of 2 °F.

The heat transfer equations discussed in the physical model will be those where the cladding, structure, additional material, and coolant are treated as separate temperature regions; that is, the no-lumping option. The detailed equations can be consulted for the heat transfer equations for the lumping option.

3.4.1 Coolant Temperature

An initial guess of the steady-state specific heat $C^0_{c,m,k}$ for the coolant is made by FORE II, based on programmed techniques. The subscripts c, m, k represent coolant, particular axial node, and channel type, respectively. The superscript 0 represents time zero or steady state.

The coolant temperature at every axial node is of the form

$$\text{Temp at node} = \text{Inlet temp of node} + \frac{\text{Energy generated at node location (Btu/sec)}}{\text{Heat capacity (Btu/sec °F)}} , \quad (4)$$

or symbolically,

$$T^0_{c,m,k} = T^{in\ (0)}_{c,\ m,\ k} + \frac{(PCON)\Lambda_m\ P^0_o\ A_f\ \lambda_a\ \Delta Z_m}{G^0_{c,k}\ C^0_{c,m,k}\ A_c} . \quad (5)$$

The λ_a input is the fractional distance from the inlet to the nodal location. PCON reflects the peaking condition for the channel type. The outlet temperature for each node is

$$T^{Out}_{c,m,k} = \overbrace{T^{0}_{c,m,k}}^{\text{Nodal}} + \overbrace{\left(T^{0}_{c,m,k} - T^{In\,(0)}_{c,m,k}\right) \frac{1-\lambda_a}{\lambda_a}}^{\text{Temp rise in node to outlet}} \quad . \tag{6}$$

Equations (5) and (6) combined imply that there is a linear relationship for each node between the inlet, nodal, and outlet temperatures. The outlet temperature for node m is set equal to the inlet for node m + 1. In this manner, the axial temperature profile in the coolant is calculated. Based on the calculated temperatures, new values for the coolant specific heat are estimated for all axial locations. This iterative process is continued until the temperature changes between iterations is within specified limits. The average temperature for a node is the arithmetic average of the final inlet and outlet temperatures and is the same as the nodal temperature for λ_a of 0.5. Nodal coolant temperature is given by $T_{c,m,k}$, average by $\overline{T}_{c,m,k}$.

3.4.2 Heat Generation Rates

The internal heat generation in different core materials due to neutron-gamma heating is estimated based on a mass weighting. The common weighting factor is

$$MULT = \frac{A_m F_\gamma A_f}{\rho_f A_f + \rho_e A_e + \rho^{0}_{c,m,k} A_c + \rho_s V_s + \rho_u V_u} \quad (ft^3/lb). \tag{7}$$

The fraction of the total neutron-gamma heating that occurs in the coolant, for example, is

$$(QU)_{c,m,k} = (MULT)\, \rho^{0}_{c,m,k}\, (PCON) \qquad \text{(Dimensionless)} \quad . \tag{8}$$

Similar equations hold for the cladding, structure, and additional material.

The total fraction of the heat produced in the fuel (due to both fission and neutron-gamma) becomes

$$(QU)_{f,m,k} = \overbrace{A_m(PCON)}^{\text{Nodal Total}} - \overbrace{\frac{A_e}{A_f}(QU)_{e,m,k}}^{\text{Cladding}} - \overbrace{\frac{A_c}{A_f}(QU)_{c,m,k}}^{\text{Coolant}} - \overbrace{\frac{V_s}{A_f}(QU)_{s,m,k}}^{\text{Structure}} - \underbrace{\frac{V_u}{A_f}(QU)_{u,m,k}}_{\text{Additional Material}} \qquad \text{(Dimensionless)} \quad . \tag{9}$$

The ratio of power production per unit volume in fuel radial node n to average power production per unit volume for the fuel is given by

$$(QU)_{n,m,k} = Y_n\, (QU)_{f,m,k} \qquad \text{(Dimensionless)} \quad . \tag{10}$$

Note that the Y's should be selected so that

$$\sum_{n=1}^{N} Y_n A_n = A_f \qquad (ft^2). \tag{11}$$

For a flat flux distribution, as is common in a fast reactor, Y_n is 1.0 (n = 1 to N).

The heat generation rate per unit volume P_o^0 is calculated from the input power (P_{in} mw) and fuel volume (V_f ft^3) by

$$P_o^0 = 948.05 \frac{P_{in}}{V_f} \quad (Btu/sec\text{-}ft^3) \ . \tag{12}$$

The heat generation rate in the fuel is

$$Q^0_{f,m,k} = (QU)_{f,m,k} P_o^0 \quad (Btu/sec\text{-}ft^3) \ . \tag{13}$$

Analogous equations hold for the other materials as well as each fuel ring, n.

3.4.3 Film Coefficients

A coolant film coefficient is calculated for the cladding, structure, and additional material by a model of the form,

$$h = \frac{\text{Thermal Conductivity}}{\text{Hydraulic Diameter}} \left[\text{Constant + Function Re and Pr numbers} \right] \ . \tag{14}$$

For the cladding, the particular equation is

$$h^{*0}_{c,m,k} = \frac{K^0_{c,m,k}}{D_{HT}} \left[A_H + C_{H,m} Re^{M_H} Pr^{N_H} \right] F^* \ , \tag{15}$$

where

$$Re = \frac{D_{HT} G^0_{c,k}}{\mu^0_{c,m,k}} \qquad \text{(Reynolds number)} \ , \tag{16}$$

and

$$Pr = \frac{\mu_{c,m,k} C^0_{c,m,k}}{K^0_{c,m,k}} \quad \text{(Prandtl number)} \tag{17}$$

The film coefficient for the cladding of Equation (15) is modified by

$$h^0_{c,m,k} = h^{*0}_{c,m,k} \left[\frac{\bar{T}^0_{c,m,k} + 460}{T^0_{E,m,k} + 460} \right]^{R_H} . \tag{18}$$

The film coefficient for the structure and additional material ($g^0_{c,m,k}$) is calculated by an equation similar to Equation (15) with the input $C_{H,m}$ replaced by the non-axial dependent quantity B_H. The axial variation of the input coefficient $C_{H,m}$ for the cladding allows the user to account properly for film trippers along the axial length in a steam-cooled system.

3.4.4 Structure and Additional Material Temperature

The structure temperature is calculated by

$$\begin{aligned} \text{Temp Structure} = {} & \text{Temp Coolant} + (\text{Heat Gen. by n,}\gamma \text{ reaction}) \\ & \times (\Sigma \text{ Convection and Conduction Resistance}) \end{aligned} \tag{19}$$

or symbolically,

$$T^0_{s,m,k} = \bar{T}^0_{c,m,k} + \left(\frac{1}{g^0_{c,m,k}} + \frac{d_s}{K_s} \right) \frac{Q^0_{s,m,k}}{G_s} . \tag{20}$$

The equation for additional material is the same as Equation (20), with subscript s replaced by u.

3.4.5 Cladding Temperature

The temperature of the outer cladding is found by using the fundamental heat convection equation, and by including both the total heat generation in the fuel and in the cladding. Thus, the outer cladding temperature is

$$T^0_{E,m,k} = \bar{T}^0_{c,m,k} + \frac{1}{2\pi R_E h^0_{c,m,k}} \left[Q^0_{f,m,k} A_f + Q^0_{e,m,k} A_e \right] . \tag{21}$$

A new film coefficient is calculated, based on a revised T_E and this iterative process is continued until the cladding surface temperature between iterations is within the specified limit.

The cladding radius at which the volume averaged temperature exists is

$$R_a = \sqrt{\frac{(\text{Radius out})^2 + (\text{Radius in})^2}{2}} = \sqrt{\frac{R_E^2 + R_e^2}{2}} . \tag{22}$$

By the standard one-dimensional heat transfer relationship, the temperature of the cladding at this location is

$$T^0_{a,m,k} = T^0_{E,m,k} + \frac{\ln\left(\frac{R_E}{R_a}\right)}{2\pi K_e} \left[Q^0_{f,m,k} A_f + Q^0_{e,m,k} A_e \right] . \quad (23)$$

In a similar manner, the temperature at the inner surface of the cladding is given by

$$T^0_{e,m,k} = T^0_{a,m,k} + \frac{\ln\left(\frac{R_a}{R_e}\right)}{2\pi K_E} \left[Q^0_{f,m,k} A_f \right] . \quad (24)$$

Note that all the heat generated in the cladding is assumed to occur at radius R_a .

3.4.6 Fuel Temperatures

FORE II contains the option that the fuel cladding gap can be set equal to a constant or calculated by the code based on the model described in subsection 3.4.8. If the gap coefficient is calculated, the initial estimate is set equal to the input value

$$C^0_{g,m,k} = h_f \; F^{**} , \quad (25)$$

where F** is the channel type factor.

The surface temperature of the fuel is

$$T^0_{f,m,k} = T^0_{e,m,k} + \underbrace{\frac{Q^0_{f,m,k} A_f}{\pi (R_f + R_e) C^0_{g,m,k}}}_{\text{Drop Across Gap}} . \quad (26)$$

The thermal conductivity of the fuel for node n (K^0_n) as a function of temperature is determined from a table input or quadratic fit. For the first calculation in steady state, K^0_n is based on T_{n+1} and for subsequent calculation upon $(T_{n+1} + T_n)/2.0$ from the previous iteration. The temperature of the boundary fuel node is

$$T^0_{N,m,k} = T^0_{f,m,k} + \left[\ln\left(\frac{R_f}{r_N}\right) \right] \frac{Q_{f,m,k} A_f}{2\pi K^0_{N,m,k}} , \quad (27)$$

and the temperature of the n^{th} fuel node is

$$\text{Temp } n = \text{Temp } (n+1) + (\Sigma \text{ Heat Gen. in 1 to n nodes}) (\text{Thermal resistance n to n} + 1). \quad (28)$$

or

$$T_{n,m,k} = T^0_{n+1,m,k} + \left(\sum_{\ell=1}^{n} A_\ell Q^0_{\ell,m,k} \right) \left(\frac{\ln \frac{r_{n+1}}{r_n}}{2\pi K^0_{n,m,k}} \right) \quad (29)$$

The center temperature is given by

$$T^0_{0,m,k} = T^0_{1,m,k} + \frac{Q^0_{1,m,k}\, r_1^2}{4\, K^0_{0,m,k}} \tag{30}$$

for no center void ($R_o = 0$) and by

$$T^0_{0,m,k} = T^0_{1,m,k} + \frac{Q^0_{1,m,k}}{4\, K^0_{0,m,k}} \left[\left(r_1^2 - R_o^2 \right) - 2R_o^2 \ln \frac{r_1}{R_o} \right] \tag{31}$$

for a center void ($R_o \neq 0$).

New values for the gap coefficient and thermal conductivity are calculated based on the new temperature profile. The iterative process is continued until all fuel temperature changes between loops are within specified limits.

3.4.7 Gap Size and Pressure

If in steady state, part of the fuel has melted and its volume is insufficient to fill the center fuel void; that is,

$$\Delta V \sum_{n=1}^{N} \delta^{MELT(0)}_{n,m,k} A_m \leq \pi R_o^2 \ , \tag{32}$$

then the steady-state gap is

$$\Delta\phi^0_{m,k} = \underbrace{(R_e - R_f)^{cold}}_{\text{Cold Gap Size}} + \underbrace{\left(\frac{\Delta L}{L}\right)^0_{e,m,k} R_e}_{\text{Cladding Expansion}} - \underbrace{\left(\frac{\Delta L}{L}\right)^0_{f,m,k} R_f}_{\text{Fuel Expansion}} \ , \tag{33}$$

where $\left(\frac{\Delta L}{L}\right)^0_{e,m,k}$ is evaluated at $T^0_{a,m,k}$ and $\left(\frac{\Delta L}{L}\right)^0_{f,m,k}$ at the average fuel temperature $\overline{T}^0_{f,m,k}$. If the melted fuel volume is greater than the volume of the center fuel void, then the gap equation is of the form

$$\Delta\phi^0_{m,k} = (\text{Eq. 33}) - \underbrace{\left[\frac{\Delta V^{MELT} R_f}{2} - \frac{(\Delta V^{MELT} + 1)\, R_o^2}{2R_f} \right] \frac{1}{A_f} \sum_{n=1}^{N} \delta^{MELT(0)}_{n,m,k} A_n}_{\text{Additional radial expansion due to melting}} \ . \tag{34}$$

If the calculated gap is greater than zero, the contact pressure is set equal to zero If the gap is less than zero (interference), the contact pressure is calculated by

$$P^0_{m,k} = - \frac{\Delta\phi^0_{m,k} E_e (R_E - R_e) (144)}{R_e^2} \quad (lb/ft^2) \tag{35}$$

The maximum contact pressure is limited by the yield point of the cladding and is given by

$$P_{max} = \frac{\sigma_{y.p.} (R_E - R_e) (144)}{R_e} \quad (lb/ft^2) \ . \tag{36}$$

In the current version of FORE II, the yield point of the cladding is not temperature dependent.

3.4.8 Gap Coefficient

Experimental results for gap coefficient are generally characterized by a wide scattering of data points. There are articles in the published literature that state the heat transfer across the interface is mainly by conduction through the gas film since so little metal is actually in physical contact, while other articles indicate that the primary mechanism is conduction through the contact points since the thermal conductivity of the fuel cladding is significantly greater than that of the gas gap.

In FORE II, two gap models are available. One is the constant gap model. In this case, the gap coefficient for the average channel is input as well as multiplying factors for the peak and hot-spot channels. The net result is that the gap coefficient varies by channel type but is not a function of axial position or time. (As indicated previously, any time dependence can be approximated by restart capability.)

The second is the variable gap model In this model the gap coefficient is calculated at any time step for all axial nodes and channel types as a function of surface roughness, type of gap gas, existing gap size, contact pressure, and temperature. Plot 9 of Appendix C, subsection C.4, indicates some typical results using the variable gap model based on the input data listed in the example problem. The variable gap model was based on work by Ross and Stoute.[3] This choice was made because of the "physical soundness" and the flexibility of the model, and the reasonable agreement between calculated and measured values. Sufficient information will be given here to run FORE II Reference (3) should be consulted for additional details, if desired. The gap coefficient is calculated by

$$C^0_{g,m,k} = \left[\underbrace{\frac{K^0_{m,k} P^0_{m,k}}{a_o \sqrt{\delta \ \ell}}}_{\text{Solid to Solid Contribution}} + \underbrace{\frac{K^0_{g,m,k}}{\delta^0_{g,m,k} + (g_f + g_e)}}_{\text{Gap Gas Contribution}} \right] F^{**} \ . \tag{37}$$

The F** is the peak or hot-spot factor for the gap coefficient.

The thermal conductivity of the gap gas ($K^0_{g,m,k}$) is based on a quadratic fit of the form

$$K^0_{g,m,k} = A_g + B_g \underbrace{\left[\frac{T^0_{e,m,k} + T^0_{f,m,k}}{2}\right]}_{\text{Average temperature of inner surface cladding and outer surface of fuel}} + C_g \left[\frac{T^0_{e,m,k} + T^0_{f,m,k}}{2}\right]^2 . \quad (38)$$

The thermal conductivity of helium is about 15 times that of fission product gas. The user should be certain that the gas composition as reflected in choice of A_g, B_g, and C_g is consistent with the core average exposure as reflected in the core power distribution.

The $(g_f + g_e)$ term is the accommodation effect which reflects the fact the average temperature gradient imposed upon the gas is less than that between the solid surfaces because the separation distance is on the same order as the mean free path of the gas in the gap.

For helium, at 1 atm,

$$g_f + g_e = 3.28 \times 10^{-5} \text{ ft},$$

and for pure fission gas, at 1 atm,

$$g_f + g_e = 0.328 \times 10^{-5} \text{ ft}.$$

For a positive gap,

$$\delta^0_{g,m,k} = \underbrace{\Delta\phi^0_{m,k}}_{\text{Equation (33) or (34)}} + \beta_o (\delta_f + \delta_e) , \quad (39)$$

and for a zero gap,

$$\delta^0_{g,m,k} = \beta_o (\delta_f + \delta_e) , \quad (40)$$

where δ_f and δ_e are the surface roughness of the fuel and cladding, respectively, and β_o is an experimental constant which Ross and Staute found to be approximately 2.5. Physically, the term $\beta_o(\delta_f + \delta_e)$ could be considered to be the average separation distance when the peaks of the cladding and fuel surfaces are in contact or when macroscopically the gap is closed.

When the contact pressure is zero, the solid to solid contribution is zero. Otherwise, $K^0_{m,k}$ is the harmonic mean conductivity of the fuel cladding defined by Ross and Staute to be

$$K^0_{m,k} = \frac{\left(K^0_{N,m,k}\right)\left(K_e\right)}{\frac{K^0_{N,m,k} + K_e}{2}} \quad (41)$$

The term δ is the effective roughness of the two surfaces given by

$$\delta = \left[\frac{\delta_f^2 + \delta_e^2}{2}\right]^{\frac{1}{2}} , \tag{42}$$

and Ψ is the Meyers hardness number which is usually taken to be three times the yield strength. The term a_o is an experimental constant determined to be approximately 0.091 ft^{-1}. It is estimated that the quoted value of a_o, β_o, and $(g_f + g_e)$ each could be in error by 25%. The user should adjust these values to agree with the best experimental data.

3.4.9 Doppler Temperatures

To obtain the Doppler feedback in later calculations, the steady-state temperature profile in the reactor must be determined both axially and radially. The axial temperature profile in each fuel ring is known for the peak and average channel. The calculational model projects radially the temperature profile for these two channels. The core is divided into two to seven equal volume regions. The radial temperature profile is effectively described by radial weighting factors, W_ℓ, for each region. Remembering that k = 2 is the peak channel and k = 1 is the average channel, the temperature (H) in the n^{th} fuel ring, m^{th} axial section, and ℓ^{th} radial region of the reactor is

$$H^0_{n,m,\ell} = \underbrace{T^0_{n,m,2}}_{\text{Peak}} - W_\ell \underbrace{\left(T^0_{n,m,2} - T^0_{n,m,1}\right)}_{\text{Temperature difference}} + 460 \quad . \tag{43}$$

Note that the hot-spot channel is not used in the projection scheme.

The radial weighting factors are input or determined by the code by the relationship

$$W_\ell = \frac{2\ell - 1}{L} \quad . \tag{44}$$

If the radial weighting factors are input, any profile may be described. For this option, there is no requirement that the peak and average channels be in any pre-defined core location. Typically, the user could input a temperature shape as in Figure 3-3 by properly adjusting W_ℓ.

When the radial weighting factors are determined by the code, it is assumed that the peak channel is the center fuel region and that the average channel is characteristic of the region of the core at a radius separating the core into equal volumes. As an example, for L = 7, $W_1 = 1/7$, $W_2 = 3/7$, $W_3 = 5/7$, $W_4 = 7/7$, $W_5 = 9/7$, $W_6 = 11/7$, and $W_7 = 13/7$. Then, for a peak temperature of 4500°F and an average temperature of 4000°F, the radial temperature profile for the particular fuel ring would appear as in Figure 3-4. The radial weighting factor calculated by the code will result in a parabolic temperature profile.

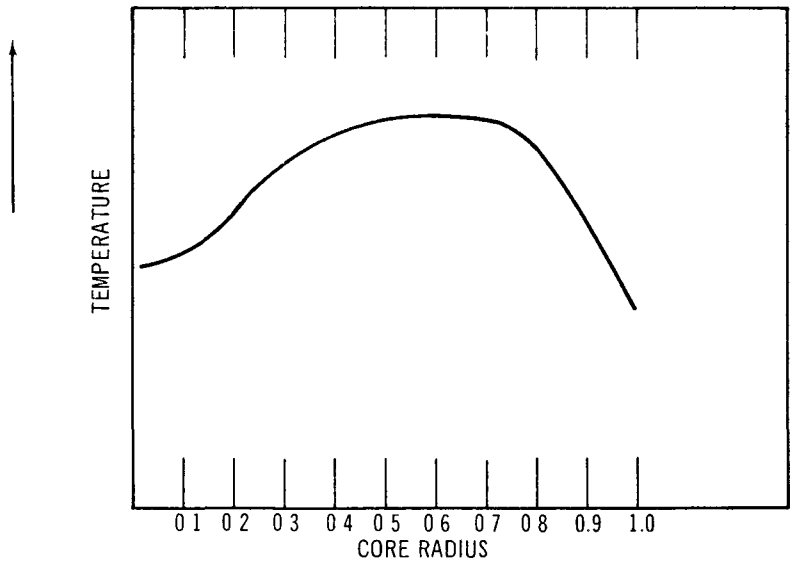


FIGURE 3-3 POSSIBLE TEMPERATURE PROFILE

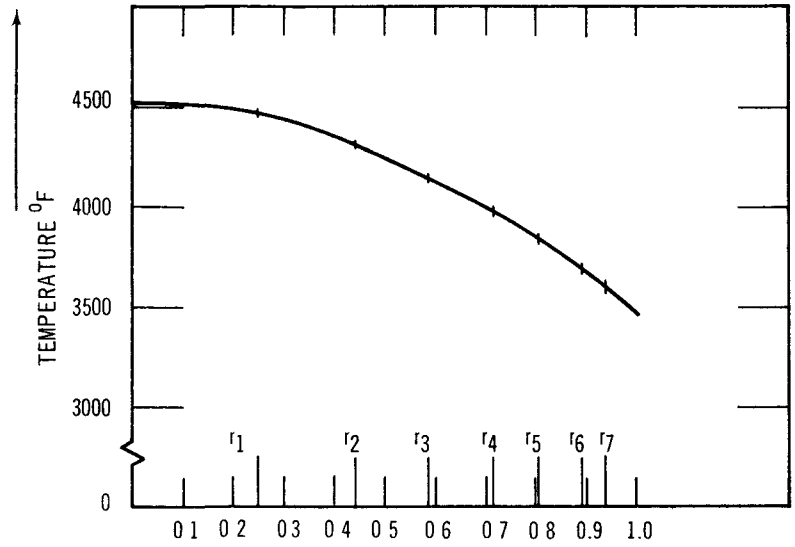


FIGURE 3-4 EXAMPLE TEMPERATURE PROFILE

Using Equation (43), the average fuel pin temperature for the m^{th} axial and ℓ^{th} radial section is

$$T^{*(0)}_{m,\ell} = \frac{\sum_{n=1}^{N} {}^{0}H_{n,m,\ell}\, A_n}{A_f} \quad . \tag{45}$$

Equation (45) represents a two-dimensional array describing the core temperature profile. For the maximum number of allowable nodes, this gives the temperature at seven axial locations for seven core radii.

The average reactor fuel temperature by volume weighting $T^{*(0)}_{m,\ell}$ is

$$\overline{T}^{0} = \frac{\sum_{\text{axial}} \sum_{\ell=1}^{L} T^{*(0)}_{m,\ell}\, (\Delta Z)_m}{L \sum_{\text{axial}} (\Delta Z)_m} \quad , \tag{46}$$

where $\sum_{\text{axial}}$ indicates that the average temperature can be based on the core only or the core plus blanket, as specified by input data.

The nodal temperature used in Doppler calculations is

$$T^{\text{Dop}(0)}_{m,\ell} = T^{*(0)}_{m,\ell} \left\{ 1 - C_D \left[\frac{T^{*(0)}_{m,\ell} - H^{0}_{N,m,\ell}}{T^{*(0)}_{m,\ell}} \right]^2 \right\} \quad , \tag{47}$$

Correction term

where C_D is input. The second term in the braces allows the user to account for the fact that the correct "average temperature" used in Doppler calculation is slightly influenced by the temperature difference between the average and surface.

3.4.10 Orificing Coefficient

In steady state, the user indicates the mass velocity for the average channel and the relative flow factors for the peak and hot-spot channels. In addition, the orificing coefficient or local loss coefficient for the peak channel is input. This portion of the code calculates the total pressure drop in steady state for the peak channel due to frictional and local losses. When the pressure drop across the core is known, the correct orificing coefficient for the average and hot-spot channels can be calculated. These orificing coefficients are assumed to remain constant for all transient calculations.

The first step is to calculate the average coolant temperature for each channel by

$$\bar{T}^0_{c,k} = \frac{\sum_{m=1}^{M} \bar{T}^0_{c,m,k} \ (\Delta Z)_m}{\sum_{m=1}^{M} (\Delta Z)_m} \tag{48}$$

The coolant viscosity and density are determined from the input tables for each channel type by using the temperature calculated in Equation (48). The Reynolds number for the average channel is

$$N^0_{R,1} = \frac{G^0_{c,1} \ D_H}{\mu^0_{c,1}} , \tag{49}$$

the peak channel

$$N^0_{R,2} = \frac{F_r \ G^0_{c,1} \ D_H}{\mu^0_{c,2}} , \tag{50}$$

and hot-spot channel

$$N^0_{R,3} = \frac{F_v \ G^0_{c,1} \ D_H}{\mu^0_{c,3}} . \tag{51}$$

The flow is turbulent if the Reynolds number is greater than

$$COMP = \frac{64}{C} \frac{1}{1-e} . \tag{52}$$

where e and c are input, and is laminar if less than or equal to COMP.

If the flow in the peak channel is laminar, the pressure drop is

$$2g \ \Delta P = \underbrace{\frac{64}{N^0_{R,2}} \frac{Z_t}{D_H} \frac{\left(F_r \ G^0_{c,1}\right)^2}{\rho^0_{c,2}}}_{\text{Laminar friction losses}} + \underbrace{B_{OR,k=2} \frac{\left(F_r \ G^0_{c,1}\right)^2}{\rho_{c \ \text{inlet}(0)}}}_{\text{Sum of local losses}} \tag{53}$$

and if the flow is turbulent the friction losses term changes and the pressure drop is now given by

$$2g\Delta P = \underbrace{\frac{C}{\left(N^0_{R,2}\right)^e}\ \frac{Z_t}{D_H}\ \frac{\left(F_r\ G^0_{c,1}\right)^2}{\rho^0_{c,2}}}_{\text{Turbulent friction losses}} + B_{OR,k=2}\ \frac{\left(F_r\ G^0_{c,1}\right)^2}{\rho_{c\ \text{inlet}(0)}} \tag{54}$$

The orificing coefficient for the average channel for laminar flow becomes

$$B_{OR,k=1} = \frac{2g\ \Delta P\ \rho_{c\ \text{inlet}(0)}}{\left(G^0_{c,1}\right)^2} - \frac{64}{N^0_{R,1}}\ \frac{Z_T}{D_H}\ \frac{\rho_{c\ \text{inlet}(0)}}{\rho^0_{c,1}}\ , \tag{55}$$

and for turbulent flow,

$$B_{OR,k=1} = \frac{2g\ \Delta P\ \rho_{c\ \text{inlet}(0)}}{\left(G^0_{c,1}\right)^2} - \frac{C}{\left(N^0_{R,1}\right)^e}\ \frac{Z_T}{D_H}\ \frac{\rho_{c\ \text{inlet}(0)}}{\rho^0_{c,1}} \tag{56}$$

Analogous equations hold for the hot-spot channel when the appropriate mass velocity peaking factor is included.

3.5 REACTIVITY EFFECTS (FEEB SUBROUTINE)

3.5.1 Programmed k versus Time

The user can specify a programmed k (due to external effects other than scram) versus time or power versus time. In either case, linear interpolation is used to find the appropriate dependent variable as a function of time.

The scram Δk insertion versus time since initiation is an independent input. The start of the scram Δk can be based on the time the coolant reaches a specified outlet temperature $\left(T_c^{SCRAM}\right)$, or the time the reactor reaches a power level (P_J) such that

$$\frac{P_J - P_o}{P_o} \geq \epsilon_{SCRAM}\ , \tag{57}$$

where P_o is the time zero power level and ϵ_{SCRAM} is input.

The total programmed k versus time is

$$k^J_p = k_{TABLE} + (\Delta k)^J_{SCRAM}\ . \tag{58}$$

The advantage of being able to specify $(\Delta k)_{SCRAM}$ as a separate table is that it is not required to know the time for initiation of insertion in advance.

Noting that the total feedback Δk from the previous time step is represented by k_f^{J-1}, the total effective multiplication factor at any step J is given for the no-extrapolation option by

$$k^J = \underbrace{\frac{k_p^{J-1} + k_p^J}{2}}_{\text{Average at midpoint}} + k_f^{J-1} , \tag{59}$$

and for the extrapolation option by

$$k^J = \frac{k_p^{J-1} + k_p^J}{2} + k_f^{J-1} + \tfrac{1}{2} (\Delta k_f)^J_{EST} \tag{60}$$

where, for $J \geq 3$,

$$(\Delta k_f)^J_{EST} \quad \tau^J \left[\frac{k_f^{J-1} - k_f^{J-2}}{\tau^{J-1}} + \left(\frac{\tau^J + \tau^{J-1}}{\tau^J + \tau^{J-2}} \right) \left(\frac{k_f^{J-1} - k_f^{J-2}}{\tau^{J-1}} - \frac{k_f^{J-2} - k_f^{J-3}}{\tau^{J-2}} \right) \right] . \tag{61}$$

The $1/2(\Delta k_f)^J_{EST}$ in Equation (60) is basically a correction term that represents a projection to the midpoint of time step J of the general trend in the feedback Δk as determined from the last two time steps.

The total feedback Δk is composed of the Doppler, radial dimensional variation, height change, density, and voiding contributions. These separate contributions will be examined.

3.5.2 Doppler Feedback

The reactor temperature profile for time step (J-1) is calculated similar to that in Equation (43) for steady state. An equivalent temperature correction is made, depending upon whether the particular nodal temperature is greater than the melting point at time J-1 as compared to its temperature in steady state. This equivalent temperature is based on a temperature rise that would have occurred for no change in phase or

$$\Delta T_E = \frac{\text{Heat of Fusion Btu/lb}}{\text{Heat Capacity Btu/lb-°F}} = \frac{B^{Melt}}{\rho_f \, C^{J-1}_{n,m,k=1}} . \tag{62}$$

The average nodal fuel pin temperature, average reactor fuel temperature, and nodal Doppler temperature are calculated for each time step analogous to Equations (45), (46), and (47), respectively, when consistent superscripts are used through the equations. The nodal Doppler contribution is

$$(\Delta k_{Dop})^{J-1}_{m,\ell} - A_{Dop} \ln \left[\frac{T^{Dop\ (J-1)}_{m,\ell}}{T^{Dop\ (0)}_{m,\ell}} \right] + \frac{B_{Dop}}{b+1} \left\{ \left[T^{Dop\ (J-1)}_{m,\ell} \right]^{b+1} - \left[T^{Dop\ (0)}_{m,\ell} \right]^{b+1} \right\} . \tag{63}$$

The user has available the three input constants, A_{Dop}, B_{Dop}, and b, to match the model given in Equation (63) with experimental or separately calculated results The total Doppler feedback is calculated by power squaring and volume weighting the nodal values as given by

$$(\Delta k)^{J-1}_{Dop} = \frac{\sum_{m-1}^{M} \sum_{\ell=1}^{L} (\Delta k_{Dop})^{J-1}_{m,1} \; P_\ell^2 \; A_m^2 \; (\Delta Z)_m}{\sum_{m=1}^{M} \sum_{\ell=1}^{L} P_\ell^2 \; A_m^2 \; (\Delta Z)_m} \quad . \tag{64}$$

The Doppler contribution calculated by Equation (64) is the one used in the feedback equations. For informational purposes, the average reactor Doppler Δk is calculated as in Equation (63) by replacing nodal temperatures by core average values, i.e.,

$$(\overline{\Delta k})^{J-1}_{Dop} = A_{Dop} \ln \left(\frac{\overline{T}^{J-1}_{core}}{\overline{T}^{0}_{core}} \right) + \frac{B_{Dop}}{b+1} \left[\left(\overline{T}^{J-1}_{core} \right)^{b+1} - \left(\overline{T}^{0}_{core} \right)^{b+1} \right] , \tag{65}$$

and the Doppler weighting factor is defined by

$$\xi = \frac{(\Delta k)^{J-1}_{Dop}}{(\overline{\Delta k})^{J-1}_{Dop}} \quad . \tag{66}$$

3.5.3 Radial Feedback

The radial feedback is caused by changes in the core radius resulting from bowing, axial pressure difference, and thermal expansion. The temperature used in the bowing equations is based on the change in the radial temperature gradient across the outside of the core. The outer core regions are shown in Figure 3-5.

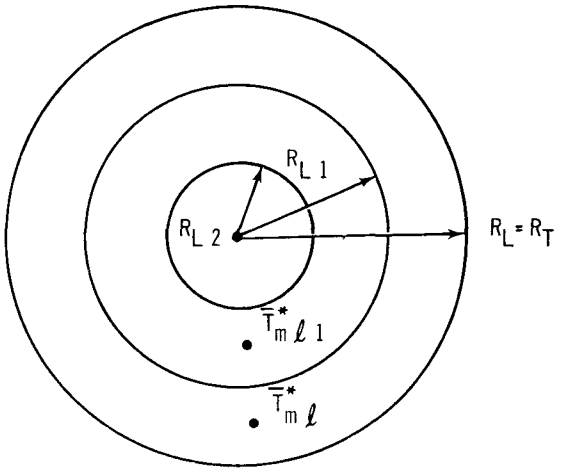


FIGURE 3 5 OUTER RADIAL CORE REGIONS

Note that with the use of proper superscripts, $T^*_{m,\ell}$ for any time step is given by Equation (45). Now, from Figure 3-5,

$$\frac{\Delta T_{B,m}}{D_B} = \frac{T^*_{m,L} - T^*_{m,L-1}}{\frac{R_L + R_{L-1}}{2} - \frac{R_{L-1} + R_{L-2}}{2}} = \frac{T^*_{m,L} - T_{m,L-1}}{\frac{R_L - R_{L-2}}{2}} , \tag{67}$$

where D_B is the diameter of the pseudo-fuel channel in the radial core region.

The radius of any radial core region is given by

$$R^2 = \frac{\ell}{L} R_L^2 . \tag{68}$$

Thus,

$$R_{L-2} = \sqrt{\frac{L-2}{L}} R_L , \tag{69}$$

and noting $R_L = R_T$ (outer radius of core) Equation (67) becomes

$$\Delta T_{B,m} = \frac{2D_B \left(T^*_{m,L} - T_{m,L-1}\right)}{R_T \left(1 - \sqrt{\frac{L-2}{L}}\right)} . \tag{70}$$

Summing over all axial nodes for time step j-1,

$$(\Delta \overline{T})^{j-1}_B = \frac{\sum_{m=1}^{M} (\Delta T)^{j-1}_{B,m} (\Delta Z)_m}{H_T} . \tag{71}$$

The steady-state value $(\Delta \overline{T})^0_B$ is similarly defined.

Five options, based on the structural connections of the core at the top and bottom, are provided for in the bowing calculations. The principles underlying Option 1 (for a channel cantilevered at the inlet, pinned at the exit) will be developed. The results for the other options will just be listed. Figure 3-6 indicates a beam corresponding to Option 1.

From fundamental strength of material relationships,

$$\frac{d^2\delta}{dx^2} = \frac{\alpha \Delta T}{D} - \frac{M}{EI} , \tag{72}$$

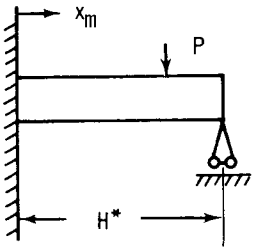


FIGURE 3-6 FUEL PIN FOR BOWING CALCULATION

where the moment (M) about the pinned end is $P(H^* - x_m)$. Integrating Equation (72) twice and using the boundary conditions,

$$\delta = 0, \; x_m = 0, \text{ and} \tag{73}$$

$$\frac{d\delta}{dx} = 0, \; x_m = 0, \tag{74}$$

one obtains

$$\delta = \frac{\alpha \Delta T}{2D} x_m^2 - \frac{PH}{ZEI} x_m^2 + \frac{P x_m^3}{6EI} \; . \tag{75}$$

By using the last boundary condition,

$$\delta = 0, \; x_m = H^* \; , \tag{76}$$

the term P can be eliminated and after manipulating one obtains

$$\frac{\delta}{R_T} = \left(\frac{\Delta R}{R_T}\right)_{B,\,m}^{j-1} = -\frac{\alpha_s' \, x_m^2}{4D_B \, R_T} \left(1 - \frac{x_m}{H^*}\right) \left[(\Delta \overline{T})_B^{j-1} - (\Delta \overline{T})_B^0\right] \; . \tag{77}$$

For the reactor, x_m is given for the bottom axial node by

$$x_{m\,1} \quad Z_o + \frac{(\Delta Z)}{2} \; m=1 \tag{78}$$

and for the other axial nodes by

$$x_m = Z_o + \sum_{\ell=1}^{m-1} (\Delta Z)_\ell + \frac{(\Delta Z)_m}{2} \tag{79}$$

for $m \geq 2$.

For a beam pinned at both ends, the result obtained in a similar manner is

$$\left(\frac{\Delta R_T}{R_T}\right)^{j-1}_{B,m} = \frac{\alpha_s''}{2 D_B R_T} \left(x_m^2 - x_m H^*\right) \left[(\Delta\bar{T})^{j-1}_B - (\Delta\bar{T})^0_B\right] , \tag{80}$$

for a beam cantilevered at the exit, pinned at the inlet

$$\left(\frac{\Delta R_T}{R_T}\right)^{j-1}_{B,m} = \frac{\alpha_s''}{4 D_B R_T} \left(2 x_m^2 - \frac{x_m^3}{H^*} - H^* x_m\right) \left[(\Delta\bar{T})^{j-1}_B - (\Delta\bar{T})^0_B\right] , \tag{81}$$

for a beam cantilevered at the exit, free at the inlet

$$\left(\frac{\Delta R_T}{R_T}\right)^{j-1}_{B,m} = \frac{\alpha_s''}{2 D_B R_T} \left(x_m^2 - 2 x_m H^* + H^{*2}\right) \left[(\Delta\bar{T})^{j-1}_B - (\Delta\bar{T})^0_B\right] , \tag{82}$$

and for a beam cantilevered at the inlet, free at the exit

$$\left(\frac{\Delta R_T}{R_T}\right)^{j-1}_{B,m} = \frac{\alpha_s''}{2 D_B R_T} x_m^2 \left[(\Delta\bar{T})^{j-1}_B - (\Delta\bar{T})^0_B\right] . \tag{83}$$

The change in core radius due to a change in axial pressure on the lower support plate is

$$\left(\frac{\Delta R_T}{R_T}\right)^{j-1}_{P,m} = \frac{x_m \Psi_o}{R_T} \left[\frac{\left(G^{j-1}_{c,1}\right)^2}{\left(G^0_{c,1}\right)^2}\right] , \tag{84}$$

and the thermal expansion of the core by

$$\left(\frac{\Delta R_T}{R_T}\right)^{j-1}_{T,m} \alpha_s' \left(T^{j-1}_{s,m,1} - T^0_{s,m,1}\right) \tag{85}$$

The total core radius change becomes

$$\left(\frac{\Delta R_T}{R_T}\right)_m^{(j-1)} = \underbrace{\left(\frac{\Delta R_T}{R_T}\right)_{B,m}^{j-1}}_{\text{Bowing}} + \underbrace{\left(\frac{\Delta R_T}{R_T}\right)_{P,m}^{j-1}}_{\text{Pressure}} + \underbrace{\left(\frac{\Delta R_T}{R_T}\right)_{T,m}^{j-1}}_{\text{Thermal}} \quad . \tag{86}$$

After summing over all axial sections and using the input core radius coefficient, the total radial feedback is

$$FB_R = \left(R_T \frac{\delta k}{\delta R_T}\right) \frac{\sum_{m=1}^{M} \left(\frac{\Delta R_T}{R_T}\right)_m^{\gamma-1} \Delta Z_m}{H_T} \quad . \tag{87}$$

3.5.4 Axial Feedback

The only axial feedback contribution is due to the expansion of the fuel. This axial expansion is

$$\left(\frac{\Delta H_T}{H_T}\right)^{j-1} = \frac{\sum_{m=1}^{M} \left[\left(\frac{\Delta L}{L}\right)_{f,m,k=1}^{j-1} - \left(\frac{\Delta L}{L}\right)_{f,m,k=1}^{0}\right] \Delta Z_m}{H_T} \tag{88}$$

and the axial feedback contribution using the input reactivity coefficient becomes

$$FB_H^{j-1} = \left(H_T \frac{\delta k}{\delta H_T}\right)\left(\frac{\Delta H_T}{H_T}\right)^{j-1} \tag{89}$$

3.5.5 Density Feedback

The density change of the fuel, cladding, coolant, structure, and additional material is considered in the total density change. For the fuel

$$\left(\frac{\Delta \bar{\rho}_{f,m}}{\bar{\rho}_{f,m}}\right)^{j-1} = -\left\{ \overbrace{C_F \left[\left(\frac{\Delta L}{L}\right)_{f,m,1}^{j-1} - \left(\frac{\Delta L}{L}\right)_{f,m,1}^{0}\right]}^{\text{Axial}} + \underbrace{2\alpha_s \left(T_{s,m,1}^{j-1} - T_{s,m,1}^{0}\right)}_{\text{Radial}} \right\} , \tag{90}$$

where C_F is an input number varying between 0 and 1. The factor C_F is intended to reflect the fraction of the axial fuel density change that can be depended upon in a transient. Because the axial fuel pin normally consists of pellets which may not be in perfect contact, and because the fuel is not of 100% theoretical density, only some portion of the possible axial density change will probably be realized.

In Equation (90), the radial fuel expansion is of the general form

$$\left(\frac{\Delta\bar{\rho}_{f,m}}{\bar{\rho}_{f,m}}\right)^{J-1}_{radial} = \frac{\pi\left(\alpha_s R\Delta T + R\right)^2 - \pi R^2}{\pi R^2} \quad . \tag{91}$$

which reduces to

$$\left(\frac{\Delta\bar{\rho}_{f,m}}{\bar{\rho}_{f,m}}\right)_{radial} = 2\alpha_s \Delta T + \left(\alpha_s \Delta T\right)^2 \approx 2\alpha_s \Delta T \quad . \tag{92}$$

where the square of linear thermal expansion coefficient has been neglected in comparison to the coefficient. This same type of approximation is used for all the density expression.

