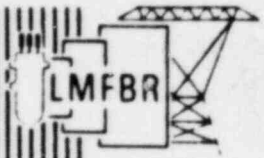


CRBRP-ARD-0257

Clinch River Breeder Reactor Plant Nuclear Island

SUPPLEMENTARY MANUAL FOR THE FØRE-2M COMPUTER PROGRAM

SEPTEMBER 1982

Prepared for the Project Management Corporation as part of the U.S. Energy Research and Development Administration Liquid Metal Fast Breeder Reactor Demonstration Program

Westinghouse Electric Corporation
ADVANCED REACTORS DIVISION
BOX 158
MADISON, PENNSYLVANIA 15663

6279-2

CRBRP-ARD-0257

SUPPLEMENTARY MANUAL FOR THE FORE-2M COMPUTER PROGRAM

SEPTEMBER, 1982

J. V. Miller*
R. D. Coffield
K. D. Daschke
J. S. Killimayer
H. C. Anderson, III
T. R. Reid

Approved by: R. A. Markley
R. A. Markley, Manager
LMFBR Core T&H Analysis

*Westinghouse Nuclear Technology Division
P.O. Box 355
Pittsburgh, Pennsylvania 15230

0243E-58E:2
(S1320) 1

ABSTRACT

FØRE-2M is a coupled thermal-hydraulics point-kinetics digital computer code designed to calculate significant reactor core parameters under steady state conditions or as functions of time during transients. 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. Various Plant Protection System trip functions can be simulated, and the control rod shutdown worth prescribed as a function of time from the trip signal. By specifying appropriate hot channel/hot spot factors, the transient behavior of an average, peak and hot fuel rod can be analyzed. The heat of fusion accompanying fuel melting and the spatial/time variation of the fuel-cladding gap coefficient (e.g., due to changes in gap size) are considered. The feedback reactivity includes contributions due to the Doppler effect, coolant density changes and dimensional changes (includes bowing and radial expansion). FØRE-2M is valid while the core retains its initial geometry.

The original FØRE-II computer model[1] was renamed FØRE-2M following the incorporation of several major changes which were made to the program.[2] Since then, additional modifications have been made to the FØRE-2M model. These include updated modeling of gap conductance heat transfer, changes affecting material properties, modifications in transient coolant flow characteristics, simulation of inter- and intra-assembly flow and heat redistribution, reactivity feedback and decay heat modifications, model changes to allow for alternate fuel rod characteristics, program corrections and program improvements to provide user flexibility. These changes are described in this supplementary manual. The required input variables associated with these changes are also presented.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

1.0 INTRODUCTION

The purpose of this report is to describe changes which have recently been made to the FØRE-2M computer program. These changes were made to incorporate additional models and/or to provide a greater degree of flexibility to the user of the program and, in general, do not affect the basic models and calculation methods. The information contained in the original FØRE-II document[1] and in the subsequent document[2] which described early modifications to program is therefore still applicable.

Revisions which have been made to the program cover a wide variety of subjects. To facilitate locating changes related to a specific topic, the discussions of the modifications have been grouped into several major categories. Each of these categories comprises a separate section of this report. For example, there is a section dealing with gap conductance heat transfer (Section 3) in which several modifications related to this subject have been grouped. Likewise, there are separate sections dealing with changes to material properties, coolant flow characteristics, reactivity feedback, etc. (Sections 4 to 8).

Other changes described in the report (Section 9) deal with corrections to programming errors or revisions in the derivation of basic equations. These errors were generally conservative in nature and did not have an appreciable impact on the calculations.

Several of the modifications made to the FØRE-2M program have been included in provide the user with a greater degree of freedom in manipulating the output from the program or for making input modifications during the course of the transient without resorting to the stop and RESTART option. These changes are described in Section 10.

Section 2.0 of the report lists all of the input data variables which have been affected by the modifications. Appendix A of the report is the complete input data list. There are on the order of 1700-1800 separate input variables available for the FØRE-2M program. While these many input variables may appear to offer an impossible task to the user in setting up a problem, it

should be noted that a typical problem uses only a fraction of these variables. The large number of input variable available results from the many possible options contained in the program. Once a base deck has been established which describes the geometry of the reactor being considered, only a few variables are changed each time a different type of transient is studied.

Another factor which reduces the number of input variables actually required for a given problem is that any zero values need not be specified. Since the input storage locations are all automatically set equal to zero at the start of the problem, only non-zero inputs need be listed. Therefore, although the input data list appears formidable at first glance, the frequent user of the program will soon discover that the amount of input data actually required for a given problem is quite manageable.

2.0 INPUT VARIABLES AFFECTED BY PROGRAM MODIFICATIONS

This section contains a list and brief description of all the input variables which have been affected by the modifications to the FØRE-2M program. A complete listing of all input variables is contained in Appendix A. As noted in the INTRODUCTION of this report, the amount of input data actually required for a specific case is generally much smaller than would be indicated by the number of possible input variables which are available. This is because there is a rather wide range of options in the FØRE-2M program, many of which will not be used for any given problem.

A complete description of the model changes which have affected the variables listed on Table 1 is given in Sections 3 through 10.

TABLE 1

INPUT VARIABLES AFFECTED BY MODEL CHANGES

Input Number	Input Variable	Description of Change
20	δ_{gap}	Several new options on variable gap conductance have been added.
22	δ_k	A new option (δ_k=3) on "fuel" thermal conductivity has been added to cover the analysis of B_4C control rods and a new Pu-UO_2 equation from TID-26666(3) has been added (δ_k=4).
31	δ_S	Option for simulating inter- and intra-assembly flow and heat redistribution (δ_S=1).
32	N_S	Option on number of alternate power shapes. (If N_S=1, an alternate axial power shape is supplied for Channel 3; Input 8182)
58	$\delta\Delta p$	A new option ($\delta\Delta p$=-2) has been added which allows individual flow coastdown to be specified for each channel.
357	EMISF	A new variable, emissivity of the fuel, has been added.
358	EMISC	A new variable, emissivity of the cladding, has been added.
827-847	F_h	If the new input 20 option (δ_{gap}=2) is used, the axial correction factors on gap conductance are now read in as the actual gap conductance in Btu/hr-ft^2-^{o}F.
848	TSWAP	New option on changing axial power shape during problem. TSWAP is time (in seconds) at which alternate axial power shape (INPUT 849-855) becomes effective.
849-855	ALTPØW(M)	Alternate power factor for axial sections 1 through 7 (see Section 10.1 of the text).
856	TJACK	New option on changing printout time. TJACK is time (in seconds) at which PJACK (INPUT 857) becomes effective.
857	PJACK	For time equal to or greater than TJACK (INPUT 856), this parameter becomes the maximum time between printouts in place of PMAX (INPUT 71).

TABLE 1 (Continued)

Input Number	Input Variable	Description of Change
948-954 955-961 962-968	RGAP(M,1) RGAP(M,2) RGAP(M,3)	If the new Input 20 options are used, axial variations in radial gap size may be specified in inches (see Table 2).
969	ØE(69)	Option indicator on fuel conductivity hot channel factor. If ØE(69) > 0.0, axial variations in hot channel factors on fuel conductivity will be used.
970-976 1181-1187 1188-1194	FCØN(M,1) FCØN(M,2) FCØN(M,3)	If Input 969 is greater than zero, axial variations in the hot channel factor on fuel conductivity are specified (default value is 1.0).
7768	IXIND	Option for alternate geometry for Channel 3. If IXIND=1, Inputs 7769 through 7790 and 8190 through 8206 must be supplied.*
7769	XRACL	Equivalent radius of coolant for alternate geometry.
7700	XRACD	Cladding inner radius for alternate geometry.
7771	XRACS	Cladding outer radius for alternate geometry.
7772-7781	XRAND (up to 10 values)	Outer radius of fuel nodes n for alternate geometry; 1 < n < NMAX.
7782	XRAVDØ	Radius of the central void for alternate geometry
7783	XVØST	Volume of structure per unit length for alternate geometry.
7784	XVØMT	Volume of additional material per unit volume for alternate geometry.
7785	XDIHY	Hydraulic diameter for alternate geometry.
7786	XDHT	Appropriate hydraulic diameter for calculating coolant heat transfer for alternate geometry.
7787	XDIST	Characteristic structural dimension for alternate geometry.