For the cladding, the density effect is

$$\left(\frac{\Delta\bar{\rho}_{e,m}}{\bar{\rho}_{e,m}}\right)^{J-1} = \left[\left(\frac{\Delta L}{L}\right)_{e,m,1} - \left(\frac{\Delta L}{L}\right)^0_{e,m,1} + 2\alpha_s\left(T^{J-1}_{s,m,1} - T^0_{s,m,1}\right)\right] \quad . \tag{93}$$

For use in the coolant density change expression, a value $\Delta^{J-1}_{e,m}$ is defined to be

$$\Delta^{J-1}_{e,m} = \left(\frac{\Delta L}{L}\right)^{J-1}_{e,m,1} - \left(\frac{\Delta L}{L}\right)^0_{e,m,1} \quad , \tag{94}$$

if the density change of the cladding is greater than that of the fuel, and is equal to

$$\Delta^{J-1}_{e,m} = C_F\left[\left(\frac{\Delta L}{L}\right)^{J-1}_{f,m,1} - \left(\frac{\Delta L}{L}\right)^0_{f,m,1}\right] \tag{95}$$

if the opposite is true. The density term for the coolant is

$$\left(\frac{\Delta\bar{\rho}_{c,m}}{\bar{\rho}_{c,m}}\right)^{J-1} = -\left[3\alpha^{J-1}_{c,m}\left(\bar{T}^{J-1}_{c,m,1} - \bar{T}^0_{c,m,1}\right) + 2\alpha_s\left(T^{J-1}_{s,m,1} - T^0_{s,m,1}\right) - \frac{2R_c^2\,\alpha_s\left(T^{J-1}_{s,m,1} - T^0_{s,m,1}\right) - 2R_e^2\,\Delta^{J-1}_{e,m}}{R_c^2 - R_e^2}\right] \tag{96}$$

and for the structure

$$\left(\frac{\Delta\bar{\rho}_{s,m}}{\bar{\rho}_{s,m}}\right)^{J-1} = -\left[\alpha_{s,ax}\left(T^{J-1}_{s,m,1} - T^0_{s,m,1}\right) + 2\alpha_s\left(T^{J-1}_{s,m,1} - T^0_{s,m,1}\right)\right] \quad , \tag{97}$$

and for the additional material,

$$\left(\frac{\Delta\bar{\rho}_{u,m}}{\bar{\rho}_{u,m}}\right)^{j-1} = \left[\left(\frac{\Delta L}{L}\right)^{j-1}_{u,m,1} - \left(\frac{\Delta L}{L}\right)^{0}_{u,m,1} + 2\alpha_s\left(T^{j-1}_{s,m,1} - T^{0}_{s,m,1}\right)\right] \quad . \tag{98}$$

The total density feedback is obtained by summing over all axial sections and using the input density coefficients or

$$FB_D^{j-1} = \sum_{m=1}^{M}\left[\left(\rho_f \frac{\delta k}{\delta\rho_f}\right)_m \left(\frac{\Delta\bar{\rho}_{f,m}}{\bar{\rho}_{f,m}}\right)^{j-1} + \left(\rho_e \frac{\delta k}{\delta\rho_e}\right)_m \left(\frac{\Delta\bar{\rho}_{e,m}}{\bar{\rho}_{e,m}}\right) + \left(\rho_c \frac{\delta k}{\delta\rho_c}\right)_m \left(\frac{\Delta\bar{\rho}_{c,m}}{\bar{\rho}_{c,m}}\right)^{j-1}\right.$$

$$\left. + \left(\rho_s \frac{\delta k}{\delta\rho_s}\right)_m \left(\frac{\Delta\bar{\rho}_{s,m}}{\bar{\rho}_{s,m}}\right)^{j-1} + \left(\rho_u \frac{\delta k}{\delta\rho_u}\right)_m \left(\frac{\Delta\bar{\rho}_{u,m}}{\bar{\rho}_{u,m}}\right)^{j-1}\right] \quad . \tag{99}$$

3.5.6 Voiding Feedback

The pressure at the void location is calculated by

$$P_z^j = P_{st} + P_{pump}\frac{\Delta P^j}{\Delta P^0} - f_z \frac{2g\Delta P^j}{(64.4)(144)} \quad . \tag{100}$$

The bulk boiling temperature of the coolant versus pressure and the cladding burnout temperature versus pressure are both table inputs. When the calculated coolant or cladding temperature at the pressure calculated by Equation (100) is equal to the specified table value, the void Δk is inserted at the specified rate. In addition, the start of void Δk insertion can also be based on when the fuel center temperature reaches a specified value. This condition could correspond to a fuel temperature at which the fuel vapor pressure is sufficient to fail the pin.

3.5.7 Total Feedback

Combining all the contributions the total feedback becomes

$$k_f^{(j-1)} = (\Delta k)^{j-1}_{Dop} + FB_H^{j-1} + FB_R^{j-1} + FB_D^{j-1} + (\Delta k)^{j-1}_{void} \quad . \tag{101}$$

Note that the feedback k_f^{j-1} is calculated when the time indicator is j. However, this feedback is used only in Equations (59), (60), and (61), which are calculated the next time for $j + 1$. Thus, before feedback is used again, k_f^{j-1} is set equal to k_f^j. On the next pass, the goal is to calculate the total effective multiplication factor for the $j + 1$ time step or k^{j+1}. The feedback from the previous time step is then correctly given by k_f^j.

3.5.8 Power Table Input

If the user has specified a power table versus time, only the reactor temperature profile and the pressure [Equation (100)] are calculated. All other calculations in subsection 3.5 (Reactivity Effects) are bypassed.

3.6 POWER (POWD SUBROUTINE)

When a power table versus time is input, the power is determined from the table by linear interpolation. For the option, the user should note that the power table is a ratio of the power at time j to that at steady state. The remainder of this section applies to the case of when a programmed k versus time table is used.

FORE II can calculate both the prompt power and total power (includes decay heat) of the reactor. The steady-state total power (P_o^0) is given by Equation (12). The steady-state prompt power (P_o^*) is obtained by

$$P_o^* = \frac{\dfrac{P_o^0}{8.6 \times 10^{-10}}}{1 + \sum_{i=1}^{IM} \dfrac{A_i}{\alpha_i} \left[a_i^{-\alpha_i} - (a_i + T_o)^{-\alpha_i} \right]} \quad \frac{\text{Fission}}{\text{cm}^3 \text{ sec}} , \tag{102}$$

where a_i, A_i, α_i, and IM are input values obtained usually from experimental data.

The total delayed neutron fraction is

$$\beta = \sum_{i=1}^{I} \beta_i , \tag{103}$$

and the steady-state neutron precursor concentration for each delayed group is

$$C_i^0 = \frac{\nu \beta_i P_o^*}{\lambda_i} \quad \frac{\text{atoms}}{\text{cm}^3} . \tag{104}$$

The total effective multiplication factor at any time j is obtained as outlined in subsection 3.5. The corresponding power of the reactor is determined from the finite difference approximation to the standard point kinetics differential equation,

$$\frac{dP^*}{dt} = \frac{k^j}{\nu \ell} \left[\sum_{i=1}^{I} C_i \lambda_i + S \right] + \frac{k^j (1-\beta) - 1 \rfloor P^*}{\ell} , \tag{105}$$

where P^* is in fission/cm^3 sec.

If $\left| k^j (1-\beta) - 1 \right|$ in Equation (105) is less than some small input value ϵ_K (typically on the order of 10^{-5}), the second term on the right-hand side is neglected because of potential numerical problems in the finite difference approximation

Letting

$$A_j = \frac{k^j}{\nu \ell} \left[\sum_{i=1}^{I} C_i \lambda_i + S \right] \quad , \tag{106}$$

to simplify nomenclature, the power at the end of some time step τ when the second term is neglected is

$$P_j^* = A_j \tau^j + P_{j-1}^* \quad , \tag{107}$$

and the average power during the step is

$$\overline{P}_j^* = P_{j-1}^* + \frac{A_j \tau^j}{2} \quad . \tag{108}$$

For the case where

$$\left| k^j (1-\beta) - 1 \right| \geq \epsilon_K \quad , \tag{109}$$

let

$$R_j = \frac{k^j (1-\beta) - 1}{\ell} \tag{110}$$

to again simplify nomenclature. The power at the end of the time step becomes

$$P_j^* = P_{j-1}^* e^{R_j \tau^j} + \frac{A_j}{R_j} \left(e^{R_j \tau^j} - 1 \right) \quad , \tag{111}$$

and the average power during the time step is obtained from

$$\overline{P}_j^* = \frac{\int_0^{\tau^j} P_j^* \, dt}{\tau^j} \tag{112}$$

or

$$\overline{P}_j^* = \frac{1}{\tau^j} \left(\frac{P_{j-1}^* + \frac{A_j}{R_j}}{R_j} \right) \left(e^{R_j \tau^j} - 1 \right) - \frac{A_j}{R_j} \quad . \tag{113}$$

The excess energy per unit volume at any time step is

$$E_j^* = E_{j-1}^* + \left(\overline{P}_j^* - P_o^*\right) \tau^j \quad . \tag{114}$$

The delayed neutron precursor concentration at any time j is obtained from the solution of the differential equation

$$\frac{d\, C_n}{dt} = \nu\beta_1 \overline{P}_j^* - \lambda_1 C_1 \ , \tag{115}$$

which in finite difference form becomes

$$C_1^j = \underbrace{C_1^{j-1}}_{\text{Previous concentration}} + \underbrace{\nu\beta_1 \overline{P}_j^* \tau^j}_{\text{Production during } \tau^j} - \underbrace{\lambda_1 C_1^{j-1} \tau^j}_{\text{Decay during } \tau^j} \quad . \tag{116}$$

3.7 COOLANT MASS VELOCITY (INFLOW SUBROUTINE)

This subroutine calculates the mass velocity for the peak and hot-spot channels during the transient. The mass velocity as a function of time for the average channel is input (locations 196 to 255). The relative flow factors for the peak and hot-spot channels for steady state are input (locations 191 and 192, respectively). This subroutine accounts for changes in the mass velocity in the peak and hot-spot channel from these steady-state flow factors due to the nonlinearity in orificing effectiveness with the variation in coolant property. It is assumed in this derivation that the inlet and outlet coolant plenums are common to each channel.

If the Reynolds number for the average channel is less than or equal to COMP [Equation (52)], the flow is laminar and the pressure drop at time j is

$$(2g\ \Delta P)^j = \underbrace{\frac{64}{N_{R,1}^j} \frac{Z_t}{D_H} \frac{\left(G_{c,1}^j\right)^2}{\rho_{c,1}^{j-1}}}_{\text{Laminar frictional loss}} + \underbrace{B_{OR,k=1} \frac{\left(G_{c,1}^j\right)^2}{\rho_c^{\text{inlet }(j-1)}}}_{\text{Local losses}} \tag{117}$$

If the Reynolds number is greater than COMP, the flow is turbulent and the pressure drop is

$$(2g\ \Delta P)^j = \underbrace{\frac{C}{\left(N_{R,1}^j\right)^e} \frac{Z_t}{D_H} \frac{\left(G_{c,1}^1\right)^2}{\rho_{c,1}^{j-1}}}_{\text{Turbulent frictional loss}} + B_{OR,k\ 1} \frac{\left(G_{c,1}^j\right)^2}{\rho_c^{\text{inlet }(j-1)}} \tag{118}$$

For laminar flow in the peak and hot-spot channel, the mass velocity for a zero orificing coefficient for the channel is

$$G^{J}_{c,k} = \frac{\rho^{J-1}_{c,k} \; D_H^2}{64 \; \mu^{J-1}_{c,k} \; Z_t} \; (2g \; \Delta P)^J \; , \tag{119}$$

and for a non-zero orificing coefficient

$$G^{J}_{c,k} = - A + \sqrt{A^2 + \frac{(2g \; \Delta P)^J \rho^{inlet \; (j-1)}_c}{B_{OR,k}}} \tag{120}$$

where

$$A = \frac{32 \; \mu^{J-1}_{c,k}}{D_H^2} \; \frac{Z_t}{B_{OR,k}} \; \frac{\rho^{inlet \; (j-1)}_c}{\rho^{J-1}_{c,k}} \; , \tag{121}$$

and $(2g \; \Delta P)^J$ is given by Equation (117) or (118).

For turbulent flow in the peak and hot-spot channel, the mass velocity for a zero orificing coefficient for the channel is

$$G^{J}_{c,k} = \left[\frac{(2g \; \Delta P) \; (D_H)^{1 \; + \; e} \; \rho^{J-1}_{c,k}}{C \; Z_t \; \left(\mu^{J-1}_{c,k} \right)^e} \right]^{\frac{1}{2-e}} \; , \tag{122}$$

and for a non-zero orificing coefficient an iterative process must be used as follows. Let

$$A_1 = 2g \; \Delta P \; , \tag{123}$$

$$A_2 = \frac{C \; Z_t \; \left(\mu^{J-1}_{c,k} \right)^e}{\rho^{J-1}_{c,k} \; D_H^{1+e}} \; , \tag{124}$$

$$A_3 = \frac{B_{OR,k}}{\rho^{inlet \; (j-1)}_c} \; , \tag{125}$$

and initially let the first estimate (G_o) for the peak and hot-spot channel be the same as the average channel; that is,

$$G^{J}_{o} = G^{J}_{c,1} \; , \tag{126}$$

then a revised estimate (G_R, R = 1) is

$$G_R = \sqrt{\frac{A_1}{A_2 \, (G_{R-1})^{-e} + A_3}} \quad . \tag{127}$$

This iterative process is continued until a converged coolant flow for the peak and hot-spot channel is achieved at each time step.

3.8 TRANSIENT TEMPERATURE (COPH SUBROUTINE)

The same physical quantities are basically calculated in this subsection for any time step j as subsection 3.4 does for steady state. The general approach is to set up a heat balance for each node. This heat balance is solved for the new temperature at the end of a time step in terms of the old temperature at the beginning of the step plus the temperature change due to heat transfer and power generation. All the temperature-dependent property values and temperature differences which establish the heat transfer rate are based on the known temperature profiles at the beginning of the time step. More specifically, the steady-state temperature distribution is calculated as in 3.4. Node by node the new temperatures for the first time step are calculated by using the property values and temperature differences that existed in steady state until a completely new temperature distribution is determined. This process is repeated for each time step using the property values and temperature difference from the previous time step.

3.8.1 Heat Generation Rates

The heat rate generation rate at any time j in the fuel due to neutron-gamma heating and fission is

$$\overline{Q}^{j}_{f,m,k} = (QU)_{f,m,k} \, \overline{P}_j \quad (\text{Btu/sec-ft}^3) \tag{128}$$

where $(QU)_{f,m,k}$ is defined in subsection 3.4.2 and $\overline{P}_j$ was determined in subsection 3.6 (POWD). Similar relationships hold for the transient heat generation rate in the cladding, coolant, structure, additional material, and each fuel ring.

3.8.2 Coolant Temperature (High Density Coolant)

For the no-lumping option, the heat transfer exchange with the structure is given by

$$B = \frac{V_s \, G_s}{A_c \left(\dfrac{1}{g^{j-1}_{c,m,k}} + \dfrac{d_s}{K_s} \right)} \left(T^{j-1}_{s,m,k} - \overline{T}^{\,j-1}_{c,m,k} \right) \quad \text{Btu/ft}^3\text{-sec} \quad . \tag{129}$$

In the case where the volume of structure per unit length of fuel (V_s) is non-zero but the exposed surface-to-volume ratio (G_s) is zero, then the heat exchange is

$$C = \frac{V_s \, \overline{Q}^{j}_{s,m,k}}{A_c} \quad \text{Btu/ft}^3\text{-sec} \quad . \tag{130}$$

For the additional material, the analogous equations are

$$G = \frac{V_u G_u}{A_c\left(\frac{1}{g^{J-1}_{c,m,k}} + \frac{d_u}{K_u}\right)} \left(T^{J-1}_{u,m,k} - \overline{T}^{J-1}_{c,m,k}\right) \text{ Btu/ft}^3\text{-sec} \tag{131}$$

and for $G_u = 0$,

$$F = \frac{V_u \overline{Q}^J_{u,m,k}}{A_c} \text{ Btu/ft}^3\text{-sec} \quad . \tag{132}$$

The heat transfer from the cladding to the coolant is

$$D = \frac{T^{J-1}_{a,m,k} - \overline{T}^{J-1}_{c,m,k}}{A_c\left(\frac{1}{2\pi R_E h^{J-1}_{c,m,k}} + \frac{\ln \frac{R_E}{R_a}}{2\pi K_e}\right)} \text{ Btu/ft}^3\text{-sec.} \tag{133}$$

The temperature change associated with mass transport is

$$E = \frac{G^{J-1}_{c,k} \tau^J}{(\Delta Z)_m \rho^{J-1}_{c,m,k}} \left[T^{\text{Out }(J-1)}_{c,m,k} - T^{\text{Out }(J-1)}_{c,m-1,k}\right] \quad ^\circ\text{F} \tag{134}$$

Finally, a common factor, A, is defined as

$$A = \frac{\tau^J}{\rho^{J-1}_{c,m,k} \; C^{J-1}_{c,m,k}} \text{ sec-ft}^3\text{-}^\circ\text{F/Btu} \tag{135}$$

The new temperature of the coolant at axial node m, for channel type k, at time step J for $G_s \neq 0$, $G_u \neq 0$ is

$$T^J_{c,m,k} = T^{J-1}_{c,m,k} + A\left[\overline{Q}^J_{c,m,k} + B + C + D\right] - E \, , \tag{136}$$

for $G_s \neq 0$, $G_u = 0$,

$$T^J_{c,m,k} \quad T^{J-1}_{c,m,k} + A\left[\overline{Q}^J_{c,m,k} + B + F + D\right] - E, \tag{137}$$

for $G_s = 0$, $G_u \neq 0$,

$$T^J_{c,m,k} - T^{J-1}_{c,m,k} + A\left[Q^J_{c,m,k} + G + C + D\right] - E. \tag{138}$$

and for $G_s = 0$, $G_u = 0$,

$$T^{J}_{c,m,k} = T^{J-1}_{c,m,k} + A \left[\overline{Q}^{J}_{c,m,k} + G + F + D \right] - E \quad . \tag{139}$$

In Equation (134), $T^{Out\ (J-1)}_{c,m-1,k}$ for $m = 1$ is given by

$$T^{Out\ (J-1)}_{c,m-1,k} = T^{inlet\ (J-1)}_{c} \tag{140}$$

The inlet temperatures to be used in the mass transport equation for the next time step are calculated by

$$T^{Out\ (J)}_{c,m,k} = T^{Out\ (J-1)}_{c,m,k} + \left(T^{J}_{c,m,k} - T^{J-1}_{c,m,k} \right) \quad . \tag{141}$$

The nodal average and channel average coolant temperatures are calculated from the new profile as in steady state. The coolant temperature equation for a low-density coolant are given in subsection 3.8.6. The equations given in this section are also correct for a low-density coolant. However, to guarantee numerical stability, the resulting time steps for a low-density coolant are so small that the total running time is at least an order of magnitude greater than that for a sodium problem. Subsection 3.8.6 contains modified equations for a low-density coolant that allows longer time steps and shorter running time. A more detailed discussion of numerical stability is contained in subsection 3.9.

3.8.3 Film Coefficient

From the tables, new values for the thermal conductivity, viscosity, density, and specific heat for the coolant are determined for the new nodal temperatures for use in the next time step. The nodal film heat transfer coefficients for the fuel, structure, and additional material are calculated as discussed in steady state (subsection 3.4.3) by replacing the superscript 0 by a J.

An additional feature is that any time the conditions specified in subsection 3.5.6 for the insertion of void Δk are met, it is possible for the film coefficient in the hot-spot channel to be set equal to a low input value. This capability accounts for the poor heat transfer coefficient of liquid metal vapors at the time of voiding.

3.8.4 Structure and Additional Material Temperature

The temperature change in the structure during any time step is due to the neutron-gamma heating in the structure plus heat exchange between the coolant and structure. The equation is

$$T^{J}_{s,m,k} = T^{J-1}_{s,m,k} + \frac{\tau^{J}}{\rho_s \, c_s} \left[\overline{Q}^{J}_{s,m,k} + \frac{G_s}{\left(\frac{1}{g^{J-1}_{c,m,k}} + \frac{d_s}{K_s} \right)} \left(\overline{T}^{J-1}_{c,m,k} - T^{J-1}_{s,m,k} \right) \right] \quad . \tag{142}$$

The equation for the additional material is identical to Equation (142) by replacing subscript s by u.

3.8.5 Cladding Temperature

The average temperature of the cladding derived from a transient heat balance is

$$T^{j}_{a,m,k} = T^{j-1}_{a,m,k} + \frac{\tau^{j}}{\rho_e C_e A_e}\left[\underbrace{\overline{Q}_{e,m,k} A_e}_{\substack{\text{Rise due to} \\ n\text{-}\gamma \text{ heating}}}\right.$$

$$+ \underbrace{\frac{T^{j-1}_{N,m,k} - T^{j-1}_{a,m,k}}{\left(\frac{\ln \frac{R_a}{R_e}}{2\pi K_e} + \frac{1}{\pi (R_f + R_e) C^{j-1}_{g,m,k}} + \frac{\ln \frac{R_f}{r_N}}{2\pi K^{j-1}_{N,m,k}}\right)}}_{\text{Temperature rise due to heat conducted in}} \tag{143}$$

$$\left. - \underbrace{\frac{T^{j-1}_{a,m,k} - \overline{T}^{j-1}_{c,m,k}}{\left(\frac{\ln \frac{R_E}{R_a}}{2\pi K_e} + \frac{1}{2\pi R_E h^{j-1}_{c,m,k}}\right)}}_{\substack{\text{Temperature drop due to heat} \\ \text{conducted out}}}\right]$$

The outer cladding temperature is determined by a heat balance of the convection and conduction contribution at time j:

$$O = 2\pi R_e h^{j}_{c,m,k}\left(T^{j}_{E,m,k} - \overline{T}^{j-1}_{c,m,k}\right) , - \frac{2\pi K_e}{\ln \frac{R_E}{R_a}}\left(T^{j}_{a,m,k} - T^{j}_{E,m,k}\right) \tag{144}$$

or solving for $T^{j}_{E,m,k}$,

$$T^{j}_{E,m,k} = \frac{\frac{K_e T^{j}_{a,m,k}}{\ln \frac{R_E}{R_a}} + R_E h^{j}_{c,m,k} \overline{T}^{j}_{c,m,k}}{R_E h^{j}_{c.m,k} + \frac{K_e}{\ln \frac{R_E}{R_a}}} \tag{145}$$

3.8.6 Coolant Temperatures (Low-Density Coolant)

For a low-density coolant and for $G_s \neq 0$ and $G_u \neq 0$, a heat balance for the coolant using the most recent known quantities yields

$$0 = \underbrace{\frac{\left(T^J_{a,m,k} - \overline{T}^J_{c,m,k}\right)}{A_c\left(\frac{\ln \frac{R_E}{R_a}}{2\pi K_e} + \frac{1}{2\pi R_E h^{J-1}_{c,m,k}}\right)}}_{\text{Cladding to coolant}} + \underbrace{\frac{V_s G_s}{A_c\left(\frac{1}{g^{J-1}_{c,m,k}} + \frac{d_s}{K_s}\right)}\left(T^J_{s,m,k} - \overline{T}^J_{s,m,k}\right)}_{\text{Structure to coolant}}$$

$$+ \underbrace{\frac{V_u G_u}{A_c\left(\frac{1}{g^{J-1}_{c,m,k}} + \frac{d_u}{K_u}\right)}\left(T^J_{u,m,k} - \overline{T}^J_{c,m,k}\right)}_{\text{Additional material to coolant}}$$

$$+ \underbrace{\frac{G^{J-1}_{c,k}\, C^{J-1}_{c,mk}}{\Delta Z_m}\left[\overline{T}^J_{c,m,k} + \left(T^0_{c,m,k} - T^{in(0)}_{c,m,k}\right)\frac{1-\lambda_a}{\lambda_a} - T^{Out(J)}_{c,m-1,k}\right]}_{\text{Mass transport}} + \underbrace{Q^J_{c,m,k}}_{\text{Heat generated in coolant}} \quad (146)$$

For a low-density coolant, the nodal and average value are at the same position; that is, λ_a is set equal to 0.5. Solving for $\overline{T}^J_{c,m,k}$, we get

$$\overline{T}^J_{c,m,k} = \frac{C_1 T^J_{E,m,k} + C_2 T^J_{s,m,k} + C_3 T^J_{u,m,k} - C_4\left(C_5 - T^{Out(J)}_{c,m-1,k}\right) + Q^j_{c,m,k}}{C_1 + C_2 + C_3 + C_4} \quad (147)$$

where

$$C_1 = \frac{1}{A_c}\left(\frac{1}{\frac{\ln \frac{R_E}{R_a}}{2\pi K_e} + \frac{1}{2\pi R_E h^{J-1}_{c,m,k}}}\right) \quad (148)$$

where

$$C_1 = \frac{2\pi R_E h^{J-1}_{c,m,k}}{A_c} \quad , \tag{148}$$

$$C_2 = \frac{V_s G_s}{A_c\left(\frac{1}{g^{J-1}_{c,m,k}} + \frac{d_s}{K_s}\right)} \quad , \tag{149}$$

$$C_3 = \frac{V_u G_u}{A_c\left(\frac{1}{g^{J-1}_{c,m,k}} + \frac{d_u}{K_u}\right)} \quad , \tag{150}$$

$$C_4 = \frac{G^{J-1}_{c,k} C^{J-1}_{c,m,k}}{\Delta Z_m} \tag{151}$$

and

$$C_5 = \left(T^{0}_{c,m,k} - T^{in(0)}_{c,m,k}\right) \frac{1-\lambda_a}{\lambda_a} \tag{152}$$

Again for G_s or G_u equal zero, Equations (120) and (123) respectively, can be used in Equation (146) for the structure or additional material to coolant term and the related equations can similarly be derived. As in subsection 3.8.2, Equations (140) and (141) are applied for a low-density coolant to find the inlet temperature to node 1 and the nodal outlet temperatures to be used for the next time step.

3.8.7 Fuel Temperature

The inner cladding surface temperature ($T_{e,m,k}$) and the outer fuel surface temperature ($T_{f,m,k}$) at time step j are determined by an iterative procedure involving a heat balance of convection and conduction contribution at these surfaces. At this point, the new coolant ($\bar{T}^{J}_{c,m,k}$) and cladding ($T^{J}_{a,m,k}$) temperatures have been calculated. The first estimate of the new inner cladding temperature is

$$T^{J}_{e,m,k} = \frac{(R_f + R_e) C^{J-1}_{g,m,k} T^{J-1}_{f,m,k} + \dfrac{2K_e}{\ln \frac{R_a}{R_e}} T^{J}_{a,m,k}}{(R_f + R_e) C^{J-1}_{g,m,k} + \dfrac{2K_e}{\ln \frac{R_a}{R_e}}}$$

Note that $T_{f,m,k}$ from step (j-1) is used in Equation (153a). The new estimate of the outer fuel surface temperature using the value $T^{j}_{e,m,k}$ from Equation (153a) is

$$T^{j}_{f,m,k} = \frac{\dfrac{2\,K^{j-1}_{N,m,k}\,T^{j}_{N,m,k}}{\ln\dfrac{R_f}{r_n}} + (R_f + R_e)\,C^{j-1}_{g,m,k}\,T^{j}_{e,m,k}}{(R_f + R_e)\,C^{j}_{g,m,k} + \dfrac{2\,K^{j-1}_{N,m,k}}{\ln\dfrac{R_f}{r_n}}} \tag{153b}$$

The outer fuel surface temperature from Equation (153b) is used in Equation (153a) in place of $T^{j-1}_{f,m,k}$. This iteration is continued until converged surface temperatures are obtained. The temperature of the outer fuel node (N) is calculated based on the same reasoning used in Equation (145) and is given by

$$T^{j}_{N,m,k} = T^{j-1}_{N,m,k} + \frac{\tau^{j}}{\rho_f\,C^{j-1}_{N,m,k}\,A_N}\left[\overline{Q}^{j}_{N,m,k}\,A_N + \frac{2\pi\,K^{j-1}_{N-1,m,k}}{\ln\dfrac{R_N}{r_{N-1}}}\left(T^{j-1}_{N-1,m,k} - T^{j-1}_{N,m,k}\right) - \frac{2\pi\,K^{j-1}_{N,m,k}}{\ln\dfrac{R_f}{r_N}}\left(T^{j-1}_{N,m,k} - T^{j-1}_{f,m,k}\right)\right]. \tag{154}$$

The equation for any fuel ring n is the same as Equation (154), with the substitution of n for N and noting that R_f is given by r_{n+1}.

Two temperatures are always calculated at every nodal location for every time step, including steady state. One is the actual temperature, and the other is an equivalent temperature which accounts for a pseudo temperature rise due to a phase change.

For the less than melt condition, the actual and equivalent temperatures are identical. For the two-phase region, the actual temperature is set equal to the melting temperature as long as the equivalent temperature is greater than melt (T_f^{MELT}) but less than or equal to the pseudo temperature ($T_f^{MELT} + B^{MELT}/\rho_f\,C^{MELT}$) associated with complete melting. By this procedure, the temperature of the fuel at any node remains at the melting temperature until the energy required to melt all the fuel in the node has been absorbed. The equivalent temperatures instead of the actual temperatures can be printed by selection of proper option in input.

3.8.8 Gap Coefficient

If the constant gap coefficient option is selected or if the fuel surface temperature is greater than melting, the gap coefficient becomes

$$C^{j}_{g,m,k} = h_f F^{**} \tag{155}$$

where F** equals 1.0 for the average channel and is equal to the input gap factor for the peak and hot-spot channels. For the variable gap coefficient option, the same model is used for the transient calculations as described in subsection 3.4.8 for steady state. The thermal conductivity of the gas in the gap, the harmonic thermal conductivity of the fuel and cladding, and the contact pressure are, of course, evaluated using the temperatures existing at the particular time. The only other difference is that the gap size is now given by one of four cases.

If in steady state, the volume of any melted fuel did not exceed that of the center fuel void; i.e.,

$$\Delta V^{MELT} \sum_{n=1}^{N} \delta^{MELT\,(0)}_{n,m,k} A_n \leq \pi R_o^2 \ , \tag{156}$$

and if this condition is still true at time j, then

$$\text{(Case 1:)} \quad \Delta\phi^{j}_{m,k} = \underbrace{\Delta\phi^{0}_{m,k}}_{\text{Steady-state gap}} + \underbrace{\left[\left(\frac{\Delta L}{L}\right)^{j}_{e,m,k} - \left(\frac{\Delta L}{L}\right)^{0}_{e,m,k}\right]}_{\text{Expansion of cladding from steady state}} R_e$$

$$- \underbrace{\left[\left(\frac{\Delta L}{L}\right)^{j}_{f,m,k} - \left(\frac{\Delta L}{L}\right)^{0}_{f,m,k}\right]}_{\text{Expansion of fuel from steady state}} R_f \ .$$

If, on the other hand, Equation (156) was true for steady state but is no longer true for time j; i.e.,

$$\Delta V^{MELT} \sum_{n=1}^{N} \delta^{MELT(j)}_{n,m,k} A_n > \pi R_o^2 \ , \tag{158}$$

the expansion of the fuel pellet to account for the additional volume change gives a gap size of

(Case 2:)

$$\Delta\phi^{j}_{m,k} = \text{Eq. (157)} - \frac{1}{A_f}\left[\frac{\Delta V^{MELT} R_f}{2} - \frac{\left(\Delta V^{MELT} + 1\right) R_o^2}{2R_f}\right] \sum_{n=1}^{N} \delta^{MELT(j)}_{n,m,k} A_n \ . \tag{159}$$

If in steady state, the volume of any melted fuel was greater than that of the center void but this condition is no longer true at time j; i.e.,

$$\Delta V^{MELT} \sum_{n=1}^{N} \left[\delta_{n,m,k}^{MELT(j)} - \delta_{n,m,k}^{MELT(0)} \right] A_n \leq \pi R_o^2 \quad , \tag{160}$$

then the gap size will increase by the amount subtracted off in steady state or

(Case 3:)

$$\Delta\phi_{m,k}^{j} = \text{Eq. (157)} + \frac{1}{A_f} \left[\frac{\Delta V^{MELT} R_f}{2} - \frac{\left(\Delta V^{MELT} + 1\right) R_o^2}{2R_f} \right] \sum_{n=1}^{N} \delta_{n,m,k}^{MELT(j)} A_n \quad . \tag{161}$$

If, on the other hand, the volume at time j is still greater than the volume of the center void, any additional expansion is accounted for by

(Case 4:)

$$\Delta\phi_{m,k}^{j} = \text{Eq. (157)} - \frac{1}{A_f} \left[\frac{\Delta V^{MELT} R_f}{2} - \frac{\left(\Delta V^{MELT} + 1\right) R_o^2}{2R_f} \right] \sum_{n=1}^{N} \left[\delta_{n,m,k}^{MELT(j)} - \delta_{n,m,k}^{MELT(0)} \right] A_n \quad . \tag{162}$$

All of the heat transfer coefficients and material preparation determined at time j are not used in the heat balance relationship until the next time step j + 1.

3.8.9 Core Energy Density Change

In steady state, the rate of energy removal from the reactor is approximately

$$\overline{Q}_{out}^{0} = \underbrace{A_c \, \overline{G}_c^{0}}_{\text{Mass}} \; \underbrace{\overline{C}_c^{0}}_{\text{Specific Heat}} \; \underbrace{\left[\overline{T}_c^{0(outlet)} - \overline{T}_c^{0(inlet)} \right]}_{\Delta T}, \tag{163}$$

where the inlet and outlet temperatures are for the average channel and the coolant property data are evaluated at the arithmetic mean of the inlet and outlet temperature

The rate of energy removal from the reactor in MW at any time j is

$$\overline{Q}_{out}^{j} = A_c \, \overline{G}_c^{j} \, \overline{C}_c^{j} \left[\overline{T}_c^{j(outlet)} - \overline{T}_c^{j(inlet)} \right] \frac{P_{in}}{\overline{Q}_{out}^{0}} \quad , \tag{164}$$

where $\overline{T}_c^{J(outlet)}$ and $\overline{T}_c^{J(inlet)}$ are the arithmetic averages of the outlet and inlet temperatures, respectively, for the beginning of the time step J-1 and the end of the time step J. The term $P_{in}/\overline{Q}_{out}^{0}$ is used to correct the approximations inherent in Equation (163).

The net energy removal from the reactor since steady state or time zero becomes

$$E_{out}^{J} = E_{out}^{J-1} + \tau^{J}\,\overline{Q}_{out}^{J} \quad . \tag{165}$$

The nuclear energy addition to the core since time zero is

$$E_{in}^{J} = E_{in}^{J-1} + \tau^{J}\,\frac{\overline{P}_{J}\;V_f}{948.05} \quad , \tag{166}$$

and the net change in energy density is

$$\Delta E^{J} = \frac{E_{in}^{J} - E_{out}^{J}}{V_{core}} \quad . \tag{167}$$

3.9 TIME STEP SIZE (STAB SUBROUTINE)

This subroutine calculates the step size that will guarantee numerical stability in the finite difference equations for transient temperatures. The user may input the step size for the code, to use instead of using the calculated size. Even though this input step size option is selected, FORE II will still calculate a step size. The only use for the calculated step size in this case is to compare with the input value. If the calculated step size to guarantee temperature stability is less than the input step size, a message is printed at the end of the computer calculations to alert the user.

Figure 3-7 indicates the cross section of a large slab with uniform cross-sectional area A for the general case of one-dimensional transient heat transfer.

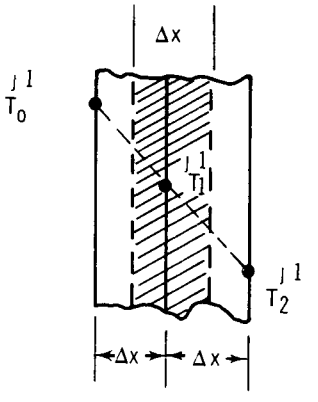


FIGURE 3.7 SLAB GEOMETRY

A heat balance using finite difference techniques yields

$$\frac{kA\left(T_o^{j-1} - T_1^{j-1}\right)}{\Delta x} - \frac{kA\left(T_1^{j-1} - T_2^{j-1}\right)}{\Delta x} = \frac{A\Delta x\rho c\left(T_1^{j} - T_1^{j-1}\right)}{\tau} , \tag{168}$$

or solving for T_1^j ,

$$T_1^j = \frac{T_o^{j-1} + (M-2)\, T_1^{j-1} + T_2^{j-1}}{M} , \tag{169}$$

where

$$M = \frac{\rho c\,(\Delta x)^2}{k\tau} . \tag{170}$$

To achieve temperature stability, the coefficient of T_1^{j-1} must be positive, or M must be at least equal to 2.0. For a zero step size τ, M is infinite from Equation (170). As the step size τ is increased, M decreases until some limiting step size is reached such that M equals 2.0.

The principle outlined in this simple example underlies the equations for determining the step size. Basically, a maximum time step to ensure temperature stability is calculated for all axial nodes and channel types for the coolant, cladding, structure, additional material, and all fuel rings. Under maximum conditions, this can result in a 7 by 3 by 14 array of time steps. The final time step is the minimum value from the above array of time steps.

For the no-lumping case and for $G_s \neq 0$ and $G_u \neq 0$, the coolant temperature is given by Equation (136) which, repeated, is

$$T_{c,m,k}^j = T_{c,m,k}^{j-1} + A\left[\overline{Q}_{c,m,k}^j + B + C + D\right] - E.$$

The expressions B, C, and D also involve the term $T_{c,m,k}^{j-1}$. In addition, the term $T_{c,m,k}^{j-1}$ is also contained in the expression for E since

$$T_{c,m,k}^{out(j-1)} - T_{c,m-1,k}^{out(j-1)} \qquad \frac{T_{c,m,k}^{j-1} - T_{c,m,k}^{in(j-1)}}{\lambda_a} \tag{171}$$

Equation (136) can be rearranged as

$$T^{J}_{c,m,k} = \left[1 - \frac{\tau^{J} V_s G_s}{A_c \left(\frac{1}{g^{J-1}_{c,m,k}} + \frac{d_s}{K_s} \right) \rho^{J-1}_{c,m,k} C^{J-1}_{c,m,k}} - \frac{\tau^{J} V_u G_u}{A_c \left(\frac{1}{g^{J-1}_{c,m,k}} + \frac{d_u}{K_u} \right) \rho^{J-1}_{c,m,k} C^{J-1}_{c,m,k}} \right.$$

$$- \frac{\tau^{J}}{\left(\frac{1}{2\pi R_E h^{J-1}_{c,m,k}} + \frac{\ln \frac{R_E}{R_a}}{2\pi K_e} \right) A_c \rho^{J-1}_{c,m,k} C^{J-1}_{c,m,k}}$$

$$\left. - \frac{\tau^{J} G^{J-1}_{c,k}}{\Delta Z_m \lambda_a \rho^{J-1}_{c,m,k}} \right] T^{J-1}_{c,m,k} + \left[\begin{array}{c} \text{Additional terms} \\ \text{not involving} \\ T^{J-1}_{c,m,k} \end{array} \right] . \qquad (172)$$

Now, by specifying that the coefficient for $T^{J-1}_{c,m,k}$ must be non-negative and solving for τ^{J}, one obtains

$$\tau^{J}_{c,m,k} = \frac{1}{\text{DENOM}} \quad , \qquad (173)$$

where

$$\text{DENOM} = \frac{V_s G_s}{A_c \left(\frac{1}{g^{J-1}} + \frac{d_s}{K_s} \right) \rho^{J-1}_{c,m,k} C^{J-1}_{c,m,k}} + \frac{V_u G_u}{A_c \left(\frac{1}{g^{J-1}_{c,m,k}} + \frac{d_u}{K_u} \right) \rho^{J-1}_{c,m,k} C^{J-1}_{c,m,k}}$$

$$+ \frac{1}{\left(\frac{1}{2\pi R_E h^{J-1}_{c,m,k}} + \frac{\ln \frac{R_E}{R_a}}{2\pi K_e} \right) A_c \rho^{J-1}_{c,m,k} C^{J-1}_{c,m,k}} + \frac{G^{J-1}_{c,k}}{\Delta Z_m \lambda_a \rho^{J-1}_{c,m,k}} . \qquad (174)$$

This same procedure is used to develop the time step equation for the other materials and radial fuel rings.

For coolants with low density (ρ_c), the factor DENOM can be large and, in turn, the time step based on coolant stability can be rather small. Specifically, the time step size can be an order of magnitude times smaller than that for a liquid metal coolant, causing prohibitively long running times on the computer. To avoid this difficulty, the user can indicate in the input that a low-density coolant is being used. This causes the time step size based on the coolant in the STAB subroutine to be bypassed. The time step size for the other materials and radial fuel rings remains the same. No numerical instability will result because the coolant time step size is bypassed, since for a low density coolant modified equations are used for the coolant transient temperature calculations (subsection 3.8.6). These modified equations do not involve $\overline{T}^{(J-1)}_{c,m,k}$ directly.

SECTION IV

OPERATION OF FORE II

4.1 FORE II SYSTEM

The FORE II code consists of the following three "independent" codes:

a.	FORE II (Labeled EEEE on Case Card)	—	Performs all calculations. Gives condensed or short edit of results.
b.	FEDIT	—	Gives detailed or long edit of results.
c.	FRCURV	—	Performs curve plotting of output.

From a programming consideration, these codes are independent. Thus, to obtain a long edit, the user must specify that FEDIT be run after FORE II. (This assumes the proper options were selected in FORE II to save the desired calculated values on tape.) From a functional consideration, FEDIT and FRCURV are not independent in that they have no purpose outside of that related to FORE II. This artificial separation was required to meet all the options available to the user and to accommodate normal tape-handling procedures at most computer installations.

Under normal, routine work assignments, the following procedure has been found to be effective:

a. Run FORE II for a small number of steps and wrap up the results on tape. Obtain only a short edit.

b. Review the verbal edit of input values and steady-state calculations.

c. Restart and run to completion. Obtain short edit.

d. Obtain long edit or plotted results if calculations from short edit look physically reasonable.

4.2 GENERAL INPUT PHILOSOPHY

4.2.1 Format

The required input cards for running FORE II are

Case Card
Data Cards
9999 Card
Last Card

The particular input for the data cards is discussed in subsection 4.3. The format for the other cards are

Case Card:

Column	Contents
1	) independent case designation
	(dependent case designation
2-5	EEEE
6-8	User's Initials
9	*
10-14	Case Number
15-27	Blank
28-34	Date

9999 Card (Sentinel Card):

Columns	Contents
1-4	9999
5-80	Blank

Last Card:

Columns	Contents
1-5	) Last
9	*

Because of tape-handling difficulties when a wrapup is requested or when computer plots are to be made, only single cases can be run in this version of the code. Future versions of the code will allow the user to run successive cases (independent or dependent).

All the input data cards have the same format. Columns 1 to 4 must be a right adjusted integer corresponding to the input location for the first input value to the right of column 4. Columns 5 to 80 contain input values in free form; that is, there is no requirement that a particular input appear in specified columns. Free form requires that each number be separated, by one or more space or by a comma, from its neighbor. The input values in columns 5 to 80 are loaded in consecutive order, with the first value corresponding to the location in columns 1 to 4. Input locations 1 to 60 are integer number. Input location beyond 60 must be external fixed point (F Field) or floating point (E Field) numbers; that is, a decimal point must be used. The exceptions are locations 851 and 852, which use the Hollerith field for tape labeling.

Repeat and skip options offer additional input flexibility. The expression 1.0 ΔRnΔ, for example, assigns 1.0 to n consecutive location. The Δ is to emphasize that a blank must be used. Similarly, the expression ΔSnΔ skips n consecutive input locations. All input values are preset to zero at the start of the program. As such, the user can input values for only the locations to be changed from zero. Any alphanumeric input in columns 5 to 80 contained within parentheses is edited in the printed output, but otherwise is ignored. This allows the user to insert comments in the input deck to identify particular portions of the input. Appendix C, C.1, contains a listing of the input for the sample problem. The input options and card format are illustrated in this listing

There is no requirement that the data cards be in any particular order. Because of this capability, it is possible to use a basic input deck with the modifications for the particular problem included before the sentinel card.

4.2.2 Restart

The user has the option in FORE II for a final and two intermediate wrapups, and for a restart with changes in input from any of these wrapups. Table 4-1 contains a list of input values that cannot be changed on restart.

Because of the restart capability, the flexibility of FORE II has been greatly extended. A typical use might be the coefficients of reactivity terms which are single value input. For the particular transient problem under consideration, the user might discover that the coefficients vary over too large a range to be approximated by a single number. This functional variation may be approximated to any degree of accuracy by repeatedly running for a specified time step and restarting with the new revised reactivity coefficients.

TABLE 4-1

VALUES NOT TO BE CHANGED AT RESTART

Location	Definition
1	Number of delay groups
7	Number of radial core regions
8	Number of vertical core sections
9	Number of radial fuel nodes
18	Lumping conditions
21	Number of channels
27	Additional material input
76	Equivalent radius of the coolant
77	Cladding inner radius
78	Cladding outer radius
79-88	Radii of the fuel nodes
90	Core outer radius
91	Volume of fuel in the core
94-100	Length of core axial sections

The input deck for a restart is as follows:

Independent case card
Data cards for input locations 29, 52, 850, and 851
Sentinel card
Dependent case card
Data cards with changes in input values
Sentinel card
Last card

Appendix C, C.2, contains the listing of the restart deck for the sample problem. Additional comments on the restart deck are given in the listing.

4.3 INPUT FOR FORE II

INTEGER VARIABLES, LOCATIONS 1 TO 60

Nodal and Tabular Options

Location	User's Symbol	Definition
1	I	Number of delay groups $1 \leq$ IMAX ≤ 6
2	IM	Number of terms in empirical fit to fission product decay [see Equation (102)] $1 \leq$ IMMAX ≤ 3
3	INUM	Number of mass velocity entries $2 \leq$ INUM ≤ 30
4	ISMAX	Number of effective multiplication factor entries (if this is input) $2 \leq$ ISMAX ≤ 30
5	J	Maximum number of time steps
6	KNUM	Number of $T_c'^{in}$ entries $2 \leq$ KNUM ≤ 30
7	L	Number of radial core regions $2 \leq L \leq 7$ ($L \neq 0, 1$)
8	M	Number of vertical core sections $1 \leq M \leq 7$
9	N	Number of radii at which fuel temperatures are calculated $1 \leq N \leq 10$
10	NUMPWR	Number of power entries (if this is an input, $2 \leq$ NUMPWR ≤ 30
11	NMVOID	Number of entries due to sodium voiding (if this is an input), 2 = NMVOID ≤ 30
12	NMSCRM	Number of Δk points due to scram (If this is an input), $2 \leq$ NMSCRM ≤ 30
13	NMCOOL	Number of bulk coolant boiling entries (if this is an input), $2 \leq$ NMCOOL ≤ 20
14	NMCLAD	Number of cladding burnout entries (if this is an input), $2 \leq$ NMCLAD ≤ 20
15	NMTERM	Channel to which temperature limits should be applied (1, 2, or 3). If 0, average channel will be used.
16	δ_ℓ	Equals 0 means use calculated W_ℓ which assumes parabolic profile Equals 1 means use input values for W_ℓ (Locations 820 - 826)

Code Options

Location	User's Symbol	Definition
17	δ_{bow}	1, Cantilevered at inlet, pinned at exit 2, Simply supported at both ends 3, Cantilevered at exit, pinned at inlet 4, Cantilevered at exit, free at inlet 5, Cantilevered at inlet, free at exit 0, No bowing
18	δ_{c}	1, If coolant, cladding, structure, and additional material are not lumped 0, If lumped
19	δ_{est}	1, For extrapolation procedure (for feedback approximation) 0, Otherwise
20	δ_{gap}	1, For variable conductance from fuel to cladding 0, Constant conductance (see location 341)
21	δ_{h}	1, Calculate temperatures for average channel only 2, Calculate temperatures for average and peak channels 3, Calculate temperatures for average, peak, and hot-spot channels
22	δ_{k}	1, Use table for fuel conductivity 0, Use curve fit
23	δ_{pwr}	1, Use power table 0, Otherwise
24	δ_{scram}	1, If scram table of reactivity is input 0, Otherwise
25	δ_{void}	1, If sodium void reactivity table is input 0, Otherwise
26	δ_{step}	1, If user has specified step size 0, For calculation of step size
27	δ_{u}	1, If additional material is used 0, Otherwise (if $\delta_u = 0$, G_u must be 0.0)
28	δ_{cof}	1, If $h_{c,m,k=3}^{(j)}$ should be calculated at time of void (set to 1 if no voiding table) 0, If it should be set equal to input constant at time of void
29	$\delta_{restart}$	1, If this is a restart 0, Otherwise
30	δ_{ave}	0, If average temperature is based on core only 1, If average temperature is based on core plus blankets

Edit Options

Location	User's Symbol	Definition
31	δ_{short}	1, Print the short edit 0, Do not print the short edit
32	NMSHRT	Number of steps/printout (short edit)
33	δ_{long}	1, Print the long edit 0, Do not print the long edit
34	NMLONG	Number of steps/printout (long edit)
35	δ_{Op1}	1, Print section D (precursor Concentrations) 0, Do not print section D
36	δ_{Op2}	1, Edit average channel only, sections E and F (Fuel and Radial Temperatures) 2, Edit average and peak channels 3, Edit average, peak, and hot-spot channels 0, Edit all channels calculated
37	δ_{temp}	1, Print fuel Equivalents 0, Print fuel Temperatures
38	MSKIP	Total number of axial sections to be bypassed in the edit of sections E and F
39-45	MDELZ	Axial section to be bypassed in the edit of sections E and F
46	δ_{Op3}	1, Print out section G (Coolant Temperature and Velocity) 0, Do not print section G
47	δ_{Op4}	1, Print section H (Cladding surface heat flux) 0, Do not print section H
48	δ_{Op5}	1, Print section I (Coefficients and Gap) 0, Do not print section I
49	δ_{wrapup}	0, No wrapup 1, Final wrapup only 2, One additional wrapup 3, Two additional wrapups
50-51	JRAPUP	Time step where wrapup is desired (if $\delta_{wrapup} = 2$, specify one value) (if δ_{wrapup} 3, specify two values)

Other Input

Location	User's Symbol	Definition
52	KNTNV	If your case is a restart: 0 means continue problem where original one left off 1 means continue problem from first wrapup 2 means continue problem from second wrapup
53	–	Blank
54	–	Blank
55	B_{Bot}	Number of axial blankets at bottom of core
56	B_{Top}	Number of axial blankets at top of core
57	$\delta_{coolant}$	0, High-density coolant (liquid metal) 1, Low-density coolant (gas or steam)
58	–	Blank
59	–	Blank
60	–	Blank

DECIMAL VARIABLES LOCATIONS GREATER THAN 60

Time and Termination Controls

Location	User's Symbol	Definition	Units
61	DELP	Maximum fractional power change per step	–
62	DELT	Initial step size (must always be input)	sec
63	HMAX	User's maximum step size (input only if $\delta_{step} = 1$)	sec
64	TMAX	Maximum running time of transient	sec
65	T_1^{Max}	Upper limit for temperature of fuel node 1	°F
66	T_1^{Min}	Lower limit for temperature of fuel node 1	°F
67	T_N^{Max}	Upper limit for fuel boundary node	°F
68	T_N^{Min}	Lower limit for fuel boundary node	°F
69	T_c^{Max}	Upper limit for coolant temperatures	°F

Time and Termination Controls (Continued)

Location	User's Symbol	Definition	Units
70	T_c^{Min}	Lower limit for coolant temperatures	°F
71	P^{Max}	Maximum time between printouts	sec
72	–	Minimum time step size	sec
73	–	Blank	
74	–	Blank	

Geometry

Location	User's Symbol	Definition	Units
75	D_B	Diameter of the fuel channel [see Equation (67)]	ft
76	R_c	Equivalent radius of the coolant	ft
77	R_e	Cladding inner radius	ft
78	R_E	Cladding outer radius	ft
79-88	R_n	Outer radius of fuel node n $1 \leq n \leq N$	ft
89	R_o	Radius of the void (fuel pin center)	ft
90	R_T	Core outer radius	ft
91	V_f	Total volume of fuel in core	ft^3
92	V_s	Volume of structure per unit length of fuel	ft^2
93	V_u	Volume of additional material per unit length of fuel	ft^2
94-100	$(\Delta Z)_m$	Length of core axial section m, $1 \cdot m \cdot M$	ft
101	Z_t	Total distance from channel inlet to outlet	ft
102	–	Blank	
103	–	Blank	
104	–	Blank	
105	–	Blank	

Material Properties

Location	User's Symbol	Definition	Units
106	F_e	Hot spot factor for thermal conductivity of the cladding	-
107	K_e	Thermal conductivity of the cladding	Btu/sec-ft-°F
108	K_s	Thermal conductivity of the structure	Btu/sec-ft-°F
109	K_u	Thermal conductivity of the additional material	Btu/sec-ft-°F
110	C_e	Specific heat of the cladding	Btu/lb-°F
111	C_s	Specific heat of the structure	Btu/lb-°F
112	C_u	Specific heat of the additional material	Btu/lb-°F
113	ρ_f	Fuel density	lb/ft^3
114	ρ_e	Cladding density	lb/ft^3
115	ρ_s	Structure density	lb/ft^3
116	ρ_u	Density of additional material	lb/ft^3
117	T_f^{MELT}	Fuel melting temperature	°F
118	K^0	Constants used in calculating thermal conductivity of the fuel (only if quadratic fit selected)	Btu/sec-ft-°F
119	K^1		Btu/sec-ft-$°F^2$
120	K^2		Btu/sec-ft-$°F^3$
121	F_k	Hot spot factor for fuel conductivity	-
122	B_K	Constants used in calculating fuel conductivity at melting (only if quadratic fit selected)	Btu/sec-ft-$°F^2$
123	C_K		Btu/sec-ft-$°F^3$
124	B^{MELT}	Fuel heat of fusion	Btu/ft^3
125-144	C'	Specific heat of fuel versus	Btu/lb-°F
145-164	T'	Temperature	°F
165-170	-	Blank	

Power and Flow Factors

Location	User's Symbol	Definition	Units
171-177	A_m	Ratio of peak power to average power for axial section m $1 \leq m \leq M$	-
178	F_γ	Fraction of power due to gamma and neutron heating	-
179	P_H	Hot-spot factor used in calculation of heat generation rates in hot-spot channel	-
180	P_r	Radial peak-to-average power density ratio in core	-
181-190	Y_n	Ratio of heat generation rate in fuel node n to fuel average heat generation rate Note: $\sum_{n=1}^{N} Y_n A_n = A_f$	-
191	F_r	Peak channel factor used in calculating $G^0_{c,k=2}$ (mass velocity for channel 2)	-
192	F_v	Hot-spot factor used in calculating $G_{c,k=3}$ (mass velocity for channel 3)	-
193-195	-	Blank	

Coolant Flow Characteristics

Location	User's Symbol	Definition	Units
196-225	G_c'	Coolant mass velocity for average channel versus	lb/ft^2-sec
226-255	T'	Time	sec
256-285	$T_c'^{Inlet}$	Coolant inlet temperature versus	°F
286-315	T'	Time	sec
316	$B_{OR,k=2}$	Sum of the local loss coefficients in peak channel (orifice, inlet, outlet, and local effects)	-
317	C	Constants needed to calculate COMP, criterion for Reynolds number	-
318	e	(Suggested values: C = 0.316, e = 0.25)	-
319	D_H	Hydraulic diameter of coolant passage	ft
320	-	Blank	

Coolant Heat Transfer Coefficient Inputs

Location	User's Symbol	Definition	Units
321	A_H	Constants used in coolant heat transfer coefficient equation $1 \leq m \leq M$ (see subsection 3.4.3)	-
322	B_H		-
323-329	$C_{H,m}$		-
330	M_H		-
331	N_H		-
332	R_H		-
333	D_{HT}	Appropriate diameter for use in calculating the coolant heat transfer coefficient	ft
334	F_h	Hot-spot factor for calculating coolant heat transfer coefficient	-
335	d_s	Characteristic structure dimension (see subsection 3.4.4)	ft
336	d_u	Characteristic dimension of the additional material (see subsection 3.4.4)	ft
337	G_s	Structure surface-to-volume ratio (see subsection 3.4.4)	ft^{-1}
338	G_u	Additional material surface-to-volume ratio (if $\delta_u = 0$, G_u must be 0.0) (see subsection 3.4.4)	ft^{-1}
339	$h_{c,3}$	Coolant heat transfer coefficient for hot-spot channel at time of void (used only if $\delta_{cof} = 0$)	$Btu/sec\text{-}ft^2\text{-}°F$
340	-	Blank	

Gap Conductivity Inputs

(See subsection 3.4.8 for locations 341 to 359)

Location	User's Symbol	Definition	Units
341	h_f	Heat transfer coefficient of fuel cladding gap (if location 20 is 0, only locations 341, 355, and 359 need be be considered in this section)	$Btu/sec\text{-}ft^2\text{-}°F$
342	A_g	Constants used in equation for calculating thermal conductivity of the gap [see Equation (38)]	$Btu/sec\text{-}ft^2\text{-}°F$
343	B_g		$Btu/sec\text{-}ft^2\text{-}°F^2$
344	C_g		$Btu/sec\text{-}ft^2\text{-}°F^3$

Gap Conductivity Inputs (Continued)

Location	User's Symbol	Definition	Units
345	a_o	Constant used in gap conductivity equation [see Equation (37)]	$ft^{\frac{1}{2}}$
346	β_o	Constant used in gap conductivity equation [see Equations (39) and (40)]	-
347	E_e	Modulus of elasticity of the cladding	$lb/in.^2$
348	g_e	Average jump distances for the fission gas at the cladding and fuel surfaces, respectively	ft
349	g_f		ft
350	$(R_e-R_f)^{cold}$	Cold cladding radius minus cold fuel radius	ft
351	δ_e	Arithmetic mean roughness heights of cladding and fuel, respectively	ft
352	δ_f		
353	J	Meyer hardness of material (use hardness value for the softer of the two materials)	lb/ft^2
354	ΔV^{MELT}	Volume increase of fuel due to melting	-
355	F_g	Hot-spot factor to calculate gap coefficient	-
356	$\sigma_{y.p.}$	Elastic yield point of cladding	$lb/in.^2$
357	-	Blank	
358	-	Blank	
359	$F_{g,p}$	Peaking factor for gap coefficient for peak channel	-

Feedback Inputs

(For power table, all feedback inputs may be omitted except 365 - 370)

Location	User's Symbol	Definition	Units
360	C_f	Relative worth of axial fuel expansion [See Equation (90)]	-
361	α_s	Linear thermal expansion coefficient of structure in the radial direction	$°F^{-1}$
362	α'_s	Effective coefficient of thermal expansion used in calculation of increase in core radius	$°F^{-1}$

Feedback Inputs (Continued)

Location	User's Symbol	Definition	Units
363	α''_s	Structure coefficient of thermal expansion (see subsection 3.5.3)	$°F^{-1}$
364	$\alpha_{s,ax}$	Linear thermal expansion coefficient of structure in the axial direction [see Equation (97)]	$°F^{-1}$
365	E_{e0}	Fit coefficients for fractional expansion of cladding from 70°F. Of the form $\frac{\Delta L}{L} = E_{e0} + E_{e1} T + E_{e2} T^2$	–
366	E_{e1}		$°F^{-1}$
367	E_{e2}		$°F^{-2}$
368	E_{f0}	Fit coefficients for fractional expansion of fuel from 70°F. Do not include discontinuity due to melting in this fit.	–
369	E_{f1}		$°F^{-1}$
370	E_{f2}		$°F^{-2}$
371	E_{u0}	Fit coefficients for fractional expansion of additional material from 70°F	–
372	E_{u1}		$°F^{-1}$
373	E_{u2}		$°F^{-2}$
374-404		Blank	
405	$R_T \frac{\delta k}{\delta R_T}$	Core radius coefficient	–
406	$H_t \frac{\delta k}{\delta H_t}$	Core height coefficient	–
407-413	$\left(\rho_e \frac{\sigma k}{\delta \rho_e}\right)_m$	Density coefficient of reactivity of the cladding for section m, $1 < m \leq M$	–
414-420	$\left(\rho_c \frac{\delta k}{\delta \rho_c}\right)_m$	Density coefficient of reactivity of the coolant for section m, $1 < m \leq M$	–
421-427	$\left(\rho_f \frac{\delta k}{\delta \rho_f}\right)_m$	Density coefficient of reactivity of the fuel for section m, $1 \leq m < M$	–
428-434	$\left(\rho_u \frac{\delta k}{\delta \rho_u}\right)_m$	Density coefficient of reactivity of the additional material for section m, $1 < m < M$	–

Feedback Inputs (Continued)

Location	User's Symbol	Description	Units
435-441	$\left(\rho_s \frac{\delta k}{\delta \rho_s}\right)_m$	Density coefficient of reactivity of the structure for section m, $1 \leq m \leq M$	-
442-471	$k_{p,s}$	Table for effective multiplication factor versus	-
472-501	t_s	Time	sec
502-531	$\Delta k'_{void}$	Δk due to sodium voiding versus	-
532-561	T'_{void}	Time since initiation	sec
562-591	$\Delta k'_{scram}$	Δk due to scram versus	-
592-621	T'_{scram}	Time since initiation	sec
622	H^*	Distance between core inlet and exit support plates	ft
623	Ψ_o	Measurement of the core lower support plate's angular deflection from the horizontal (at steady state)	radians
624	Z_o	Distance from core inlet support to actual core inlet	ft
625	A_{Dop}	Input constants used in Doppler feedback equations	-
626	B_{Dop}		-
627	b		
628-634	P_ℓ	Spacial power weighting factor, $1 \leq \ell \leq L$, radial direction	-
635	C_D	Doppler correction for temperature profile	-

Power Inputs

Location	User's Symbol	Definition	Units
636	P_{in}	Input power	MW
637-666	P'	Normalized power versus	-
667-696	T'_p	Time	sec
697-699	A_{im}	Terms used in empirical expression for decay of fission products $1 \leq im \leq IMMAX$	t^{α}

Power Inputs (Continued)

Location	User's Symbol	Definition	Units
700-702	α_{im}	Terms used in empirical expression for decay of fission products $1 \leq im \leq$ IMMAX (cannot be equal to 0, 1)	t^{α}
703-705	a_{im}	Terms used in empirical expression for decay of fission products $1 \leq im \leq$ IMMAX	sec
706	S	Source	fissions/cc-sec
707	T_o	Length of time prior to start of problem for which the reactor was operated at the constant power, P_o	sec
708-713	β_i	Delayed neutron fraction, i^{th} group $1 \leq i \leq I$	sec^{-1}
714-719	γ_i	Decay constants of i^{th} group $1 \leq i \leq I$	sec^{-1}
720	ν	Neutrons per fission	-
721	ℓ	Neutron lifetime	sec
722-727	C_i	Delayed neutron precursor concentration for i^{th} group $1 \leq i \leq I$	cc^{-1}
728	ϵ_k	Small constant determining appropriate solution to power equations	-
729	ϵ_{pwr}	Criterion for power and energy accumulation (suggested input: 1.0×10^{-7})	-

Miscellaneous

Location	User's Symbol	Definition	Units
730	ϵ_T	Convergence criterion for initial fuel temperature calculations	-
731	λ_a	Constant used to indicate location to calculate coolant temperature	-
732	T_c^{Scram}	Scram initiation temperature	°F
733	ϵ_{Scram}	Small constant to determine start of scram reactivity	-
734-753	$T_c'^{Boil}$	Coolant's bulk boiling temperature versus	°F
754-773	P_c'	Absolute pressure	$lb/in.^2$

Miscellaneous (Continued)

Location	User's Symbol	Definition	Units
774-793	$T_e^{'\ Burnout}$	Cladding burnout temperature versus	°F
794-813	P_e'	Absolute pressure	lb/in.^{2}
814	f_Z	Fractional of channel frictional pressure drop inlet to void	–
815	P_{St}	Static head pressure at channel inlet	lb/in.^{2}
816	P_{Pump}	Pump head pressure at channel inlet	lb/in.^{2}
817	T_f^{Vapor}	Fuel temperature at which vaporization occurs	°F
818	W_f	Convergence weighting factor for gap coefficient in steady state	
819	–	Blank	
820-826	W_ℓ	Regional weighting factor for core radial temperature profile (must be input if $\delta_\ell = 1$)	
827-849	–	Blank	
850	ILABL1	Name of tape to be saved for long edit and restart (not to exceed 6 Hollerith characters)	–
851	ILABL2	Tape label name for new tape when restarting a problem (not to exceed 6 Hollerith characters)	–
852-860	–	Blank	
861-880	K_f'	Table for fuel conductivity versus	Btu/ft-sec-°F
881-900	T_{fuel}'	Temperature (input only if δ_k equals 1)	°F
901-980	–	Blank	

BUILT-IN TABLES

(Appendix B contains a list of built-in values which are for sodium, these tables need be considered only when an overlay of data is desired)

Location	User's Symbol	Definition	Units
981-1000	K_c	Thermal conductivity of coolant versus	Btu/sec-ft
1001-1020	T_c	Temperature	°F

BUILT-IN TABLES (Continued)

Location	User's Symbol	Definition	Units
1021-1040	α_c	Coolant coefficient of expansion versus	$°F^{-1}$
1041-1060	T_c	Temperature	°F
1061-1080	μ_c	Dynamic viscosity of coolant versus	lb/ft-sec
1081-1100	T_c	Temperature	°F
1101-1120	C_c	Specific heat of coolant versus	Btu/lb-°F
1121-1140	T_c	Temperature	°F
1141-1160	P_c	Density of coolant versus	lb/ft^3
1160-1180	T_c	Temperature	°F

4.4 CURVE-PLOTTING PROGRAM

4.4.1 General Input-Output Philosophy

Forty-six output quantities from the FORE II program can be plotted by the FRCURV program. A total of 30 graphs per case, with a limit of 10 curves per graph, can be plotted. The three types of graphs which FRCURV will plot are:

a. Specified variable versus time,

b. Temperature versus radial location for desired time values, and

c. Specified axial variable versus axial location for desired time values.

Only seven radial and three axial graphs can be plotted per case. The number of time graphs is, then, 30 minus the number of radial and axial graphs requested.

The required input cards to FRCURV are

Case Card
Data Cards
Last Card

The data cards are read by the DTA subroutine. The portion of DTA pertinent to FRCURV is discussed in this report. More detailed information can be obtained from the DTA subroutine description. The data cards use the free-form input, allowing data to be punched in columns 2 to 80 without being confined to specific columns. In addition, the data cards are not required to be in any particular order. The following general rules apply to the data cards:

a. Any necessary indexing associated with an input symbol must be contained within parentheses and not separated from the identifying symbol by blanks.

b. The general format for a data card is an identifying symbol, an equal sign, and input values. The input values must be separated by a comma or by one or more blanks.

c. Skipping locations in a normal sequence is done by a blank or comma and slash (/), followed by an integer equal to the number of locations to be skipped.

d. Repeating a given value for consecutive locations can be achieved by a blank, an asterisk (*), followed by the integer equal to the number of times the value is repeated.

e. Comments must be enclosed within parentheses and the left parenthesis should always be preceded by a blank.

f. Input values for labels are of the general form nH ----- where n is the number of characters following the H.

g. The dollar sign ($) will terminate input loading of a card. The use of the termination symbol is not mandatory, but advisable because it reduces read-in time.

h. The double dollar sign ($$) will terminate all data loading. It should be separated from the last input value by a blank or comma. A separate card with the $$ is strongly advised since it can be used for case after case and is not likely to be forgotten.

These rules are best illustrated by the examples in subsection 4.4.3 and reference to the sample problem input listing for FRCURV in Appendix C, subsection C 1.

The first item on a data card is a symbol which is of three general types:

a. A definition of a variable to be plotted,

b. An indicator that the input values after the equal sign are labels for the graphs, or

c. Operational or control instructions.

Subsection 4.4.2 contains a list of the input for these three categories. Subsection 4.4.3 contains a discussion of the input with examples. Appendix C, C.3, is the input for FRCURV for the sample problem, with additional comments included on the listing. The sample problem listing is particularly useful since the plotted output is contained in Appendix C, C.4.

4.4.2 FRCURV Input

4.4.2.1 Quantities Available for Plotting

	Symbol	Dimension	Definition
1.	TCDAV	(M, K)	Volumetric average temperature of the cladding, $1 \leq M \leq 7$, $1 \leq K \leq 3$
2.	TST	(M, K)	Structure temperature
3.	TMT	(M, K)	Temperature of the additional material
4.	DKVOID	1	Cumulative feedback Δk due to sodium voiding
5.	REACT	1	Total Δk
6.	QH	(M, K)	Cladding-surface heat flux
7.	TVDO	(M, K)	Fuel center temperature
8.	DELPHI	(M, K)	Width of fuel cladding gap
9.	EVDO	(M, K)	Fuel center equivalent temperature
10.	TCORAV	1	Average temperature of the core (°K)
11.	DKDOP	1	Cumulative Doppler feedback Δk
12.	RFDBK	1	Total feedback Δk
13.	FBD	1	Cumulative feedback Δk due to density changes
14.	FBR	1	Cumulative feedback Δk due to core radius changes
15.	FBH	1	Cumulative feedback Δk due to core height change
16.	PROG	1	Programmed Δk
17.	EOUT	1	Net energy removal from core since time zero
18.	ENAD	1	Nuclear energy addition to core since time zero
19.	DELEN	1	Change in core energy density since time zero
20.	SQGL	1	Doppler weighting factor
21.	PREC	(I)	Delayed neutron precursor concentration $1 \leq I \leq 6$
22.	TCLAV	(M, K)	Coolant average temperature
23.	VELCL	(K)	Mass velocity of the coolant (lb/ft^2-sec) $1 \leq K \leq 3$
24.	CFLCL	(M, K)	Gap coefficient
25.	HTCL	(M, K)	Cladding-coolant transfer coefficient (for unlumped system)
26.	TCL	(M, K)	Nodal coolant temperature
27.	TCDS	(M, K)	Outer cladding surface temperature
28.	TCD	(M, K)	Inner cladding surface temperature
29.	PSTR	1	Prompt power
30.	POWER	1	Total power
31.	TOUT	(K)	Core outlet temperature
32.	TCINLT	1	Core inlet temperature

	Symbol	Dimension	Definition
33.	TND	(N, M, K)	Fuel node temperature $1 \leq N \leq 10$, $1 \leq M \leq 7$, $1 \leq K \leq 3$
34.	TCDO	(M, K)	Average cladding temperature
35.	TFL	(M, K)	Fuel surface temperature
36.	EQTND	(N, M, K)	Fuel node equivalent temperature
37.	EFL	(M, K)	Fuel surface equivalent temperature
38.	HTSTR	(M, K)	Cladding-coolant heat transfer coefficient (for lumped system)
39.	REACT1	1	Total Δk minus 1
40.	PROGMO	1	Programmed Δk minus 1
41.	CORAV	1	Average temperature of the core (°F)
42.	PSTRNM	1	Normalized prompt power
43.	PWRNM	1	Normalized total power
44.	VELCL1	1	Velocity of the coolant, average channel (ft/sec)
45.	VELCL2	1	Velocity of the coolant, peak channel (ft/sec)
46.	VELCL3	1	Velocity of the coolant, hot-spot channel (ft/sec)

4.4.2.2 Labels for Graphs

LABLXY	Axes labeling
LABLMH	Main heading
LABLSH	Sub-headings
KEE	Curve description

4.4.2.3 Operational and Control Symbols

All Plots

CONTROL	Three control input values for each plot

Time Plot Symbols

MINJ	Initial time step for j^{th} plot
MAXJ	Final time step for j^{th} plot
IDELJ	Plot every IDELJth step which has been put on tape

Semi-Log Plot Symbols

PWRLOG	Plot prompt and or total power on semi-log grid

Axial Plot Symbols

KCHAX	Specify which graphs will have axial location as the abscissa
KSTEP	Time step(s) at which variable should be plotted for a specific axial plot

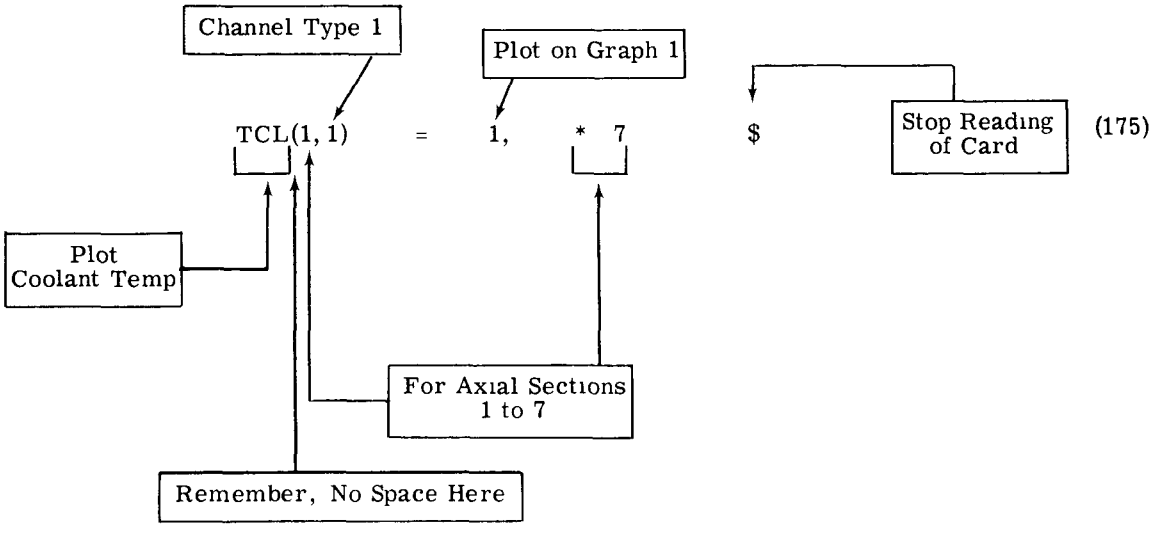
	Radial Plot Symbols
IDLRAD	Total number of radial plots (can not exceed 7 for any one case)
NCHANN	Channel type(s) for a specific radial plot
NAXNOD	Axial section(s) for a specific radial plot. This word must contain a 1 for each axial section selected. For example, NAXNOD (2, 1) = 1 should plot axial section 2 on radial graph 1.
NSTEP	Time step(s) at which variable should be plotted for a specific radial plot
	Normalized Plot Symbols
DIVISR	Divisor to obtain normalized power if so specified
	DIVISR (1) for prompt power
	DIVISR (2) for total power
RHO	Density of the coolant if velocity in ft/sec is desired

4.4.3 Discussion of FRCURV Input

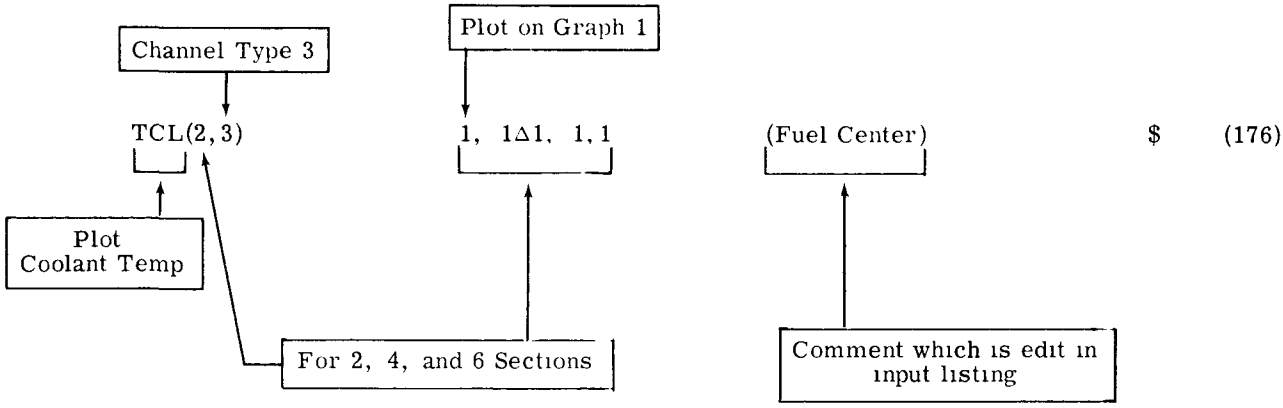
4.4.3.1 Quantities Available for Plotting

All 46 quantities defined in subsection 4.4.2.1 are available for plotting as a function of time. The user is cautioned that in case of more than one type of curve per graph, the curves are plotted in the same sequence as the symbols in subsection 4.4.2.1 and not in the order as specified in the input. This statement is illustrated by examples in the discussion on labels in subsection 4.4.3.2. As previously indicated, only temperature can be plotted as a function of radial positions over the range R_o for the inner radius of the fuel to R_c for the outer radius of the coolant. For radial plots, additional operational and control symbols must be used to indicate the number of radial plots, the channel type(s), the axial section(s), and the time step(s) for plotting. For axial plots, only the dimension variables in subsection 4.4.2.1 with subscript m are available for plotting. Again, special operational and control symbols must be used for the axial plots to indicate which graphs are axial plots and the time step(s) that should be printed.

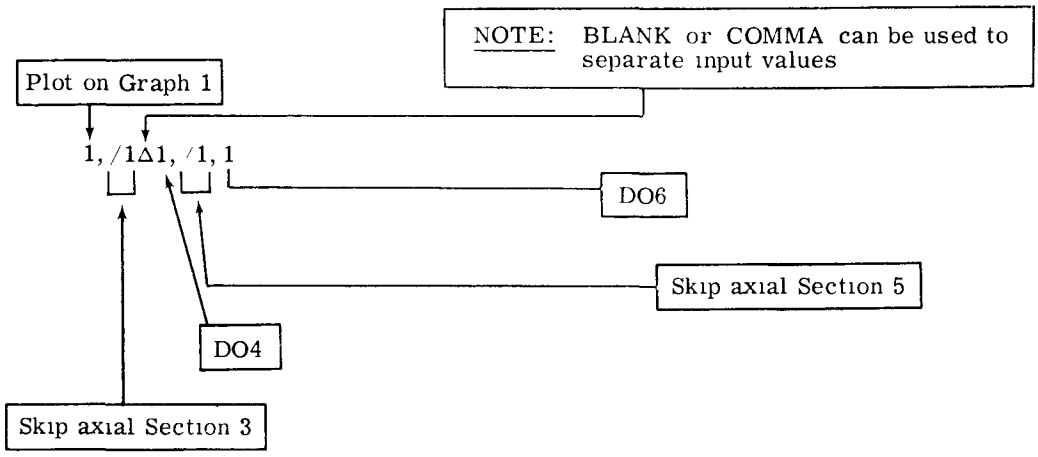
A typical input for a time plot might be



This instruction will result in the coolant temperature for all seven axial sections to be plotted on Graph 1 as a function of time. Another example would be



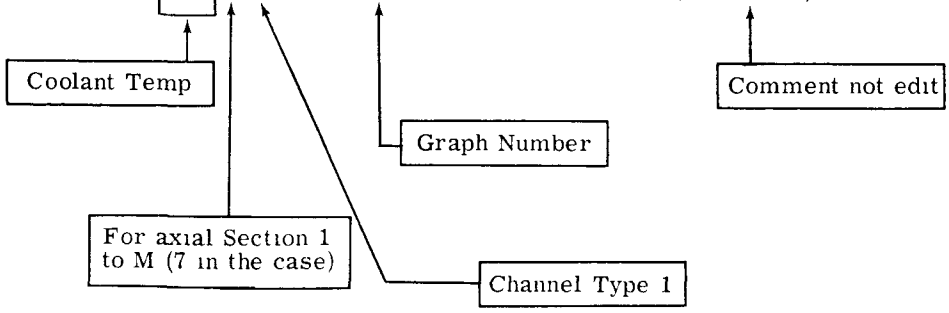
This latter instruction causes three additional coolant temperature curves for axial sections 2, 4, and 6 for the hot channel to be plotted on Graph 1. In more detail, the right-hand side of the last expression can be described as



Briefly, an axial plot of the coolant temperature would be expressed by

KCHAX(1) 3 $ (177)

TCL(1,1) = 3 $ (Axial Plot) (178)



Equation (177) is an operational and control statement that indicates to FRCURV that there is one axial graph and it is Graph Number 3 Equation (178) will plot the coolant temperature on Graph 3 as a function of axial

position. Additional operational and control statements discussed in subsection 4.4.3.3 are required to complete the input. The axial plot is introduced here only for comparison purposes with the time plots.

An example of the input for a non-dimension variable (time plots only) is

RFDBK = 5 (179)

Graph 5 will be a plot of feedback reactivity versus time.

4.4.3.2 Labels for Graphs

Labels are available for indicating the

a. x and y axes (LABLXY)

b. Main heading (LABLMH)

c. Four lines of subheading (LABLSH)

d. Key for the different curves on one graph (KEE)

The format for LABLXY is

LABLXY(Index 1, Index 2) = nH Title x axis Title y axis $ (180)

Six Hollerith words of six letters each for a total of 36 characters are allowed for the xy labels. Thus, the maximum value of n is 36. The first 18 characters are the label for x axis and the second 18 characters are the label for the y axis. Index 1 is the number of the first Hollerith word and Index 2 is the graph number. An example is

LABLXY(1, 1) = 36HΔΔTIMEΔ(SECONDS)ΔΔΔΔΔCOOLANTΔTEMPΔΔΔΔΔ$ (181)

x - axis y - axis

FRCURV will label the x and y axes on Graph 1 as indicated in Equation (181).

The format for LABLMH is

LABLMH(Index 1, Index 2) = nH Title $ (182)

For the main heading, seven Hollerith words of six letters each for a total of 42 characters are allowed for the main heading. In this case, all the n Hollerith characters are printed on one line at the top of the graph. The other items in Expression (182) have the same meaning as for LABLXY. An example is

LABLMH(1, 3) = 42HΔΔΔΔΔΔFLOWΔBLOCKAGEΔ:ΔPOWERΔCONSTANTΔΔΔΔΔΔΔΔ$ (183)

An identical instruction, but in a slightly different form is

LABLMH(2,3) = 30HFLOWΔBLOCKAGEΔ;ΔPOWERΔCONSTANTΔΔ$ (184)

Expression (184) indicates to FRCURV to start with the second Hollerith word and read five (30/6 = 5) Hollerith words. The first and last Hollerith words are assumed to be blanks.

The actual total and prompt power or the normalized total and prompt power can be plotted on semi-logarithmic paper. Because of programming complications, the labeling flexibility for the semi-logarithmic plots is restricted. In particular, the main label for semi-logarithmic plots can consist of only 18 characters instead of 42.

The format for LABLSH is

LABLSH(INDEX 1, INDEX 2, INDEX 3) nH SUB-TITLE $ (185)

Five Hollerith words of six letters each for a total of 30 characters are allowed for the subheading labels. In addition, four lines (30 characters each) are permitted. Index 1 is the first Hollerith word, Index 2 is the line number of the subheading (1 to 4), and Index 3 is the graph number. An example is

LABLSH(1,2,3) = 30HΔΔΔΔCOOLANTΔTEMPΔVSΔHEIGHTΔΔΔΔΔΔ$ (186)

LABLSH(1,3,3) = 24HΔΔΔΔAVERAGEΔCHANNELΔΔΔΔΔΔ$ (187)

LABLSH(1,4,3) = 18HΔΔΔΔCASEΔ5310Δ;ΔBL (188)

The first subheading is blank, the other lines will appear as

COOLANT TEMP VS HEIGHT

AVERAGE CHANNEL

CASE 5310 ; BL

No subheadings are allowed for semi-logarithmic plots.

The format for KEE is

KEE(INDEX1, INDEX 2, INDEX 3) nHA - IDENTIFICATION $ (189)

Six Hollerith words for a total of 36 characters are allowed. Index 2 indicates the curve number (1 to 10) on a graph. The other indexes are the same as for LABLSH. The plot points on a graph are shown by numbers, starting with 1, in the order in which the curves are drawn. When more than one variable is plotted on a single graph, the order in which the ones are drawn is based on the sequence of symbols in subsection 4.3.2.1. For example, the input instructions

TCDS(3,1) 4, *3 $ (190)

TCL(3, 1) = 4, *3 $ (191)

TCD(3, 1) = 4, *3 $ (192)

will plot nine curves on Graph 4 in the following order:

TCL(3, 1)
TCL(4, 1)
TCL(5, 1)
TCDS(3, 1)
TCDS(4, 1)
TCDS(5, 1)
TCD(3, 1)
TCD(4, 1)
TCD(5, 1)

The first four KEE symbols might typically appear as

KEE(1, 1, 4) = 30H1-ΔCOOLΔTEMPΔ;ΔAXIALΔSECTIONΔ1ΔΔ (193)

KEE(1, 2, 4) = 30H2-ΔCOOLΔTEMPΔ;ΔAXIALΔSECTIONΔ2ΔΔ (194)

KEE(1, 3, 4) = 30H3-ΔCOOLΔTEMPΔ:ΔAXIALΔSECTIONΔ3ΔΔ (195)

KEE(1, 4, 4) = 36H4-ΔOUTERΔCLADΔTEMPΔ;ΔAXIALΔSECTIONΔ1ΔΔ (196)

The KEE symbol is not used for semi-logarithmic plots.

4.4.3.3 Operational and Control Symbols

A CONTRL symbol must be used for every graph. The format of the CONTRL symbol is normally

CONTRL(INDEX 1, INDEX 2) = INPUT 1, INPUT 2, INPUT 3 $ (197)

where

INDEX 1 = First curve on graph to which input values apply (normally this is 1. DTA subroutine will keep advancing the index so that the input values will apply to all the curves on one graph)

INDEX 2 = Graph number

	Content	Result
INPUT 1 =	0	Include zero on both areas
	1	Add zero to x-axis, if necessary
	2	Add zero to y-axis, if necessary
	3	Do not add the zero point to either axis

	Content	Result
INPUT 2 =	1	Connect points with line
	2	Plot points only

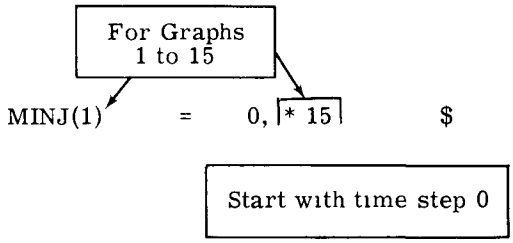
	Content	Result
INPUT 3 =	1	Label every plotted point
	2	Label every second point
	3	Label every third point
	etc.	

An example is

```
CONTRL(1,6) = 0,1,2        $                                    (198)
```

which tells FRCURV to include zeros on both axes, connect the plotted points with a line, and to indicate every other plot point by the correct number for all the curves on Graph 6.