*All geometric dimensions are in the same units as used in original FØRE-II program.(1)

TABLE 1 (Continued)

Input Number	Input Variable	Description of Change
7788	XDIMT	Characteristic structural dimension for alternate geometry.
7789	XGST	Structure surface-to-volume ratio of alternate geometry.
7790	XGMT	Additional material surface-to-volume ratio for alternate geometry.
7791-7797	PS_m	Axial variation in hot spot factor on heat generation for the alternate power shape in Channel 3 (Inputs 8182-8188)*
7798	IFEEB	Option on alternate Doppler and coolant density reactivity feedback. (If IFEEB=1, inputs 8140 to 8160 and 8161 to 8181 must be supplied).
7799	IPUMP	Option on pump trip. If IPUMP=1, flow coastdowns begin at time of scram plus pump delay (Input 8189).
7800-7819	TIMEZ (up to 20 values)	Table of times (seconds) for flow coast-down values for Channel 2 and Channel 3 (Inputs 7820-7839 and 7840-7859). First value must be equal to 0.0.
7820-7839	GPEAK (up to 20 values)	Normalized values of flow coastdown for Channel 2 corresponding to values of TIMEZ.
7840-7859	GHØT (up to 20 values)	Normalized values of flow coastdown for Channel 3 corresponding to values of TIMEZ.
7860-7879	$(G/G_{in})_1$ (up to 20 values)	Values of local flow rate in axial Section 1 of Channel 3 relative to inlet flow of Channel 3. Values correspond to times specified in TIMEZ (Input 7800-7819)
7880-7899	$(G/G_{in})_2$	Same as 7860-7879 but for axial Section 2
7900-7919	$(G/G_{in})_3$ (up to 20 values)	Same as 7860-7879 but for axial Section 3

*If any value of PS_m is equal to zero, a value of 1.0 will be used.

TABLE 1 (Continued)

Input Number	Input Variable	Description of Change
7920-7939	$(G/G_{in})_4$	(As above but for Section 4)
7940-7959	$(G/G_{in})_5$	(As above but for Section 5)
7960-7979	$(G/G_{in})_6$	(As above but for Section 6)
7980-7999	$(G/G_{in})_7$	(As above but for Section 7)
8000-8019	QEXS (up to 20 values)	Excess energy (BTU/sec) supplied to axial Section 1 of Channel 3. Values correspond to times specified in TIMEZ (Inputs 7800-7819)
8020-8039	"	(As above but for Section 2)
8040-8059	"	(As above but for Section 3)
8060-8079	"	(As above but for Section 4)
8080-8099	"	(As above but for Section 5)
8100-8119	"	(As above but for Section 6)
8120-8139	"	(As above but for Section 7)
8140-8146	FDØP(M,1)	Alternate Doppler coefficient for Channel 1 axial Section 1 to 7
8147-8153	FDØP(M,2)	(As above for Channel 2)
8154-8160	FDØP(M,3)	(As above for Channel 3)
8161-8167	CØFBK(M,1)	Alternate coolant density reactivity feedback coefficient for Channel 1, Axial Section 1 to 7
8168-8174	CØFBK(M,2)	(As above for Channel 2)
8175-8181	CØFBK(M,3)	(As above for Channel 3)
8182-8188	XPØWR(M)	Alternate axial power shape for Channel 3. ($1 \leq M \leq MMAX$)
8189	TPUMP	Pump trip delay (seconds); value added to scram time to determine flow coastdown if IPUMP = 1
8190	XRHØFL	Density of fuel (lbs/ft^3) for alternate geometry

TABLE 1 (Continued)

Input Number	Input Variable	Description of Change
8191	XLIQ	Liquidus temperature for alternate geometry
8192	XSØLID	Solidus temperature for alternate geometry
8193	XCAH	Constants used in coolant heat transfer coefficient equation (see Inputs 321 to 332, Appendix A)
8194	XCBH	
8195-8201	XCCH(M)	
8202	XCHM	
8203	XCNH	
8204	XCRH	
8205	XRHØ1	Fractional density of as-manufactured fuel for alternate geometry
8206	XRHØ2	Fractional density of sintered fuel for alternate geometry
8207	IDECAY	Option for alternate decay heat model (IDECAY=1)
8208	IREG	Option of using core or Channel K as reactor power indicator. If IREG=0, core average power is used; if IREG=K, Channel K power is used. (K=1, 2 or 3).
8209-8211	FREG(K)	Fractional power of reactor associated with regions corresponding to Channels 1, 2 and 3. $\sum_{k=1}^{3} r_{REG}(K)=1.0$
8212-8231	TDECAY (up to 20 values)	Times (seconds) at which decay heat for individual channels will be specified
8232-8251	PDECAY(1) (up to 20 values)	Fraction of power attributed to decay heat for Channel 1 for times corresponding to TDECAY.
8252-8271	PDECAY(2) (up to 20 values)	Decay power values for Channel 2.

TABLE 1 (Continued)

Input Number	Input Variable	Description of Change
8272-8291	PDECAY(3) (up to 20 values)	Decay power values for Channel 3.
8282	IXCP	Channel to which alternate specific heat of fuel applies.
8293-8312	XCPFIT (up to 20 values)	Alternate fuel specific heat table (Btu/lb-^{o}F).
8313-8332	XTEMP (up to 20 values)	Temperature (^{o}F) corresponding to alternate specific heat table.
8333	ISPEC	Option for selecting special reactivity feedback subroutine.*
8334	IREX	Index to determine which channel (i.e., 1, 2 or 3) will be used with Inputs 165 and 320.
8335	ISTART	Indicator for start of decay heat curves (Inputs 8232 to 8291). If ISTART=0, time is measured from steady state (τ=0). If ISTART=1, time is measured from point of scram.
8336	IPRØP	Option for using curve fit of sodium properties: IPRØP=1 use curve fit IPRØP=0 use tabular data
8337	IPLØT	Option for storage of data on TAPE 2 for subsequent use with a plotting routine. (IPLØT=1, selected data will be written on TAPE 2.)
8338	ITMAX	Option for searching for maximum value of certain critical parameters. (ITMAX=1, 2 or 3 depending on which channel is of interest.)
8339	ICPF	Option for using curve fit of fuel specific heat: ICPF=1 use curve fit ICPF=0 use tabular properties Note: If ICPF=1, INPUTS 8340 through 8345 must be specified.

*See Section 7.4.

TABLE 1 (Continued)

Input Number	Input Variable	Description of Change
8440	$A(C_p)_f$	Constants used in curve fit of fuel specific heat $C_p = A + B \cdot T + C \cdot T^2 + D \cdot T^3 + E \cdot T^4$ where T is in ^oF.
8441	$B(C_p)_f$	
8442	$C(C_p)_f$	
8443	$D(C_p)_f$	
8444	$E(C_p)_f$	
8445	$F(C_p)_f$	Effective heat capacity of fuel between the solidus and liquidus temperatures.

3.0 GAP CONDUCTANCE HEAT TRANSFER

One very important factor in calculating the steady state and transient fuel temperatures is the determination of the conductance and evaluation of the resulting heat transfer coefficient for the fuel/cladding gap. In FØRE-2M, two options for calculating heat transfer across the fuel-cladding gap were available. For the first of these (Input 20 = 0), the user specified a single value of gap conductance for the average channel which remained invariant throughout the transient. Input multipliers on this constant value were available (Input 355 and 359) to alter the values for the hot and peak channels. These values also remain constant throughout the transient. Likewise, this option allowed fixed, but axially varying, gap conductance values to be input to all three channels via Input 827 to 847[2].

For the second of the two options (Input 20 = 1), a variable gap conductance is calculated based upon the local gap conditions existing at every point in the transient. This model[1] was based upon the work of Ross and Stoute[4]. The local gap coefficient for each position is calculated by:

$$H_{gap} = (H_{cont} + H_{cond}) \cdot F^{**}$$

where:

H_{gap} is the overall gap conductance

H_{cont} is the portion attributed to solid-to-solid conduction

H_{cond} is the portion attributed to gap gas conduction

and F^{**} is the channel multiplier on gap conductance

(F^{**} = 1.0 for average channel;

F^{**} = Input 359 for peak channel; and

F^{**} = Input 355 for hot channel.)

The individual components of the gap conductance are calculated as follows:

$$H_{cont} = \frac{K_m P_c}{\alpha_o \sqrt{\delta_r \psi}}$$

$$H_{cond} = \frac{K_g}{\delta_g + (g_f + g_c)}$$

where K_m is the harmonic mean thermal conductivity of the fuel (K_1) and cladding (K_2) defined as:

$$K_m = \frac{2K_1 K_2}{K_1 + K_2}$$

P_c is the contact pressure (proportional to the interference between fuel and cladding); when P_c is zero (no interference), the contribution of H_{cont} is zero.

α_o an experimental constant[4] determined to be approximately 0.091 $ft^{1/2}$.

δ_r is the effective roughness of the two surfaces and is defined as:

$$\delta_r = \left[\frac{\delta_f^2 + \delta_c^2}{2}\right]^{1/2}$$

where δ_f and δ_c are the respective roughnesses (in feet) of the fuel and cladding.

ψ is the Meyers hardness number of the softer material which is usually[1] taken to be on the order of three times the yield strength.*

*Reference 5 provides additional information on the selection of values for this paramater.

K_g is the conductivity of the gas in the gap and is calculated from:

$$K_g = A_g + B_g \cdot T_{avg} + C_g \cdot T_{avg}^2$$

where A_g, B_g and C_g are input variables and T_{avg} is the average local temperature of the gap.