The symbols MINJ, MAXJ, and IDELJ apply only to time plots. These symbols indicate the initial time step, the final step, and the frequency at which points should be plotted from the FORE II output tape, respectively. The format for MINJ is



(199)

Another example is

```
MINJ(1) = 0, * 6          $                                    (200)

MINJ(7) = 100, * 10       $                                    (201)
```

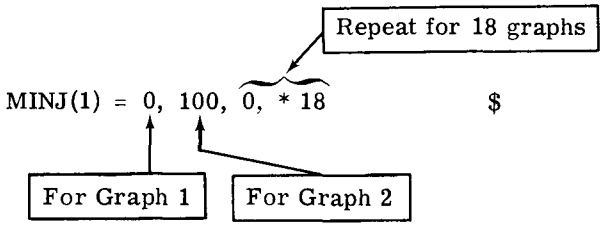
In Equation (200), the instruction is to start the first six graphs from time step 0 and Graphs 7 to 16 from time step 100. Equations (200) and (201) could be written on one line as

```
MINJ(1) = 0, * 6, 100, *10                                     (202)
```

A final example is

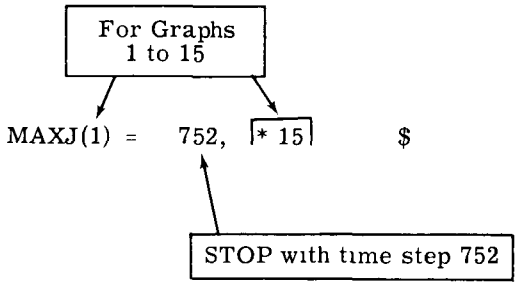
```
MINJ(1) = 0, * 20        $                                    (203)

MINJ(2) = 100            $                                    (204)
```

Equations (203) and (204) state that Graphs 1 to 20 should start at time step 0, except for Graph 2, which should start at time step 100. Note the overlay technique used in Equation (204). This could be written on one line as



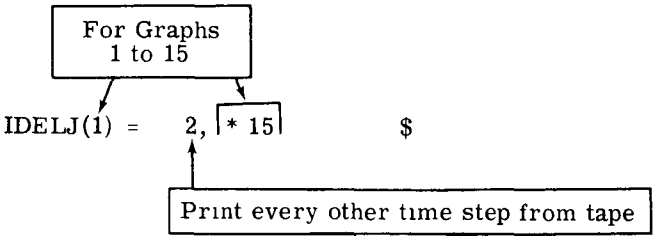
(205)

The formats for MAXJ and IDELJ are analogous to MINJ. Examples are



(206)

and



(207)

The output tape from FORE II is used for printing in FEDIT. The 2 in Equation (207) is identical to the instruction to plot every second value of the printed output.

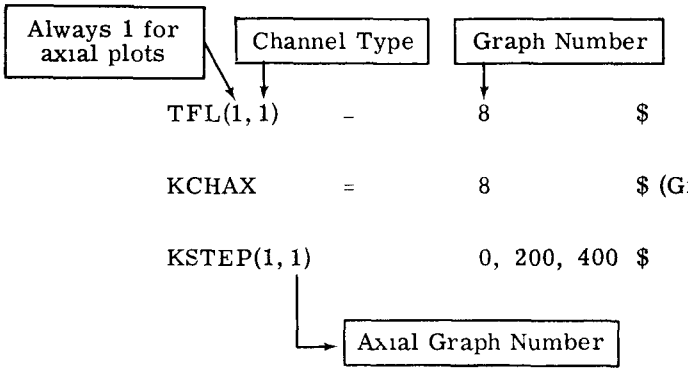
The symbol PWRLOG is used only when a semi-logarithmic scale for power versus time curves is preferred. In subsection 4.4.2.3 the prompt and total power are given by items 29 and 30, and the normalized prompt and total power by 42 and 43, respectively. The normalized power plots require the user to input additional operational and control symbols, to be discussed later. To plot the total power on a semi-logarithmic scale on Graph 7, the following two statements are required:

```
POWER  = 7                                                    (208)

PWRLOG = 7                                                    (209)
```

The omission of Equation (209) will result in the total power being plotted on a rectangular scale. A maximum of two power curves per semi-log graph can be plotted. The actual power curves and the normalized power curves cannot be drawn on the same graphs.

The user is limited to three axial plots per case. Besides indicating which variables to plot versus axial location, two additional inputs are required: KCHAX and KSTEP. KCHAX indicates which time steps to plot.

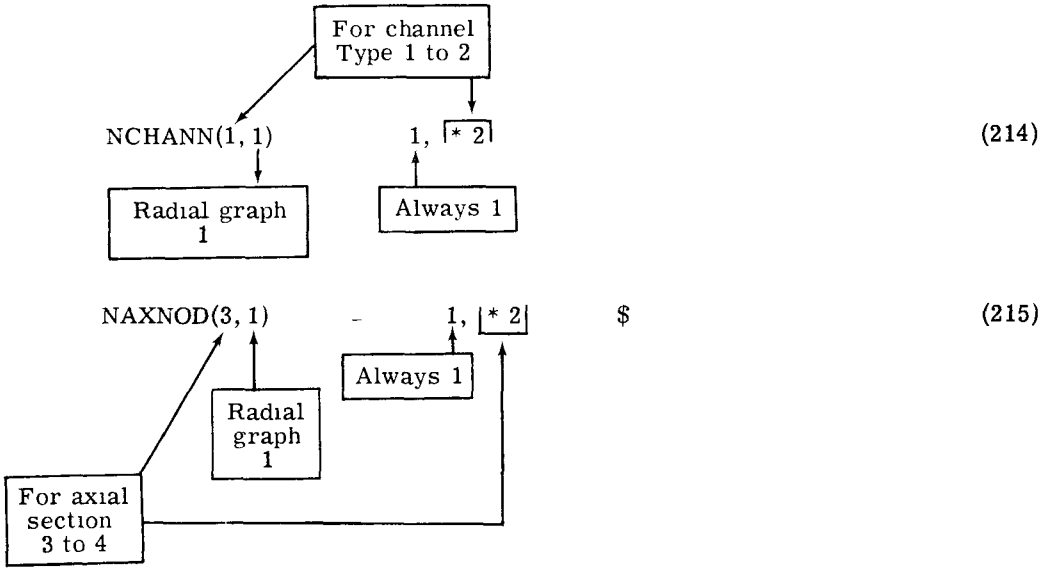
An example is

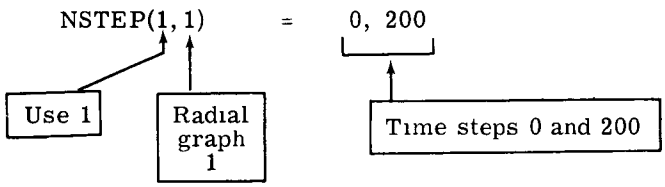


Graph 8 would show the fuel surface temperature for the average channel for time steps 0, 200, and 400.

The input symbols used solely for radial plots are IDLRAD, NCHANN, NAXNOD, and NSTEP. An example is

IDLRAD = 1 $ (There is one radial graph) (213)





(216)

Radial graph 1 should consist of eight curves plotted in the following order:

Curve No.	Axial Section	Channel	Time Step
1	3	Average	0
2	4	Average	0
3	3	Peak	0
4	4	Peak	0
5	3	Average	200
6	4	Average	200
7	3	Peak	200
8	4	Peak	200

The symbol DIVISR is the steady-state power, and the symbol RHO is the density of the coolant. DIVISR is used to obtain normalized power graphs, and RHO is used to obtain coolant velocity in feet per second. Both of these input values are decimal numbers, whereas all the other inputs to FRCURV are integers. In addition, a DIVISR and RHO symbol must be used for each curve on a graph.

4.5 TERMINATION MODES AND RUNNING TIME

Normal, non-error stops will occur when the program has reached any of the following conditions specified by the user:

a. Maximum time step number
b. Maximum transient time
c. Upper or lower limit for fuel temperature in node 1
d. Upper or lower limit for fuel surface temperature
e. Upper or lower limit for coolant temperature
f. Calculated time limit

Under such circumstances, the particular reason for the stop will be identified by a statement at the end of the short exit.

Any of the following types of input errors will cause immediate exit from the computer, without any calculation being performed:

a. Changes in input data at restart as prohibited by Table 4-1
b. Illegal input character
c. Fuel radii (R_0 to R_N) not in ascending order
d. Failure to use a dependent case card before listing the new data for a restart (see Appendix C, C.3, for an example).
e. Restart tape label not identical to label listed in restart input deck

During the running of a problem, any of the following errors will cause termination:

a. Any system error (for example, square root of a negative number)
b. Programmed k range too small
c. Turbulent mass velocity for peak and hot spot channel does not converge in 10 iterations

The programmed k at any time is not determined by the tabular look-up subroutine. As such, the last time in the input table must be greater than the actual time during a transient. It is correspondingly recommended that the last time in the input table be set to some number two or three times the expected transient time.

For turbulent flow and non-zero local losses, the mass velocity for the peak and hot channels must be determined by iteration with the known value for the average channel at each time step as a starting point. If this mass velocity does not converge within ten iterations, there are likely to be input values which are not physically compatible, and the problem is terminated. A wrapup, if requested, will be obtained for all normal stops and for all error stops that occur beyond the check of input values.

Table 4-2 gives the approximate time in minutes for running the sample problem for each of the codes composing the FORE II system.

TABLE 4-2

TIME FOR RUNNING SAMPLE PROBLEM

Code	10 μsec Machine	1 μsec Machine
FORE II (EEEE)	35	4.5
FEDIT	3.2	2.0
FRCURV	6.0	0.8

Thus, the computers with low data access times can lead to moderate savings in calculation cost in spite of the higher cost per unit time.

The transient time for the sample problem was 1.50 seconds. The calculation time for longer or shorter transients can be estimated by the ratio of the transient times. Similarly, the calculation time for a different number of channel types, axial fuel nodes, fuel rings, or edit frequency can be estimated by the ratio of the appropriate quantities times the values in Table 4-2.

APPENDIX A

NOMENCLATURE

A.1 MAJOR SUBSCRIPTS

- c -- Coolant
- e -- Cladding
  - E -- outer surface
  - a -- volumetric average radius
  - e -- inner surface
- f -- Fuel
- u -- Additional material
- s -- Structure
- n -- Fuel ring n
- m -- Axial section m
- k -- Channel type k
- ℓ -- Radial core region

A.2 MAJOR SUPERSCRIPTS

- j -- Time step j
- 0 -- Time step zero

(Inclusion of a single superscript within parentheses is optional)

A.3 ENGLISH

Analytic Symbol	Where Calculated	Definition
A^j	POWD	Variable used in kinetics equation to simplify nomenclature
A_c	FINPT	Cross-sectional area of the coolant
A_{Dop}	Input	Constant used in Doppler equations
A_e	FINPT	Cross-sectional area of the cladding
A_f	FINPT	Cross-sectional area of the fuel
A_g	Input	Constant used in calculating thermal conductivity of the gap
A_H	Input	Constant used in calculating coolant heat transfer coefficient
A_{im}	Input	Term used in empirical expression for decay of fission products
A_m	Input	Ratio of peak power to average power for axial section m
A_n	FINPT	Cross sectional area, n^{th} node of fuel
a_o	Input	Constant used in gap conductivity equation
B_{Dop}	Input	Constant used in Doppler equations
B^{MELT}	Input	Fuel heat of fusion

Analytic Symbol	Where Calculated	Definition
B_g	Input	Constant used in calculating thermal conductivity of the gap
B_H	Input	Constant used in calculating coolant heat transfer coefficient
B_K	Input	Constant used in calculating fuel conductivity at melting
$B_{OR,k}$	INIT,(Input)	Sum of the local loss coefficient in particular channel (input for peak)
b	Input	Input constant used in Doppler feedback equation
C	Input	Constant needed to calculate COMP criterion for Reynolds number
C^{MELT}	FINPT	Specific heat of molten fuel
COMP	INIT	Criterion for Reynolds number
$\overline{C}_c^j$	INIT, COPH	Specific heat of the coolant based on the average of inlet and outlet temperatures
C_D	Input	Doppler correction for temperature profile
$C_c^{(j)inlet}$	COPH	Specific heat of the coolant based on core inlet temperature
C_e	Input	Specific heat of the cladding
C_f	Input	Relative worth of axial fuel expansion
C_f'	Input	Table of specific heat of fuel
C_g	Input	Constant used in calculating thermal conductivity of the gap
C_K	Input	Constant used in calculating fuel conductivity at melting
C_i^j	INIT, FEEB	Delayed neutron precursor concentration for i^{th} group
C_u	Input	Specific heat of the additional material
C_s	Input	Specific heat of the structure
$C_{H,m}$	Input	Constant used in calculating coolant heat transfer coefficient, section m
$C_{c,m,k}^j$	INIT, COPH	Specific heat of the coolant in section m, channel k
$C_{g,m,k}^j$	INIT, COPH	Fuel cladding gap coefficient section m, channel k
$C_{g,m,k}^{Old(o)}$	INIT	Weighted gap coefficient (used in iteration procedure for steady state)
$C_{n,m,k}^j$	INIT, COPH	Specific heat of fuel node n, section m, channel k
D_B	Input	Diameter of the fuel channel
D_H	Input	Hydraulic diameter of coolant passage
D_{HT}	Input	Appropriate diameter for calculating heat transfer coefficient
d_u	Input	Characteristic dimension of the additional material used in heat transfer equation
d_s	Input	Characteristic structure dimension

Analytic Symbol	Where Calculated	Definition
E_e	Input	Modulus of elasticity of the cladding
E_{in}^J	INIT, COPH	Nuclear energy addition to core since time zero
E_J	POWD	Total energy at end of time step J
E_J^*	POWD	Prompt energy during time step J
E_{out}^J	INIT, COPH	Net energy removal from core since time zero
$E_{b,m,k}^J$	INIT, COPH	Fuel boundary equivalent temperature (includes heat of fusion)
$E_{n,m,k}^J$	INIT, COPH	Fuel equivalent temperature of node n, section m, channel k
$E_{o,m,k}^J$	INIT, COPH	Center fuel equivalent temperature, section m, channel k
e	Input	Constant needed to calculate COMP
F^*	INIT	Factor to calculate coolant heat transfer coefficient for a specific channel
F**	INIT	Factor to calculate gap conductivity for a specific channel
F***	INIT	Factor to calculate fuel conductivity for a specific channel
FB_D^J	FEEB	Cumulative feedback Δk due to density changes
FB_H^J	FEEB	Cumulative feedback Δk due to core height change
FB_R^J	FEEB	Cumulative feedback Δk due to core radius change
F_e	Input	Hot-spot factor for thermal conductivity of the cladding
F_{fuel}	INIT	Fraction of heat produced in fuel
F_g	Input	Hot-spot factor for gap conductivity
$F_{g,p}$	Input	Peak factor for gap conductivity
F_h	Input	Hot-spot factor for calculating heat transfer coefficient
F_k	Input	Hot-spot factor for fuel conductivity
F_r	Input	Peak channel factor for mass velocity
F_v	Input	Hot-spot factor for mass velocity
F_γ	Input	Fraction of power due to gamma-neutron heating
$F_{n,m,1}^J$	FEEB	Averaged nodal temperature across core region 1 for node n, section m
$\bar{f}_{in}$	POWD	Empirical expression for decay of fission products
f_z	Input	Fraction of channel frictional pressure drop inlet to void
G_c^J	INIT, COPH	Average mass velocity

Analytic Symbol	Where Calculated	Definition
G_c'	Input	Table of coolant mass velocity in average channel (versus time)
G_u, G_s	Input	Surface to volume ratio, additional material and structure
$G^j_{c,k}$	INFLOW	Mass velocity in channel k
$G^j_{n,m,k}$	FEEB	Equivalent temperature used in calculating Doppler feedback
g_e	Input	Average jump distance for the fission gas at the cladding surface
g_f	Input	Average jump distance for the fuel
$g^j_{c,m,k}$	INIT, COPH	Structure-to-coolant heat transfer coefficient
H*	Input	Distance between core inlet and exit support plates
H_T	Input	Active core height
$H_T \frac{\delta k}{\delta H_T}$	Input	Core height coefficient
$H^0_{n,m,1}$	INIT	Temperature calculated at steady state and used in Doppler feedback calculations
h_f	Input	Heat transfer coefficient of fuel cladding gap
$h_{c,3}$	Input	Coolant heat transfer coefficient for hot-spot channel at time of void (input only if $\delta_{cof} = 0$)
$h^j_{c,m,k}$	INIT, COPH	Cladding-coolant heat transfer coefficient for non-lumped system
$h^{*(j)}_{c,m,k}$	INIT, COPH	Cladding-coolant heat transfer coefficient modified by temperature ratio
I	Input	Number of decay group
J	Input	Maximum number of time steps
j	–	Used as a superscript to denote a particular time
K^0, K^1, K^2	Input	Constants used in calculating thermal conductivity of the fuel
K_c'	FINPT	Thermal conductivity of the coolant (versus temperature)
K_e	Input	Thermal conductivity of the cladding
K_s	Input	Thermal conductivity of the structure
K_u	Input	Thermal conductivity of the additional material
$K^j_{m,k}$	INIT, COPH	Harmonic conductivity of the fuel-cladding interface at contact, section m, channel k
$K^j_{c,m,k}$	INIT, COPH	Thermal conductivity of the coolant in section m, channel k
$K^j_{g,m,k}$	INIT, COPH	Thermal conductivity of the gas in the fuel-cladding gap, section m, channel k

Analytic Symbol	Where Calculated	Definition
$K^J_{n,m,k}$	INIT COPH	Thermal conductivity of the fuel in node n, section m, channel k
k	–	Subscript used to denote a particular channel type
k^J	FEEB	Total effective multiplication factor
k^J_f	FEEB	Total feedback Δk
k^J_p	FEEB	Programmed Δk for time step
$k_{p,s}$	Input	Table of effective multiplication factor (versus time)
ℓ	Input	Neutron lifetime
ℓ	–	An index to denote a particular core region
M_H	Input	Constant used in calculating coolant heat transfer coefficient
N_H	Input	Constant used in calculating coolant heat transfer coefficient
$N_{R,k}$	INIT INFLOW	Reynolds number for channel k
P_H	Input	Hot-spot factor for calculating heat generation rates
P_{in}	Input	Input power
P_j	POWD	Total power per unit fuel volume at end of time step j
P^*_j	POWD	Prompt power per unit fuel volume during step j
$\overline{P}_j$	POWD	Average power per unit fuel volume at end of time step j
$\overline{P}_j{}^*$	POWD	Average power per unit fuel volume during time step j
P_ℓ	Input	Core radial power factor
P^*_o	INIT	Initial power per unit fuel volume
P_{pump}	Input	Pump head pressure at channel inlet
P_r	Input	Radial peak-to-average power density ratio in core
P_{st}	Input	Static head pressure at channel inlet
P_z	FEEB	Absolute pressure at axial location Z
$P^J_{m,k}$	INIT, COPH	Pressure between fuel and cladding, section m, channel k
Q_j	POWD	Intermediate variable used to simplify nomenclature in kinetics equation
$Q^J_{n,m,k}$	INIT, COPH	Cladding surface heat flux section m, channel k
$\overline{Q}^J_{x,m,k}$	INIT, COPH	Heat generation rate in x, section m, channel k where x equals e - cladding c - coolant f - fuel u - additional material n - fuel node n s - structure
R_H	Input	Constant used in calculating coolant heat transfer coefficient

Analytic Symbol	Where Calculated	Definition
R_J	POWD	Intermediate variable used to simplify nomenclature in kinetics equation
R_x	Input	Radius to x where x equals e - inner cladding E - outer cladding c - coolant f - fuel n - fuel node n o - fuel pin center T - outer radius of core
$R_T \frac{\delta k}{\delta R_T}$	Input	Core radius expansion coefficient
S	Input	Source
T_o	Input	Length of time prior to start of problem for which the reactor was operated at constant power P_o
$T_c^{'Boil}$	Input	Table of coolant bulk boiling temperature (versus absolute pressure)
$\overline{T}_c^{(j)inlet}$	INIT, COPH	Average core inlet temperature
$\overline{T}_c^{(j)outlet}$	INIT, COPH	Average core outlet temperature
$T_e^{'Burnout}$	Input	Table of cladding burnout temperature (versus absolute pressure)
T_f^{vapor}	Input	Fuel temperature at which vaporization occurs
T_f^{MELT}	Input	Fuel melting temperature
$\overline{T}^J_{c,\,k}$	INIT, COPH	Average coolant temperature in channel k
$\overline{T}^*_{m,1}$	FEEB	Average temperature of section m, core region 1
$\overline{T}^j_{m,1}$	INIT, FEEB	Average temperature of section m in core region 1
$T^{in(j)}_{c,m,k}$	INIT, COPH	Coolant inlet temperature to section m, channel k
$T^{Out(j)}_{c,m,k}$	INIT, COPH	Coolant outlet temperature
$\overline{T}_{c,m,k}$	INIT, COPH	Average coolant temperature, section m, channel k
$\overline{T}^j_{e,m,k}$	INIT, COPH	Volumetric average temperature of cladding
$\overline{T}^j_{f,m,k}$	INIT, COPH	Average fuel temperature, section m, channel k
$T^j_{x,m,k}$	INIT, COPH	Temperature at section m, channel k for x equal e - inner cladding surface a - average cladding E - outer cladding surface c - nodal coolant f - fuel u - additional material n - fuel node n o - inner fuel surface

Analytic Symbol	Where Calculated	Definition
V_{core}	FINPT	Volume of the core
V_f	Input	Total volume of the fuel in core
V_s	Input	Volume of structure per unit length of fuel
V_u	Input	Volume of additional material per unit length of fuel
W_f	Input	Convergence weighting factor
W_ℓ	FINPT or Input	Used to calculate core radial temperature profile
X_m	FINPT	Distance from core inlet support to actual core inlet, section m
Y_n	Input	Ratio of heat generation rate in fuel node n to fuel average heat generation rate
Z_O	Input	Distance from core inlet support to actual core inlet
Z_T	Input	Total distance from channel inlet to outlet

A.4 GREEK

Analytic Symbol	Where Calculated	Definition
α_s	Input	Linear thermal expansion coefficient of structure in radial direction
α_s'	Input	Effective thermal expansion coefficient of structure for core radius change
α_s''	Input	Thermal expansion coefficient of structure for bowing calculations
α_{im}	Input	Term used in empirical expression for decay of fission products
$\alpha_{s,ax}$	Input	Linear thermal expansion coefficient of structure in the axial direction
$\alpha^J_{c,m,k}$	FEEB	Coefficient of expansion for coolant based on average coolant temperature
β	POWD	Total delayed neutron fraction
β_i	Input	Delayed neutron fraction for the i^{th} group
β_o	Input	Constant used in gap conductivity equation
γ_i	Input	Decay constant of a i^{th} delayed neutron group
$(\overline{\Delta T})^J_B$	INIT, FEEB	Average radial temperature drop across outside fuel bundles
$\left(\frac{\Delta R_T}{R_T}\right)^J_{B,m}$	FEEB	Change in core radius due to fuel bowing, section m
$\left(\frac{\Delta \rho_{x,m}}{\rho_{x,m}}\right)^J$	FEEB	Density change in x, section m where x equal c - coolant e - cladding f - fuel u - additional material

Analytic Symbol	Where Calculated	Definition
$(\Delta P)^J_{core}$	INIT, COPH	Change in core energy density since time zero
$(\Delta K_{Dop})^J_{m,1}$	FEEB	Cumulative Doppler feedback delta k, section m, core region 1
$(\Delta o)^J_{m,k}$	INIT, COPH	Calculated separation distance of peaks of fuel and cladding surfaces
$(\Delta V)^{MELT}$	Input	Percent volume increase of fuel due to melting
$(\Delta Z)_m$	Input	Length of core axial section m
$(\Delta K)^J_{Dop}$	FEEB	Total cumulative Doppler feedback for the core
$(\Delta K)^J_{scram}$	FEEB	Total Δk due to scram
$(\Delta K)^J_{void}$	FEEB	Total Δk due to voiding
$\left(\frac{\Delta L}{L}\right)^J_{x,m,k}$	FEEB	Fractional linear expansion from 70°F where x equals e - cladding f - fuel u - additional material
$\left(\frac{\Delta H_T}{H_T}\right)^J$	FEEB	Core height change
δ_e	Input	Arithmetic mean roughness height of the cladding
δ_f	Input	Arithmetic mean roughness height of the fuel
$\delta^J_{g,m,k}$	INIT, COPH	Fuel-cladding gap size including average separation when peaks in contact
$\delta^{MELT(J)}_{n,m,k}$	INIT, COPH	Melting indicator, node n, section m, channel k
ϵ_k	Input	Small constant to determine solution to power equation
ϵ_T	Input	Convergence criterion for initial fuel temperature
ϵ_{pwr}	Input	Criterion for power and energy accumulation
λ_a	Input	Constant used to indicate location to calculate nodal coolant temperature
$\mu^J_{c,k}$	INIT INFLOW	Dynamic viscosity of coolant in channel k based on $\overline{T}^j_{c,k}$
$\mu^J_{c,m,k}$	INIT, COPH	Dynamic viscosity of coolant in section m, channel k, based on $\overline{T}^J_{c,m,k}$
$\rho_x\left(\frac{\delta k}{\delta \rho_x}\right)_m$	Input	Density coefficient of reactivity for sections m where x equal e - cladding c - coolant f - fuel u - additional material s - structure

Analytic Symbol	Where Calculated	Definition
$\left(\frac{\Delta R_T}{R_T}\right)^J_{P,m}$	FEEB	Core shape change due to axial pressure difference across core, for section m
ρ	Input	Density
τ^J	STAB	Length of J^{th} time step
ν	Input	Neutrons per fission
Ψ_o	Input	Angular deflection of the core lower support plates from the horizontal at steady state
Ψ	Input	Meyers hardness of softer material

APPENDIX B

BUILT-IN TABLES

Thermal Conductivity of Sodium, K_c'	vs.	Temperature, T_c'
.0145 BTU/SEC-FT-F		200° F
.0136		300
.01303		400
.01248		500
.012		600
.01155		700
.01136		750
.01117		800
.01097		850
.0108		900
.01047		1000
.01031		1050
.01017		1100
.00989		1200
.0096		1300
.00937		1400
.00915		1500
.00894		1600
.00875		1700
.00857		1800

Thermal Expansion Coefficient of Sodium, α_c'	vs.	Temperature, T_c'
47.48×10^{-6}		200° F
48.23		300
48.93		400
49.64		500
50.36		600
51.02		700
51.50		750
51.99		800
52.34		850
52.79		900
53.62		1000
54.04		1050
54.47		1100
55.35		1200
56.26		1300
57.26		1400
58.24		1500
59.31		1600
60.35		1700
61.50		1800

Dynamic Viscosity of Sodium, μ_c'	vs.	Temperature, T_c'
.000489 #/ft-sec		200° F
.000372		300
.0003		400
.000256		500
.000224		600
.0002		700
.000192		750
.000190		800
.000178		850
.000169		900
.000157		1000
.000150		1050
.000144		1100
.000133		1200
.000125		1300
.000117		1400
.000111		1500
.000106		1600
.0001		1700
.0000944		1800

Specific Heat of Sodium, C_c'	vs.	Temperature, T_c'
0.33 BTU/#-F		200° F
0.3245		300
0.3195		400
0.3145		500
0.3105		600
0.307		700
0.306		750
0.3045		800
0.3035		850
0.3025		900
0.301		1000
0.3005		1050
0.300		1100
0.300		1200
0.3005		1300
0.3015		1400
0.304		1500
0.3065		1600
0.3095		1700
0.314		1800

Density of Sodium ρ_c'	vs.	Temperature, T_c'
57.7 #/FT^3		200° F
56.8		300
56.0		400
55.2		500
54.35		600
53.55		700
53.19		750
52.75		800
52.3		850
51.9		900
51.1		1000
50.7		1050
50.3		1100
49.5		1200
48.7		1300
47.9		1400
47.0		1500
46.2		1600
45.4		1700
44.58		1800

APPENDIX C

SAMPLE PROBLEM

APPENDIX C

C.1 INPUT FOR SAMPLE PROBLEM

```
)EEEEREL*TC102                19SEP66
      (NOTE LETTERS EEEE ON CASE CARD TO AVOID CONFUSING WITH FORE 1)
      (USE OF EEEE IS MANDATORY)
      ($2.00/SEC. RAMP REACTIVITY INSERTION, SAMPLE PB FOR MANUAL)
      ( 1000 MWE REACTOR)
    (XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX)
    (XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX)
      (INTEGER VARIABLES***** 1 TO 60 ************************************)
  1               6             3             3             2             1
  6               2             7             7            10             0
 11               4             0            20            20             1
 16               0             1             1             1             1
 21               3             1             0             0             1
 26               0             1             0             0             0
 30     1    (AVERAGE TEMPERATURE IS BASED ON CORE PLUS BLANKET)
      (EDIT OPTION*********************************************************)
 31               1            01             1            01             1
 36          3
 46               1             1             1
 55     1    (AXIAL BLANKET - CORE BOTTOM)
 56     1    (AXIAL BLANKET - CORE TOP)
      ( TIME AND TERMINATION CONTROL***************************************)
 61            0.10         .0001             0          1.75        9500.0
 66           100.0        6550.0         100.0        2100.0         500.0
 71            .045            53
 72       .00001
    (GEOMETRY**************************************************************)
 75            0.65
 76         .013872       .010292       .011125       .003275       .004050
 81            .004825       .005560       .006375       .007150       .007925
 86            .00870        .009475      .010292        0.0025          5.75
 91           172.4         .95E-4       .604E-4           1.5           .25
                                                     09-27-66   PAGE 001
```

```
 96            .25          .333          .25          .25          1.5
101           7.00
      ( MATERIAL PROPERTIES**********************************************)
106           1.05         .0035         .0035        0.009         .135
111           .135          0.46         583.0        486.0        486.0
116          189.0        4928.0     .00120555  -6.58333E-7  1.208333E-10
121           1.00           0.0           0.0      62300.0
125       (SPECIFIC HEATS OF FUEL FOLLOW )           .069
126           .071          .073         .0745         .076          .077
131           .078          .079          .080         .0815          .083
136          .0835          .084          .085         .0855          .086
141          .0875          .088          .089          .089
145       (TEMPS FOR SPECIFIC HEATS FOLLOW)          500.0
146          750.0         1000.0        1250.0        1500.0        1750.0
151         2000.0         2250.0        2500.0        2750.0        3000.0
156         3250.0         3500.0        3750.0        4000.0        4250.0
161         4500.0         4750.0        5000.0        5000.0
      ( POWER AND FLOW FACTORS*****************************************)
              ( 171 TO 177 MID-CYCLE POWER SHAPE)
171           .231          2.504         2.802      2.963964         2.802
176          2.504          .231           0.1          1.38          1.23
181            1.0           1.0           1.0           1.0           1.0
186            1.0           1.0           1.0           1.0           1.0
191           1.23          1.23
      ( COOLANT FLOW CHARACTERISTICS***********************************)
196          942.0         942.0         942.0    (COOLANT MASS VEL)
226            0.0           0.0001        10.0     (VS TIME)
256          800.0         800.0        (COOLANT INLET TEMP)
286            0.0           10.0         ( VS TIME)
316            2.60          0.316         0.25         .00766           0
      ( COOLANT HEAT TRANSFER COEFFICIENTS*****************************)
321            5.47
331             S2                        .007660          1.0          .00133
336           .0223     375.0     180.0
339  0.1     (HC3 CONSTANT)
      ( GAP CONDUCTIVITY INPUT*****************************************)
              (MID-CYCLE GAS IN GAP...      .10 HE,  .90 FISSION GAS)
341            0.42      1.56E-6         2.28E-9           0.0          0.0910
346             2.5        2.8E+7         .312E-5      .312E-5         .832E-4
351          1.5E-6        3.0E-6         .864E+7          .096            1.0
356         20000.0      .1325E-4          .9E-5
```

```
359       1.0
      ( FEEDBACK INPUT*************************************************)
360       1.0
361         13.1E-6       13.1E-6       13.1E-6       13.1E-6
365   -6.16E-4  8.75E-6  6.125E-10      (DELTA L/L VS T FOR CLAD)
368   -4.95E-4  3.84E-6  9.000E-10      (DELTA L/L VS T FOR FUEL)
371   -1.09E-4  4.16E-6 4.7235E-10      (DELTA L/L VS T FOR BEO )
405     .0422  0.252  (DENSITY COEF . 407 TO 441)
407     -.000222, -.00437, -.00545, -.00815, -.00545, -.00437, -.000222
414     -.000043, -.00087, -.00108, -.00162, -.00108, -.00087, -.000043
421     .00289,  .0570,  .0708,  .1060,  .0708,  .0570,  .00289
428     -.00012, -.00236, -.00293, -.00440, -.00293, -.00236, -.00012
435     -.000222, -.00437, -.00545, -.00815, -.00545, -.00437, -.000222
442     1.0   1.07   (REACTIVITY)
472     0.0  10.0     (VS TIME),
502   0.0,  0.00021,  0.0056,  0.0056  (SODIUM VOIDING REACTIVITY)
532   0.0,  0.08,     0.18,    10.0     ( VS. TIME SINCE INITIATION)
622       23.0      0.0      0.837     -.0092
628       1.1971  1.1314  1.0657  1.0000  (SPATIAL PWR WGT FACTOR)
632       0.9343  0.8686  0.8029          (SPATIAL PWR WGT FACTOR)
635       0.0
      ( POWER INPUTS***************************************************)
636            2500.0
697           .020            -.174         0.0           .2             .2
702           .2              10.0          2.0E+7        1.0
707           1.53E+7
708          0.9E-4      0.745E-3      0.662E-3      0.125E-2      0.567E-3
713       0.185E-3          .013          .0315          .136          .349
718            1.38          3.8           2.95      0.576E-6
728          0.1E-4        1.0E-7
      ( MISCELLANEOUS**************************************************)
730           .0001       0.5
734   1560.0, 1640.0, 1695.0, 1740.0  (COOLANT BULK BOILING TEMP)
738   1780.0, 1815.0, 1842.0, 1882.0  (COOLANT BULK BOILING TEMP)
742   1905.0, 1930.0, 1955.0, 1975.0  (COOLANT BULK BOILING TEMP)
746   2000.0, 2015.0, 2040.0, 2055.0  (COOLANT BULK BOILING TEMP)
750   2070.0, 2100.0, 2228.0, 2330.0  (COOLANT BULK BOILING TEMP)
754   10.0,15.0,20.0,25.0,30.0,35.0,40.0,45.0 (VS. ABSOLUTE PRESSURE)
762   50.0,55.0,60.0,65.0,70.0,75.0,80.0,85.0 (VS. ABSOLUTE PRESSURE)
770   90.0,100.0,150.0,200.0                  (VS. ABSOLUTE PRESSURE)
774   1560.0, 1640.0, 1675.0, 1740.0  (CLAD BURNOUT TEMPERATURE)
```

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```
 778   1780.0, 1815.0, 1842.0, 1882.0   (CLAD BURNOUT TEMPERATURE)
 782   1905.0, 1930.0, 1955.0, 1975.0   (CLAD BURNOUT TEMPERATURE)
 786   2000.0, 2015.0, 2040.0, 2055.0   (CLAD BURNOUT TEMPERATURE)
 790   2070.0, 2100.0, 2228.0, 2330.0   (CLAD BURNOUT TEMPERATURE)
 794   10.0,15.0,20.0,25.0,30.0,35.0,40.0,45.0 (VS. ABSOLUTE PRESSURE)
 802   50.0,55.0,60.0,65.0,70.0,75.0,80.0,85.0 (VS. ABSOLUTE PRESSURE)
 810   90.0,100.0,150.0,200.0                   (VS. ABSOLUTE PRESSURE)
 814     0.4    21.8    65.0    6500.0    0.8
 850       6HTESTBB
 861    6.96E-4   6.04E-4   5.20E-4   4.44E-4   4.05E-4   3.82E-4   (K OF FUEL)
 867    3.64E-4   3.50E-4   3.40E-4   3.32E-4   3.20E-4   3.30E-4   (K OF FUEL)
 873    3.36E-4   3.40E-4   3.44E-4   3.58E-4   3.72E-4   3.92E-4   (K OF FUEL)
 879    4.40E-4   4.40E-4
 881    0.0       500.0     1000.0    1500.0    1800.0    2000.0    (VS TEMP)
 887    2200.0    2400.0    2600.0    2800.0    3000.0    3400.0    (VS TEMP)
 893    3800.0    4000.0    4200.0    4400.0    4600.0    4800.0    (VS TEMP)
 899    4928.0    15000.0
       ( ARE YOU READY COMPUTER)
9999
)LAST    *
```

C.2 RESTART FOR SAMPLE PROBLEM

```
)EEEE    *TC102                21SEP66
           (RESTART OF $2.00/SEC REACTIVITY INSERTION)
  29       1    (THIS IS A RESTART)
  52       0   (CONTINUE FROM FINAL WRAPUP)
 850       6HTESTPB     (OLD TAPE LABEL)
 851       6HTESTPB     (NEW TAPE LABEL,NEED NOT BE THE SAME AS OLD LABEL)
9999
(EEEE    *TC102                21SEP66
   5       900   (NUMBER OF TIME STEPS)
  64       1.75   (MAXIMUM PROBLEM TIME)
  31                 1              15              1              15              0
  49        3             300             600
         (NOTE LOCATION NUMBERS NEED NOT BE IN SEQUENCE)
9999
)LAST    *
```

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C.3 PLOTTING INPUT FOR SAMPLE PROBLEM

```
)ERCUREL*TC102                    27SEP66
      REACT1  =  1   $ (TOTAL DELTA K, GRAPH 1)
      PROGMO  =  1   $ (PROGRAMMED DELTA K, GRAPH 1)
      REDRK   =  1   $ (TOTAL FEEDBACK DELTA K, GRAPH 1)
      QH(1,1) =  2, *7 $ (HEAT FLUX,AVERAGE , ALL 7 AXIAL SECTIONS, GRAPH 2)
      TVDO(1,1) = 3,*7 $(FUEL CENTER TEMP,AVG, 7 AXIAL SECTIONS, GRAPH 3)
      TCL(1,1) =  4, *7 $(COOLANT TEMP, GRAPH 4)
      TCL(4,1) =  5 $   (COOLANT TEMP FOR AXIAL SECTION 4 ONLY, BOTH AVG... )
      TCL(4,3) =  5 $   (...AND HOT SPOT CHANNELS, VS.TIME, GRAPH 5)
      PSTRNM   =  6   $  (NORMALIZED PROMPT POWER, GRAPH 6)
      PWRNM    =  6   $  (DITTO TOTAL POWER)
      PWRLOG  =  6 $ (INDICATES SEMI-LOGARITHMIC SCALE FOR GRAPH 6)
      MINJ   =  0, *6 $ (START WITH TIME STEP 0, ALL SIX TIME GRAPHS)
      MAXJ =  557, *6 $ (GO TO TIME STEP 557 - ALL SIX GRAPHS)
      IDELJ(1) =  2, *6 $ (PLOT ALTERNATE STEPS, INDEX 1 IS OPTIONAL)
      CONTRL(1,1) = 1,1,2 $ (GRAPH 1, 0 TO X-AXIS,CONNECT POINTS,LABEL ALT.)
      CONTRL(1,2) = 1,1,2 $ (GRAPH 2 )
      CONTRL(1,3) = 1,1,2 $ (GRAPH 3 )
      CONTRL(1,4) = 1,1,2 $ (GRAPH 4 )
      CONTRL(1,5) = 1,1,2 $ (GRAPH 5 )
      CONTRL(1,6) = 1,1,2 $ (GRAPH 6 )
      DKDOP   =  1 $ (DOPPLER DELTA K, GRAPH 1)
      DKVOID  =  1 $ (SODIUM VOIDING DELTA K, GRAPH 1)
         (CURVES FOR A GRAPH NEED NOT BE SPECIFIED TOGETHER)
      KEE(1,1,1) = 18H1--VOID DELTA K        $ (LABELS FOR INDIVIDUAL CURVES ...)
      KEE(1,2,1) = 18H2--DOPPLER DK          $ (... ON GRAPH 1, NOTE CURVES ...)
      KEE(1,3,1) = 18H3--TOTAL FEEDBACK      $ (... ARE PLOTTED IN ORDER ...    )
      KEE(1,4,1) = 18H4--TOTAL DK            $ (... SYMBOLS ARE DEFINED IN ...)
      KEE(1,5,1) = 18H5--PROGAMMED DK        $ (...MANUAL )
      KEE(1, 1, 2) =  36H1 - AXIAL SECTION 1                          $
      KEE(1, 2, 2) =  36H2 - AXIAL SECTION 2                          $
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```
KEF(1, 3, 2) =  36H3 - AXIAL SECTION 3                          $
KEF(1, 4, 2) =  36H4 - AXIAL SECTION 4                          $
KEF(1, 5, 2) =  36H5 - AXIAL SECTION 5                          $
KEF(1, 6, 2) =  36H6 - AXIAL SECTION 6                          $
KEF(1, 7, 2) =  36H7 - AXIAL SECTION 7                          $
KEF(1, 1, 3) =  36H1 - AXIAL SECTION 1                          $
KEF(1, 2, 3) =  36H2 - AXIAL SECTION 2                          $
KEF(1, 3, 3) =  36H3 - AXIAL SECTION 3                          $
KEF(1, 4, 3) =  36H4 - AXIAL SECTION 4                          $
KEF(1, 5, 3) =  36H5 - AXIAL SECTION 5                          $
KEF(1, 6, 3) =  36H6 - AXIAL SECTION 6                          $
KEF(1, 7, 3) =  36H7 - AXIAL SECTION 7                          $
KEF(1,1,5) = 36H1--AXIAL SECT 4, AVG CHANNEL            $
KEF(1,2,5) = 36H2--AXIAL SECT 4, HOT SPOT CHANNEL       $
DIVISR(1)=2500.0 $ (NORMALIZING FACTOR FOR POWER CURVE ONE    )
DIVISR(2)=2500.0 $ (NORMALIZING FACTOR FOR POWER CURVE TWO    )
KCHAX(1) = 7 $  (GRAPH 7 IS AN AXIAL PLOT)
TCL(1,1) = 7 $  (PLOT COOLANT TEMP,AVG CHANNEL, VS AXIAL POSITION,GRAPH 7)
   (NOTE SIXTH EXPRESSION IS EFFECTIVELY 7 INSTRUCTIONS IN ONE)
   (THESE ARE TCL(1,1) = 4, TCL(2,1) = 4, ETC )
   (LAST INSTRUCTION TCL(1,1) = 7 OVERLAYS TCL(1,1) = 4 )
   (ALSO SEVENTH EXPRESSION IS TCL(4,1) = 5)
   (THIS AGAIN OVERLAYS TCL(4,1) =4)
   (THE RESULT IS GRAPH 4 WILL ONLY CONTAIN 5 CURVES)
   (SECTION 2,3,5,6,AND 7)
   (THE LABELS CURVES FOR 4 BECOME)
KEF(1, 1, 4) =  36H2 - AXIAL SECTION 2                          $
KEF(1, 2, 4) =  36H3 - AXIAL SECTION 3                          $
KEF(1, 3, 4) =  36H5 - AXIAL SECTION 5
KEF(1, 4, 4) =  36H6 - AXIAL SECTION 6                          $
KEF(1, 5, 4) =  36H7 - AXIAL SECTION 7                          $
CONTRL(1,7)= 1,1,1 $ (ON GRAPH 7,0 X-AXIS,CONNECT POINTS,LABEL EVERY PT)
KSTEP(1,1)= 0,92,182,272,362,452,557, $ (TIME STEPS SELECTED FROM PRINT.*) \
LABLMH(1,7) = 42H  INSERTION OF 0.0070 DELTA K PER SECOND    $
LABLXY(1,7) = 36HAXIAL LOCATION-IN.   COOLANT TEMP     $
LABLSH(1,1,7) = 30H PLOT NO. 7-- AVERAGE CHANNEL    $
LABLMH(1,1) = 42H  INSERTION OF 0.0070 DELTA K PER SECOND    $ (MAIN TITLE)
LABLMH(1,2) = 42H  INSERTION OF 0.0070 DELTA K PER SECOND    $ (MAIN TITLE)
LABLMH(1,3) = 42H  INSERTION OF 0.0070 DELTA K PER SECOND    $ (MAIN TITLE)
LABLMH(1,4) = 42H  INSERTION OF 0.0070 DELTA K PER SECOND    $ (MAIN TITLE)
LABLMH(1,5) = 42H  INSERTION OF 0.0070 DELTA K PER SECOND    $ (MAIN TITLE)
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```
      LABLMH(1,6) = 18H 0.0070 DEL K/SEC  $ (MAIN HEADING SEMI-LOG)
      LABLXY(1,1) = 36H TIME (SECONDS)        DELTA K          $ (AXES LABELS)
      LABLXY(1,2) = 36H TIME (SECONDS)        HEAT FLUX        $
      LABLXY(1,3) = 36H TIME (SECONDS)     FUEL CENTER TEMP    $
      LABLXY(1,4) = 36H TIME (SECONDS)      COOLANT TEMP       $
      LABLXY(1,5) = 36H TIME (SECONDS)      COOLANT TEMP       $
      LABLXY(1,6) = 36H TIME (SECONDS)         POWER           $
      LABLSH(1,1,1) = 30H            PLOT NO. 1                $
      LABLSH(1,1,2) = 30H PLOT NO. 2-- AVERAGE CHANNEL         $
      LABLSH(1,1,3) = 30H PLOT NO. 3-- AVERAGE CHANNEL         $
      LABLSH(1,1,4) = 30H PLOT NO. 4-- AVERAGE CHANNEL         $
      LABLSH(1,1,5) = 30H            PLOT NO. 5                $
      KEF(1,1,7) =  24H1 - AT 0.00 SECONDS          $
      KEF(1,2,7) =  24H2 - AT 0.25 SECONDS          $
      KEF(1,3,7) =  24H3 - AT 0.50 SECONDS          $
      KEF(1,4,7) =  24H4 - AT 0.75 SECONDS          $
      KEF(1,5,7) =  24H5 - AT 1.00 SECONDS          $
      KEF(1,6,7) =  24H6 - AT 1.25 SECONDS          $
      KEF(1,7,7) =  24H7 - AT 1.50 SECONDS          $
      IOLRAD = 1 $ (ONE RADIAL GRAPH)
      NCHANN(1,1)= 1 $ (AVERAGE CHANNEL)
      NAXNOD(4,1)= 1 $ (AXIAL SECTION 4)
      NSTEP(1,1) = 0,92,182,272,362,452,557 $
      CONTRL(1,8)= 1.1,1 $ (0 TO X-AXIS,CONNECT POINTS,LABEL EVERY PT,RADIAL GR)
      LABLMH(1,8) = 42H  INSERTION OF 0.0070 DELTA K PER SECOND    $
      LABLXY(1,8) = 36HRADIUS  INCHES        TEMPERATURE (F)   $
      LABLSH(1,1,8) = 30H PLOT NO. 8-- AVERAGE CHANNEL    $
      KEF(1,1,8) =  24H1 - AT 0.00 SECONDS          $
      KEF(1,2,8) =  24H2 - AT 0.25 SECONDS          $
      KEF(1,3,8) =  24H3 - AT 0.50 SECONDS          $
      KEF(1,4,8) =  24H4 - AT 0.75 SECONDS          $
      KEF(1,5,8) =  24H5 - AT 1.00 SECONDS          $
      KEF(1,6,8) =  24H6 - AT 1.25 SECONDS          $
      KEF(1,7,8) =  24H7 - AT 1.50 SECONDS          $
      LABLSH(1,2,1) = 30H    DELTA K  VS  TIME                $ (SECOND LINE)
      LABLSH(1,3,1) = 30H SAMPLE PROBLEM FOR MANUAL           $ (THIRD LINE)
      LABLSH(1,4,1) = 30H  TC102   B F LAWLER                 $  (FOURTH LINE)
      $$
)ERCUREL*TC102              29SEP66
      (NOTE TAPE WITH LONG EDIT IS STILL AVAILABLE FOR ADDITIONAL PLOTTING )
      KCHAX(1) =  1 $ (GRAPH 1 IS AN AXIAL PLOT)
```

```
      CELCL(1,1) = 1 $ (GAP COEFFICIENT, AVG, GRAPH 1)
      CELCL(1,3) = 1 $ (DITTO HOT SPOT)
      CONTRL(1,1)= 3,1,1 $
      XSTEP(1,1) = 0, 557  $ (FIRST AND LAST PRINT OUT)
      LABLMH(1,1) =  42H   INSERTION OF 0.007 DELTA K PER SECOND    $
      LABLXY(1,1) =  36HAXIAL LOCATION-IN. GAP COEFFICIENT      $
      LABLSH(1,1,1) = 30H  PLOT NO. 9 --GAP COEFFICIENT$
      KEE(1,1,1) = 24H1 -AVG AT 0.00 SECONDS          $
      KEE(1,2,1) = 24H2 -H.S. AT 0.00 SECONDS         $
      KEE(1,3,1) = 24H3 -AVG AT 1.50 SECONDS          $
      KEE(1,4,1) = 24H4 -H.S. AT 1.50 SECONDS         $
      $$
)LAST   *
```

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C 4 PLOTTED OUTPUT

The basic purpose of the sample problem is to demonstrate the use of FORE II and FRCURV rather than provide a totally accurate investigation of a $2.00/sec reactivity insertion. For this reason, some of the input to FORE II should be viewed as estimates and not the results of detailed independent investigations. However, some of the significant features of this problem are discussed.

In the input, it was specified that when the temperature in the inner fuel pin node for the hot-spot channel reached the vaporization temperature at any axial location, a specified positive Δk as a function of time would be inserted. This positive Δk was the contribution due to sudden vaporization of the sodium when brought in contact with the hot, exploding fuel pin. The vaporization temperature in the hot channel was achieved in 1.408 seconds. Plot 1 indicates that the voiding effect quickly becomes the predominant reactivity contribution.

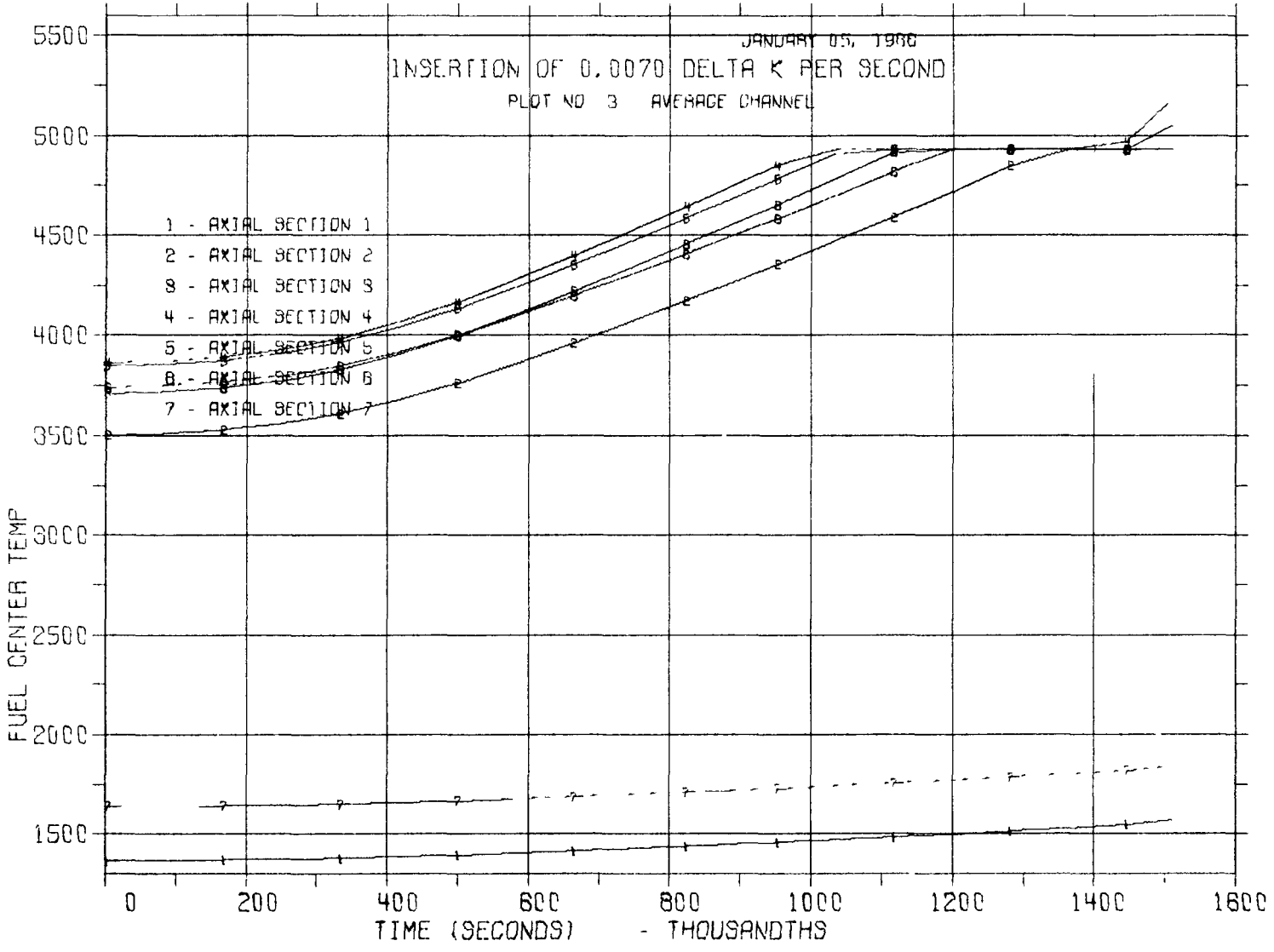
Plot 2 indicates that the heat addition to the coolant in the core is so large that eventually the top blanket acts like a heat sink. The seemingly irregularity in the curves for axial sections 2 to 4 is primarily due to the increase in the gap coefficient with time (see Plot 9). A small improvement in the smoothness of the curves can be obtained by taking an edit every 10 steps instead of 15, and by plotting every edited step instead of alternative steps.

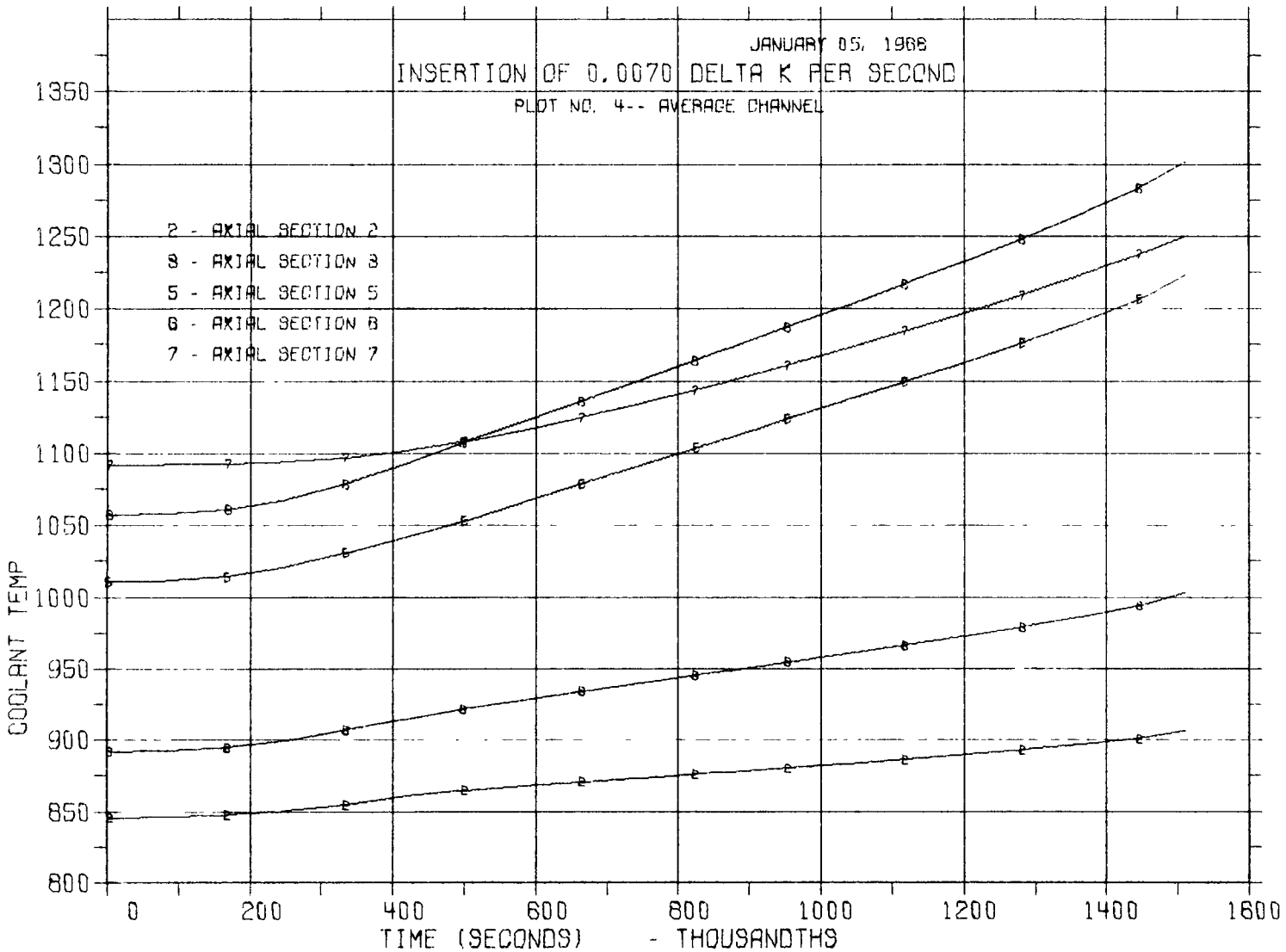
In Plot 3, note the dwell time required to melt all the fuel in the inner fuel node. Comments in the listing of the input to FRCURV explain the reason for only five axial coolant sections to be plotted on Plot 4. An understanding of the overlay feature is essential for accurately labeled graphs.

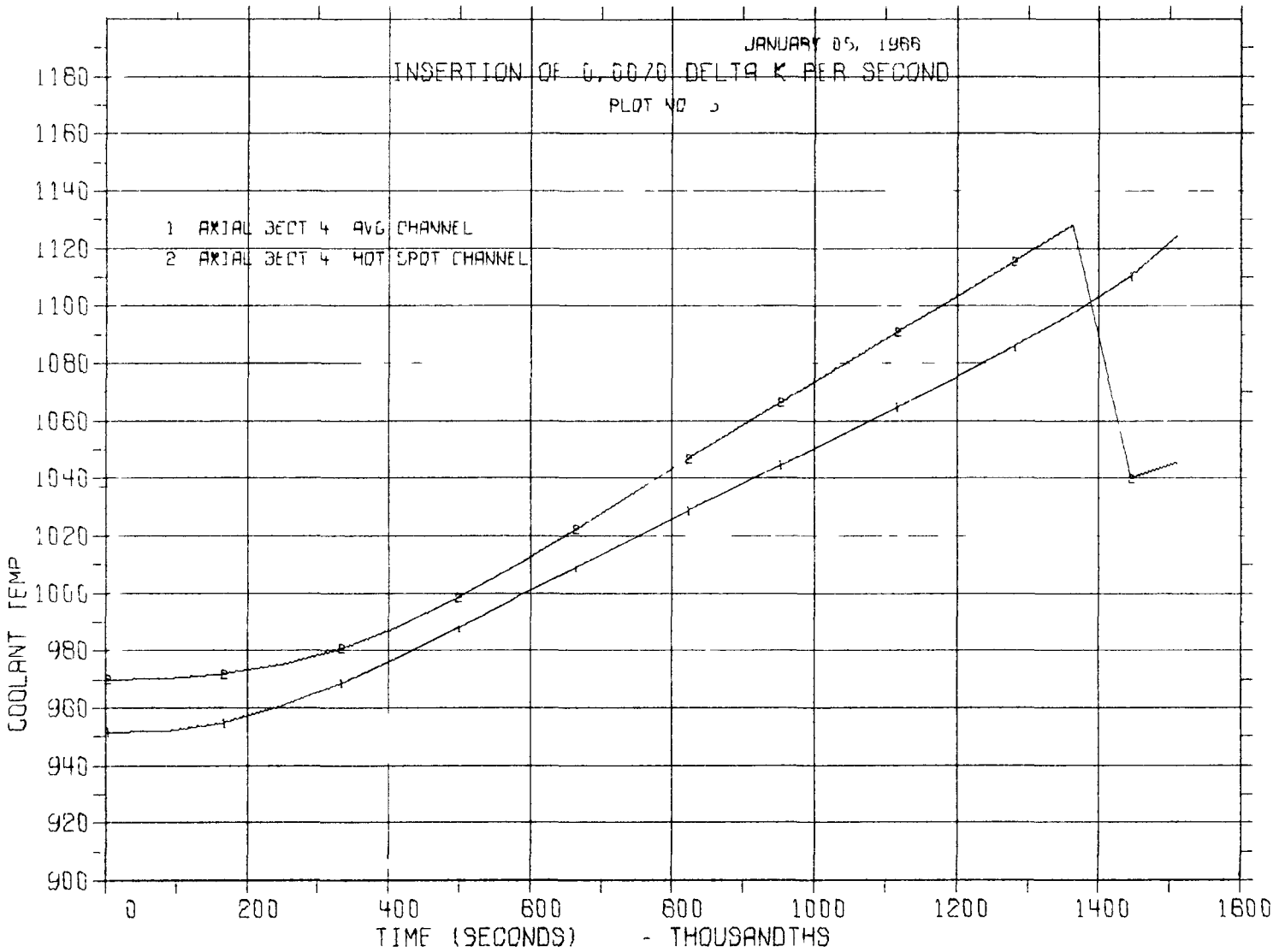
In Plot 5, the decrease in the coolant temperature for the hot-spot channel results from the low film coefficient used at the time of voiding. The magnitude of the drop reflects the value of the input film coefficient. As previously indicated, the true voiding time occurred at 1.408 seconds. The indicated break time in Plot 5 results from the inherent characteristics of the plotter when a coarse data point spacing is used.

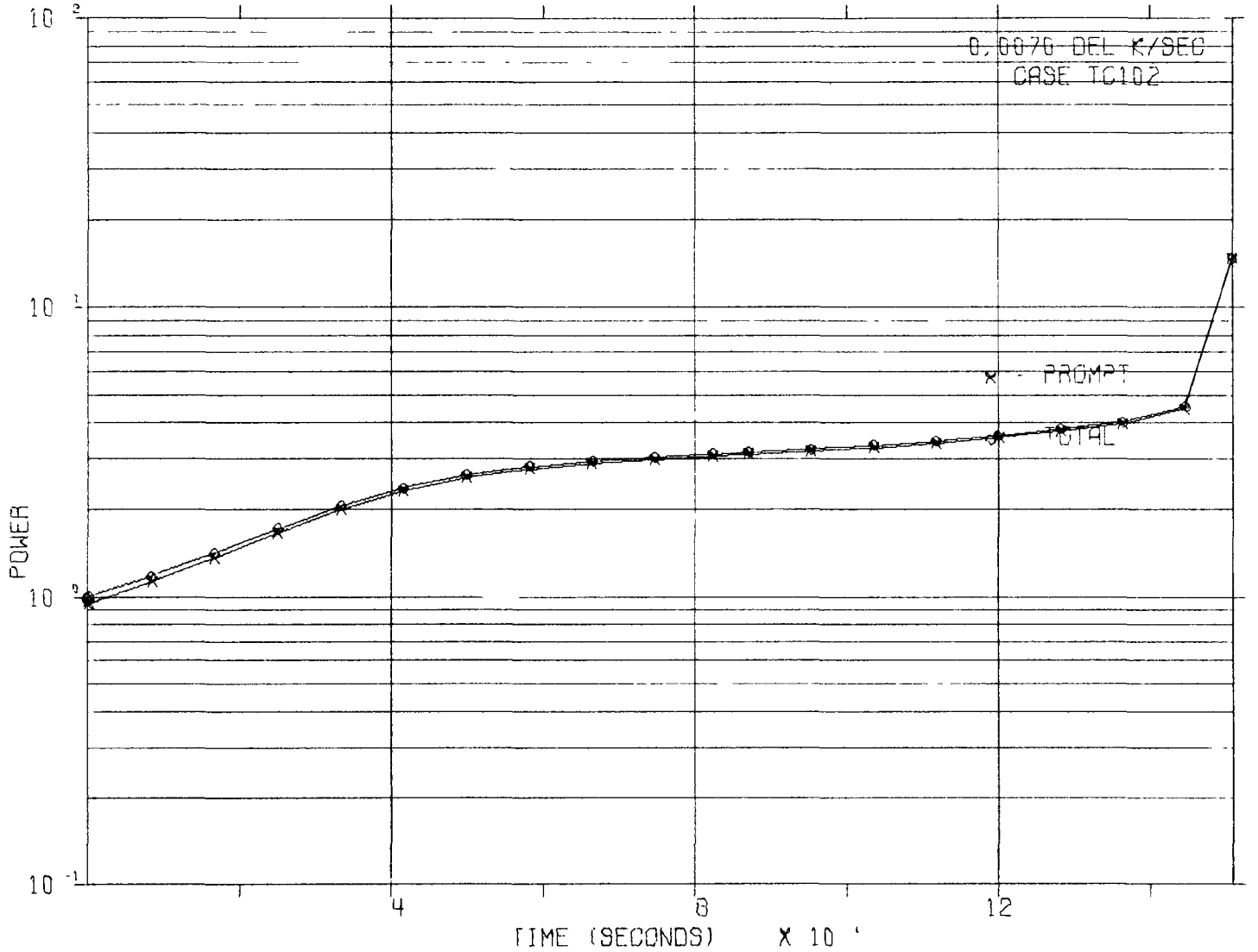
In Plot 6, the increase in power with the start of sodium voiding can be observed. Plot 7 again indicates that the top blanket becomes a heat sink as the transient progresses. Plot 8 indicates the change in the temperature profile across a typical fuel pin section with time.

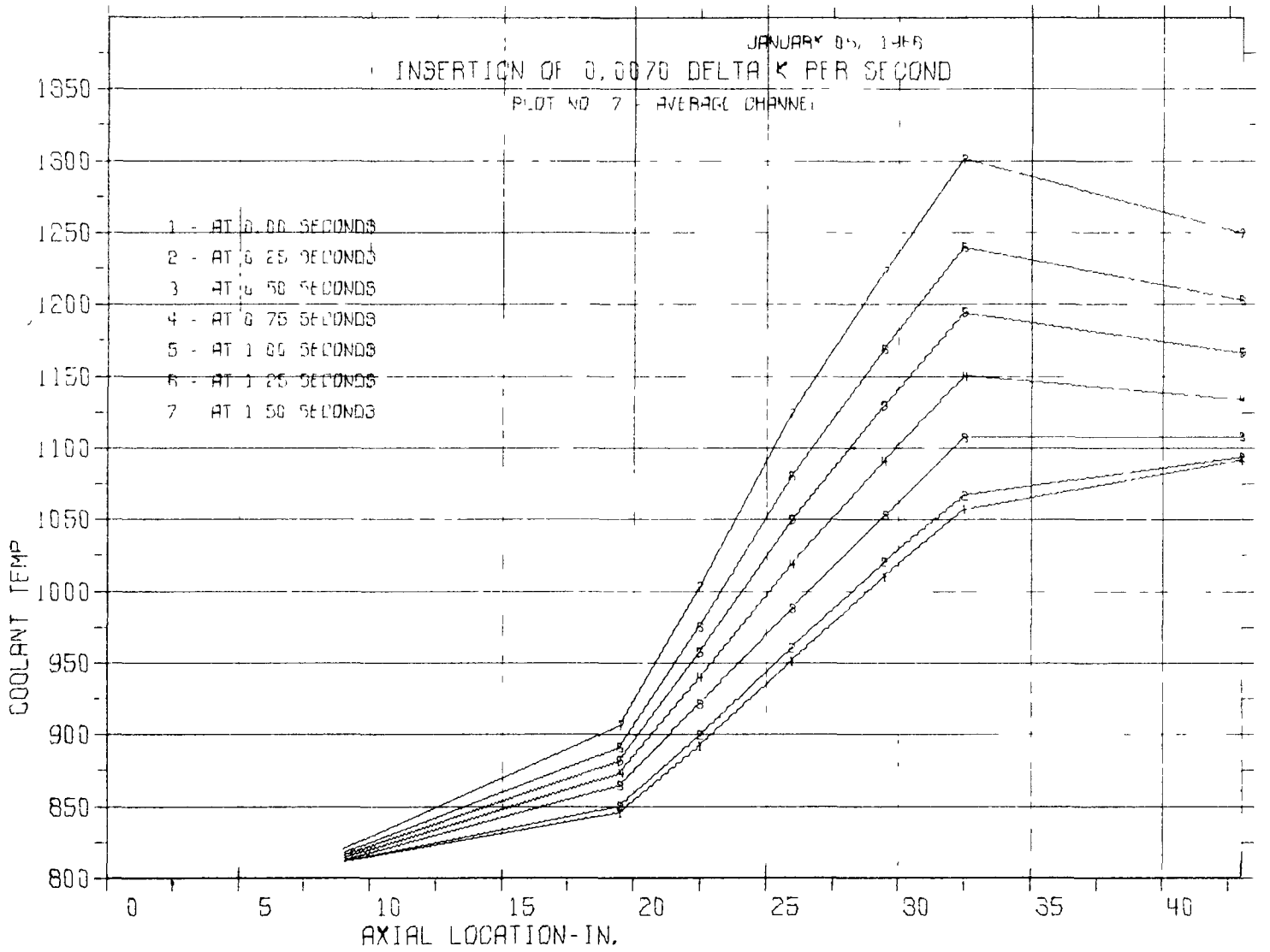
Plot 9 shows the variation in gap coefficient with axial position, channel type, and time for the particular set of input data. The hump in Curve 4 in the center of the core is due to the sodium voiding in that region.

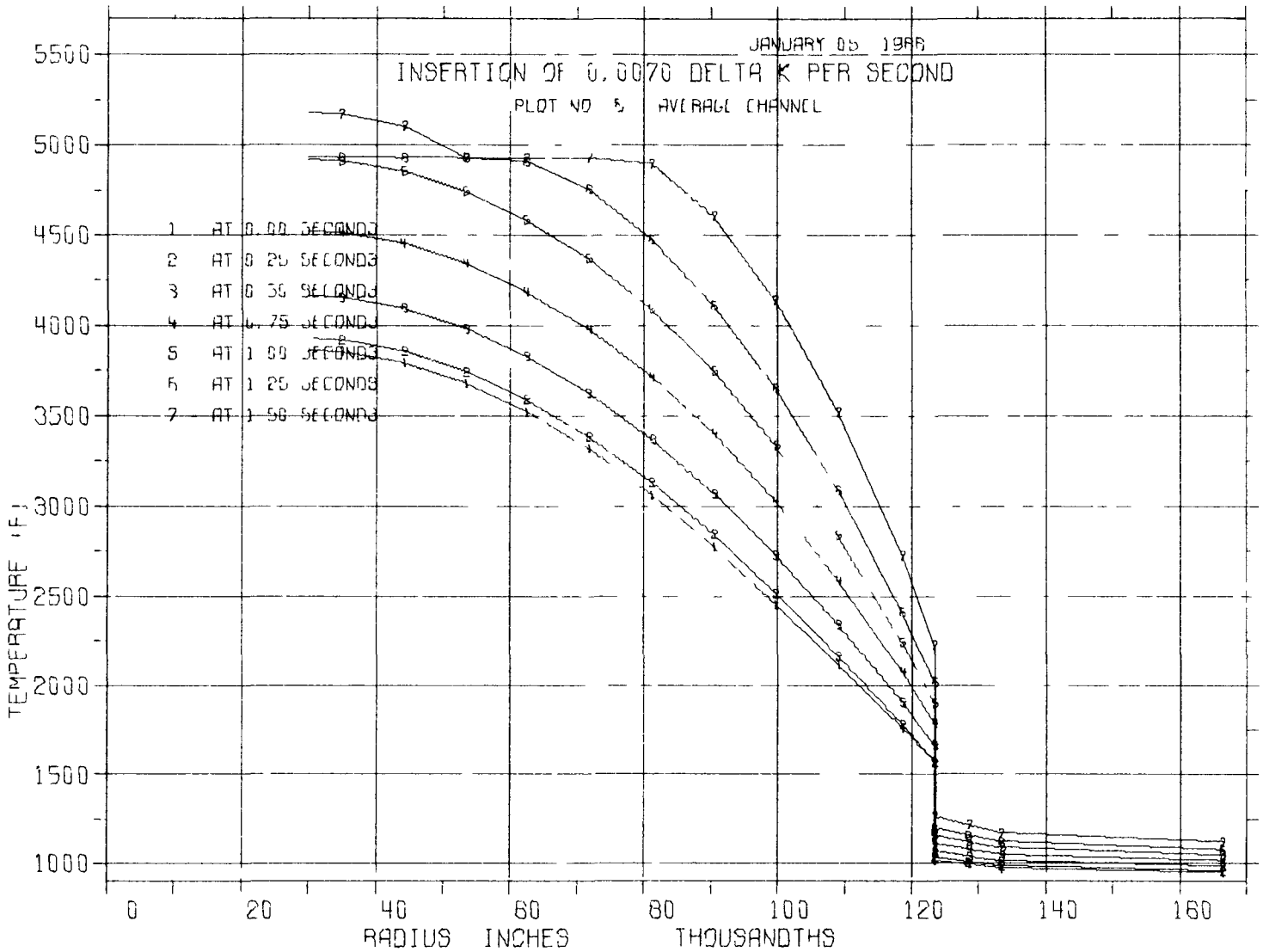

JANUARY 05, 1968
INSERTION OF 0.0070 DELTA K PER SECOND
PLOT NO 3 AVERAGE CHANNEL
1 - AXIAL SECTION 1
2 - AXIAL SECTION 2
3 - AXIAL SECTION 3
4 - AXIAL SECTION 4
5 - AXIAL SECTION 5
6 - AXIAL SECTION 6
7 - AXIAL SECTION 7
FUEL CENTER TEMP
5500
5000
4500
4000
3500
3000
2500
2000
1500
0
200
400
600
800
1000
1200
1400
1600
TIME (SECONDS) - THOUSANDTHS

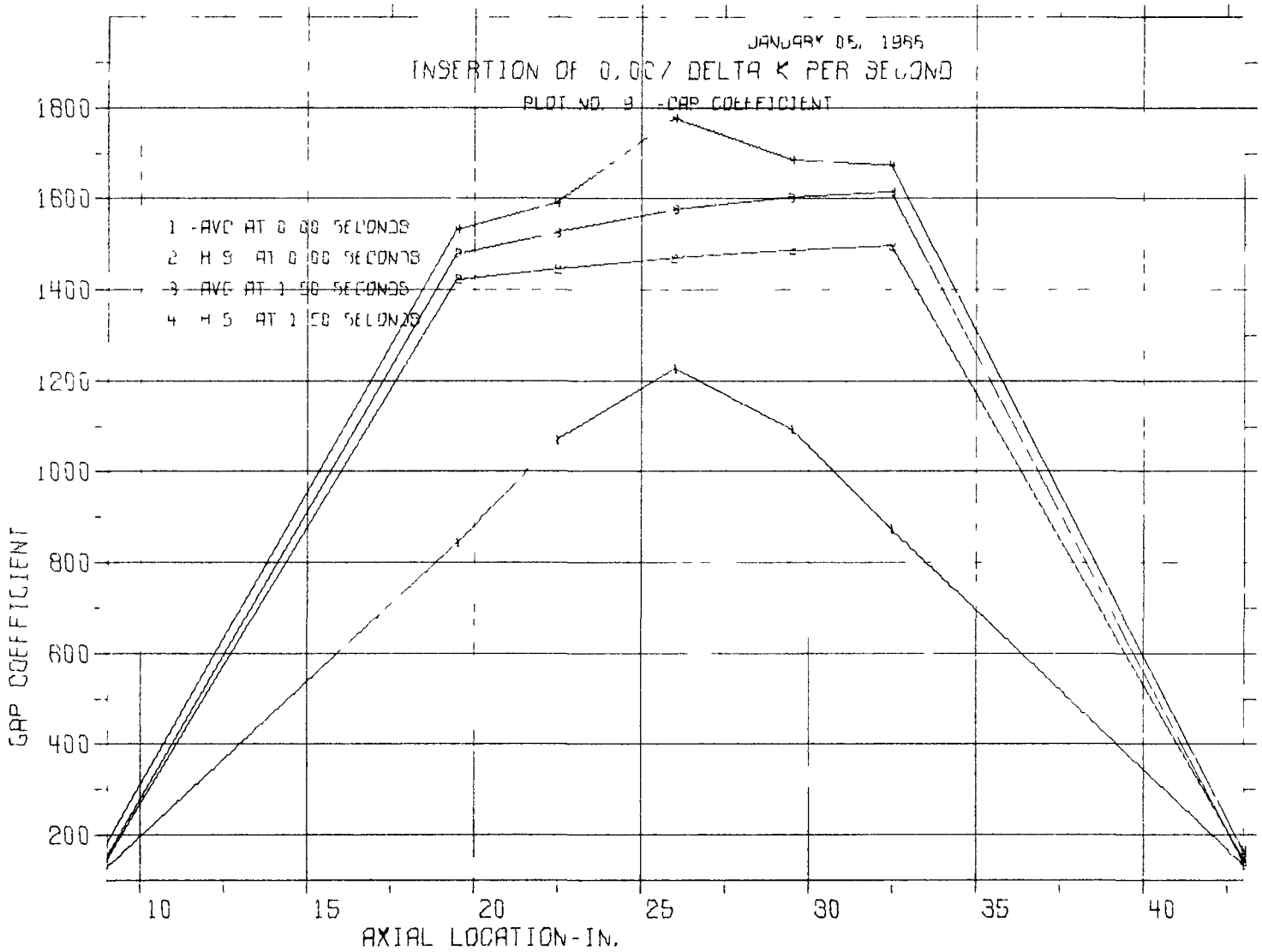

JANUARY 05, 1968
INSERTION OF 0.0070 DELTA K PER SECOND
PLOT NO. 4-- AVERAGE CHANNEL
2 - AXIAL SECTION 2
3 - AXIAL SECTION 3
5 - AXIAL SECTION 5
6 - AXIAL SECTION 6
7 - AXIAL SECTION 7
COOLANT TEMP
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
0
200
400
600
800
1000
1200
1400
1600
TIME (SECONDS) - THOUSANDTHS


JANUARY 05, 1966
INSERTION OF 0.0070 DELTA K PER SECOND
PLOT NO 5
1 AXIAL SECT 4 AVG CHANNEL
2 AXIAL SECT 4 HOT SPOT CHANNEL
COOLANT TEMP
1180
1160
1140
1120
1100
1080
1060
1040
1020
1000
980
960
940
920
900
0
200
400
600
800
1000
1200
1400
1600
TIME (SECONDS) - THOUSANDTHS


0.0070 DEL K/SEC
CASE TC102
x - PROMPT
TOTAL
POWER
10 2
10 1
10 0
10 -1
4
8
12
TIME (SECONDS) X 10 '


JANUARY 05, 1968
INSERTION OF 0.0070 DELTA K PER SECOND
PLOT NO 7 - AVERAGE CHANNEL
1 - AT 0.00 SECONDS
2 - AT 0.25 SECONDS
3 - AT 0.50 SECONDS
4 - AT 0.75 SECONDS
5 - AT 1.00 SECONDS
6 - AT 1.25 SECONDS
7 - AT 1.50 SECONDS
COOLANT TEMP
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
0
5
10
15
20
25
30
35
40
AXIAL LOCATION-IN.


JANUARY 05 1988
INSERTION OF 0.0070 DELTA K PER SECOND
PLOT NO 5 AVERAGE CHANNEL
1 AT 0.00 SECONDS
2 AT 0.25 SECONDS
3 AT 0.50 SECONDS
4 AT 0.75 SECONDS
5 AT 1.00 SECONDS
6 AT 1.25 SECONDS
7 AT 1.50 SECONDS
TEMPERATURE (F)
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
0
20
40
60
80
100
120
140
160
RADIUS INCHES
THOUSANDTHS


JANUARY 05, 1966
INSERTION OF 0.00 / DELTA K PER SECOND
PLOT NO. 9 -GAP COEFFICIENT
1 -AVG AT 0.00 SECONDS
2 H.S. AT 0.00 SECONDS
3 -AVG AT 1.50 SECONDS
4 H.S. AT 1.50 SECONDS
GAP COEFFICIENT
1800
1600
1400
1200
1000
800
600
400
200
10
15
20
25
30
35
40
AXIAL LOCATION-IN.

APPENDIX D

DETAILED EQUATIONS

SUBROUTINE FINPT

FUNCTION

Process input.
Assign values for material properties tables.
Calculate miscellaneous constants used in the various subroutines.

PROCEDURE

A. Set up material properties tables .

B. Read input data.

C. Calculate the following:

1. Geometric Parameters

a. $R_a = \sqrt{\frac{R_E^2 + R_e^2}{2}}$

$R_f = R_N$

b. $A_c = \pi (R_c^2 - R_E^2)$

$A_e = \pi (R_E^2 - R_e^2)$

$A_f = \pi (R_f^2 - R_o^2)$

$A_n = \pi (R_n^2 - R_o^2)$ for $n = 1$

$A_n = \pi (R_n^2 - R_{n-1}^2)$ for $2 \leq n \leq N$

2. Specific Heat of Molten Fuel

$C^{Melt} = f(T_f', C_f', T_f^{Melt})$

3. Active Core Height

$H_T = \sum_{m=1}^{M} (\Delta Z)_m$

4. Distance from core inlet support to actual core inlet

$$X_{m=1} = Z_o + \frac{(\Delta Z)_{m=1}}{2}$$

for $2 \leq m \leq M$:

$$X_m = Z_o + \sum_{\ell=1}^{m-1} (\Delta Z)_\ell + \frac{(\Delta Z)_m}{2}$$

5. Thermal conductivity of Molten Fuel

$$K_f^{Melt} = K^{(0)} + K^{(1)} T_f^{Melt} + K^{(2)} (T_f^{Melt})^2 \quad \text{if } \delta_k = 0$$

$$K_f^{Melt} = f(K_f', T_f', T_f^{Melt}) \quad \text{if } \delta_k = 1$$

6. Radii at which fuel temperatures are calculated

$$r_n = \sqrt{\frac{R_n^2 + R_o^2}{2}} \qquad \text{for } n = 1$$

$$r_n = \sqrt{\frac{R_n^2 + R_{n-1}^2}{2}} \qquad \text{for } 2 \leq n \leq N$$

7. Logarithms

$$(LN)_n = \ln\left(\frac{r_n + 1}{r_n}\right) \quad \text{for } 1 \leq n \leq N-1$$

$$(LN)_n = \ln\left(\frac{R_n}{r_n}\right) \qquad \text{for } n = N$$

$$\ln \frac{R_f}{r_N}$$

$$\ln \frac{r_1}{R_o}$$

$$\ln \frac{R_E}{R_a}$$

$$\ln \frac{R_a}{R_e}$$

$$\ln \frac{R_E}{R_e}$$

8. Miscellaneous Groupings

2Π	$\frac{E_e (R_E - R_e)\ 144}{R_a^2}$
4Π	
$2\Pi\ R_c$	$a_o \left(\frac{\delta_f^2 + \delta_e^2}{2} \right)^{\frac{1}{4}} \varphi$
$2\Pi\ R_E$	
$2\Pi\ R_N$	$\beta_o (\delta_f + \delta_e)$
$\frac{d_s}{K_s}$	$\frac{1 - \lambda_a}{\lambda_a}$
$\frac{d_u}{K_u}$	if $\delta_L = 0$:
	$W_\ell = \frac{2\ell - 1}{L}$ for $1 \leq \ell \leq L$

D. End of FINPT

SUBROUTINE INIT

FUNCTION

Calculates initial conditions based on steady-state power.

PROCEDURE

A. Evaluate core inlet temperature and determine channel types.

1. By linear interpolation, find inlet temperature

$$T_c^{Inlet(0)} = f\,(T_c^{'Inlet},\ T^{'},\ T)$$

where $T_c^{'Inlet}$ and $T^{'}$ are inputs.

2. Initialize K, number of Channels

If $\delta_H = 1$, calculate average channel; set K = 1

If $\delta_H = 2$, calculate average & peak channels; set K = 2

If $\delta_H = 3$, calculate average, peak & hot spot channels; set K = 3

B. Calculate steady-state conditions.

1. Initial power

$$P_o^{(0)} = 948.05\ \frac{P_{in}}{V_f}$$

2. Initial velocity

$$G_{c,k=1}^{(0)} = f\,(T^{'},\ G_c^{'},\ T)$$

$$G_{c,k=2}^{(0)} = G_{c,k=1}^{(0)}\ F_r$$

$$G_{c,k=3}^{(0)} = G_{c,k=1}^{(0)}\ F_v$$

3. Setting up constants

a. For k = 1:

$F^{*} = 1.0$

$F^{**} = 1.0$

$F^{***} = 1.0$

$PC\emptyset N = 1.0$

b. For k = 2:

$F^{*} = 1.0$

$F^{**} = F_{g,p}$

$F^{***} = 1.0$

$PC\emptyset N = P_r$

c. For k = 3:

$F^{*} = F_h$

$F^{**} = F_g$

$F^{***} = F_k$

$K_e = K_e F_e$

Sections B.4 through B11. k are calculated for $1 \leq k \leq K$

4. Coolant temperatures and properties; heat generation rates.

a. Find C_c as a function of $\bar{T}^{(0)}_{c,m,k}$ by an iterative procedure.

(1) $C^{(0)}_{c,m,k} = f\,(C_c', T_c, T_c^{Inlet(0)})$

(2) $\bar{T}^{Old} = \bar{T}^{(0)}_{c,m,k}$

(3) for m=1

$$T^{in(0)}_{c,m,k} = T_c^{inlet(0)}$$

$$T^{(0)}_{c,m,k} = T^{in(0)}_{c,m,k} + \lambda_a \frac{A_m (PC\emptyset N)\, P_o\, A_f\, (\Delta Z)_m}{G^{(0)}_{c,k}\; C^{(0)}_{c,m,k}\; A_c}$$

$$T^{Out}_{c,m,k} = T^{(0)}_{c,m,k} + \left(T^{(0)}_{c,m,k} - T^{in(0)}_{c,m,k}\right)\left(\frac{1-\lambda_a}{\lambda_a}\right)$$

if $2 \leq m \leq M$

$$T^{in(0)}_{c,m,k} = T^{Out(0)}_{c,m-1,k}$$

$$T^{(0)}_{c,m,k} = T^{Out(0)}_{c,m-1,k} + \lambda_a \frac{A_m (PC\emptyset N)\ P_o\ A_f\ (\Delta Z)_m}{G^{(0)}_{c,k}\ C^{(0)}_{c,m,k}\ A_c}$$

$$T^{Out(0)}_{c,m,k} = T^{(0)}_{c,m,k} + (T^{(0)}_{c,m,k} - T^{in(0)}_{c,m,k}) \left(\frac{1 - \lambda_a}{\lambda_a} \right)$$

for $1 \leq m \leq M$

$$\overline{T}^{(0)}_{c,m,k} = \frac{T^{in(0)}_{c,m,k} + T^{Out(0)}_{c,m,k}}{2}$$

for $m = M$

$$T^{Out(0)}_{c,k} = T^{Out(0)}_{c,M,k}$$

(4) if $/\overline{T}^{(0)}_{c,m,k} - \overline{T}^{Old}/ > .001$

find by linear interpolation

$$\rho^{(0)}_{c,m,k} = f(\rho'_c, T'_c, \overline{T}^{(0)}_{c,m,k})$$

$$C^{(0)}_{c,m,k} = f(C'_c, T'_c, \overline{T}^{(0)}_{c,m,k})$$

go to B.4.a.2 and continue the iteration.

(5) if $/\overline{T}^{(0)}_{c,m,k} - \overline{T}^{Old}/ \leq .001$ continue loop on m.

b. Coolant Properties.

(1) Conductivity

$$K^{(0)}_{c,m,k} = f(K'_c, T_c, \overline{T}^{(0)}_{c,m,k})$$

(2) Dynamic viscosity.

$$\mu^{(0)}_{c,m,k} = f(\mu'_c, T'_c, \overline{T}^{(0)}_{c,m,k})$$

(3) Structure-to coolant heat transfer coefficient.

$$g^{(0)}_{c,m,k} = \frac{K^{(0)}_{c,m,k}}{D_{HT}} \left[A_H + B_H \left(\frac{D_{HT}\, G^{(0)}_{c,k}}{\mu^{(0)}_{c,m,k}} \right)^{M_H} \left(\frac{\mu^{(0)}_{c,m,k}\, C^{(0)}_{c,m,k}}{K^{(0)}_{c,m,k}} \right)^{N_H} \right] F^*$$

(4) Clad-coolant heat transfer coefficient (for lumped system)

$$h^{*(0)}_{c,m,k} = \frac{K^{(0)}_{c,m,k}}{D_{HT}} \left[A_H + C_{H,m} \left(\frac{D_{HT}\, G^{(0)}_{c,k}}{\mu^{(0)}_{c,m,k}} \right)^{M_H} \left(\frac{\mu^{(0)}_{c,m,k}\, C^{(0)}_{c,m,k}}{K^{(0)}_{c,m,k}} \right)^{N_H} \right] F^*$$

c. Heat generation rate constants.

$$\text{for } 1 \le m \le M$$

$$(MULT) = \frac{A_m\, F_\delta\, A_f}{\rho_f A_f + \rho_e A_e + \rho^{(0)}_{c,m,k} A_c + \rho_s V_s + \rho_u V_u}$$

$$(OU)_{c,m,k} = (MULT)\, \rho^{(0)}_{c,m,k}\, (PCON)$$

$$(OU)_{e,m,k} = (MULT)\, \rho_e\, (PCON)$$

$$(OU)_{s,m,k} = (MULT)\, \rho_s\, (PCON)$$

$$(OU)_{u,m,k} = (MULT)\, \rho_u\, (PCON)$$

$$(OU)_{f,m,k} = A_m (PCON) - \frac{A_e}{A_f} (OU)_{e,m,k} - \frac{A_c}{A_f} (QU)_{c,m,k} - \frac{V_s}{A_f} (QU)_{s,m,k} - \frac{V_u}{A_f} (OU)_{u,m,k}$$

$$\text{for } 1 \le n \le N$$

$$(OU)_{n,m,k} = Y_n (OU)_{f,m,k} \quad \left(\text{NOTE: } \sum_{n=1}^{N} Y_n A_n = A_f\right)$$

d. Fraction of Heat Produced in Fuel

$$F_{Fuel} = \frac{\sum_{m=1}^{M} (\Delta Z)_m\, (OU)_{f,m,1}}{\sum_{m=1}^{M} (\Delta Z)_m}$$

e. Heat generation rates

for $1 \leq m \leq M$

$$Q^{(0)}_{e,m,k} = (QU)_{e,m,k} P^{(0)}_o$$

$$Q^{(0)}_{c,m,k} = (QU)_{c,m,k} P^{(0)}_o$$

$$Q^{(0)}_{s,m,k} = (QU)_{s,m,k} P^{(0)}_o$$

$$Q^{(0)}_{f,m,k} = (QU)_{f,m,k} P^{(0)}_o$$

$$Q^{(0)}_{u,m,k} = (QU)_{u,m,k} P^{(0)}_o$$

$$Q^{(0)}_{n,m,k} = (QU)_{n,m,k} P^{(0)}_o \qquad 1 \leq n \leq N$$

5. Structure Temperatures

a. No structure area, or lumping ($G_s = 0.0$ or $\delta_c = 0$)

for $1 \leq m \leq M$

$$T^{(0)}_{s,m,k} = \bar{T}^{(0)}_{c,m,k}$$

Go to B.6

b. With structure area and no lumping ($G_s \neq 0.0$ and $\delta_c = 1$)

for $1 \leq m \leq M$

$$T^{(0)}_{s,m,k} = \bar{T}^{(0)}_{c,m,k} + \left(\frac{1}{g^{(0)}_{c,m,k}} + \frac{d_s}{K_s} \right) \frac{Q^{(0)}_{s,m,k}}{G_s}$$

Go to B.6

6. Temperature of Additional Material

a. Not present (if $\delta_u = 0$)

for $1 \leq m \leq M$

$$T^{(0)}_{u,m,k} = 0.0$$

Go to B.7

b. Present. but no area ($G_u = 0.0$ or $\delta_c = 0$)

for $1 \leq m \leq M$

$$T^{(0)}_{u,m,k} = \overline{T}^{(0)}_{c,m,k}$$

Go to B.7

c. Area included ($G_u \neq 0.0$ and $\delta_c \neq 0$)

for $1 \leq m \leq M$

$$T^{(0)}_{u,m,k} = \overline{T}^{(0)}_{c,m,k} + \left(\frac{1}{g^{(0)}_{c,m,k}} + \frac{d_u}{K_u} \right) \frac{Q^{(0)}_{u,m,k}}{G_u}$$

Go to B.7

7. Check for clad, coolant, structure and additional material lumping.

a. $\delta_c = 1$, <u>go to B.9</u> (not lumped)

b. $\delta_c = 0$, <u>go to B.8</u> (lumped)

8. Clad temperature when clad, coolant, structure and additional material are lumped together.

($\delta_c = 0$)

for $1 \leq m \leq M$

a. $\overline{T}^{(0)}_{e,m,k} = \overline{T}^{(0)}_{c,m,k}$

b. Go to B.10

9. Clad temperature and clad-coolant heat transfer coefficient when clad, coolant, structure and additional material are treated individuallv.

($\delta_c = 1$)

for $1 \leq m \leq M$

a. Initial guess

$$T^{(0)}_{E,m,k} = \overline{T}^{(0)}_{c,m,k} + \frac{1}{2\pi\ R_E\ h^{*(0)}_{c,m,k}} \left[Q^{(0)}_{f,m,k}\ A_f + Q^{(0)}_{e,m,k}\ A_e \right]$$

$$h^{(0)}_{c,m,k} = h^{*}_{c,m,k} \left[\frac{\overline{T}_{c,m,k} + 460}{T^{(0)}_{E,m,k} + 460} \right]^{R_H}$$

b. $T^{Old}_{E} = T^{(0)}_{E,m,k}$

c. $$T^{(0)}_{E,m,k} = \overline{T}^{(0)}_{c,m,k} + \frac{1}{2\pi\ R_E\ h^{(0)}_{c,m,k}} \left[Q^{(0)}_{f,m,k}\ A_f + Q^{(0)}_{e,m,k}\ A_e \right]$$

d. if $/T^{(0)}_{E,m,k} - T^{Old}_{E}\ /> \varepsilon_T$

then continue the iteration

if $/T^{(0)}_{E,m,k} - T^{Old}_{E}\ /\leq \varepsilon_T$

recalculate $h^{(0)}_{c,m,k}$ and continue loop on m.

e. $$T^{(0)}_{a,m,k} = T^{(0)}_{E,m,k} + \frac{\ell n\left(\frac{R_E}{R_a}\right)}{2\pi\ K_e} \left[Q^{(0)}_{f,m,k}\ A_f + Q^{(0)}_{e,m,k}\ A_e \right]$$

f. $\overline{T}^{(0)}_{e,m,k} = T^{(0)}_{a,m,k}$

Go to B.10

10. Obtain first set of Fuel Temperature values

for $1 \leq m \leq M$

a. $C^{(0)}_{g,m,k} = h_f$ F**

$C^{Old}_{g,m,k} = (C^{(0)}_{g,m,k})\ w_f$

b. Check δ_c

if $\delta_c = 0$, go to B.10.d (Clad, coolant, structure, etc. are lumped)

if $\delta_c \neq 0$, go to B.10.c (Clad, coolant, structure, etc. not lumped)

c. Clad, coolant, structure, etc. not lumped ($\delta_c \neq 0$) for $1 \leq m \leq M$ and the subscript N referring to the fuel boundary node (i.e., n = N)

$$T^{(0)}_{e,m,k} = T^{(0)}_{a,m,k} + \frac{\ell n \frac{R_a}{R_e}}{2\pi K_e} \left[Q^{(0)}_{f,m,k} A_f \right]$$

$$T^{(0)}_{f,m,k} = T^{(0)}_{e,m,k} + (Q^{(0)}_{f,m,k} A_f) \frac{1}{\pi (R_f + R_e) C^{(o)}_{g,m,k}}$$

if $\delta_k > 0$, go to (2): otherwise continue.

if $T^{(0)}_{f,m,k} \geq T^{Melt}_f$ then

(1) $K^{(0)}_{N,m,k} = K^{Melt}_f \left[1 + B_K (T^{(0)}_{f,m,k} - T^{Melt}_f) + C_K (T^{(0)}_{f,m,k} - T^{Melt}_f)^2 \right]$ F ***

if $T^{(0)}_{f,m,k} < T^{Melt}_f$ then

$$K_{N,m,k} = \left[K^{(0)} + K^{(1)} T^{(0)}_{f,m,k} + K^{(2)} (T^{(0)}_{f,m,k})^2 \right] \text{ F ***}$$

Go to (3)

(2) $K^{(0)}_{N,m,k} = f (K'_f, T'_f, T^{(0)}_{f,m,k})$

(3) $T^{(0)}_{N,m,k} = T^{(0)}_{f,m,k} + \frac{\ell n \left(\frac{R_f}{r_N} \right)}{2\pi K^{(0)}_{N,m,k}} \left[Q^{(0)}_{f,m,k} A_f \right]$

Go to B.10.e

d. Clad, coolant, structure, etc. lumped ($\delta_c = 0$)
for $1 \leq m \leq M$ and the subscript N refering to the fuel boundary node (i.e., n = N)

$$(1)\quad T^{(0)}_{f,m,k} = \overline{T}^{(0)}_{c,m,k} + \left(Q^{(0)}_{f,m,k} A_f \right) \left\{ \frac{Q^{(0)}_{f,m,k} A_f + Q^{(0)}_{e,m,k} A_e}{Q^{(0)}_{f,m,k} A_f} \left[\frac{\ell n \frac{R_E}{R_e}}{2\pi K_e} + \frac{1}{h^{*(0)}_{c,m,k} 2\pi R_E} \right] + \frac{1}{\pi (R_e + R_f) C^{(o)}_{g,m,k}} \right\}$$

if $\delta_k > 0$, go to (2); otherwise continue

if $T^{(0)}_{f,m,k} < T^{Melt}_f$ then

$$K_{N,m,k} = \left[K^{(0)} + K^{(1)} T^{(0)}_{f,m,k} + K^{(2)} (T^{(0)}_{f,m,k})^2 \right] \quad F^{***}$$

if $T^{(0)}_{f,m,k} \geq T^{Melt}_f$ then

$$K_{N,m,k} = K^{Melt}_f \left[1 + B_K (T^{(0)}_{f,m,k} - T^{Melt}_f) + C_K (T^{(0)}_{f,m,k} - T^{Melt}_f)^2 \right] F^{***}$$

Go to (3)

$$(2)\quad K^{(0)}_{N,m,k} = f\ (K'_f,\ T'_f,\ T^{(0)}_{f,m,k})$$

$$(3)\quad T^{(0)}_{N,m,k} = T^{(0)}_{f,m,k} + \frac{\ell n \frac{R_f}{r_N}}{2\pi K^{(0)}_{N,m,k}} \left(Q^{(0)}_{f,m,k} A_f \right)$$

e. for $1 \leq m \leq M$ and $n = N$

if $\delta_k > 0$, go to (2); otherwise continue

(1) if $T^{(0)}_{N,m,k} < T^{Melt}_f$

$$K^{(0)}_{N-1,m,k} = \left[K^{(0)} + K^{(1)} T^{(0)}_{N,m,k} + K^{(2)} \left(T^{(0)}_{N,m,k} \right)^2 \right] F^{***}$$

Go to B.10.f

(2) if $T^{(0)}_{N,m,k} \geq T^{Melt}_{f}$

$$K^{(0)}_{N-1,m,k} = K^{Melt}_{f} \left[1 + B_k (T^{(0)}_{N,m,k} - T^{Melt}_{f}) + C_k (T^{(0)}_{N,m,k} - T^{Melt}_{f})^2 \right] \quad F^{***}$$

Go to B.10.f

(3) $K^{(0)}_{N-1,m,k} = f\ (K'_f,\ T'_f,\ T^{(0)}_{N,m,k})$

f. Fuel Temperature and Conductivity for nodes $1 \leq n \leq N$

If N = 1 go to B.10.g

If N > 1 then

for $1 \leq m \leq M$ and
for J = 1, N - 1
set n = N - J (i.e., n = N-1, N-2, ... 1)

$$T^{(0)}_{n,m,k} = T^{(0)}_{n-1,m,k} + \left(\sum_{\ell=1}^{n} A_\ell \, Q^{(0)}_{\ell,m,k} \right) \left(\frac{(LN)_n}{2\pi \, K^{(0)}_{n,m,k}} \right)$$

if $\delta_k > 0$, go to (3), otherwise continue.

(1) if $T^{(0)}_{n,m,k} < T^{Melt}_{f}$ then

$$K^{(0)}_{n-1,m,k} = \left[K^{(0)} + K^{(1)} T^{(0)}_{n,m,k} + K^{2)} (T^{(0)}_{n,m,k})^2 \right] \quad F^{***}$$

Go to B.10.g

(2) if $T^{(0)}_{n,m,k} \geq T^{Melt}_{f}$ then

$$K^{(0)}_{n-1,m,k} = K^{Melt}_{f} \left[1 + B_k (T^{(0)}_{n,m,k} - T^{Melt}_{f}) + C_k (T^{(0)}_{n,m,k} - T^{Melt}_{f})^2 \right] F^{***}$$

Go to B.10.g

(3) $K^{(0)}_{n-1,m,k} = f\ (K'_f,\ T'_f,\ T^{(0)}_{n,m,k})$

g. Fuel Temperature and Conductivity at Center

(1) If $\delta_k > 0$ $K^0_{0,m,k} = \neq (K'_f, T'_f\ T^0_{1,m,k})$

Go to h

(2) If $T^0_{1,m,k} < T^{MELT}_f$

$$K^0_{0,m,k} = K^{(0)} + K^{(1)}\ T^{(0)}_{1,m,k} + K^{(2)}\ (T^{(0)}_{1,m,k})^2$$

Go to h

(3) If $T^0_{1,m,k} \geq T^{MELT}_f$

$$K^0_{0,m,k} = K^{MELT}_f [1 + B_k\ (T^{(0)}_{1,m,k} - T^{MELT}_f) + C_k\ (T^{(0)}_{1,m,k} - T^{MELT}_f)^2] \ *(F***)$$

h. Fuel Center Temperature

(1) If $R_o \neq 0$ $X = r_1^2 - R_o^2 - 2R_o^2\ \ell n \frac{r_1}{R_o}$

(2) If $R_o = 0$ $X = r_1^2$

$$T^0_{0,m,k} = T^0_{1,m,k} + \frac{Q^{(0)}_{1,m,k}}{4K^{(0)}_{0,m,k}}\ (X)$$

i. Average Fuel Temperature

$$\overline{T}^{(0)}_{f,m,k} = \frac{\sum_{n=1}^{N} T^{(0)}_{n,m,k}\ A_n}{A_f}$$

11. Steady-State Temperatures (Start of iteration)

for $1 \geq m \leq M$

Iterate for Steady-State Temperatures (converge one section (i.e., m = 1) before proceeding to the next.

a. Fuel-clad gap conductivity

If $\delta_{gap} \neq 0$ go to b

If $\delta_{gap} = 0$ then

$$C^{(0)}_{g,m,k} = h_f \, F^{**}$$

$$C^{Old(0)}_{g,m,k} = C^{(0)}_{g,m,k} \quad w_f$$

Go to d

b. Melting Indicator

for $1 \leq n \leq N$

If $T^{(0)}_{n,m,k} \geq T^{Melt}_f$, then $\delta^{(0)}_{n,m,k} = 1$

If $T^{(0)}_{n,m,k} < T^{Melt}_f$, then $\delta^{(0)}_{n,m,k} = 0$

Go to c

c. $\delta_{gap} = 0$

If $R_o \neq 0$, go to c.1

If $R_o = 0$, go to c.2

(1) $R_o \neq 0$:

$$\text{If } \Delta V^{MELT} \sum_{n=1}^{N} \delta^{Melt(0)}_{n,m,k} \, A_n \leq \pi \, R_o^2$$

$$\Delta\phi^{(0)}_{m,k} = (R_e - R_f)^{Cold} + R_e\left(\frac{\Delta L}{L}\right)^{0}_{e,m,k} - R_f \left(\frac{\Delta L}{L}\right)^{(0)}_{f,m,k}$$

Go to c.3

If $\Delta V^{Melt} \sum_{n=1}^{N} \delta_{n,m,k}^{Melt(0)} A_n > \Pi R_o^2$

$$\Delta\phi_{m,k}^{(0)} = (R_e - R_f)^{Cold} + R_e\left(\frac{\Delta L}{L}\right)_{e,m,k}^{(0)} - R_f\left(\frac{\Delta L}{L}\right)_{f,m,k}^{(0)}$$

$$-\left[\frac{\Delta V^{Melt} R_f}{2} - \frac{(\Delta V^{Melt} + 1)R_0^2}{2 R_f}\right] \frac{1}{A_f} \sum_{n=1}^{N} \delta_{n,m,k}^{(0)} A_n$$

Go to c.3

(2) $\Delta\phi_{m,k}^{(0)} = (R_e - R_f)^{Cold} + \bar{\alpha}_e R_e (\bar{T}_{e,m,k}^{(0)} - 70) - \bar{\alpha}_f R_f (\bar{T}_{f,m}^{(0)} - 70) - \left(\frac{R_f}{2}\right)(\Delta V^{Melt})\left(\frac{1}{A_f}\right)$

$$\left(\sum_{n=1}^{N} \delta_{n,m,k}^{(0)} A_n\right)$$

(3) if $\Delta\phi_{m,k}^{(0)} > 0.0$ then

$P_{m,k}^{(0)} = 0.0$

if $\Delta\phi_{m,k}^{(0)} \leq 0.0$ then

$$P_{m,k}^{(0)} = -\frac{\Delta\phi_{m,k}^{(0)} E_e (R_E - R_e) (144.0)}{R_e^2}$$

If $P_{m,k}^{(0)} > P_{Max}$, then $P_{m,k}^{(0)} = P_{Max}$ (where $P_{Max} = \frac{\sigma_{Y.P.} (R_E - R_e) (144)}{R_e}$)

$$K_{m,k}^{(0)} = \frac{2(K_{N,m,k}^{(0)})(K_e)}{K_{N,m,k}^{(0)} + K_e}$$

if $\Delta\phi_{m,k}^{(0)} > 0.0$ then

$\delta_{g,m,k}^{(0)} = \Delta\phi_{m,k}^{(0)} + \beta_o (\delta_f + \delta_e)$

if $\Delta\phi_{m,k}^{(0)} \leq 0.0$ then

$\delta_{g,m,k}^{(0)} = \beta_o (\delta_f + \delta_e)$

if $\delta_c = 0$ then

$$K^{(0)}_{g,m,k} = A_g + B_g \left(\frac{\overline{T}^{(0)}_{e,m,k} + T^{(0)}_{f,m,k}}{2} \right) + C_g \left(\frac{\overline{T}^{(0)}_{e,m,k} + T^{(0)}_{f,m,k}}{2} \right)^2$$

if $\delta_c \neq 0$ then