$(g_f + g_c)$ is the accommodation distance (approx. 3.3×10^{-5} ft for helium at 1 atmosphere)*

δ_g is the effective radial gap dimension. For a positive gap

$$\delta_g = \Delta_g + \beta_o (\delta_f + \delta_c)$$

and for a zero gap

$$\delta_g = \beta_o (\delta_f + \delta_c)$$

Δ_g is the calculated hot radial gap

δ_o is an experimentally determined constant which varies[4] from 2.5 at low interfacial pressure (~1400 psi) to 1.5 at high interfacial pressures (~7000 psi).

---

*Reference 5 provides additional information on the selection of values for this parameter.

3.1 RADIATION HEAT TRANSFER BETWEEN FUEL AND CLADDING

As can be seen from the equations, the Ross and Stoute model neglects radiant heat transfer across the gap. This is understandable because in their experiments, the surfaces were in contact and typically measured gap conductances ranged from 500 to over 5000 Btu/hr-ft^2-^{o}F. Figure 1 shows that for this range of values, the contribution due to radiation is quite small being on the order of a few percent at most.

When overall gap conductance is relatively low, however, the effect of radiant heat transfer becomes important and could account for as much as 20 to 50 percent (Figure 2) of the total heat transferred when the overall gap coefficient is on the order of 100 Btu/hr-ft^2-^{o}F. Such a situation could occur even with a pure helium atmosphere for large radial gap dimensions (e.g., 0.015 inches or greater). While dimensions of this magnitude are not typical of fuel rods, the radial gap size in a boron carbide control rods (see Section 4.2) could, for example, be in the range where radiation heat transfer becomes an important factor for reasonably large values of emissivity.* Fuel rods containing a large percentage of fission gases might also be in the range where radiant heat transfer could account for ten percent or more of the total conductance. It was, therefore, considered prudent to modify the Ross and Stoute model to account for radiant heat transfer. The resulting equation is:

$$H_{gap} = (H_{cont} + H_{cond}) \quad F^{**} + H_{RAD}$$

where

H_{RAD} is the radiant heat transfer component and the other terms are as previously described.

---

*It should be noted that while the emissivity of bright stainless steel is on the order of 0.2 to 0.3, heating of the steel can quickly increase the emissivity to the 0.6 to 0.7 range (see Reference 6).

Figure 1 Effect of Radiation Heat Transfer at High Overall Values of Gap Conductance

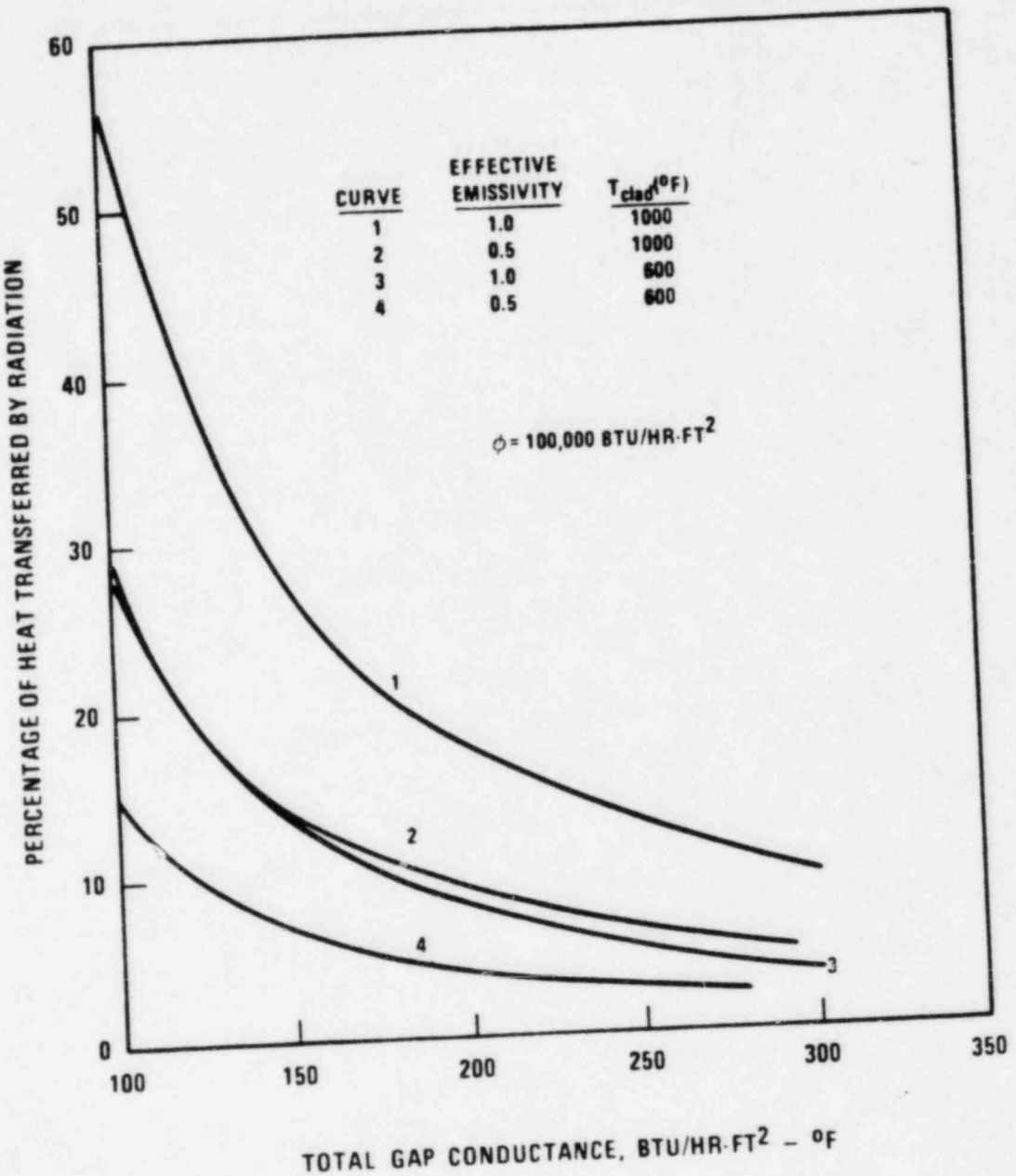


Figure 2 Effect of Radiation Heat Transfer at Low Overall Values of Gap Conductance

3487-2

The contribution to the gap coefficient which is attributed to radiation can be derived by noting that:

$$H_{RAD} = \frac{(q/A_f)}{(T_f - T_c)}$$

and

$$(q/A_f) = \sigma F \left[(T_f + 460)^4 - (T_c + 460)^4\right]$$

where

q	is the heat transferred by radiation
A_f	is the surface area of the fuel
σ	is the Stefan-Boltzmann constant
F	is the emissivity form factor between the fuel and cladding
T_f	is the surface temperature of the fuel
T_c	is the inside surface temperature of the cladding

Since the emissivity form factor is given by[7]

$$F = \left[\frac{1}{\varepsilon_f} + \frac{A_f}{A_c}\left(\frac{1}{\varepsilon_c} - 1\right)\right]^{-1}$$

the radiant heat transfer coefficient across the fuel/cladding gap can be written as:

$$H_{RAD} = \frac{\sigma\left[(T_f + 460)^4 - (T_c + 460)^4\right]}{\left[\frac{1}{\varepsilon_f} + \frac{A_f}{A_c}\left(\frac{1}{\varepsilon_c} - 1\right)\right]\left[T_f - T_c\right]} \cdot \left[\frac{2\,A_f}{A_f + A_c}\right]$$

where the previously undefined symbols are:

ε_f	the emissivity of the fuel
ε_c	the emissivity of the cladding
A_c	the inside surface area of the cladding

The additional factor $[2A_f/(A_f + A_c)]$ is required to normalize the radiant heat transfer to the mean area of the gap which is the parameter used in FØRE-2M as the reference heat transfer area.

Figures 3, 4, and 5 show some typical results obtained with and without radiant heat transfer for a boron carbide control rod subjected to a transient caused by insertion of the control assembly into the reactor. As can be seen, the effect of radiant heat transfer has a marked impact on the results. Figure 4, for example, shows that the maximum cladding temperature is reduced by over 100°F when radiation is included. The extra heat transfer from radiation (prior to shutdown) decreases the stored heat (i.e., temperature) of the B_4C (see Figure 5) and thus less energy is available to be deposited into the coolant during the transient.