$$K^{(0)}_{g,m,k} = A_g + B_g \left(\frac{T^{(0)}_{e,m,k} + T^{(0)}_{f,m,k}}{2} \right) + C_g \left(\frac{T^{(0)}_{e,m,k} + T^{(0)}_{f,m,k}}{2} \right)^2$$

$$C^{Calc.(0)}_{g,m,k} = \left[\frac{K^{(0)}_{m,k}}{a_o} \frac{P^{(0)}_{m,k}}{\sqrt{\delta}\ \psi} + \frac{K^{(0)}_{g,m,k}}{\delta^{(0)}_{g,m,k} + (g_f + g_e)} \right] \quad F^{**}$$

$$C^{wt(0)}_{g,m,k} = C^{Old}_{g,m,k} + (1.0 - w_f)\ C^{Calc(0)}_{g,m,k})$$

$$C^{Old(0)}_{g,m,k} = C^{wt(0)}_{g,m,k}\ w_f$$

d. Fuel Node temperatures and conductivities

for n = N

if $\frac{T^{(0)}_{f,m,k}}{2} + T^{(0)}_{N,m,k} < T^{Melt}_f$ then

$$K^{(0)}_{N,m,k} = \left[K^{(0)} + K^{(1)} \left(\frac{T^{(0)}_{f,m,k} + T^{(0)}_{N,m,k}}{2} \right) + K^{(2)} \left(\frac{T^{(0)}_{f,m,k} + T^{(0)}_{N,m,k}}{2} \right)^2 \right] F^{***}$$

if $\frac{T^{(0)}_{f,m,k} + T^{(0)}_{N,m,k}}{2} \geq T^{Melt}_{f}$ then

$$K^{(0)}_{N,m,k} = K^{Melt}_{f} \left[1 + B_k \left(\frac{T^{(0)}_{f,m,k} + T^{(0)}_{N,m,k}}{2} - T^{Melt}_{f} \right) + C_K \left(\frac{T^{(0)}_{f,m,k} + T^{(0)}_{N,m,k}}{2} - T^{Melt}_{f} \right)^2 \right] F^{***}$$

e. Temperature for N^{th} fuel node and fuel boundary

If $\delta_c \neq 0$ go to B.11.f

If $\delta_c = 0$ then for n = N

$$T^{Old}_{N} = T^{(0)}_{N,m,k}$$

$$T^{(0)}_{f,m,k} = \overline{T}^{(0)}_{c,m,k} + (Q^{(0)}_{f,m,k} A_f) \left(\frac{Q^{(0)}_{e,m,k} A_e + Q^{(0)}_{f,m,k} A_f}{Q^{(0)}_{f,m,k} A_f} \right) \left[\frac{\ell n \left(\frac{R_E}{R_e} \right)}{2\pi K_e} + \frac{1}{h^{*(0)}_{c,m,k} 2\pi R_E} \right] + \frac{1}{\pi (R_f + R_e) C^{wt(0)}_{g,m,k}}$$

$$T^{(0)}_{N,m,k} = T^{(0)}_{f,m,k} + \frac{\ell n \frac{R_f}{r_N}}{2\pi K^{(0)}_{N,m,k}} \left(Q^{(0)}_{f,m,k} A_f \right)$$

Go to B.11.g

f. $\delta_c \neq 0$ and n = N

$$T_N^{Old} = T_{N,m,k}^{(0)}$$

$$T_{f,m,k}^{(0)} = T_{e,m,k}^{(0)} + \frac{1}{\pi(R_f + R_e)\, C_{g,m,k}^{wt(0)}} \left(Q_{f,m,k}^{(0)}\ A_f\right)$$

$$T_{N,m,k}^{(0)} = T_{f,m,k}^{(0)} + \frac{\ln\left(\frac{R_f}{r_N}\right)}{2\pi\, K_{N,m,k}^{(0)}} \left[Q_{f,m,k}^{(0)}\ A_f \right]$$

g. Temperature for remaining fuel nodes N-1 to 1

if N = 1 go to B.11.g.2.

if N > 1 then

for J = 1, N - 1

set n = N - J (i.e., n = N-1, N-2, . . . 1)

$$T_n^{Old} = T_{n,m,k}^{(0)}$$

$$\text{if } \frac{T_{n+1,m,k}^{(0)} + T_{n,m,k}^{(0)}}{2} \geq T_f^{Melt} \text{ then}$$

$$K_{n,m,k}^{(0)} = K_f^{Melt} \left[1 + B_k \left(\frac{T_{n+1,m,k}^{(0)} + T_{n,m,k}^{(0)}}{2} - T_f^{Melt} \right) + C_k \left(\frac{T_{n+1,m,k}^{(0)} + T_{n,m,k}^{(0)}}{2} - T_f^{Melt} \right)^2 \right] F^{***}$$

$$\text{if } \frac{T_{n+1,m,k}^{(0)} + T_{n,m,k}^{(0)}}{2} < T_f^{Melt} \text{ then}$$

$$\overline{K}^{(0)}_{n,m,k} = K^{(0)} + K^{(1)}\left(\frac{T^{(0)}_{n+1,m,k} + T^{(0)}_{n,m,k}}{2}\right) + K^{(2)}\left(\frac{T^{(0)}_{n+1,m,k} + T^{(0)}_{n,m,k}}{2}\right)^2 \Bigg] F^{***}$$

$$T^{(0)}_{n,m,k} = T^{(0)}_{n+1,m,k} + \left(\sum_{\ell=1}^{n} A_\ell \, Q^{(0)}_{\ell,m,k}\right) \frac{(LN)_n}{2\pi \, K^{(0)}_{n,m,k}}$$

g.2 Temperature for center

$$T^{Old}_0 = T^0_{0,m,k}$$

$$K^0_{0,m,k} = f\left[K^1_f, T^1_f, \left(T^0_{1,m,k} + T^0_{0,m,k}\right)\Big/2\right]$$

if $R_o \neq 0$ $\quad \chi = r_1^2 - R_o^2 - 2R_o^2 \ln \frac{r_1}{R_o}$

if $R_o = 0$ $\quad \chi = r_1^2$

$$T^0_{0,m,k} = T^0_{1,m,k} + \frac{Q^{(0)}_{1,m,k}}{4\, K^0_{0,m,k}} \chi$$

h. Clad-surface heat flux

if $\delta_c \neq 0$ then

$$Q^{(0)}_{h,m,k} = h^{(0)}_{c,m,k}\left(T^{(0)}_{E,m,k} - \overline{T}^{(0)}_{c,m,k}\right)$$

if $\delta_c = 0$ then

$$Q^{(0)}_{h,m,k} = \left(T^{(0)}_{f,m} - \overline{T}^{(0)}_{c,m,k}\right) \frac{1}{\frac{Q^{(0)}_{f,m,k} A_f}{Q^{(0)}_{f,m,k} A_f + Q^{(0)}_{e,m,k} A_e}\left(\frac{2R_E}{C^{(j-1)}_{g,m,k}(R_f + R_e)}\right) + \left[\frac{R_E \ln \frac{R_E}{R_e}}{k_e} + \frac{1}{h^{*(j-1)}_{c,m,k}}\right]}$$

i. Average fuel temperature

$$\bar{T}^{(0)}_{f,m,k} = \frac{\sum_{n=1}^{N} T^{(0)}_{n,m,k} \; A_n}{A_f}$$

j. End of iterative loop. Check for convergence

If for $0 \leq n \leq N$

$$/T^{Old}_n - T^{(0)}_{n,m,k}/ \leq \varepsilon_T$$

then continue loop on m. When m = M go to B.11.l

If for $0 \leq n \leq N$

$$/T^{Old}_n - T^{(0)}_{n,m,k}/ > \varepsilon_T$$

return to B.11.a and continue the iteration.

k. End of loop on k

12. If K = 3 then set $K_e = K_e/F_e$

Go to C.

C. Equivalent Temperatures

1. Fuel nodes

for $0 \leq n \leq$ ', $1 \leq m \leq M$ and $1 \leq k \leq 2$

If $T^{(0)}_{n,m,k} < T^{Melt}_f$ then $E^{(0)}_{n,m,k} = T^{(0)}_{n,m,k}$

If $T^{(0)}_{n,m,k} \geq T^{Melt}_f$ then $E^{(0)}_{n,m,k} = \frac{E^{Melt}}{\rho C^{Melt}_f} + T^{(0)}_{n,m,k}$

2. Fuel boundary

$$\text{for } 1 \leq m \leq M$$

$$E^{(0)}_{f,m,k} = E^{(0)}_{N,m,k} - \frac{\ell n \frac{R_f}{r_N}}{2\pi K^{(0)}_{N,m,k}} \left[O^{(0)}_{f,m,k} \quad A_f \right]$$

D. Feedback Temperatures

$$\text{for } 1 \leq n \leq N \text{ and } 1 \leq \ell \leq L$$

1. $$H^{(0)}_{n,m,\ell} = T^{(0)}_{n,m,k=2} - W_\ell (T^{(0)}_{n,m,k=2} - T^{(0)}_{n,m,k=1}) + 460$$

$$\text{for } 1 \leq \ell \leq L$$

2. $$T^{*(0)}_{m,\ell} = \frac{\sum_{n=1}^{N} H^{(0)}_{n,m,\ell} \; A_n}{A_f}$$

$$T^{DOP(0)}_{m,\ell} = T^{*(0)}_{m,\ell} \left[1 - C_D \left(\frac{T^{*(0)}_{m,\ell} - H^{(0)}_{N,m,\ell}}{T^{*(0)}_{m,\ell}} \right)^2 \right]$$

3. Average temperature of the core

if B_{Bot} and B_{Top} = 0, go to D.3.a

if δ_{Ave} > 0, go to D.3.a

otherwise set mb = B_{Bot} + 1

and MT = M - B_{Top}

Go to D.3.b to calculate average temperature of core only.

a. Set mb = 1

MT = M

b. $$\bar{T}^{(o)}_{Core} = \sum_{m=mb}^{MT} \sum_{\ell=1}^{L} T^{*(0)}_{m,\ell} \, (\Delta z)_m \Big/ \left(L \sum_{m=mb}^{MT} (\Delta z)_m \right)$$

4. Temperature Drops

a. Radial

$$(\Delta T)^{(0)}_{B,m} = \frac{2D_B}{R_T \left(1 - \sqrt{\frac{L-2}{L}}\right)} \left(T^{*(0)}_{m,L} - T^{*(0)}_{m,L-1}\right)$$

b. Average

$$(\bar{\Delta T})^{(0)}_{B} = \frac{\sum_{m=1}^{M} (\Delta T)^{(0)}_{B,m} \, (\Delta z)_m}{H_T}$$

E. Specific Heat

for $0 \leq n \leq N$, $1 \leq m \leq M$, and $1 \leq k \leq K$

if $T^{(0)}_{n,m,k} < T^{Melt}_{f}$

$$C^{(0)}_{n,m,k} = f\left(C'_f, T'_f, T^{(0)}_{n,m,k}\right)$$

if $T^{(0)}_{n,m,k} \geq T^{Melt}_{f}$ then

$$C^{(0)}_{n,m,k} = C^{Melt}$$

F. Average Coolant temperature in the three channel types; clad and fuel coefficients of expansion

1. for $1 \leq k \leq K$

$$\overline{T}^{(0)}_{c,k} = \frac{\sum_{m=1}^{M} \overline{T}^{(0)}_{c,m,k} \quad (\Delta Z)_m}{\sum_{m=1}^{M} (\Delta Z)_m}$$

2. for $1 \leq k \leq K$
for $1 \leq m \leq M$

Find fractional linear thermal expansion of the clad and fuel

$$\left(\frac{\Delta L}{L}\right)^{(0)}_{e,m,k} = E^{(0)}_e + E^{(1)}_e \overline{T}^{(0)}_{e,m,k} + E^{(2)}_e \left(\overline{T}^{(0)}_{e,m,k}\right)^2$$

$$\left(\frac{\Delta L}{L}\right)^{(0)}_{f,m,k} = E^{(0)}_f + E^{(1)}_f \overline{T}^{(0)}_{f,m,k} + E^{(2)}_f \left(\overline{T}^{(0)}_{f,m,k}\right)^2$$

if $\delta_H = 1$, go to H.

G. Orificing Coefficient

1. $COMP = \left(\frac{64}{C}\right)^{\frac{1}{1-e}}$

2. Coolant viscosity

Evaluate using linear interpolation:

$1 \leq k \leq K$

$$\mu^{(j)}_{c,k} = f\left(\mu'_c, \overline{T}'^{(0)}_{c,k}\right)$$

where μ'_c and T'_c are built in fits

3. $$N^{(0)}_{R,k=1} = \frac{D_H \, G^{(0)}_{c,k=1}}{\mu^{(0)}_{c,k=1}}$$

4. $N^{(0)}_{R,k=2} = \dfrac{F_r \; G^{(0)}_{c,k=1} \; D_H}{\mu_{c,k=2}}$

5. By linear interpolation

$$\rho^{(0)}_{c,k} = f\,(\rho'_c,\ T'_c\ \bar{T}^{(0)}_{c,k}) \qquad \text{for } 1 \le k \le K$$

$$\rho^{inlet(0)}_{c} = f\,(\rho'_c,\ T'_c,\ T^{inlet(0)}_{c})$$

6. If $N_{R,k=2} \le COMP$, then

$$(2g)\ \Delta P = \frac{\dfrac{64}{N^{(0)}_{r,k=2}}\ \dfrac{Z_t}{D_H}\ \left(\dfrac{F_r\ G^{(0)}_{c,k=1}}{\rho^{(0)}_{c,k=2}}\right)^2 + B_{OR,k=2}\ \left(\dfrac{F_r\ G^{(0)}_{c,k=1}}{\rho^{inlet(0)}_{c}}\right)^2}{}$$

go to 7

7. If $N^{(0)}_{R,k=2} > COMP$, then

$$(2g)\ \Delta P = \frac{C}{(N^{(0)}_{R,k=2})^e}\ \frac{Z_t}{D_H}\ \left(\frac{F_r\ G^{(0)}_{c,k=1}}{\rho^{(0)}_{c,k=2}}\right)^2 + B_{OR,k=2}\ \left(\frac{F_r\ G^{(0)}_{c,k=1}}{\rho^{inlet(0)}_{c}}\right)^2$$

8. If $N_{R,k=1} \le COMP$ then

$$B_{OR,k=1} = \frac{(2g)\ \Delta P\ \rho^{inlet(0)}_{c}}{(G^{(0)}_{c,k=1})^2} - \frac{64}{N^{(0)}_{R,k=1}}\ \frac{Z_T}{D_H}\ \frac{\rho^{inlet(0)}_{c}}{\rho^{(0)}_{c,k=1}}$$

go to 10.

9. If $N^{(0)}_{R,k=1} > COMP$ then

$$B_{OR,k=1} \quad \frac{(2g)\ \Delta P\ \rho^{inlet(0)}_{c}}{(G^{(0)}_{c,k=1})^2} - \frac{C}{(N^{(0)}_{R,k=1})^e}\ \frac{Z_T}{D_H}\ \frac{\rho^{inlet(0)}_{c}}{\rho^{(0)}_{c,k=1}}$$

10. If $\delta_H = 2$ go to I

    If $\delta_H = 3$ go to G.11

11. $$N^{(0)}_{R,k=3} = \frac{F_v \; G^{(0)}_{c,k=1} \; D_H}{\mu_{c,k=3}}$$

12. If $N^{(0)}_{R,k=3} \leq COMP$

$$B_{OR,k=3} = \frac{(2g)\ \Delta P\ \rho_c^{inlet(0)}}{(F_v\ G^{(0)}_{c,k=1})^2} - \frac{64}{N^{(0)}_{R.k=3}} \frac{Z_t}{D_H} \frac{\rho_c^{inlet(0)}}{\rho^{(0)}_{c,k=3}}$$

go to H

13. If $N^{(j)}_{R,k=3} > COMP$

$$B_{OR.k=3} = \frac{(2g)\ \Delta P\ \rho_c^{inlet(0)}}{(F_v\ G^{(0)}_{c,k=1})^2} - \frac{C}{(N^{(0)}_{R,k=3})^e} \frac{Z_T}{D_H} \frac{\rho_c^{inlet(0)}}{\rho^{(0)}_{c,k=3}}$$

H. Set up initial values needed to calculate energy removal from and energy addition to Core.

1. $$\overline{Q}^{(0)}_{\phi UT} = A_c\ \overline{\Psi}_c{}^{(0)}\ \overline{C}^{(0)}_c\ [\overline{T}_c{}^{(0)Outlet} - \overline{T}^{(0)Inlet}_c]$$

   where $\overline{\Psi}^{(0)}_c = \overline{\Psi}^{(0)}_{c,1}$

$$\overline{T}^{(0)Outlet}_c = T^{(0)Out}_{c,1}$$

$$\overline{T}^{(0)Inlet}_c = T^{(0)Inlet}_c$$

$$\overline{C}^{(0)}_c = f\left(\frac{\overline{T}^{(0)Inlet}_c + \overline{T}^{(0)Outlet}_c}{2}\right)$$

2. $E_{\phi UT}^{(0)} = 0.0$

3. $E_{IN}^{(0)} = 0.0$

4. $\Delta E_{CORE}^{(0)} = 0.0$

I. Delayed neutron precursor concentrations

$$P_o^* = \frac{P_o^0}{1 + \sum_{im=1}^{IM} \left[\frac{A_{im}}{\alpha_{im}} \left(a_{im}^{-\alpha_{im}} - (a_{im} + T_o)^{-\alpha_{im}} \right) \right]}$$

If $C_i \neq 0.0$ for i=1, I, go to J

If $C_i = 0.0$ for i=1, I, then

$$C_i^{(0)} = \frac{\nu \beta_i P_o^*}{\lambda_i}$$

J. End of INIT

SUBROUTINE FEEB

FUNCTION

This subroutine finds the programmed k at any time, t, from the set of input values for time and k, and computes the total k for each new time step. The various Δk feedbacks due to temperature changes are calculated: these include the Doppler, fuel bowing, radial and axial expansion of the core, and core density changes. The Δk feedbacks caused by sodium voiding and scram are found by searching an input table for each, if either or both are inputs.

PROCEDURE

A. Core Reactivity

If $\delta_{pwr} \neq 0$, go to B

If $\delta_{pwr} = 0$ and $i = 0$, to to A.1

If $\delta_{pwr} = 0$ and $j \neq 0$, go to A.2

1. Initialize the following:

$k_f^{(j)} = 0.0$

$k^{(j)} = k_{p,s=1}$

$k_p^{(j)} = k_{p,s=1}$

$k_f^{(j-1)} = k_f^{(j-2)} = k_f^{(j-3)} = 0.0$

$T_{init}^{scram} = 0.0$

$T_{init}^{void} = 0.0$

$(\Delta\kappa)_{scram} = 0.0$

$(\Delta\kappa)_{void} = 0.0$

Go to H.

2. Check Δk feedback due to scram.

(This is calculated here because it is included in the programmed reactivity equation - see A.3.a)

for $1 \leq k \leq K$

a. If $T_{c,k}^{(j-1)Out} \geq T_c^{scram}$, go to A.2.b

If $T_{c,k}^{(j-1)Out} < T_c^{scram}$

(1) If $\frac{P_j - P_o}{P_o} \geq \varepsilon_{scram}$, go to A.2.b

(2) If $\frac{P_j - P_o}{P_o} < \varepsilon_{scram}$, go to A.2.d

b. If $T_{init}^{scram} \neq 0.0$, $T^{scram} = T - T_{init}^{scram}$

Go to A.2.c

If $T_{init}^{scram} = 0.0$

(1) $T_{init}^{scram} = t$

(2) $T^{scram} = 0.0$

Go to A.2.c

c. $(\Delta k)_{scram}^{(j)} = \int (\Delta k'_{scram}, T'_{scram}, T^{scram})$

Go to A.3

d. $(\Delta k)_{scram}^{(j)} = 0.0$

3. Check indicator for feedback approximation· calculate programmed k and total k.

a. If $\delta_{est} = 0$:

(1) Programmed k

If j = 1, set $k_p^{(j-1)} = k^{(j-1)}$

$$k_p^{(j)} = k_{p,s} + \left(\frac{k_{p,s+1} - k_{p,s}}{t_{s+1} - t_s}\right)(t-t_s) + (\Delta k)_{scram}^{(j)}$$

where $t_s \leq t \leq t_{s+1}$

(2) Total k

$$k^{(j)} = \frac{k_p^{(j-1)} + k_p^{(j)}}{2} + k_f^{(j-1)}$$

Go to B

b. If $\delta_{est} \neq 0$·

(1) Programmed k

If j = 1, set $(\Delta k_f)_{est} = 0$

If j = 2, set $(\Delta k_f)_{est} = \frac{\tau^{(j)}\, k_f^{(j-1)}}{\tau^{(j-1)}}$

If $j \geq 3$

$$(\Delta k_f)_{est}^{(j)} = \tau^{(j)} \left[\frac{k_f^{(j-1)} - k_f^{(j-2)}}{\tau^{(j-1)}} + \left(\frac{\tau^{(j)} + \tau^{(j-1)}}{\tau^{(j-1)} + \tau^{(j-2)}}\right)\left(\frac{k_f^{(j-1)} - k_f^{(j-2)}}{\tau^{(j-1)}} - \frac{k_f^{(j-2)} - k_f^{(j-3)}}{\tau^{(j-2)}}\right)\right]$$

$$k_p^{(j)} = k_{p,s} + \left(\frac{k_{p,s+1} - k_{p,s}}{t_{s+1} - t_s}\right)(t - t_s) + (\Delta k)_{scram}^{(j)}$$

(2) Total reactivity

$$k^{(j)} = \frac{k_p^{(j-1)} + k_p^{(j)}}{2} + k_f^{(j-1)} + \frac{1}{2}(\Delta k_f)_{est}^{(j)}$$

B. Doppler Effect

For $1 \leq m \leq M$, $1 \leq n \leq N$

1. Doppler Temperatures

$$G_{n.m,k}^{(j-1)} = T_{n,m,k}^{(o)} + E_{n,m,k}^{(j-1)} - E_{n,m,k}^{(o)} \qquad 1 \leq k \leq 2$$

For $1 \leq \ell \leq L$

$$F_{n,m,\ell}^{(j-1)} = G_{n,m,k=2}^{(j-1)} - W_\ell \left(G_{n,m,k=2}^{(j-1)} - G_{n,m,k=1}^{(j-1)}\right) + 460$$

If $H_{n,m,\ell}^{(o)} \geq T_f^{Melt} + 460$

$$F_{n,m,\ell}^{(j-1)} = F_{n,m,\ell}^{(j-1)} + \frac{B^{Melt}}{\rho_f C_{n,m,k=1}^{(j-1)}}$$

If $H_{n,m,\ell}^{(o)} < T_f^{Melt} + 460$

$$F_{n,m,\ell}^{(j-1)} = F_{n,m,\ell}^{(j-1)}$$

If $F_{n,m,\ell}^{(j-1)} < T_f^{Melt} + 460$

$$T_{n,m,\ell}^{*(j-1)} = F_{n,m,\ell}^{(j-1)}$$

If $F_{n,m,\ell}^{(j-1)} \geq T_f^{Melt} + 460$

$$\text{If } F^{(j-1)}_{n,m,\ell} \geq T^{Melt}_{f} + 460 + \frac{B^{Melt}}{\rho_f \, C^{(j)}_{n,m,k=1}}$$

Then

$$T^{*(j-1)}_{n,m,\ell} = F^{(j-1)}_{n,m,\ell} - \frac{B^{Melt}}{\rho_f \, C^{(j-1)}_{n,m,k=1}}$$

$$\text{If } F^{(j-1)}_{n,m,\ell} < T^{Melt}_{f} + 460 + \frac{B^{Melt}}{\rho_f \, C^{(j-1)}_{n,m,k=1}}$$

$$T^{*(j-1)}_{n,m,\ell} = T^{Melt}_{f} + 460$$

$$\overline{T}^{*(j-1)}_{m,\ell} = \frac{\sum_{n=1}^{N} T^{*(j-1)}_{n,m,\ell} \; A_n}{A_f}$$

If $\delta_{pwr} \neq 0$. go to 3b then F.

$$T^{Dop(j-1)}_{m,\ell} = \overline{T}^{*(j-1)}_{m,\ell} \left[1 - C_D \left(\frac{\overline{T}^{*(j-1)}_{m,\ell} - T^{*(j-1)}_{N,m,\ell}}{\overline{T}^{*(j-1)}_{m,\ell}} \right)^2 \right]$$

$$(\Delta k_{Dop})^{(j-1)}_{m,\ell} = A_{Dop} \ln \left(\frac{T^{Dop(j-1)}_{m,\ell}}{T^{Dop(o)}_{m,\ell}} \right) + \frac{B_{Dop}}{b+1} \left[(T^{Dop(j-1)}_{m,\ell})^{b+1} - (T^{Dop(o)}_{m,\ell})^{b+1} \right]$$

2. Total Doppler Δk

$$(\Delta k)^{(j-1)}_{Dop} = \frac{\sum_{m=1}^{M} \sum_{\ell=1}^{L} (\Delta k_{Dop})^{(j-1)}_{m,\ell} \; p^2_{\ell} \; A^2_m \; (\Delta Z)_m}{\sum_{m=1}^{M} \sum_{\ell=1}^{L} p^2_{\ell} \; A^2_m \; (\Delta Z)_m}$$

3. Average temperature of the core

If B_{Bot} and $B_{Top} = 0$, go to a.

If $\delta_{Ave} > 0$, go to a.

Otherwise set $mb = B_{Bot} + 1$ and $MT = M - B_{Top}$

Go to b and calculate average temperature of core only.

a. Set $mb = 1$

and $MT = M$

b. $$\bar{T}^{(j-1)}_{Core} = \frac{\sum_{m=mb}^{MT} \sum_{\ell=1}^{L} \bar{T}^{*(j-1)}_{m,\ell} (\Delta Z)_m}{L \sum_{m=mb}^{MT} (\Delta Z)_m}$$

4. Doppler Weighting Factor

$$(\bar{\Delta k})^{(j-1)}_{Dop} = A_{Dop} \ln \left(\frac{\bar{T}^{(j-1)}_{Core}}{\bar{T}^{(o)}_{Core}}\right) + \frac{B_{Dop}}{b+1} \left[(\bar{T}^{(j-1)}_{Core})^{b+1} - (\bar{T}^{(o)}_{Core})^{b+1} \right]$$

$$\xi = \frac{(\Delta K)^{(j-1)}_{Dop}}{(\overline{\Delta K})^{(j-1)}_{Dop}}$$

Go to C.

C. Bowing

1. Check for fuel bowing

If $\delta_{bow} = 0$

$$\left(\frac{\Delta R_T}{R_T}\right)^{(j-1)}_{B,m} = 0 \text{ for } 1 \leq m \leq M$$

Go to D

If $\delta_{bow} \neq 0$

$$(\Delta T)_{B,m}^{(i-1)} = \frac{2D_B}{R_T\left(1 - \sqrt{\frac{L-2}{L}}\right)} \left(\bar{T}_{m,L}^{*(j-1)} - \bar{T}_{m,L-1}^{*(j-1)}\right) \quad 1 \leq m \leq M$$

$$(\bar{\Delta T})_B^{(i-1)} = \frac{\sum_{m=1}^{M} (\Delta T)_{B,m}^{(i-1)} (\Delta Z)_m}{H_T}$$

2. Change in Core Radius as a function of type of bowing

a. Centilivered at inlets, pinned at exit ($\delta_{bow} = 1$)

$$\left(\frac{\Delta R_T}{R_T}\right)_{B,m}^{(j-1)} = \frac{-\alpha_s'' X_m^2}{4D_B R_T} \left(1 - \frac{X_m}{H^*}\right) \left[(\bar{\Delta T})_B^{(j-1)} - (\bar{\Delta T})_B^{(o)}\right] \quad 1 \leq m \leq M$$

b. Simply supported at both ends ($\delta_{bow} = 2$)

$$\left(\frac{\Delta R_T}{R_T}\right)_{B,m}^{(j-1)} = \frac{\alpha_s''}{2D_B R_T} (X_m^2 - X_m H^*) \left[(\bar{\Delta T})_B^{(j-1)} - (\bar{\Delta T})_B^{(o)}\right] \quad 1 \leq m \leq M$$

c. Centilivered at exit, pinned at inlet ($\delta_{bow} = 3$)

$$\left(\frac{\Delta R_T}{R_T}\right)_{B,m}^{(j-1)} = \frac{\alpha_s''}{4D_B R_T} \left(2X_m^2 - \frac{X_m^3}{H^*} - H^* X_m\right) \left[(\bar{\Delta T})_B^{(j-1)} - (\bar{\Delta T})_B^{(o)}\right] \quad 1 \leq m \leq M$$

d. Centilivered at exit, free at inlet ($\delta_{bow} = 4$)

$$\left(\frac{\Delta R_T}{R_T}\right)_{B,m}^{(j-1)} = \frac{\alpha_s''}{2D_B \quad R_T}\left(X_m^2 - 2X_m H^* + H^{*2}\right)\left[\left(\overline{\Delta T}\right)_B^{(j-1)} - \left(\overline{\Delta T}\right)_B^{(o)}\right] \qquad 1 \le m \le M$$

e. Centilivered at inlet, free at exit ($\delta_{bow} = 5$)

$$\left(\frac{\Delta R_T}{R_T}\right)_{B,m}^{(j-1)} = \frac{\alpha_s''}{2D_B \quad R_T} X_m^2 \left[\left(\overline{\Delta T}\right)_B^{(j-1)} - \left(\overline{\Delta T}\right)_B^{(o)}\right] \quad 1 \le m \le M$$

D. Various Core Changes

for $1 \le m \le M$

1. Core Shape Change due to axial pressure differences across the core

$$\left(\frac{\Delta R_T}{R_T}\right)_{P,m}^{(j-1)} = \frac{X_m \quad \psi_o}{R_T}\left[\frac{G_{c,k=1}^{(j-1)^2}}{G_{c,k=1}^{(o)^2}}\right]$$

2. Thermal Expansion of the Core

$$\left(\frac{\Delta R_T}{R_T}\right)_{T,m}^{(j-1)} = \alpha_s' \left(T_{s,m,k=1}^{(j-1)} - T_{s,m,k=1}^{(o)}\right)$$

3. Total Core Radius Change

$$\left(\frac{\Delta R_T}{R_T}\right)_m^{(j-1)} = \left(\frac{\Delta R_T}{R_T}\right)_{B,m}^{(j-1)} + \left(\frac{\Delta R_T}{R_T}\right)_{P,m}^{(j-1)} + \left(\frac{\Delta R_T}{R_T}\right)_{T,m}^{(j-1)}$$

4. Core Height Change

$$\frac{\Delta H_T}{H_T}^{(j-1)} = \frac{\sum_{m=1}^{M}\left[\left(\frac{\Delta L}{L}\right)_{f,m,k=1}^{(j-1)} - \left(\frac{\Delta L}{L}\right)_{f,m,k=1}^{(0)}\right](\Delta Z)_m}{H_T}$$

E. Density Changes

for $1 \leq m \leq M$

1. $$\left(\frac{\overline{\Delta\rho}_{f,m}}{\overline{\rho}_{f,m}}\right)^{(j-1)} = - C_f \left\{ \left(\frac{\overline{\Delta L}}{L}\right)^{(j-1)}_{f,m,k=1} - \left(\frac{\overline{\Delta L}}{L}\right)^{(0)}_{f,m,k=1} \right\} + 2\alpha_s \left(\overline{T}^{(j-1)}_{s,m,k=1} - \overline{T}^{(o)}_{s,m,k=1}\right)$$

2. $$\left(\frac{\overline{\Delta\rho}_{e,m}}{\overline{\rho}_{e,m}}\right)^{(j-1)} = - \left(\frac{\overline{\Delta L}}{L}\right)^{j-1}_{e,m,k=1} - \left(\frac{\overline{\Delta L}}{L}\right)^{(0)}_{e,m,k=1} + 2\alpha_s \left(\overline{T}^{(j-1)}_{s,m,k=1} - \overline{T}^{(o)}_{s,m,k=1}\right)$$

3. If $$\left(\frac{\overline{\Delta L}}{L}\right)^{(j-1)}_{e,m,k=1} - \left(\frac{\overline{\Delta L}}{L}\right)^{(0)}_{e,m,k=1} \geq C_f \left[\left(\frac{\overline{\Delta L}}{L}\right)^{(j-1)}_{f,m,k=1} - \left(\frac{\overline{\Delta L}}{L}\right)^{(0)}_{f,m,k=1}\right]$$

then

$$\Delta^{(j-1)}_{e,m} = \left(\frac{\overline{\Delta L}}{L}\right)^{(j-1)}_{e,m,k=1} - \left(\frac{\overline{\Delta L}}{L}\right)^{(0)}_{e,m,k=1}$$

4. If $$\left|\left(\frac{\overline{\Delta L}}{L}\right)^{(j-1)}_{e,m,k=1} - \left(\frac{\overline{\Delta L}}{L}\right)^{(0)}_{e,m,k=1}\right| < C_f \left[\left(\frac{\overline{\Delta L}}{L}\right)^{(j-1)}_{f,m,k=1} - \left(\frac{\overline{\Delta L}}{L}\right)^{(0)}_{f,m,k=1}\right]$$

$$\Delta^{(j-1)}_{e,m} = C_f \left[\left(\frac{\overline{\Delta L}}{L}\right)^{(j-1)}_{f,m,k=1} - \left(\frac{\overline{\Delta L}}{L}\right)^{(0)}_{f,m,k=1}\right]$$

5. Using linear interpolation,

$$\alpha^{(j-1)}_{c,m} = f\left(\alpha'_c, T'_c, \overline{T}^{(j-1)}_{c,m,k=1}\right)$$ where α'_c and T'_c are input fits

$$\left(\frac{\overline{\Delta\rho}_{c,m}}{\overline{\rho}_{c,m}}\right)^{(j-1)} = -\left\{3\alpha_{c,m}^{(j-1)}\left(\overline{T}_{c,m,k=1}^{(j-1)} - \overline{T}_{c,m,k=1}^{(o)}\right) + 2\alpha_s\left(T_{s,m,k=1}^{(j-1)} - T_{s,m,k=1}^{(o)}\right) - \frac{2R_c^2\ \alpha_s\left(T_{s,m,k=1}^{(j-1)} - T_{s,m,k=1}^{(o)}\right) - 2R_e^2\ \Delta_{e,m}^{(j-1)}}{R_c^2 - R_e^2}\right\}$$

$$6.\left(\frac{\overline{\Delta\rho}_{s,m}}{\overline{\rho}_{s,m}}\right)^{(j-1)} = -\left[2\alpha_s\left(T_{s,m,k=1}^{(j-1)} - T_{s,m,k=1}^{(o)}\right) + \alpha_{s,ax}\left(T_{s,m,k=1}^{(j-1)} - T_{s,m,k=1}^{(o)}\right)\right]$$

7. If $\delta_u = 0$, go to F

   If $\delta_u \neq 0$, go to E.8

8. Find fractional linear thermal expansion of the additional material

$$\left(\frac{\Delta L}{L}\right)_{u,m,k}^{(j-1)} = E_u^{(0)} + E_u^{(1)}\ T_{u,m,k=1}^{(j-1)} + E_u^{(2)}\ \left(T_{u,m,k=1}^{(j-1)}\right)^2$$

$$\left(\frac{\overline{\Delta\rho}_{u,m}}{\overline{\rho}_{u,m}}\right)^{(j-1)} = -\left[\left\{\left(\frac{\Delta L}{L}\right)_{u,m,k=1}^{(j-1)} - \left(\frac{\Delta L}{L}\right)_{u,m,k=1}^{(0)}\right\} + 2\alpha_s\left(T_{s,m,k=1}^{(j-1)} - T_{s,m,k=1}^{(o)}\right)\right]$$

F. Check for sodium voiding

If $\delta_{void} = 0$, go to G.

If $\delta_{void} \neq 0$, calculate absolute pressure:

1. $P_Z^{(j)} = P_{st} + P_{pump}\ \frac{2g\Delta P^{(j-1)}}{2g\Delta P^{(o)}} - f_Z\ \frac{2g\Delta P^{(j-1)}}{(64.4)(144)}$

$$T_c^{Boil} = f\ (P_c', T_c'^{Boil}, P_Z^{(j)})$$

for $1 \leq k \leq K$
and $1 \leq m \leq M$

If $T_{c,m,k}^{(j)} < T_c^{Boil}$, go to F.3

If $T_{c,m,k}^{(j)} \geq T_c^{Boil}$,

$$(\Delta k)_{void}^{(j)} = f\ [(\Delta k)_{void}', T_{void}', T^{void}]$$