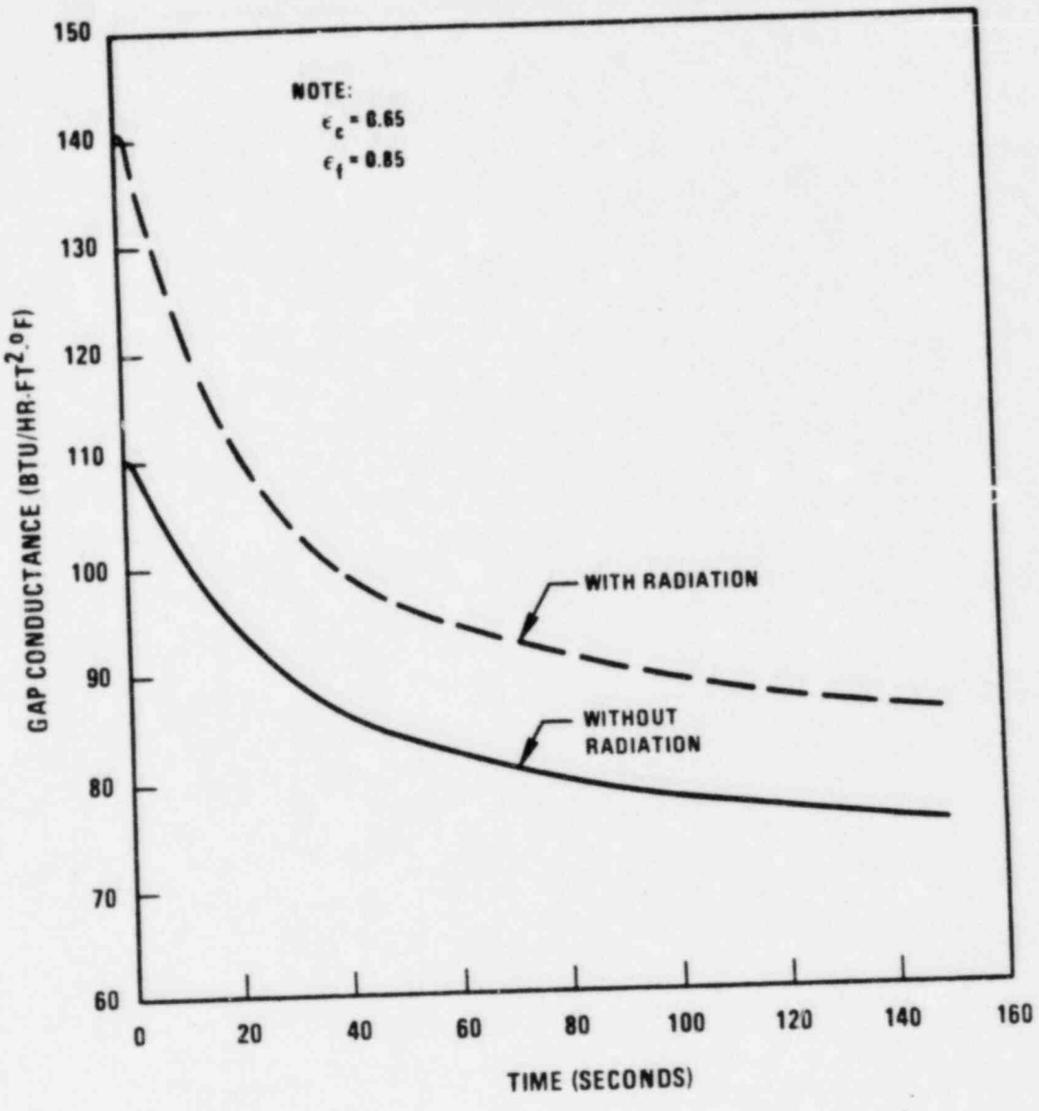


Figure 3 Typical Variation in Transient B_4C/Cladding Gap Conductance with and without Radiation Heat Transfer Component

3487-3

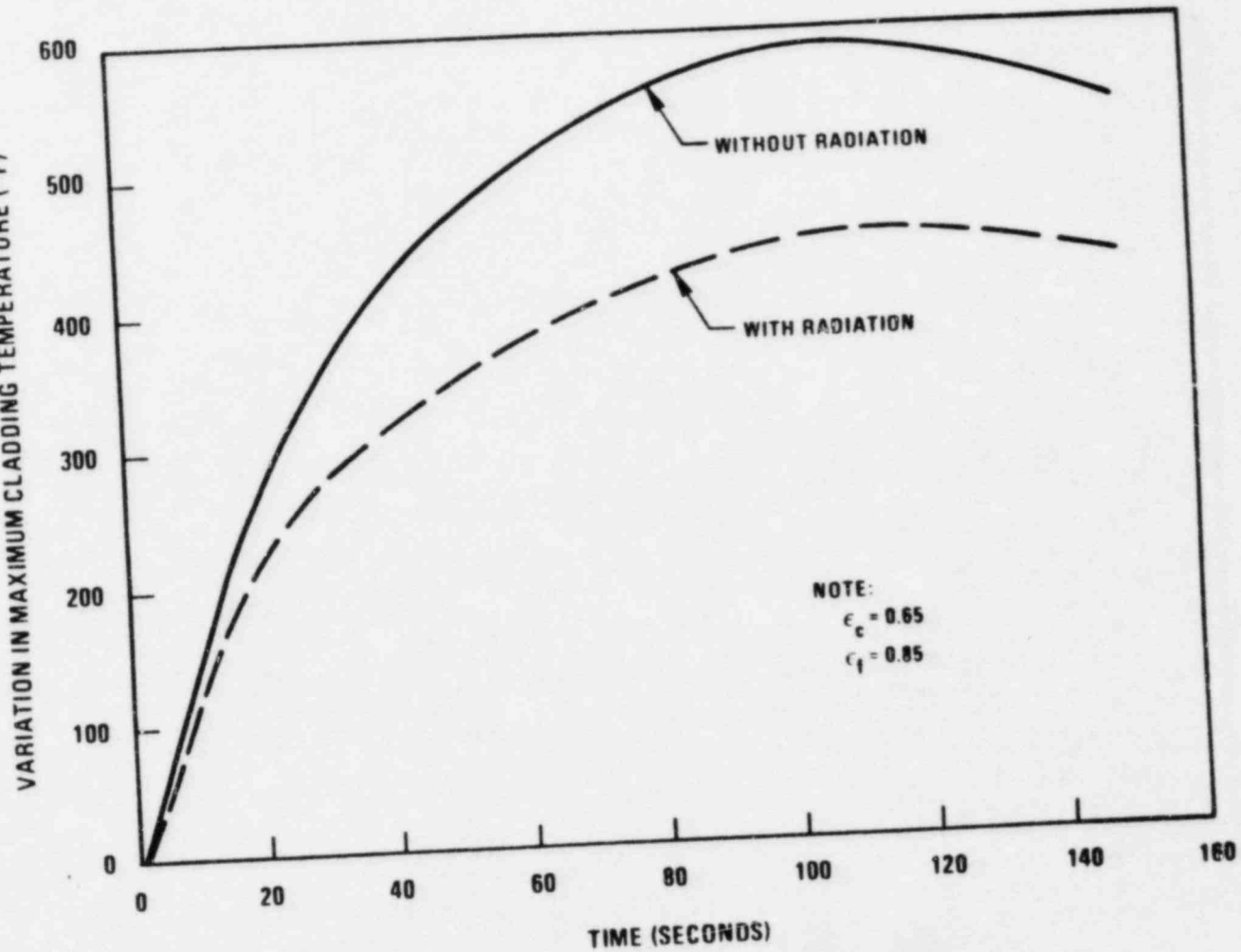


Figure 4 Typical Variation in Control Rod Maximum Cladding Temperature with and without Radiation Heat Transfer Component