3. $T_E^{Burnout} = f\ (P_E', T_E'^{Burnout}, P_Z^{(j)})$

For $1 \leq k \leq K$
and $1 \leq m \leq M$

If $T_{E,m,k}^{(j)} < T_E^{Burnout}$, go to F.4

If $T_{E,m,k}^{(j)} \geq T_E^{Burnout}$, continue

$$\Delta k_{void}^{(j)} = f\ (\Delta k_{void}', T_{void}', T^{void})$$

Go to G.

4. Check for fuel vaporization

for $1 \leq k \leq K$
and $1 \leq m \leq M$

If $T_{l,m,k}^{(j)} < T_f^{Vapor}$, go to G.

If $T_{l,m,k} \geq T_f^{Vapor}$, continue

$$\Delta k_{void}^{(j)} = f\ (\Delta k_{void}' \quad T_{void}', T^{void})$$

If $\delta_{pwr} \neq 0$, go to H

If $\delta_{pwr} \neq 0$, continue

G. Total Feedback Reactivity

$$FB_H^{(j-1)} = H_T \left(\frac{\delta_k}{\delta_{H_T}}\right) \left(\frac{\Delta H_T}{H_T}\right)^{(j-1)}$$

$$FB_R^{(j-1)} = R_T \left(\frac{\delta_k}{\delta_{R_T}}\right) \left(\frac{\sum_{m=1}^{M} \left(\frac{\Delta R_T}{R_T}\right)_m^{(j-1)} (\Delta Z)_m}{H_T}\right)$$

$$FB_D^{(j-1)} = \sum_{m=1}^{M} \left(\bar{\rho}_f \left(\frac{\delta_k}{\delta \bar{\rho}_f}\right)_m \left(\frac{\Delta \bar{\rho}_{f,m}}{\bar{\rho}_{f,m}}\right)^{(j-1)} + \left(\bar{\rho}_e \frac{\delta_k}{\delta \bar{\rho}_e}\right)_m \left(\frac{\Delta \bar{\rho}_{e,m}}{\bar{\rho}_{e,m}}\right)^{(j-1)}\right.$$

$$+ \left(\bar{\rho}_c \left(\frac{\delta_k}{\delta \bar{\rho}_c}\right)_m \left(\frac{\Delta \bar{\rho}_{c,m}}{\bar{\rho}_{c,m}}\right)^{(j-1)} + \left(\bar{\rho}_s \frac{\delta_k}{\delta \bar{\rho}_s}\right)_m \right.$$

$$\left.\left. \left(\frac{\Delta \bar{\rho}_{s,m}}{\bar{\rho}_{s,m}}\right)^{(j-1)} + \left(\bar{\rho}_u \left(\frac{\delta_k}{\delta \bar{\rho}_u}\right)_m \left(\frac{\Delta \bar{\rho}_{u,m}}{\bar{\rho}_{u,m}}\right)^{(j-1)}\right)\right)$$

$$k_f^{(j-1)} = (\Delta k)_{Dop}^{(j-1)} + FB_H^{(j-1)} + FB_R^{(j-1)} + FB_D^{(j-1)} + (\Delta k)_{void}^{(j-1)}$$

H. END OF FEEB

SUBRØUTINE PØWD

FUNCTION

Calculates prompt power, average power and prompt energy during the j^{th} step; also, total power, average power and total energy at the end of the j^{th} step. Delayed neutron precursors are also computed.

PROCEDURE

A. Check for power table

If $\delta_{pwr} \neq 0$, go to G.

If $\delta_{pwr} = 0$, go to B.

B. On the first time step (when j = 1) calculate

1. Total delayed neutron fraction

$$\beta = \sum_{i=1}^{I} \beta_i$$

2. Initialization

$$E_j^* = 0.0$$

$$E_j = 0.0$$

$$P_j^* = P_o^*$$

C. Kinetics Equations

1. $$R_j = \frac{k^{(j)}(1-\beta) - 1}{\ell}$$

2. $$A_j = \frac{k^{(j)}}{\nu\ell} \left[\sum_{i=1}^{I} \lambda_i C_i^{(j-1)} + S \right]$$

3. If $\left| k^{(j)} (1 - \beta) - 1 \right| < \varepsilon_K$

a. $$\bar{P}^*_j = \frac{P^*_{j-1}\,\tau^{(j)} + \frac{A_j}{2}\,\tau^{(j)^2}}{\tau^{(j)}}$$

If J > 1, go to (2)

If J = 1, go to (1)

(1) If $\left|\bar{P}^*_j - P^*_o\right| / \bar{P}^*_j \leq \varepsilon_{pwr}$

Set $\bar{P}^*_j = P^*_o$

Go to C.3.b

If $\left|\bar{P}^*_j - P^*_o\right| / \bar{P}^*_j > \varepsilon_{pwr}$, go to C.3.b

(2) If $\left|\bar{P}^*_j - \bar{P}^*_{j-1}\right| / \bar{P}^*_j \leq \varepsilon_{pwr}$

Set $\bar{P}^*_j = \bar{P}^*_{j-1}$

Go to b

If $\left|\bar{P}^*_j - \bar{P}^*_{j-1}\right| / \bar{P}^*_j > \varepsilon_{pwr}$, go to C.3.b

b. $P^*_j = A_j\tau^{(j)} + P^*_{j-1}$

If J > 1, go to (2)

If J = 1, go to (1)

(1) If $\left|P^*_j - P^*_o\right| / P^*_j \leq \varepsilon_{pwr}$

Set $P^*_j = P^*_o$

Go to D.

If $\left|P^*_j - P^*_o\right| / P^*_j > \varepsilon_{pwr}$, go to D.

(2) If $\left|P^*_j - P^*_{j-1}\right| / P^*_j \leq \varepsilon_{pwr}$

Set $P^*_j = P^*_{j-1}$

Go to D

If $\left|P^*_j - P^*_{j-1}\right| / P^*_j > \varepsilon_{pwr}$, go to D.

4. If $\left| k^{(j)} (1 - \beta) - 1 \right| \geq \varepsilon_K$

$$Q_j = \frac{A_j}{R_j}$$

a. If $R_j \tau^{(j)} > -80$, then

$$\bar{P}_j^* = \frac{1}{\tau^{(j)}} \left(\frac{P_{j-1}^* + Q_j}{R_j} \right) \left(e^{R_j \tau^{(j)}} - 1 \right) - Q_j$$

$$P_j^* = P_{j-1}^* e^{R_j \tau^{(j)}} + Q_j \left(e^{R_j \tau^{(j)}} - 1 \right)$$

Go to C.4.c

b. If $R_j \tau^{(j)} \leq -80$, then

$$\bar{P}_j^* = - \frac{1}{\tau^{(j)}} \left(\frac{P_{j-1}^* + Q_j}{R_j} \right) - Q_j$$

$$P_j^* = - \frac{A_j}{R_j}$$

Go to C.4.c

c. If J > 1, go to (2)

If J = 1, go to (1)

(1) If $\left| \bar{P}_j^* - P_o^* \right| / \bar{P}_j^* \leq \varepsilon_{Pwr}$

Set $\bar{P}_j^* = P_o^*$

If $\left| P_j^* - P_o^* \right| / P_j^* \leq \varepsilon_{pwr}$

Set $P_j^* = P_o^*$

If $\left| \bar{P}_j^* - P_o^* \right| / \bar{P}_j^* > \varepsilon_{pwr}$, $\bar{P}_j^* = \bar{P}_j^*$

If $\left| P_j^* - P_o^* \right| / P_j^* > \varepsilon_{pwr}$, $P_j^* = P_j^*$

Go to D.

(2) If $\left| \bar{P}^*_j - \bar{P}^*_{j-1} \right| / \bar{P}^*_j \leq \varepsilon_{pwr}$

Set $\bar{P}^*_j = \bar{P}^*_{j-1}$

If $\left| P^*_j - P^*_{j-1} \right| / P^*_j \leq \varepsilon_{pwr}$

Set $P^*_j = P^*_{j-1}$

If $\left| \bar{P}^*_j - P^*_{j-1} \right| / \bar{P}^*_j > \varepsilon_{pwr}$, $\bar{P}^*_j = \bar{P}^*_j$

If $\left| P^*_j - P^*_{j-1} \right| / P^*_j > \varepsilon_{pwr}$, $P^*_j = P^*_j$

Go to D.

D. Excess Energy

1. $E^*_j = E^*_{j-1} + (\bar{P}^*_j - P^*_o)\, \tau^{(j)}$

2. For $1 \leq im \leq IM$

If $T_o = 0$, set $T_o = 1.0 \times 10^{25}$

$$x = \frac{t}{a_{im} + T_o}$$

If $x > .05$, set

$$\bar{g}_{im} = \frac{A_{im}}{\alpha_{im}} (a_{im} + T_o)^{1-\alpha_{im}} \left[x - \frac{1}{(1-\alpha_{im})} \left\{ (1+x)^{1-\alpha_{im}} - 1 \right\} \right]$$

If $x \leq .05$, set

$$\bar{g}_{im} = \frac{A_{im}(a_{im} + T_o)^{1-\alpha_{im}}}{2} \left[x^2 \left\{ 1 - \frac{(1 + \alpha_{im})}{3} x \right. \right.$$

$$+ \frac{(1 + \alpha_{im})(2 + \alpha_{im})}{12} x^2 - \frac{(1 + \alpha_{im})(2 + \alpha_{im})(3 + \alpha_{im})}{60} x^3$$

$$\left. \left. + \frac{(1 + \alpha_{im})(2 + \alpha_{im})(3 + \alpha_{im})(4 + \alpha_{im})}{360} x^4 \right\} \right]$$

3. for $1 \leq im \leq IM$

$$y = \frac{t}{a_{im}}$$

If $y > .05$

$$\bar{\bar{g}}_{im} = \frac{A_{im}}{\alpha_{im}} a_{im}^{-\alpha_{im}} \left[1 - \frac{1}{y(1-\alpha_{im})} \left\{ (1+y)^{1-\alpha_{im}} - 1 \right\} \right]$$

$$\bar{f}_{im} = \frac{A_{im} a_{im}^{-(1+\alpha_{im})}}{\alpha_{im} y} \left[1 - (1+y)^{-\alpha_{im}} \right]$$

If $y \leq .05$

$$\bar{\bar{g}}_{im} = \frac{A_{im}}{2} a_{im}^{-\alpha_{im}} y \left[1 - \frac{(1+\alpha_{im})}{3} y + \frac{(1+\alpha_{im})(2+\alpha_{im})}{12} y^2 - \frac{(1+\alpha_{im})(2+\alpha_{im})(3+\alpha_{im})}{60} y^3 + \frac{(1+\alpha_{im})(2+\alpha_{im})(3+\alpha_{im})(4+\alpha_{im})}{360} y^4 \right]$$

$$\bar{f}_{im} = A_{im} a_{im}^{-(1+\alpha_{im})} \left[1 - \frac{(1+\alpha_{im})}{2} y + \frac{(1+\alpha_{im})(2+\alpha_{im})}{6} y^2 - \frac{(1+\alpha_{im})(2+\alpha_{im})(3+\alpha_{im})}{24} y^3 + \frac{(1+\alpha_{im})(2+\alpha_{im})(3+\alpha_{im})(4+\alpha_{im})}{120} y^4 \right]$$

4. $$E_j = E_j^* \left[1 + \sum_{i=1}^{I} \bar{\bar{g}}_{im} \right] + P_o^* \sum_{i=1}^{I} \bar{g}_{im}$$

If $J > 1$, go to b

If $J = 1$, go to a

a. If $E_j / (\overline{P}^*_j \quad \tau^{(j)}) > \varepsilon_{pwr}$, go to E.

If $E_j / (\overline{P}^*_j \quad \tau^{(j)}) \leq \varepsilon_{pwr}$

Set $E_j = 0.0$

Go to E.

b. If $\left|E_j - E_{j-1}\right| / (\overline{P}^*_j \quad \tau^{(j)}) > \varepsilon_{pwr}$, go to E

If $\left|E_j - E_{j-1}\right| / (\overline{P}^*_j \quad \tau^{(j)}) \leq \varepsilon_{pwr}$

Set $E_j = E_{j-1}$

Go to E.

E. Delayed Neutron Precursor Concentration

$$C_i^{(j)} = C_i^{(j-1)} + \nu\beta_i \quad \overline{P}^*_j \quad \tau^{(j)} - \lambda_i \quad C_i^{(j-1)} \quad \tau^{(j)}$$

F. Average Power

1. $$P_j = \left\{ P^*_j + E^*_j \sum_{i=1}^{I} \overline{f}_{im} + P_o^* \sum_{i=1}^{I} \left[\frac{A_{im}}{\alpha_{im}} \quad a_{im}^{-\alpha_{im}} - (a_{im} + t + T_o)^{-\alpha_{im}} \right] \right\} C_h \quad \text{where } C_h = 8.6\text{x}10^{-10}$$

2. $$\overline{P}_j = P_o + \frac{C_h}{\tau^{(j)}} \quad (E_j - E_{j-1})$$

Go to H.

G. By linear interpolation find

P_j as a function of T

$$P_j^{Ratio} = f(P_j^{'Ratio}, T', T)$$

where $P_j^{'Ratio}$ and T' are input values.

$$P_o^* = P_o / 8.6 \times 10^{-10}$$

$$P_j^* = P_o^* \times P_j^{Ratio}$$

$$P_j = P_j^* \ (8.6 \times 10^{-10})$$

$$\overline{P}_j = (P_{j-1} + P_j)/2$$

H. End of PØWD

SUBROUTINE INFLOW

FUNCTION

Calculates mass velocity of the reactor coolant in the peak and hot spot fuel channels. The velocity for the average channel is selected from user's input table.

PROCEDURE

A. By linear interpolation, find coolant velocity for the average channel and core inlet temperature.

$G^{(j)}_{c,k=1} = f\ (G^{A}_{c}, T', T)$ where G^{A}_{c} and T' are input.

$T^{inlet(j)}_{c} = f\ (T^{FIT}_{c}, T^{FIT}, T)$ where T^{FIT}_{c} & T^{FIT} are inputs.

B. By linear interpolation, find dynamic viscosity of the coolant for

$$1 \leq k \leq K$$

$$\mu^{(j-1)}_{c,k} = f\ (\mu'_{c}, T'_{\mu}, \overline{T}^{(j-1)}_{c,k})$$

C. Calculate Reynolds number for all channels

$$N^{(j)}_{R,k=1} = \frac{G^{(j)}_{c,k=1}\ D_H}{\mu^{(j)}_{c,k=1}}$$

for $2 \leq k \leq 3$

$$N^{(j)}_{R,k} = \frac{G^{(j-1)}_{c,k}\ D_H}{\mu^{(j-1)}_{c,k}}$$

If $N_{R,k=1} = 0.0$, set $G^{(j)}_{c,k=2}$ and $G^{(j)}_{c,k=3}$ equal to 0.0 and go to H.

If $N_{R,k=1} \neq 0.0$, continue

D. Compute pressure drop.

If $N_{R,k=1}^{(j)} = COMP$, then

$$2g\Delta P^{(j)} = \frac{64}{N_{P,k=1}^{(j)}} \frac{z_t}{D_H} \frac{(G_{c,k=1}^{(j)})^2}{\rho_{c,k=1}^{(j-1)}} + B_{\emptyset R,k=1} \frac{(G_{c,k=1}^{(j)})^2}{\rho_{c}^{inlet(j-1)}}$$

Go to E.

If $N_{r,k=1}^{(j)} > COMP$, then

$$2g\Delta P^{(j)} = \frac{C}{(N_{R,k=1}^{(j)})^e} \frac{z_t}{D_H} \frac{(G_{c,k=1}^{(j)})^2}{\rho_{c,k=1}^{(j-1)}} + B_{\emptyset R,k=1} \frac{(G_{c,k=1}^{(j)})^2}{\rho_{c}^{inlet(j-1)}}$$

Go to F.

E. If $N_{R,k}^{(j)} \leq COMP$, go to F

If $N_{R,k}^{(j)} > COMP$, go to G

F. Laminar Flow. Calculate the velocity of the coolant for $2 \leq k \leq K$

1. If $B_{\emptyset R,k} = 0$

$$G_{c,k}^{(j)} = \frac{\rho_{c,k}^{(j-1)} D_H^2}{64 \mu_{c,k}^{(j-1)} z_t} (2g \Delta P)^{(j)}$$

Go to G.

2. If $B_{\emptyset R,k} \neq 0$

$$G_{c,k}^{(j)} = \frac{-32 \mu_{c,k}^{(j-1)}}{D_H^2} \frac{z_t}{B_{\emptyset R,k}} \frac{\rho_{c}^{inlet(j-1)}}{\rho_{c,k}^{(j-1)}} + \sqrt{\left(\frac{32 \mu_{c,k}^{(j-1)} z_t}{D_H^2 B_{\emptyset R,k}} \frac{\rho_{c}^{inlet(j-1)}}{\rho_{c,k}^{(j-1)}}\right)^2 + \frac{(2g\Delta P)^{(j)} \rho_{c}^{inlet(j-1)}}{B_{\emptyset R,k}}}$$

Go to H.

G. Turbulent Flow. Calculate the velocity of the coolant for $2 \leq k \leq K$

1. If $B_{\emptyset R,k} = 0$

$$G_{c,k}^{(j)} = \left[\frac{(2g\ \Delta P)\ D_H^{(1+e)}\ \rho_{c,k}^{(j-1)}}{C\ \mathcal{Z}_t\ (\mu_{c,k}^{(j-1)})^e} \right]^{\frac{1}{2-e}}$$

Go to H.

2. If $B_{\emptyset R,k} \neq 0$

a. $A_1 = 2g\ \Delta P$

b. $A_2 = \dfrac{C\ \mathcal{Z}_t\ (\mu_{c,k}^{(j-1)})^e}{\rho_{c,k}^{(j-1)}\ D_H^{1+e}}$

c. $A_3 = \dfrac{B_{\emptyset R,k}}{\rho_c^{inlet(j-1)}}$

Iterate for value of $G_{c,k}^{(j)}$

d. Let $G_o = G_{c,k=1}^{(j)}$

e. For $1 \leq R \leq 10$

$$G_R = \sqrt{\frac{A_1}{A_2\ (G_{R-1})^{-e} + A_3}}$$

f. If $\left| G_R - G_{R-1} \right| \leq .0001$

Set $G_{c,k}^{(j)} = G_R$

Go to H.

g. If $\left|G_R - G_{R-1}\right| > .0001$ and $R < 10$, return to e

h. If $\left|G_R - G_{R-1}\right| > .0001$ and $R \geq 10$, error

H. End of INFLØW

SUBROUTINE CØPH

FUNCTION

Calculates heat generation rates, temperatures, material properties, etc for each new time step.

PROCEDURE

Sections A Through N·17 are calculated for $1 \leq k \leq K$

A. Find average heat generation rates based on calculated average power for this time step

for $1 \leq m \leq M$

1. $\bar{Q}^{(j)}_{e,m,k} = (QU)_{e,m,k} \bar{P}_j$

2. $\bar{Q}^{(j)}_{c,m,k} = (QU)_{c,m,k} \bar{P}_j$

3. $\bar{Q}^{(j)}_{s,m,k} = (QU)_{s,m,k} \bar{P}_j$

4. $\bar{Q}^{(j)}_{u,m,k} = (QU)_{u,m,k} \bar{P}_j$

5. $\bar{Q}^{(j)}_{f,m,k} = (QU)_{f,m,k} \bar{P}_j$

6. $\bar{Q}^{(j)}_{n,m,k} = (QU)_{n,m,k} \bar{P}_j \qquad 1 \leq n \leq N$

B. Coolant Temperatures and Properties.

1. Inlet temperature when m = 1 and j = 1; if $\delta_{coolant}$=1, calculate $C_{m,k}$

$$T^{in(j)}_{c,m,k} = T^{inlet(j)}_{c}$$

if $\delta_{coolant} = 0$, go to B.2

if $\delta_{coolant} = 1$:

$$C_{m,k} = (T^{(o)}_{c,m,k} - T^{in(o)}_{c,m,k}) \frac{1 - \lambda_a}{\lambda_a}$$

2. Coolant nodal temperatures for $1 \leq m \leq M$

a. if $\delta_c = 0$:

$$T^{(j)}_{c,m,k} = T^{(j-1)}_{c,m,k} + \frac{\tau^{(j)}}{(\rho_e C_e A_e + \rho^{(j-1)}_{c,m,k} C^{(j-1)}_{c,m,k} A_c + \rho_s C_s V_s + \rho_u C_u V_u)}$$

$$\left\{ \bar{Q}^{(j)}_{c,m,k} A_c + \bar{Q}^{(j)}_{s,m,k} V_s + \bar{Q}^{(j)}_{u,m,k} V_u \right.$$

$$\left. + \frac{T^{(j-1)}_{N,m,k} - \bar{T}^{(j-1)}_{c,m,k}}{DEN\emptyset M} - \frac{G^{(j-1)}_{c,k} A_c}{(\Delta z)_m} (T^{Out(j-1)}_{c,m,k} C^{(j-1)}_{c,m,k} - T^{Out(j-1)}_{c,m-1,k} C^{(j-1)}_{c,m,k}) \right\}$$

where $DEN\emptyset M = \left[\frac{\ln \frac{R_E}{R_e}}{2\pi k_e} + \frac{1}{2\pi R_E h^{*(j-1)}_{c,m,k}} \right] + \left[\frac{\bar{Q}^{(j)}_{f,m,k} A_f}{\bar{Q}^{(j)}_{f,m,k} A_f + \bar{Q}^{(j)}_{e,m,k} A_e} \right]$

$$\left[\frac{1}{\pi (R_e + R_f) C^{(j-1)}_{g,m,k}} + \frac{\ln \frac{R_f}{r_n}}{2\pi K^{(j-1)}_{N,m,k}} \right]$$

Go to B.3

b. If $\delta_c \neq 0$, check coolant: If $\delta_{coolant} \neq 0$, go to C

If $\delta_{coolant} = 0$, continue

$$A = \frac{\tau^{(j)}}{\rho^{(j-1)}_{c,m,k} C^{(j-1)}_{c,m,k}}$$

$$B = \frac{V_s G_s}{A_c \left(\frac{1}{g^{(j-1)}_{c,m,k}} + \frac{d_s}{k_s} \right)} (T^{(j-1)}_{s,m,k} - \bar{T}^{(j-1)}_{c,m,k})$$

$$C = \frac{V_u G_u}{A_c \left(\frac{1}{g^{(i-1)}_{c,m,k}} \right) + \frac{d_u}{K_u}} (T^{(j-1)}_{u,m,k} - \bar{T}^{(j-1)}_{c,m,k})$$

$$D = \frac{T_{a,m,k}^{(j-1)} - \overline{T}_{c,m,k}^{(j-1)}}{A_c\left(\frac{1}{2\pi R_E h_{c,m,k}^{(j-1)}} + \frac{\ln \frac{R_E}{R_a}}{2\pi K_e}\right)}$$

$$E = \frac{G_{c,k}^{(j-1)} \tau^{(j)}}{(\Delta Z)_m \rho_{c,m,k}^{(j-1)}} \left(T_{c,m,k}^{Out(j-1)} - T_{c,m-1,k}^{Out(j-1)}\right)$$

$$F = \frac{V_u \overline{Q}_{u,m,k}^{(j)}}{A_c}$$

$$G = \frac{V_s \overline{Q}_{s,m,k}^{(j)}}{A_c}$$

(1) and $G_s \neq 0$, $G_u \neq 0$

$$T_{c,m,k}^{(j)} = T_{c,m,k}^{(j-1)} + A\left\{\overline{Q}_{c,m,k}^{(j)} + B + C + D\right\} - E$$

(2) and $G_s \neq 0$, $G_u = 0$

$$T_{c,m,k}^{(j)} = T_{c,m,k}^{(j-1)} + A\left\{\overline{Q}_{c,m,k}^{(j)} + B + F + D\right\} - E$$

(3) and $G_s = 0$, $G_u \neq 0$

$$T_{c,m,k}^{(j)} = T_{c,m,k}^{(j-1)} + A\left\{\overline{Q}_{c,m,k}^{(j)} + G + C + D\right\} - E$$

(4) and $G_s = 0$, $G_u = 0$

$$T_{c,m,k}^{(j)} = T_{c,m,k}^{(j-1)} + A\left\{\overline{Q}_{c,m,k}^{(j)} + G + F + D\right\} - E$$

3. Inlet and Outlet Temperature for Each Section

$$1 \leq m \leq M$$

$$T^{in(j)}_{c,m,k} = T^{in(j-1)}_{c,m,k} + (T^{(j)}_{c,m,k} - T^{(j-1)}_{c,m,k})$$

$$T^{Out(j)}_{c,m,k} = T^{Out(j-1)}_{c,m,k} + (T^{(j)}_{c,m,k} - T^{(j-1)}_{c,m,k})$$

4. Core Outlet Temperature

$$T^{Out(j)}_{c,k} = T^{Out(j)}_{c,M,k}$$

5. Average Temperature of the Coolant

for $m \leq l \leq M$

$$\overline{T}^{(j)}_{c,m,k} = \frac{T^{in(j)}_{c,m,k} + T^{in(j)}_{c,m+1,k}}{2}$$

6. Average Coolant Temperature

$$\overline{T}^{(j)}_{c,k} = \frac{\sum_{m=1}^{M} \overline{T}^{(j)}_{c,m,k} (\Delta Z)_m}{\sum_{m=1}^{M} (\Delta Z)_m}$$

7. Calculate $\rho^{(j)}_{c,m,k}$, $C^{(j)}_{c,m,k}$, $K^{(j)}_{c,m,k}$ and $\mu^{(j)}_{c,m,k}$ by linear interpolation.

8. Coolant Heat Transfer Coefficients

for $1 \leq m \leq M$

a. Structure-to-Coolant

$$g^{(j)}_{c,m,k} = \frac{K^{(j)}_{c,m,k}}{D_{HT}} \left[A_H + B_H \left(\frac{D_{HT} G^{(j)}_{c,k}}{\mu^{(j)}_{c,m,k}} \right)^{M_H} \left(\frac{\mu^{(j)}_{c,m,k} C^{(j)}_{c,m,k}}{K^{(j)}_{c,m,k}} \right)^{N_H} \right] F^*$$

b. Clad-Coolant (For Lumped System)

$$h^{*(j)}_{c,m,k} = \frac{K^{(j)}_{c,m,k}}{D_{HT}} \left[A_H + C_{H,m} \left(\frac{D_{HT}\, G^{(j)}_{c,k}}{\mu^{(j)}_{c,m,k}} \right)^{M_H} \left(\frac{\mu^{(j)}_{c,m,k}\; C^{(j)}_{c,m,k}}{K^{(j)}_{c,m,k}} \right)^{N_H} \right] F^*$$

c. Clad-Coolant (For Non-lumped System)

$$h^{(j)}_{c,m,k} = h^{*(j)}_{c,m,k} \left[\frac{\bar{T}^{(j-1)}_{c,m,k} + 460}{T^{(j-1)}_{E,m,k} + 460} \right]^{R_H}$$

d. Coefficient for Hot Spot Channel

If $k < 3$, to to C

If $k = 3$:

If $\delta_c = 0$, go to C

If $\delta_c \neq 0$:

If $\delta_{cof} \neq 0$, go to C

If $\delta_{cof} = 0$:

for $1 \leq m \leq M$

If $T^{(j)}_{c,m,3} \geq T^{Boil}_c$, set $h_{c,m,3} = h_{c,3}$

go to C.

If $T^{(j)}_{c,m,3} < T^{Boil}_c$, continue

If $T^{(j)}_{E,m,3} \geq T^{Burnout}_E$, set $h_{c,m,3} = h_{c,3}$

go to C

If $T_{E,m,3} < T^{Burnout}_E$, continue

If $T^{(j)}_{1,m,3} \geq T^{Vapor}_f$, set $h_{c,m,3} = h_{c,3}$

If $T_{1,m,3} < T^{Vapor}_f$, $h^{(j)}_{c.m,3} = h^{(j)}_{c,m,3}$

C. Structure Temperature

1. If $G_s = 0$ or $\delta_c = 0$

$$1 \leq m \leq M$$

$$T^{(j)}_{s,m,k} = \overline{T}^{(j)}_{c,m,k}$$

Go to D.

2. If $G_s \neq 0$, $\delta_c = 1$

$$\text{for } 1 \leq m \leq M$$

$$T^{(j)}_{s,m,k} = T^{(j-1)}_{s,m,k} + \frac{\tau^{(j)}}{\rho_s C_s} \overline{Q}^{(j)}_{s,m,k} + \left\{ + \frac{G_s}{\frac{1}{g^{(j-1)}_{c,m,k}} + \frac{d_s}{K_s}} \left(\overline{T}^{(j-1)}_{c,m,k} - T^{(j-1)}_{s,m,k} \right) \right\}$$

D. Added Material Temperature

1. If $\delta_u = 0$

$$\text{for } 1 \leq m \leq M$$

$$T^{(j)}_{u,m,k} = 0.0$$

Go to E.

2. If $G_u = 0$ or $\delta_c = 0$

$$1 \leq m \leq M$$

$$T^{(j)}_{u,m,k} = \overline{T}^{(j)}_{c,m,k}$$

Go to E.

3. If $G_u \neq 0.0$ and $\delta_c = 1$

for $1 \leq m \leq M$

$$T_{u,m,k}^{(i)} = T_{u,m,k}^{(j-1)} + \frac{\tau^{(j)}}{\rho_u C_u} \overline{Q}_{u,m,k}^{(j)} +$$

$$\frac{G_u}{\frac{1}{g_{c,m,k}^{(j-1)}} + \frac{d_u}{K_u}} \left(\overline{T}_{c,m,k}^{(j-1)} - T_{u,m,k}^{(j-1)}\right)$$

E. Clad Temperatures

1. If $\delta_c = 0$ go to E.2

   If $\delta_c \neq 0$ go to E.3

2. Average Clad Temperature when $\delta_c = 0$

for $1 \leq m \leq M$

$$\overline{T}_{e,m,k}^{(j)} = \overline{T}_{c,m,k}^{(j)}$$

Go to G.

3. Temperature of the middle of the clad.

for $1 \leq m \leq M$

$$T^{(j)}_{a,m,k} = T^{(j-1)}_{a,m,k} + \frac{\tau^{(j)}}{\rho_e C_e A_e} \left\{ \overline{Q}^{(j)}_{e,m,k} A_e + \frac{(T^{(j-1)}_{N,m,k} - T^{(j-1)}_{a,m,k})}{\left(\frac{\ln \frac{R_a}{R_e}}{2\pi K_e} + \frac{1}{\pi (R_f + R_e) C^{(j-1)}_{g,m,k}} + \frac{\ln \frac{R_f}{r_n}}{2\pi K^{(j-1)}_{n,m,k}} \right)} - \frac{(T^{(j-1)}_{a,m,k} - T^{(j-1)}_{c,m,k})}{\left(\frac{\ln \frac{R_E}{R_e}}{2\pi K_e} + \frac{1}{2\pi R_E h^{(j-1)}_{c,m,k}} \right)} \right\}$$

4. Average Clad Temperature When $\delta_c \neq 0$

for $1 \leq m \leq M$

$$\overline{T}^{(j)}_{e,m,k} = T^{(j)}_{a,m,k}$$

If $\delta_{coolant} = 0$, go to G

If $\delta_{coolant} \neq 0$, go to F

F. Coolant Temperatures (when $\delta_{coolant} = 1$ and $\delta_c \neq 0$)

$$\text{Con 1} = \frac{1}{A_c} \left(\frac{1}{\frac{1}{2\pi R_E h^{(j-1)}_{c,m,k}} + \frac{\ln \frac{R_E}{R_a}}{2\pi K_e}} \right)$$

$$\text{Con 2} = \frac{V_s \quad G_s}{A_c \left(\frac{1}{g^{(j-1)}_{c,m,k}} + \frac{d_s}{K_s} \right)}$$

$$\text{Con 3} = \frac{V_u \quad G_u}{A_c \left(\frac{1}{g^{(j-1)}_{c,m,k}} + \frac{d_u}{K_u} \right)}$$

$$\text{Con 4} = \frac{V_s \quad Q^{(i)}_{s,m,k}}{A_c}$$

$$\text{Con 5} = \frac{V_u \quad Q^{(j)}_{u,m,k}}{A_c}$$

$$\text{Con 6} = \frac{G^{(j-1)}_{c,k} \quad C^{(j-1)}_{c,m,k}}{\quad}$$

1. If $G_s \neq 0$ and $G_u \neq 0$

$$T^{(j)}_{c,m,k} = [(\text{Con 1}) \; T^{(j)}_{a,m,k} + (\text{Con 2}) \; T^{(j)}_{s,m,k} + (\text{Con 3}) \; T^{(j)}_{u,m,k} - (\text{Con 6})$$

$$(C_{m,k} - T^{Out(j)}_{c,m-1,k}) + Q^{(j)}_{c,m,k}] \; / (\text{Con 1} + \text{Con 2} + \text{Con 3} + \text{Con 6})$$

Go to F.5

2. If $G_s \neq 0$ and $G_u = 0$

$$T^{(j)}_{c,m,k} = [(\text{Con 1}) \; T^{(j)}_{a,m,k} + (\text{Con 2}) \; T^{(j)}_{s,m,k} + \text{Con 5} - \text{Con 6} \; (C_{m,k} - T^{Out(j)}_{c,m-1,k})$$

$$+ Q^{(j)}_{c,m,k}] \; / \; (\text{Con 1} + \text{Con 2} + \text{Con 6})$$

Go to F.5

3. If $G_u \neq 0$ and $G_s = 0$

$$T^{(j)}_{c,m,k} = [(\text{Con 1})\ T^{(j)}_{a,m,k} + \text{Con 4} + (\text{Con 3})\ T^{(j)}_{u,m,k} - C_{m,k} - T^{out(j)}_{c.m-1,k})$$

$$\text{Con 6}) + Q^{(j)}_{c,m,k}] \ / \ (\text{Con 1} + \text{Con 3} + \text{Con 6})$$

Go to F.5

4. If $G_s = 0$ and $G_u = 0$

$$T^{(j)}_{c,m,k} = [(\text{Con 1})\ T^{(j)}_{a,m,k} + \text{Con 4} + \text{Con 5} - \text{Con 6}\ (C_{m,k} - T^{Out(j)}_{c,m-1,k})$$

$$+ Q^{(j)}_{c,m,k}] \ / \ \text{Con 1} + \text{Con 6})$$

5. Calculate $T^{In(j)}_{c,m,k}$, $T^{Out(j)}_{c,m,k}$, $\overline{T}^{(j)}_{c,m,k}$, $T^{Out(j)}_{c,k}$, $\overline{T}^{(j)}_{c,k}$,

coolant properties, and coolant heat transfer coefficients as specified in Section C.3 through C.8.

Then go to G.

G. Fuel Boundary Node (n=N)

for $\delta_c \neq 0$:

for $1 \leq m \leq M$

$$E^{(j)}_{N,m,k} = E^{(j-1)}_{N,m,k} + \frac{\tau^{(j)}}{\rho_f C^{(j-1)}_{N,m,k} A_N} \left\{ \overline{Q}^{(j)}_{N,m,k} A_N + \frac{2\pi K^{(j-1)}_{N-1,m,k}}{(LN)_{N-1}} \right.$$

$$\left. \left(T^{(j-1)}_{N-1,m,k} - T^{(j-1)}_{N,m,k}\right) - \frac{T^{(j-1)}_{N,m,k} - T^{(j-1)}_{a,m,k}}{\left(\frac{\ell n \frac{R_f}{r_N}}{2\pi K^{(j-1)}_{N,m,k}} + \frac{1}{\pi (R_f + R_e) C^{(j-1)}_{g,m,k}} + \frac{n \frac{R_a}{R_e}}{2\pi K_e} \right)} \right\}$$

for $S_c = 0$

$$E^{(j)}_{N,m,k} = E^{(j-1)}_{N,m,k} + \frac{(j)}{\rho_f \, C^{(j-1)}_{N,m,k} \, A_N} \left\{ \overline{Q}^{\,(j)}_{N,m,k} \, A_N + \frac{2\pi \, K^{(j-1)}_{N-1,m,k}}{(LN)_{N-1}} \left(T^{(j-1)}_{N-1,m,k} - T^{(j-1)}_{N,m,k} \right) - \frac{\left(T^{(j-1)}_{N,m,k} - \overline{T}^{(j-1)}_{c,m,k} \right)}{DENØM} \right\}$$

where

$$DENØM = \left(\frac{\overline{Q}^{(j)}_{f,m,k} \, A_f + \overline{Q}^{(j)}_{e,m,k} \, A_e}{\overline{Q}^{\,j}_{f,m,k} \, A_f} \right) \left(\frac{\ell n \, \frac{R_E}{R_e}}{2\pi \, K_e} + \frac{1}{2\pi \, R_L \, h^{*(j-1)}_{c,m,k}} \right) + \left(\frac{1}{\pi (R_f + R_e) \, C^{(j-1)}_{g,m,k}} + \frac{\ell n \, \frac{R_f}{r_N}}{2\pi \, K^{(j-1)}_{N,m,k}} \right)$$

for $1 \leq m \geq M$

If $E_{N,m,k} > T^{Melt}_f$ go to G.2

If $E_{N,m,k} \leq T^{Melt}_f$ go to G.1

1. $T^{(j)}_{N,m,k} = E^{(j)}_{N,m,k}$

   Go to G.3

2. If $E^{(j)}_{N,m,k} > T^{Melt}_f + \frac{B^{Melt}}{\rho_f C^{Melt}}$, $T^{(j)}_{N,m,k} = E^{(j)}_{N,m,k} - \frac{B^{Melt}}{\rho_f C^{Melt}}$

   Go to G.3

   If $E^{(j)}_{N,m,k} \leq T^{Melt}_f + \frac{B^{Melt}}{\rho_f C^{Melt}}$, $T^{(j)}_{N,m,k} = T^{Melt}_f$

3. End of loop on m.

H. Fuel Boundary Temperatures

1. If $\delta_c = 0$ go to H.2

   If $\delta_c \neq 0$ go to H.3

2. for $1 \leq m \leq M$

$$A = \frac{2\pi K_{N,m,k}^{(j-1)}}{LN \frac{R_f}{r_N}} T_{N,m,k}^{(j-1)} + \frac{\bar{T}_{c,m,k}^{(j-1)}}{\frac{O_{f,m,k}^{(j-1)} A_f + O_{e,m,k}^{(j-1)} A_e}{O_{f,m,k}^{(j-1)} A_f} \frac{\ln \frac{R_E}{R_e}}{2\pi K_e} + \frac{1}{2 R_e h_{c,m,k}^{*(j-1)}}} + \frac{1}{\pi(R_e+R_f) C_{g,m,k}^{(j-1)}}$$

$$B = \frac{2\pi K_{N,m,k}^{(j-1)}}{\ln \frac{R_f}{r_N}} + \frac{1}{\frac{O_{f,m,k}^{(j-1)} A_f + O_{e,m,k}^{(j-1)} A_e}{O_{f,m,k}^{(j-1)} A_f} \frac{\ln \frac{R_E}{R_e}}{2\pi K_e} + \frac{1}{2\pi R_E h_{c,m,k}^{*(j-1)}}} + \frac{1}{\pi(R_e+R_f) C_{g,m,k}^{(j-1)}}$$

$$T'^{(j)}_{f,m,k} = \frac{A}{B}$$

Go to H.4

3.1 Clad outer surface temperature

for $1 < m > M$

$$T_{E,m,k}^{(j)} = \frac{\frac{K_e T_{a,m,k}^{(j)}}{\ln \frac{R_E}{R_a}} + R_E h_{c,m,k}^{(j)} \bar{T}_{c,m,k}^{(j)}}{R_E h_{c,m,k}^{(j)} + \frac{K_e}{\ln \frac{R_E}{R_a}}}$$

3.2 Iterative loop for outer fuel and inner clad surface temperatures.

a. $T'^{(j)}_{f,m,k} = T^{j-1}_{f,m,k}$ (initial guess)

b. $$T_{e,m,k}^{(j)} = \frac{(R_f+R_e) C_{g,m,k}^{(j-1)} T'^{(j)}_{f,m,k} + \frac{2 K_e}{\ln \frac{R_a}{R_e}} T_{a,m,k}^{(j)}}{\frac{2 K_e}{\ln \frac{R_a}{R_e}} + (R_f+R_e) C_{g,m,k}^{(j-1)}}$$

c. $$T'^{(j)}_{f,m,k} = \frac{\frac{2k^{(j-1)}_{N,m,k}\, T^{(j)}_{N,m,k}}{\ell n \frac{R_f}{r_n}} + (R_f+R_e)\, C^{(j-1)}_{g,m,k}\, T^{(j-1)}_{e,m,k}}{\frac{2k^{(j-1)}_{N,m,k}}{\ell n \frac{R_f}{r_N}} + (R_f+R_e)\, C^{(j-1)}_{g,m,k}}$$

Go to b. Repeat 10 times.

Continue

4. If $T^{(j)}_{N,m,k} < T^{Melt}_f$, go to H.5

If $T^{(j)}_{N,m,k} \geq T^{Melt}_f$, go to H.7

5. If $T'^{(j)}_{f,m,k} < T^{Melt}_f$, go to C.6

If $T'^{(j)}_{f,m,k} \geq T^{Melt}_f$

Set $T^{(j)}_{f,m,k} = T^{Melt}_f$

$E^{(j)}_{f,m,k} = T'^{(j)}_{f,m,k}$

Go to I.

6. $T^{(j)}_{f,m,k} = T'^{(j)}_{f,m,k}$

$E^{(j)}_{f,m,k} = T'^{(j)}_{f,m,k}$

Go to I.

7. $T^{(j)}_{f,m,k} = T'^{(j)}_{f,m,k}$

$E^{(j)}_{f,m,k} = T'^{(j)}_{f,m,k} + (E^{(j)}_{N,m,k} - T^{(j)}_{N,m,k})$

Continue

I. Conductivity and Specific Heat for Fuel Node n = N, for $1 \leq m \leq M$

if $\delta_k > 0$, go to I.4

1. If $\frac{T^{(j)}_{N,m,k} + T^{(j)}_{f,m,k}}{2} < T^{Melt}_f$ go to I.3

If $\frac{T^{(j)}_{N,m,k} + T^{(j)}_{f,m,k}}{2} \geq T^{Melt}_{f}$ go to I.2

2. $K^{(j)}_{N,m,k} = K^{Melt}_{f} \left[1 + B_K \left(\frac{T^{(j)}_{f,m,k} + T^{(j)}_{N,m,k}}{2} \right)^2 + C_K \left(\frac{T^{(j)}_{f,m,k} + T^{(j)}_{N,m,k}}{2} \right) \right]$ F***

go to 5

3. $K^{(j)}_{N,m,k} = \left[K^{(0)} + K^{(1)} \frac{T^{(j)}_{f,m,k} + T^{(j)}_{N,m,k}}{2} + K^{(2)} \left(\frac{T^{(j)}_{f,m,k} + T^{(j)}_{N,m,k}}{2} \right)^2 \right]$ F***

4. $K^{(j)}_{N,m,k} = f \left(K'_f, T'_f, \frac{T^{(j)}_{f,m,k} + T^{(j)}_{N,m,k}}{2} \right)$

5. $C^{(j)}_{N,m,k} = f \left(C'_f, T'_f, T^{(j)}_{N,m,k} \right)$

Continue

J. Temperature, Conductivity, and Heat Transfer Coefficient for Fuel Nodes

$n = 1, N - 1.$

If $N = 1$ go to b.1.1 if $R_o = 0.0$, otherwise b.2.1.

If $N > 1$ then

for $1 \leq m \leq M$ and

for $n - 1, N - 1$

set $n = N - 1$ (i.e., $n = N-1, N-2, \ldots 1$)

1. Temperature

a. for $2 \leq n \leq N-1$:

$$E^{(j)}_{n,m,k} = E^{(j-1)}_{n,m,k} + \frac{\tau^{(j)}}{\rho_f C^{(j-1)}_{n,m,k} A_n} \left\{ \bar{Q}^{(j)}_{n,m,k} A_n + \frac{2\Pi K^{(j-1)}_{n-1,m,k}}{(LN)_{n-1}} (T^{(j-1)}_{n-1,m,k} - T^{(j-1)}_{n,m,k}) - \frac{2\Pi K^{(j-1)}_{n,m,k}}{(LN)_n} (T^{(j-1)}_{n,m,k} - T^{(j-1)}_{n+1,m,k}) \right\}$$

b.1.1 For $R_o = 0.0$, $n = 1$

$$E^{(j)}_{n,m,k} = E^{(j-1)}_{n,m,k} + \frac{\tau^{(j)}}{\rho_f \, C^{(j-1)}_{n,m,k} \, A_n} \left\{ \frac{\overline{Q}^{(j)}_{n,m,k} \, A_n}{2} + 4\pi \, K^{(j-1)}_{0,m,k} \left(E^{(j-1)}_{0,m,k} - E^{(j-1)}_{n,m,k} \right) - \frac{2\pi \, K^{(j-1)}_{n,m,k}}{(LN)_n} \left(T^{(j-1)}_{n,m,k} - T^{(j-1)}_{n+1,m,k} \right) \right\}$$

b.1.2 For $R_o = 0.0, n = 0.$

$$E^{(j)}_{0,m,k} = E^{(j-1)}_{0,m,k} + \frac{\tau^{(j)}}{\rho_f \, C^{(j-1)}_{0,m,k} \left(\frac{A_1}{2} \right)} \left\{ \frac{\overline{Q}^{(j)}_{1,m,k} \, A_1}{2} - 4\pi \, K^{(j-1)}_{0,m,k} \left(E^{(j-1)}_{0,m,k} - E^{(j-1)}_{1,m,k} \right) \right\}$$

Go to c.

b.2.1 For $R_o \neq 0.0$, $n = 1$.

$$E^{(j)}_{m,m,k} = (\text{Eq. for } R_o = 0.0,\ n = 1) + \frac{\tau^{(j)}}{\rho_f \, C^{(j-1)}_{n,m,k} \, A_n} \left(\overline{Q}^{(j)}_{n,m,k} \, 2\pi \, R_o^2 \, \ell n \, \frac{r_1}{R_o} \right)$$

b.2.2 For $R_o \neq 0.0$, $n = 0$.

$$E^{(j)}_{0,m,k} = (\text{Eq. for } R_o = 0.0,\ n = 0) - \frac{\tau^{(j)}}{\rho_f \, C^{(j-1)}_{o,m,k} \left(\frac{A_1}{2} \right)} \left(\overline{Q}^{(j)}_{1,m,k} \, 2\pi \, R_o^2 \, \ell n \, \frac{r_1}{R_o} \right)$$

c. If $E^{(j)}_{n,m,k} > T^{Melt}_f$ go to J.1.e

If $E^{(j)}_{n,m,k} \leq T^{Melt}_f$ go to J.1.d

d. $T^{(j)}_{n,m,k} = E^{(j)}_{n,m,k}$

Go to J.1.h

e. If $E^{(j)}_{n,m,k} > T^{Melt}_f + \frac{B^{Melt}}{\rho_f C^{Melt}}$ go to J.1.f

If $E^{(j)}_{n,m,k} \leq T_f^{Melt} + \frac{B^{Melt}}{\rho_f C^{Melt}}$ go to J.1.g

f. $T^{(j)}_{n,m,k} = E^{(j)}_{n,m,k} - \frac{B^{Melt}}{\rho_f C^{Melt}}$

Go to J.1.h

g. $T^{(j)}_{n,m,k} = T_f^{Melt}$

if $\delta_k > 0$, go to J.2.c, otherwise contine

h. If $\frac{T^{(j)}_{n+1,m,k} + T^{(j)}_{n,m,k}}{2} \geq T_f^{Melt}$ go to J.2.a

If $\frac{T^{(j)}_{n+1,m,k} + T^{(j)}_{n,m,k}}{2} < T_f^{Melt}$ go to J.2.b

2. Fuel Conductivity for Fuel Nodes n = 0, N-1

a. $K^{(j)}_{n,m,k} = K_f^{Melt} \left[1 + B_K \left(\frac{T^{(j)}_{n+1,m,k} + T^{(j)}_{n,m,k}}{2} \right) + C_K \left(\frac{T^{(j)}_{n+1,m,k} + T^{(j)}_{n,m,k}}{2} \right)^2 \right]$ F***

go to J.3

b. $K^{(j)}_{n,m,k} = K^{(0)} + K^{(1)} \left(\frac{T^{(j)}_{n+1,m,k} + T^{(j)}_{n,m,k}}{2} \right) + K^{(2)} \left(\frac{T^{(j)}_{n+1,m,k} + T^{(j)}_{n,m,k}}{2} \right)^2$ F***

go to J.3

c. $K^{(j)}_{n,m,k} = f\left(K_f', T_f', \frac{T^{(j)}_{n+1,m,k} + T^{(j)}_{n,m,k}}{2}\right)$

Continue

3. Specific Heat for Fuel Nodes n=1, N-1

a. If $T^{(j)}_{n,m,k} \geq T^{Melt}_{f}$

$$C^{(j)}_{n,m,k} = C^{Melt}$$

Go to J.4

b. If $T^{(j)}_{n,m,k} \leq T^{Melt}_{f}$

$$C^{(j)}_{n,m,k} = f\ (C'_f,\ T'_f,\ T^{(j)}_{n,m,k})$$

4. End of Loop on m.

K. Clad-surface Heat Flux

for $1 \leq m \leq M$

If $\delta_c = 0$, go to L.1

If $\delta_c \neq 0$, go to L.2

1. $$Q^{(j)}_{h,m,k} = (T^{(j-1)}_{f,m,k} - \overline{T}^{(j-1)}_{c,m,k}) \frac{1}{\frac{Q^{(j-1)}_{f,m,k} A_f}{Q^{(j-1)}_{f,m,k} A_f + Q^{(j-1)}_{e,m,k} A_e} \left(\frac{2 R_E}{C^{(j-1)}_{g,m,k} (R_f + R_e)} \right) + \left[\frac{R_E \ell n \frac{R_E}{R_e}}{k_e} + \frac{1}{h^{*(j-1)}_{c,m,k}} \right]}$$

   Go to M.

2. $$Q^{(j)}_{h,m,k} = h^{(j-1)}_{c,m,k} (T^{(j-1)}_{E,m,k} - \overline{T}^{(j-1)}_{c,m,k})$$

L. Average Fuel Temperature

$$\overline{T}^{(j)}_{f,m,k} = \frac{\sum_{n=1}^{N} T^{(j)}_{n,m,k} A_n}{A_f}$$

M. Fuel-Clad Gap, Conductivity and Heat Transfer Coefficient

for $1 \leq m \leq M$

1. Melting indicator

   for $1 \leq n \leq N$

   If $T^{(j)}_{n,m,k} \geqslant T^{Melt}_f$, set $\delta^{(j)}_{n,m,k} = 1$

   If $T^{(j)}_{n,m,k} < T^{Melt}_f$, set $\delta^{(j)}_{n,m,k} = 0$

2. Find fractional linear thermal expansion of the clad and fuel

$$\left(\frac{\Delta L}{L}\right)^{(j)}_{e,m,k} = E^{(0)}_e + E^{(1)}_e \overline{T}^{(j)}_{e,m,k} + E^{(2)}_e (\overline{T}^{(j)}_{e,m,k})^2$$

$$\left(\frac{\Delta L}{L}\right)^{(j)}_{f,m,k} = E^{(0)}_f + E^{(1)}_f \overline{T}^{(j)}_{f,m,k} + E^{(2)}_f (\overline{T}^{(j)}_{f,m,k})^2$$

3. Constant or variable gap conductivity

   a. If $\delta_{gap} = 0$ go to N.4

   b. If $\delta_{gap} \neq 0$ go to N.5

4. $$C^{(j)}_{g,m,k} = h_f \quad F^{**}$$

   go to N.17

5. If $T^{(j)}_{f,m,k} \geq T^{Melt}_f$ go to N.6

   If $T^{(j)}_{f,m,k} < T^{Melt}_f$ go to N.7

6. $C_{g,m,k}^{(j)} = h_f \quad F^{**}$

Go to N.17

7. If $R_o \neq 0$, go to N.7.b

If $R_o = 0$, go to N.7.a

a. $$\Delta\phi_{m,k}^{(j)} = \Delta\phi_{m,k}^{(0)} + R_e \left[\left(\frac{\Delta L}{L}\right)_{e,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{e,m,k}^{(0)} \right] - R_f \left[\left(\frac{\Delta L}{L}\right)_{f,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{f,m,k}^{(0)} \right]$$

$$- \frac{1}{A_f} \left(\sum_{n=1}^{N} \left[\delta_{n,m,k}^{Melt(j)} - \delta_{n,m,k}^{Melt(0)} \right] A_n \right)$$

Go to N.8

b. If $\Delta V^{Melt} \sum_{n=1}^{N} \delta_{n,m,k}^{Melt(o)} > \Pi R_o^2$, go to (3)

If $\Delta V^{Melt} \sum_{n=1}^{N} \delta_{n,m,k}^{Melt(o)} A_n \leq \Pi R_o^2$ and

If $\Delta V^{Melt} \sum_{n=1}^{N} \delta_{n,m,k}^{Melt(j)} A_n > \Pi R_o^2$, go to (1)

If $\Delta V^{Melt} \sum_{n=1}^{N} \delta_{n,m,k}^{Melt(j)} A_n \leq \Pi R_o^2$, go to (2)

(1) $$\Delta\phi_{m,k}^{(j)} = \Delta\phi_{m,k}^{(0)} + R_e \left[\left(\frac{\Delta L}{L}\right)_{e,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{e,m,k}^{(0)} \right] - R_f \left[\left(\frac{\Delta L}{L}\right)_{f,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{f,m,k}^{(0)} \right]$$

$$- \frac{1}{A_f} \left[\frac{\overline{\Delta V^{Melt}} R_f}{2} - \frac{(\Delta V^{Melt}+1) R_o^2}{2 R_f} \right] \sum_{n=1}^{N} \delta_{n,m,k}^{Melt(j)} A_n$$

Go to N.8

(2) $$\Delta\phi_{m,k}^{(j)} = \Delta\phi_{m,k}^{(0)} + R_e \left[\left(\frac{\Delta L}{L}\right)_{e,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{e,m,k}^{(0)} \right] - R_f \left[\left(\frac{\Delta L}{L}\right)_{f,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{f,m,k}^{(0)} \right]$$

Go to N.8

(3) If $\Delta V^{Melt} \sum_{n=1}^{N} \delta_{n,m,k}^{Melt(j)} A_n \leq \pi R_o^2$, go to (4)

$$\Delta\phi_{m,k}^{(j)} = \Delta\phi_{m,k}^{(0)} + R_e \left[\left(\frac{\Delta L}{L}\right)_{e,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{e,m,k}^{(0)} \right] - R_f \left[\left(\frac{\Delta L}{L}\right)_{f,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{f,m,k}^{(0)} \right]$$

$$- \frac{1}{A_f} \left[\frac{\overline{\Delta V^{Melt}} R_f}{2} - \frac{(\Delta V^{Melt}+1) R_o^2}{2 R_f} \right] \sum_{n=1}^{N} \left[\delta_{n,m,k}^{Melt(j)} - \delta_{n,m,k}^{Melt(o)} \right] A_n$$

Go to N.8

(4) $$\Delta\phi_{m,k}^{(j)} = \Delta\phi_{m,k}^{(0)} + R_e \left[\left(\frac{\Delta L}{L}\right)_{e,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{e,m,k}^{(0)} \right] - R_f \left[\left(\frac{\Delta L}{L}\right)_{f,m,k}^{(j)} - \left(\frac{\Delta L}{L}\right)_{f,m,k}^{(0)} \right]$$

$$+ \frac{1}{A_f} \left[\frac{\overline{\Delta V^{Melt}} R_f}{2} - \frac{(\Delta V^{Melt}+1) R_o^2}{2 R_f} \right] \sum_{n=1}^{N} \delta_{n,m,k}^{(o)} A_n$$

Go to N.8

8. If $\Delta\phi_{m,k}^{(j)} > 0$ go to N.9

   If $\Delta\phi_{m,k}^{(j)} \leq 0$ go to N.10

9. $P_{m,k}^{(j)} = 0$

   $\delta_{g,m,k}^{(j)} = \Delta\phi_{m,k}^{(j)} + \beta_o (\delta_f + \delta_e)$

   If $\delta_c = 0$, go to N.14

   If $\delta_c \neq 0$, go to N.15

10. $$P_{m,k}^{(j)} = \frac{-\Delta\phi_{m,k}^{(j)} \; E_e \; (R_E - R_e)(144)}{R_a^2 \; (1 - \nu/2)}$$

If $P_{m,k}^{(i)} \quad P_{max}$. then set $P_{m,k}^{(i)} = P_{max}$

where $P_{max} = \frac{\sigma_{Y.P} \; (R_E - R_e) \; 144}{R_e}$

11. $$K_{m,k}^{(i)} = \frac{2 \; (K_{N,m,k}^{(\cdot)}) K_e}{K_{N,m,k}^{(i)} + K_e}$$

12. If $\Delta\phi_{m,k}^{(i)} > 0.0$ then

$$\delta_{g,m,k}^{(j)} = \Delta\phi_{m,k}^{(i)} + \beta_o \; (\delta_f + \delta_e)$$

Go to N.14

13. If $\Delta\phi_{m,k}^{(j)} \leq 0.0$ then

$$\delta_{g,m,k}^{(j)} = \beta_o \; (\delta_f + \delta_e)$$

14. If $\delta_c = 0$ then

$$K_{g,m,k}^{(j)} = A_g + B_g \left(\frac{\overline{T}_{e,m,k}^{(i)} + T_{f,m,k}^{(j)}}{2} \right) + C_g \left(\frac{\overline{T}_{e,m,k}^{(i)} + T_{f,m,k}^{(j)}}{2} \right)^2$$

Go to N.16

15. If $\delta_c \neq 0$ then

$$K_{g,m,k}^{(i)} = A_g + B_g \left(\frac{T_{e,m,k}^{(i)} + T_{f,m,k}^{(j)}}{2} \right) + C_g \left(\frac{T_{e,m,k}^{(j)} + T_{f,m,k}^{(i)}}{2} \right)^2$$

16. $$C_{g,m,k}^{(j)} = \left[\frac{K_{m,k}^{(j)} \; P_{m,k}^{(j)}}{a_o \; \sqrt{\delta} \; \varphi} + \frac{K_{g,m,k}^{(j)}}{\delta_{g,m,k}^{(j)} + (g_f + g_e)} \right]$$ F**

17. End of loop on m

N. Core Energy

1. Net Energy Removal From Core Since Time 0

a. $$\overline{Q}_{Out}^{(j)} = A_c \; \overline{G}_c^{(j)} \; \overline{C}_c^{(j)} \; [\overline{T}_c^{(j)Outlet} - \overline{T}_c^{(j)Inlet}] \; \frac{P_{in}}{\overline{Q}_{Out}^{(0)}}$$

where $$\overline{T}_c^{(j)Outlet} = \frac{T_{c,1}^{(j)Out} + T_{c,1}^{(j-1)Out}}{2}$$

$$\overline{T}_c^{(j)Inlet} = \frac{T_c^{(j)Inlet} + T_c^{(j-1)Inlet}}{2}$$

$$\overline{C}_c^{(j)} = f\left(\frac{\overline{T}_c^{(j)Outlet} + \overline{T}_c^{(j)Inlet}}{2} \right)$$

$$\overline{G}_c^{(j)} = \frac{G_{c,1}^{(j-1)} + G_{c,1}^{(j)}}{2}$$

b. $$E_{Out}^{(j)} = E_{Out}^{(j-1)} + \tau^{(j)} \; \overline{Q}_{Out}^{(j)}$$

2. Nuclear Energy Addition to Core since time 0

$$E_{IN}^{(j)} = E_{IN}^{(j-1)} + \tau^{(j)} \; \overline{P}_j \; V_{f/948.05}$$

3. Change in Core Energy Density since time 0.

$$\Delta E_{CORE}^{(j)} = \frac{E_{IN}^{(j)} - F^{(j)}}{V_{CORE}}$$

0. Evaluate $\overline{\rho}_{c,k}$ and $\overline{\rho}_c^{\,Inlet}$ by linear interpolation

$$1 \leq k \leq K$$

1. $\overline{\rho}_{c,k} = f\ (\rho_c', T_c', \overline{T}_{c,k})$

2. $\rho_c^{Inlet} = f\ (\rho_c', T_c', T_c^{Inlet})$

SUBROUTINE STAB

FUNCTION

This subroutine calculates, for each of the materials, (fuel, clad, coolant, additional material) the maximum step size required to prevent instability or oscillations in their temperatures. It compares these step sizes and selects the smallest one. This is done for each new time step.

PROCEDURE

A. Calculate the maximum time step to insure stability of clad temperatures.

If k=1, set $\tau^{(j)}$ = 25.0 (arbitarily large number)

If $\delta_c \neq 0$, go to A.1

If $\delta_c = 0$, go to A.3

1. For k = 1 and 2

$$\tau_{e,m,k} = \frac{\overline{\rho_e}\, C_e\, A_e}{\left(\frac{\ell n \frac{R_f}{r_N}}{2\pi K_{N,m,k}^{(j-1)}} + \frac{1}{\pi (R_f + R_e)\, C_{g,m,k}^{(j-1)}} + \frac{\ell n \frac{R_a}{R_e}}{2\pi K_e}\right) + \left(\frac{\ell n \frac{R_E}{R_a}}{2\pi K_e} + \frac{1}{2\pi K_E\, h_{c,m,k}^{(j-1)}}\right)}$$

Calculate A.2 only if K=3

2. For k=3

$\tau_{e,m,k}$ = Same equation as A.1 with K_e replaced by $K_e F_e$ where F_e is the hot spot factor for the thermal conductivity of the clad.

Search all elements for the smallest value and compare with $\tau^{(j)}$. If less than, replace value in $\tau^{(j)}$.

3. If $\delta_c = 0$, go to B.2

If $\delta_c \neq 0$, check $\delta_{coolant}$

If $\delta_{coolant} > 0$, go to C

If $\delta_{coolant} = 0$, go to B.1

B. Calculate the maximum time step to insure stability of coolant temperatures

1. If $\delta_c \neq 0$:

for $1 \leq m \leq M$

$$\tau^{(j)}_{c,m,k} = \frac{1}{DENOM}$$

where DENOM:

$$\frac{1}{\left(\frac{1}{2\pi R_E h^{(j-1)}_{c,m,k}} + \frac{\ln\frac{R_E}{R_a}}{2\pi K_e}\right)\rho^{(j-1)}_{c,m,k} C^{(j-1)}_{c,m,k} A_c} + \frac{G^{(j-1)}_{c,k}}{\rho^{(j-1)}_{c,m,k}(\Delta Z)_m \lambda_a} + \frac{V_s G_s}{\rho^{(j-1)}_{c,m,k} C^{(j-1)}_{c,m,k} A_c \left(\frac{1}{h^{(j-1)}_{c,m,k}} + \frac{d_s}{K_s}\right)}$$

$$+ \frac{V_u G_u}{\rho^{(j-1)}_{c,m,k} C^{(j-1)}_{c,m,k} A_c \left(\frac{1}{h^{(j-1)}_{c,m,k}} + \frac{d_u}{K_u}\right)}$$

Compare each value calculated with $\tau^{(j)}$, resulting in the smallest value being set equal to $\tau^{(j)}$

Go to C.

2. If $\delta_c = 0$

for $1 \leq m \leq M$

$$\tau^{(j)}_{c,m,k} = \frac{1}{DENOM}$$

where DENOM $= \left[\frac{1}{(\rho_e C_e A_e)+(\rho^{(j-1)}_{c,m,k} C^{(j-1)}_{c,m,k} A_c)+(\rho_s V_s G_s)+(\rho_u V_u G_u)}\right]$

$$\frac{1}{\left(\frac{\ell n \frac{R_E}{R_e}}{2\pi K_e} + \frac{1}{2\pi R_E h^{*(j-1)}_{c,m,k}}\right) + \left(\frac{\bar{Q}^{(j)}_{f,m,k} A_f}{\bar{Q}^{(j)}_{f,m,k} A_f + \bar{Q}^{(j)}_{e,m,k} A_e}\right)\left(\frac{1}{\pi(R_f+R_e) C^{(j-1)}_{g,m,k}} + \frac{\ell n \frac{R_f}{r_n}}{2\pi K^{(j-1)}_{N,m,k}}\right)}$$

$$+ \frac{G^{(j-1)}_{c,m,k} C^{(j-1)}_{c,m,k} A_c}{(\Delta Z_m) \lambda_a}$$

Search for the smallest value and place it in $\tau^{(j)}$.

Go to C.

C. To insure stability in structure temperatures

1. If $G_s = 0$, go to D.

2. If $G_s \neq 0$

for $1 \leq m \leq M$

$$\tau^{(j)}_{s,m,k} = \frac{\rho_s C_s}{G_s}\left(\frac{1}{g^{(j-1)}_{c,m,k}} + \frac{d_s}{K_s}\right)$$

Search all elements for the smallest value and compare with $\tau^{(j)}$. If less than, replace value in $\tau^{(j)}$. Go to D.

D. To insure stability in temperatures of additional material

1. If $G_u = 0$, go to E

2. If $G_u \neq 0$

for $1 \leq m \leq M$

$$\tau^{(j-1)}_{u,m,k} = \frac{\rho_u C_u}{G_u}\left(\frac{1}{g^{(j-1)}_{c,m,k}} + \frac{d_u}{K_u}\right)$$

Search all elements for the smallest value and compare with $\tau^{(j)}$. If less than, replace value in $\tau^{(j)}$.

Go to E.

E. To insure stability in fuel boundary node temperatures:

for $1 \leq m \leq M$

For $\delta_c \neq 0$

$$\tau^{(j)}_{N,m,k} = \frac{\rho_f C^{(j-1)}_{N,m,k} A_N}{\frac{2\pi K^{(j-1)}_{n-1,m,k}}{(LN)_{N-1}} + \left(\frac{1}{\frac{\ell n \frac{R_f}{r_N}}{2\pi K^{(j-1)}_{N,m,k}} + \frac{1}{\pi(R_f+R_e) C^{(j-1)}_{g,m,k}} + \frac{\ell n \frac{R_a}{R_e}}{2\pi K_e}}\right)}$$

For $\delta_c \neq 0$

$$\tau^{(j)}_{N,m,k} = \frac{\rho_f \, C^{(j-1)}_{N,m,k} \, A_N}{\frac{2\pi \, K^{(j-1)}_{N-1,m,k}}{(LN)_{N-1}} + \text{CONSTI}}$$

where CONSTI is

$$\text{CONSTI} = \frac{1}{\left(\frac{\bar{Q}^{(j)}_{f,m,k} \, A_f + \bar{Q}^{(j)}_{e,m,k} \, A_e}{\bar{Q}^{(j)}_{f,m,k} \, A_f}\right)\left(\frac{\ell n \, \frac{R_E}{R_e}}{2\pi \, K_e} + \frac{1}{2\pi \, R_E \, h^{*(j-1)}_{c,m,k}}\right) + \frac{1}{\pi (R_f + R_e) \, C^{(j-1)}_{g,m,k}} + \frac{\ell n \, \frac{R_f}{r_N}}{2\pi \, K^{(j-1)}_{N,m,k}}}$$

F. To insure stability in fuel temperatures for nodes $2 \leq n \leq N-1$:

for $1 \leq m \leq M$

$$\tau^{(j)}_{n,m,k} = \frac{\rho_f \, C^{(j-1)}_{n,m,k} \, A_n}{\frac{2\pi \, K^{(j-1)}_{n-1,m,k}}{(LN)_{n-1}} + \frac{2\pi \, K^{(j-1)}_{n,m,k}}{(LN)_n}}$$

G. To insure stability in fuel nodes 1 and 0

for $1 \leq m \leq M$

$$\tau^{(j)}_{1,m,k} = \frac{\rho_f \, C^{(j-1)}_{1,m,k} \, A_1}{\frac{2\pi \, K^{(j-1)}_{1,m,k}}{(LN)_1} + 4\pi \, K^{(j-1)}_{0,m,k}}$$

$$\tau^{(j)}_{0,m,k} = \frac{\rho_f C^{(j-1)}_{0,m,k} \, A_1}{8\pi \, K^{(j-1)}_{0,m,k}}$$

Search $\tau^{(j)}_{n,m,k}$ for $0 \leq n \leq N$, $1 \leq m \leq M$ and if any less than $\tau^{(j)}$, replace value in $\tau^{(j)}$

H. If $\delta_{step} = 0$, go to J.

If $\delta_{step} \neq 0$: go to I.1

1. If user's step size $\leq \tau^{(j)}$

   a. If J > 2, go to I.3

   b. If J = 2, set $\tau_{dif} = 0.0$

      Go to I.3

2. If user's step size > $\tau^{(j)}$

   a. If J = 2, set τ_{dif} = HMAX - $\tau^{(j)}$

      Go to I.3

   b. If J > 2

      (1) If (HMAX-$\tau^{(j)}$)$\leq$ τ_{dif}, go to I.3

      (2) If (HMAX -$\tau^{(j)}$)> τ_{dif}, set τ_{dif} = HMAX-$\tau^{(j)}$

          Go to I.3

3. Set $\tau^{(j)}$ = HMAX

I. End of STAB

SUBROUTINE TERM

FUNCTION

This subroutine checks to determine if any one of the terminating criteria has been reached or exceeded. There are limits on the following: problem time, number of time steps, coolant temperature, fuel temperature, and calculated computer time limit.

PROCEDURE

A. Check limit on number of time steps

If $j < J$, go to B

If $j \geq J$, go to E.1

B. Check limit on problem time

If $t < T$, go to C

If $t \geq T$, go to E.1

C. Check upper and lower limits on the coolant temperature, fuel node 1 temperature and fuel boundary temperature.

Determine channel to which temperature limits should be applied:

If $k_{term} = 0$ or 1, average channel will be used.

If $k_{term} = 2$, peak channel will be used.

If $k_{term} = 3$, hot spot channel will be used.

1. Fuel node 1:

a. If $T_1^{Max} > T_{1,m,k=1,2or3}^{(j)}$, go to C.1.b

If $T_1^{Max} \leq T_{1,m,k=1,2or3}^{(j)}$, go to E.1

b. If $T_1^{Min} \geq T_{1,m,k=1,2or3}^{(j)}$, go to E.1

If $T_1^{Min} < T_{1,m,k=1,2or3}^{(j)}$, go to C.2

2. Fuel boundary:

   a. If $T_1^{Max} > T^{(j)}_{N,m,k=1,2or3}$, go to C.2.b

      If $T_N^{Max} \leq T^{(j)}_{N,m,k=1,2or3}$, go to E.1

   b. If $T_N^{Min} \geq T^{(j)}_{N,m,k=1,2or3}$, go to E.1

      If $T_N^{Min} < T^{(j)}_{N,m,k=1,2or3}$, go to C.3

3. Coolant:

   a. If $T_c^{Max} > T^{Out(j)}_{k=1,2or3}$ or $T^{(j)}_{c,m,k=1,2or3}$, go to C.2.b

      If $T_c^{Max} \leq T^{Out(j)}_{k=1,2or3}$ or $T^{(j)}_{c,m,k=1,2or3}$, go to E.1

   b. If $T_c^{Min} \geq T^{Out(j)}_{k=1,2or3}$ or $T^{(j)}_{c,m,k=1,2or3}$, go to E.1

      If $T_c^{Min} < T^{(j)}_{k=1,2or3}$ or $T^{(j)}_{c,m,k=1,2or3}$, go to D

D. Check Toggle 5 for Operator Force-off because calculated time limit was reached or exceeded

   If Toggle 5 up, go to E.1

   Otherwise, go to E.2

E. Set termination indicator

   1. Problem should be terminated

      Set $\delta_{end} = 1$

   2. Problem should not be terminated

      Set $\delta_{end} = 0$

F. End of TERM

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