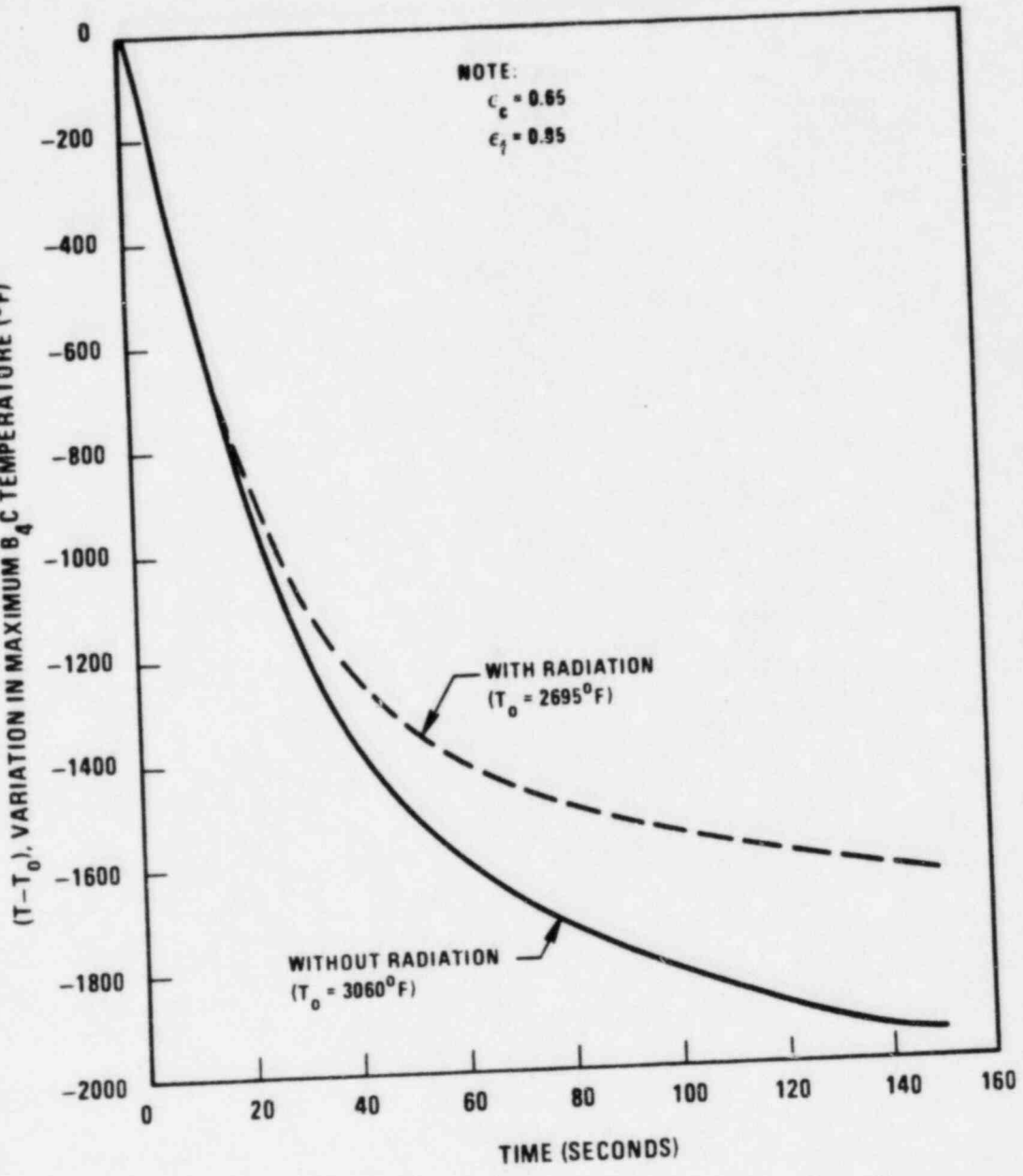


Figure 5 Typical Variation in Maximum B_4C Temperature with and without Radiation Heat Transfer Component

3487-5

3.2 ALTERNATE GAP CONDUCTANCE MODEL

In addition to modifying the Ross and Stoute gap conductance model to include radiant heat transfer (Section 3.1), a new model has also been added to the FØRE-2M computer program. This option (Input 20 = 2) allows the user to specify an axial variation in the hot radial gap dimension (Inputs 948-968) and to specify the overall steady-state gap conductance associated with each of these input dimensions using Inputs 827 to 847*.

Since the steady-state values are specified by the user with this option, the method of handling the transient variation in the gap conductance is somewhat different, although quite analogous, to the procedure used in Ross and Stoute model. The basic gap conductance equation is given by

$$H_{gap} = H_{cont} + H_{cond} + H_{RAD}$$

(Note that the F** multiplier is not used in this model since individual values of H_{gap} are specified by the user.)

With the steady-state value of H_{gap} specified, an iterative procedure to determine the proper steady-state conductance is not required as in the modified Ross and Stoute model. However, once the initial temperature distributions have been determined, the steady-state values of H_{RAD} and H_{cont} (if appropriate) are determined using the same equations as in the modified Ross and Stoute model. After these two components are subtracted from the total, the remaining portion of the steady-state (S.S.) gap conductance is then assumed to be associated with conduction across the gas gap. Thus,

$$(H_{cond})_{S.S.} = H_{gap} - (H_{cont} + H_{RAD})_{S.S.}$$

---

*When Input 20 = 2, the gap conductance (Inputs 827-847) are specified in Btu/hr-ft^2-^{o}F; otherwise, Inputs 827 to 847 are dimensionless correction factors.

At any position and at any point in the transient, the gap conductances associated with H_{RAD} and H_{cont} (if appropriate) are calculated in the identical manner as in the modified Ross and Stoute model. However, the portion of the gap conductance attributed to conductance across the gap is found by calculating the ratio between the steady-state and transient value of the parameters affecting conduction and multiplying these ratios by the steady-state value of H_{cond}. The transient (τ) value of the gas conduction portion of the gap conductance at any position is therefore given by:

$$(H_{cond})_\tau = (H_{cond})_{S.S.} \left[\frac{\delta_g + (g_f + g_c)}{K_g}\right]_{S.S.} \cdot \left[\frac{K_g}{\delta_g + (g_f + g_c)}\right]_\tau$$

where the nomenclature is as defined previously. The difference is that the hot gap calculation is initialized using Inputs 948 to 968. The transient hot gap (Δ_g) for this option is givey by*:

$$\Delta_g = RAD(M,K) + \Delta C - \Delta F$$

where

RAD(M,K) is the input (hot, steady-state value of the radial gap dimension.

ΔC is the radial change in cladding dimension due to the change in average temperature from the steady-state value.

ΔF is the radial change in fuel dimension due to the change in average fuel temperature from the steady-state value.

The fact that the conduction portion of the gap conductance is obtained by the method described above makes this model somewhat empirical in nature.

---

*This equation relpaces equations (33) and (34) of Reference 1.

However, the model will yield the same results as the modified Ross and Stoute model provided the input values of overall gap conductance are in perfect agreement with the corresponding hot, radial gap dimensions which are specified for this model. This model provides some additional user flexibility for evaluating situations which may be considered non-typical of an idealized fuel rod (e.g., evaluating explicit experimental data where the apparent gap sizes differ from those expected).

To demonstrate the application of this new FØRE-2M capability, a typical undercooling transient was analyzed for a large diameter, blanket rod. For this type of oxide rod, the transient release of stored heat affects the performance characteristics. The power decreases rapidly early in the transient; however, the heat flux from the cladding remains relatively large. In fact, the heat flux-to-flow ratio remains greater than 1.0 early in the flow coastdown and results in a cladding temperature increase. Figure 6 shows the FØRE-2M predictions with a fixed temporal value of gap conductance (Input 20 = 0) and for a dynamically varying gap conductance (Input 20 = 2). The initial conditions used for the gap dimensions and gap conductance for the latter case were directly calculated with the LIFE-III computer code[8] and are listed below as a function of axial position from the bottom of the heated length (X/L = 0.0):

Axial Position, X/L	Radial Gap Size*, (in.)	Gap Conductance*, Btu/hr-Ft^2-^{o}F
0.11	0.0005	1000.0
0.28	0.0005	4641.0
0.39	0.0030	1209.0
0.50	0.0230	347.0
0.61	0.0020	1703.0
0.73	0.0000	8389.0
0.89	0.0000	1000.0

*Prior to shutdown.

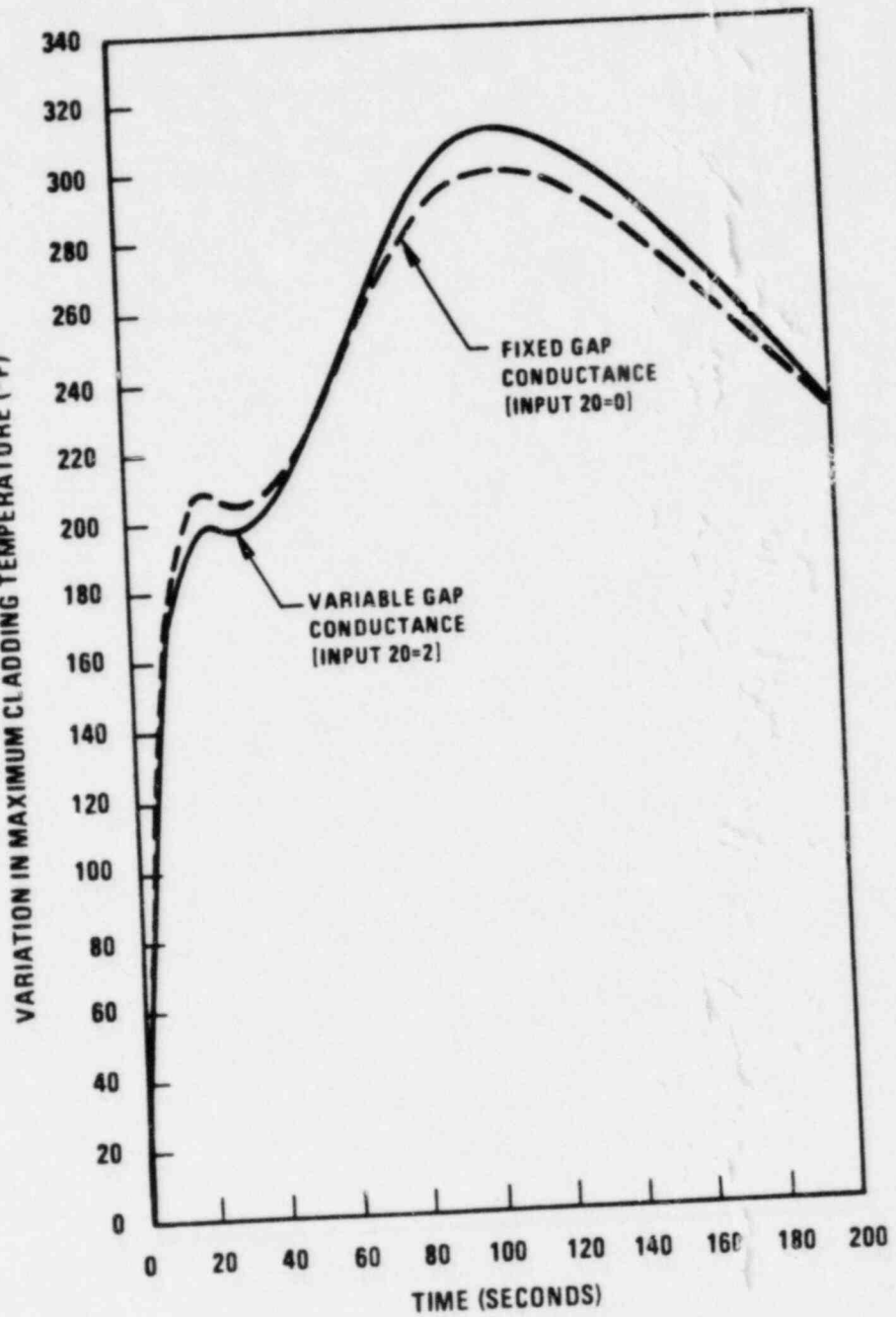


Figure 6 Typical Effect of New Variable Gap Conductance Option on Large Diameter Oxide Blanket Rod Performance During an Undercooling Transient

3487-6

As can be noted from the figure, the temperature predictions are somewhat altered by using the new option. Due to a gap conductance decrease (from its initial value) early in the transient, the stored heat release is likewise delayed in the transient and thus lower temperatures result initially. Later in the transient, when the flow has decayed to lower values, more energy is thus available and consequently somewhat higher temperatures result. The importance of this example is simply to indicate that the new option is a viable means of linking FØRE-2M to a steady state fuel performance code such as LIFE.

3.3 COMBINATION GAP CONDUCTANCE MODELS

In order to provide still more flexibility to the FØRE-2M user, some of the features of the two variable gap conductance models were combined into two additional models. For these models, the axial variation in the radial gap dimension is specified (Inputs 948-968) and the gap conductance is calculated using the Ross-Stoute model modified with radiant heat transfer (Section 3.1). The difference between the two additional models is that either cold gap variations (Input 20 = -1) or the hot gap variations (Input 20 = -2) may be specified. Table 2 summarizes the pertinent information for all of the gap conductance models.

These models allow the user to analyze many additional types of gap conditions that may occur. For example, variations in cladding and fuel swelling, variable pellet diameters or combinations of these conditions may be simulated with this model. Again, it is noted that these models will yield the same results as the other two models if the input conditions are in agreement.

TABLE 2

SUMMARY OF GAP CONDUCTANCE MODELS IN FØRE-2M

Model	Value of Input 20	Type of Variation	Hot or Cold Gap Specified	Inputs Required For Gap	Conductance Model Used
A	0	None (constant)	-	341	Constant
B	+1	With time	Cold (feet)	350	Ross and Stoute*
C	+2	Time and space	Hot (inches)	{827 to 847} {948 to 968}	Alternate Model (Section 3.2)
D	-1	Time and space	Cold (inches)	948 to 968	Ross and Stoute*
E	-2	Time and space	Hot (inches)	948 to 968	Ross and Stoute*

*With radiation heat transfer

3.4 REQUIREMENT FOR REALISTIC INPUT VALUES

A word of caution to the user of the variable gap conductance options in FØRE-2M may be appropriate at this point. An examination of the equation for H_{cont} and H_{cond} will show that it is possible to have a zero or near zero denominator in these equations if certain input parameters are not properly specified. The denominator for H_{cond}, for example, is composed of three components: the accommodation effect $(g_f + g_c)$; the surface roughness effect $\beta_o (\delta_f + \delta_c)$; and the radial gap dimension (δ_g).

If the user would, for example, fail to specify values for g_f, g_c and β_o (Inputs 346, 348 and 349), the denominator of H_{cond} would be controlled completely by the radial gap dimension. If during the transient the thermal expansion of the fuel and cladding were such as to make the fuel/cladding gap dimension approach zero, the value of H_{cond} would become infinite.

To prevent an indefinite condition (i.e., division by zero), the FØRE-2M program automatically sets g_f, g_c and β_o to very small values (i.e., 10^{-25}) if the user fails to specify an input value for any of these parameters. However, this precaution does not prevent the value of H_{cond} from still approaching an extremely large value if the radial gap dimension should approach zero. Thus, while the computer program will run, the answer may, in fact, be in error. To bring this potential problem to the attention of the user, a "CAUTION" message is printed out at the beginning of the output listing, instructing the user to check those input parameters which could possibly invalidate the gap conductance calculations. The user may then wish to change the input values to more realistic values and rerun the problem.

4.0 CHANGES AFFECTING MATERIAL PROPERTIES

In order to improve the computational efficiency of FØRE-2M, options have been incorporated into the program to allow the user to either specify tabular or curve-fit properties for the fuel specific heat and the sodium properties. Several changes in the fuel thermal conductivity properties have also been made and axial variations in the associated hot channel factor are now allowed. These changes are briefly discussed in the following subsections.

4.1 NEW THERMAL CONDUCTIVITY EQUATION FOR FUEL

An additional equation (Input No. 22 = 4) has been added to the fuel thermal conductivity option. This equation is of the form:

$$K = FP \left[\frac{1}{A+BT} + CT^3\right]$$

where

K = thermal conductivity, W/M - ^oK

T = temperature, ^oK

$$FP = \frac{1.079\ (1-P)}{(1.0 + 0.5P + 4.62P^2)}$$

P = fractional porosity

$A = -6.0656 \times 10^{-4}$

$B = 3.04212 \times 10^{-4}$

$C = 0.75137 \times 10^{-10}$

If either thermal conductivity option 2 or 4 is selected, the initial and as-sintered densities must also be specified. (Inputs 858 and 859; also Inputs 8205 and 8206 if alternate geometry option is used.)

This new thermal conductivity equation for mixed oxide fuel is quite similar to the equation previously included[2] in the computer program and has been included to reflect the August 1977 revision to the Property Code 3112 equation in TID-26666.[3]

4.2 THERMAL CONDUCTIVITY OF B_4C

In addition to being used to evaluate the transient behavior of fuel rods, the FØRE-2M program is frequently used to analyze other cylindrical, heat generating elements. One such application is the transient analysis of boron carbide control rods. To improve the flexibility of the computer program for this particular application, a new "fuel" thermal conductivity option (Input number 22 = 3) has been added. When this option is selected, the thermal conductivity of the B_4C pellets is evaluated using the following equation[9]:

$$K = \left(\frac{1}{6.87 + .0095T}\right)\left(\frac{1 - \phi}{1 + 2.2\,\phi}\right)(0.10210 - 14.492)$$

where

K is the local thermal conductivity, Btu/hr-Ft-^{o}F
T is the local, absolute temperature, ^{o}R
ϕ is the pore volume fraction
θ is the irradiation temperature, ^{o}F

In the program, it is assumed that the initial or steady state temperature is the irradiation temperature. Local, steady state temperatures at each radial and axial location are stored and the appropriate value is recalled when the transient B_4C thermal conductivity is required at any particular location.

4.3 AXIAL VARIATION IN FUEL THERMAL CONDUCTIVITY HOT CHANNEL FACTORS

In the previous version of the FØRE computer program, a single input value (Input No. 121) was used to specify a hot channel multiplier on the fuel thermal conductivity. This multiplier was used to either increase ($F_K > 1.0$) or decrease ($F_K < 1.0$) the local fuel thermal conductivity in the "hot channel" (i.e., Channel 3).

A new option has been added which allows the user to specify an axial variation in the multiplier for all three channels. To use this option, the user sets the fuel conductivity axial variation indicator (Input 969 > 0.0) and then specifies the appropriate correct factors, FCØN(M,K) . Since the program automatically sets the default value of 1.0 if no value is given, only those values which are not 1.0 need be specified. The values for the average channel (Channel 1) are input into locations 970 to 976; values for the peak channel (Channel 2) are input into locations 1181 to 1187; and those for the hot channel (Channel 3) use locations 1188 to 1194.

It is important to note that if this option is used, the original hot channel multiplier on fuel thermal conductivity (Input 121) will be overridden by the specified FCØN values for Channel 3.

4.4 CURVE FIT OF THE SODIUM PROPERTIES

Calculation of values of the sodium properties is performed a significant number of times during the course of a typical transient. Each calculation using the tabular input option requires a systematic search through the appropriate table utilizing a linear interpolation routine. This procedure is time consuming and results in an inefficient use of the computer.

To provide the program user with the choice of using a more efficient method of determining the sodium properties, an option (IPRØP) has been added which allows the user to select a curve fit routine (INPUT 8336=1) for calculating sodium properties. The equations which have been programmed into the FØRE-2M program are quadratic temperature fits of the properties[10] listed in Appendix C. The resulting equations are summarized below:

a. Thermal conductivity of sodium, Btu/sec-ft-^{o}F

$$K = 1.5072 \times 10^{-2} - 5.2 \times 10^{-6} \cdot T + 5.75 \times 10^{-10} \cdot T^2$$

b. Thermal expansion coefficient of sodium, ^{o}F^{-1}

$$\alpha = 44.514 \times 10^{-6} + 9.0125 \times 10^{-9} \cdot T + 5.9375 \times 10^{-13} \cdot T^2$$

c. Dynamic viscosity of sodium, lb/ft-sec

For $T \geq 600^{o}$F,

$$\mu = 3.741 \times 10^{-4} - 3.0008 \times 10^{-7} \cdot T + 81.25 \times 10^{-12} \cdot T^2$$

For $T < 600^{o}$F,

$$\mu = 7.414 \times 10^{-4} - 1.564 \times 10^{-6} \cdot T + 1.1675 \times 10^{-9} \cdot T^2$$

d. Specific heat of sodium, Btu/lb-^{o}F

$$C_p = 0.34552 - 7.8906 \times 10^{-5} \cdot T + 3.3984 \times 10^{-8} \cdot T^2$$

e. Density of sodium, lb/ft^3

$$\rho = 59.588 - 8.0925 \times 10^{-3} \cdot T - 1.0625 \times 10^{-7} \cdot T^2$$

Sample calculations performed using both the tabular and curve fit method of determining sodium properties indicate that the latter method will reduce the computer execution time of a typical problem by nearly 15 percent.

4.5 CURVE FIT OF THE SPECIFIC HEAT OF MIXED OXIDE FUELS

For the same reasons discussed in the previous section, an option (ICPF) has been included which allows the user to specify whether a tabular set of fuel specific heat will be used (INPUT 8339=0) or whether a fourth degree polynomial describing the fuel specific heat will be utilized (INPUT 8339=1). Unlike the sodium properties, however, the fuel specific heat is not unique and may vary depending upon the composition of the fuel being analyzed. The user must, therefore, supply six constants (INPUTS 8340 to 8345) which define the fuel specific heat. The model used is that described in the original FØRE-2M manual[2] where an "effective heat capacity" is used to describe the transition region between the solidus temperature and the liquidus temperature for mixed oxide fuels.

This effective heat capacity is determined using the following expression:

$$C_{p(eff)} = L/\bar{\rho}_f \cdot (T_L - T_S)$$

where

$C_{p(eff)}$ is the effective heat capacity (Btu/lb-^oF)

L is the latent heat of fusion (Btu/ft^3)

$\bar{\rho}_f$ is the average density of the fuel between the solidus and liquidus (lb/ft^3)

T_L is the liquidus temperature of the fuel (^oF)

T_S is the solidus (melting) temperature of the fuel (^oF)

Table 3 shows three sets of values (-3σ, nominal, +3σ) for mixed oxide fuel heat capacity using the effective heat capacity for fuel melting and the tabular input option (INPUT 8339=0).

The following mixed oxide input information typifies the coefficients of the minimum, nominal and maximum (-3σ, nominal, +3σ, respectively) fuel specific heat equations using the curve fitting option (INPUT 8339 = 1). It was found that a fourth degree polynomial fits the data (Reference 12) very well with a maximum of 1.6% error difference.

Input	Minimum C_p	Nominal C_p	Maximum C_p
[8340] (A)	5.9205×10^{-2}	5.9841×10^{-2}	6.0477×10^{-2}
[8341] (B)	2.4780×10^{-5}	2.3894×10^{-5}	2.3008×10^{-5}
[8342] (C)	-1.5593×10^{-8}	-1.0643×10^{-8}	-5.6927×10^{-9}
[8343] (D)	4.7107×10^{-12}	1.9322×10^{-12}	-8.4621×10^{-13}
[8344] (E)	-4.1776×10^{-16}	1.9405×10^{-13}	4.2164×10^{-16}
[8345] (F)	1.105	1.105	1.105

The heat capacity of the fuel at any temperature (T,°F) is then determined in the following manner:

a. For $T < T_{SOLIDUS}$

$$C_p(f) = A + B \cdot T + C \cdot T^2 + D \cdot T^3 + E \cdot T^4$$

b. For $T_{SOLIDUS} \leq T \leq T_{LIQUIDUS}$

$$C_p(f) = F$$

c. For $T > T_{LIQUIDUS}$

$$C_p(f) = A + B \cdot T_{SOLIDUS} + C \cdot T^2_{SOLIDUS} + D \cdot T^3_{SOLIDUS} + E \cdot T^4_{SOLIDUS}$$

where $T_{SOLIDUS}$ and $T_{LIQUIDUS}$ are the appropriate solidus and liquidus temperatures (Figure 7) defined respectively by INPUT 193 and INPUT 194. From sample calculations made using the curve fit option for fuel specific heat, it is estimated that the computer execution time can be reduced 15 to 20 percent over the tabular option, depending on the number of fuel nodes used in a particular problem. Of course, when using this option, it will be necessary for the user to determine the appropriate values of A, B, C, D, E and F in order to properly represent the specific heat of the fuel being analyzed.

TABLE 3

TYPICAL TABLE OF HEAT CAPACITY FOR MIXED OXIDE FUEL
USING EFFECTIVE HEAT CAPACITY MODEL IN MELTING REGION
(REFERENCE 12)

Temperature (^{o}F)	Heat Capacity, $\frac{Btu}{lb-^{o}F}$			Comments
	Minimum C_p (-3σ)	Nominal C_p	Maximum C_p ($+3\sigma$)	
440.6	0.0664	0.0685	0.0706	Values Computed From Reference 12
1340.6	0.0751	0.0774	0.0797	
2240.6	0.0792	0.0817	0.0842	
3140.6	0.0873	0.0900	0.0927	
4040.6	0.1056	0.1106	0.1156	
4500.0	0.1126	0.1287	0.1453	
4940.6	0.1203	0.1523	0.1843	
4999.0	0.1218	0.1560	0.1895	
5000.0	1.1050	1.1050	1.1050	Effective value for melting region
5115.0	1.1050	1.1050	1.1050	
5116.0	0.1218	0.1560	0.1895	Values for liquid fuel assumed equal to pre-melting value
7000.0	0.1218	0.1560	0.1895	

*Special note to users of FØRE-2M: If this tabular procedure is used, an artificially high melting point (INPUT Value 117) must be used. This value must be equal to or less than the highest temperature in the table of specific heat vs temperature (i.e., from the above table $T_{melt} \leq 7000^{o}F$).

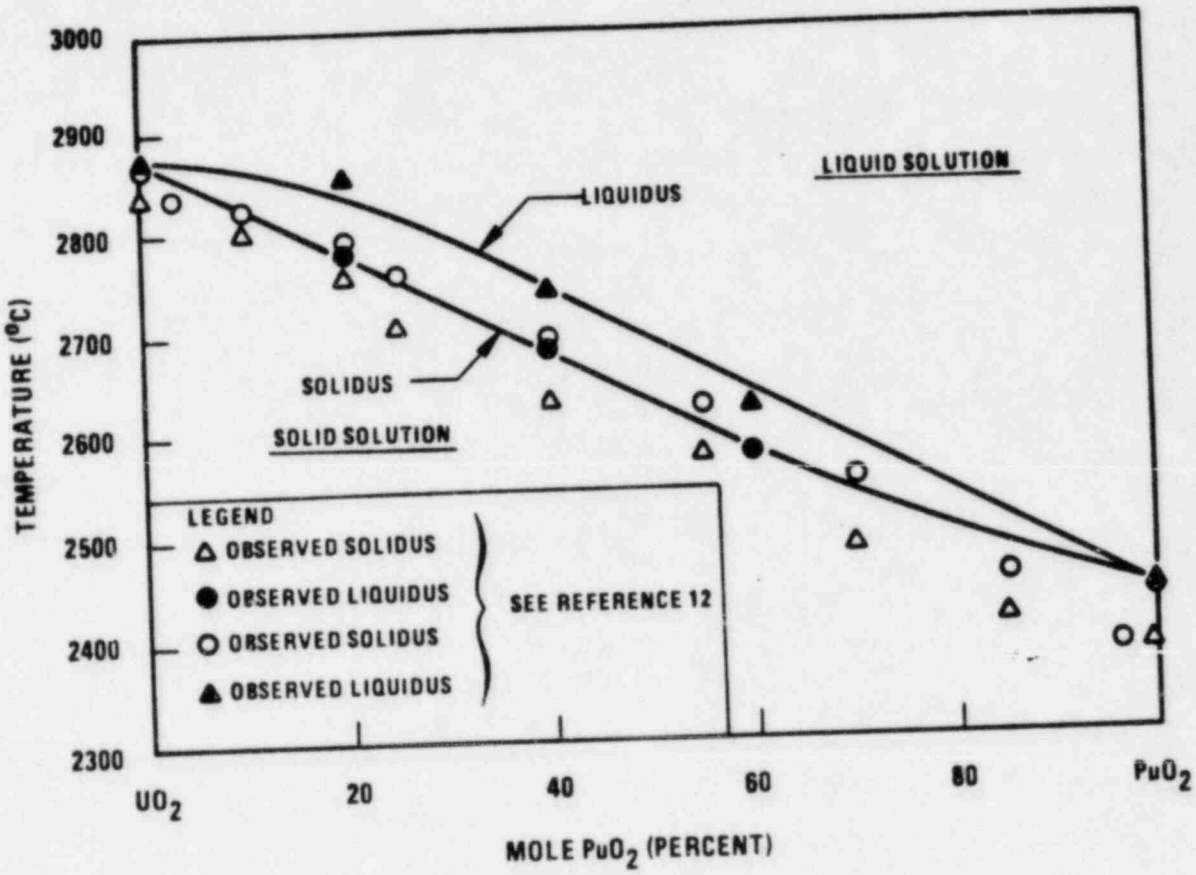


Figure 7 Phase Diagram for UO_2-PuO_2

3487-7

4.6 ALTERNATE SPECIFIC HEAT TABLE

In many cases the properties of the fuel used in the blanket rods may be different than that of the driver fuel (e.g., UO_2 in the blanket and Pu-U in the driver rods). To cover this possibility in the event that the alternate fuel geometry option is used (see Section 8.1), an alternate specific heat table is also available.

The option for the alternate specific heat (IXCP) is Input 8293. The tabular values of specific heat as a function of temperature associated with this option are Inputs 8293 to 8312 (specific heat values) and 8313 to 8332 (temperature values). A value of IXCP is selected to correspond to the channel to which the alternate specific heat values will be applied. For example, if IXCP is equal to 2, the alternate specific heat table will be applied to the peak channel fuel (i.e., Channel 2). Normally, this option would be used with the alternate fuel rod in Channel 3 (i.e., IXCP=3).

However, note that it is not necessary to utilize the alternate fuel rod geometry option (Section 8.1) to specify an alternate table of fuel specific heat. The alternate table of fuel specific heat may be used with or without the alternate geometry option.

5.0 MODIFICATIONS TO TRANSIENT FLOW CHARACTERISTICS

Several modifications related to the transient coolant flow behavior were included in the modifications to the FØRE-2M program. These changes are discussed in this section.

5.1 PUMP TRIP AND TIME DELAY

The flow coastdown in the FØRE-2 program was controlled by specification of a time versus flow table (Inputs 196 to 225 and 226 to 255). If the user wished to begin the flow coastdown at a point in the transient other than time-zero, it was necessary to modify the shape specified in the table to achieve the desired coastdown.

This situation has been changed by the addition of a pump trip and delay time in the program. Now, if the user specifies a pump trip (Input 7799=1), the pump coastdown will not begin until a reactor scram has occurred. That is, the times specified in the table (Inputs 226-255) will be referenced to the time of scram rather than to time-zero.

An additional time delay may also be included by specifying the desired delay interval using Input 8189. When a value other than zero has been used, the times specified in the flow coastdown table will be referenced to the sum of the scram time and the delay time. With these changes, the user may now include those features without having to generate a new set of table values for each type of transient.

5.2 INDIVIDUAL FLOW COASTDOWN FOR EACH CHANNEL

The number of options available for pressure drop and/or transient flow rate calculations (Input 58) has been increased. The new option (Input 58=-2) allows the user to specify the relative flow rate between channels throughout the transient. This is accomplished by specifying the following input.

a) Input 58=-2		(Option for selecting individual flow coastdown)
b) Inputs 7800-7819	TIMEZ	Time entries (seconds) for flow coastdown in Channels 2 and 3. First entry is equal to zero.
c) Inputs 7820-7839	GPEAK(τ)	Relative mass velocity in peak channel (Channel 2) associated with TIMEZ entries.
d) Inputs 7840-7859	GHØT(τ)	Relative mass velocity in hot channel (Channel 3) associated with TIMEZ entries.
e) Inputs 196-225	$(G/G_o)_1$	Coolant mass velocity - Channel 1
226-255	TIME	Time for Channel 1 entries
f) Input 166	G_o	If Inputs 196-225 are normalized, this is initial mass velocity in Channel 1 ($lb/sec\text{-}ft^2$).
g) Input 191	F_r	Peak channel factor for mass velocity in Channel 2.
h) Input 192	F_v	Hot spot factor for mass velocity in Channel 3.

The mass velocity in Channel 1 is given by:

$$VELØC(1) = G_o \quad (G/G_o)_1$$

If G_o is equal to zero, the values of G/G_o are equal to the mass velocity in Channel 1 so that

$$VELØC(1) = (G/G_o)_1$$

For Channel 2, the mass velocity with the new option is then given by:

$$VEL\emptyset C(2) = VEL\emptyset C(1) \cdot F_r \cdot GPEAK(\tau)$$

and for Channel 3

$$VEL\emptyset C(3) = VEL\emptyset C(1) \cdot F_v \cdot GH\emptyset T(\tau)$$

Note that the correction factor for the mass velocity in both Channel 2 and Channel 3 is composed of two values. For Channel 2, the correction factor is:

$$F_r \times GPEAK(\tau)$$

and for Channe' 3

$$F_v \times GH\emptyset T(\tau)$$

The flow coastdown for these two channels can be specified in either of two ways. First F_r and F_v can be set equal to 1.0. In this case, the tabular values of GPEAK and GHØT represent the flow rate of Channels 2 and 3 relative to Channel 1.

In the second method, the values of F_r and F_v are selected to represent the relative (steady state) flow rate of the two channels. The tabular values of GPEAK and GHØT then represent the normalized values of the flow coastdown in the representative channel. In this case, the initial entry on each of the two tables would be 1.0 at time zero whereas in the previous case the values at time zero would be equal to F_r and F_v.

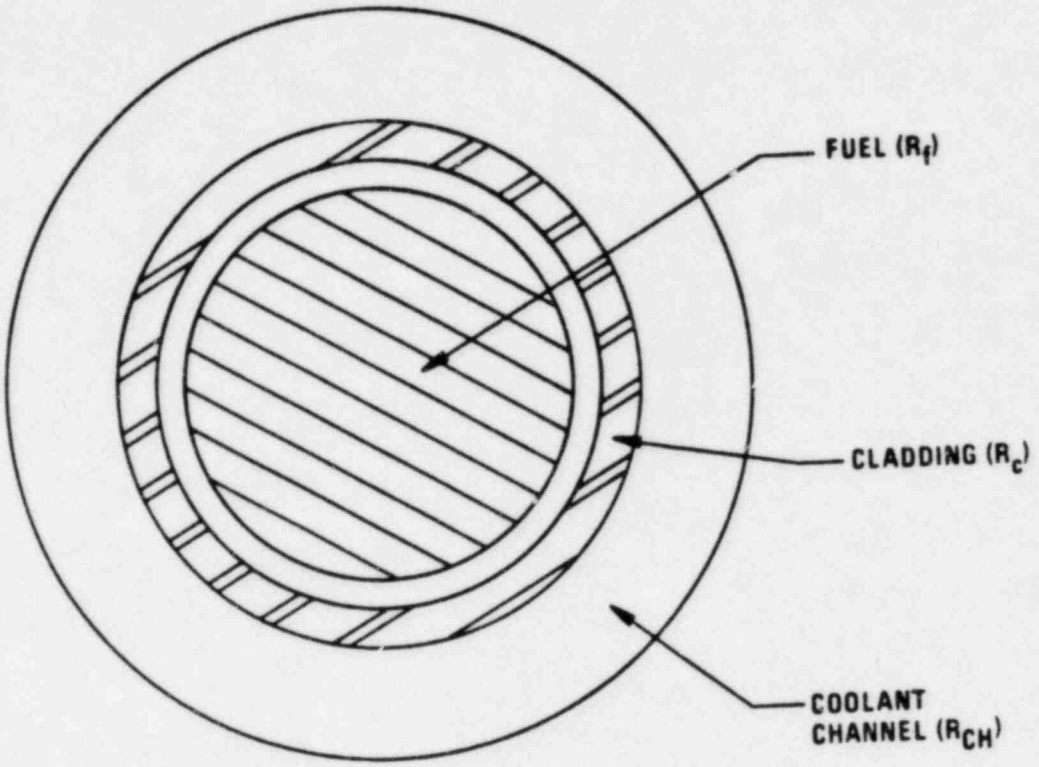
The other pressure drop/flow relationships available with Input 58 remain the same as previously documented.[2] These options are summarized below:

Value of Input 58	Option
-2	As described in this section
-1	No redistribution of flow. Flow in Channels 2 and 3 maintains same relationship to Channel 1 flow as exists in steady state
0	Original[1] FØRE-2 pressure/drop flow redistribution model
+1	Revised[2] FØRE-2 pressure drop/flow redistribution model

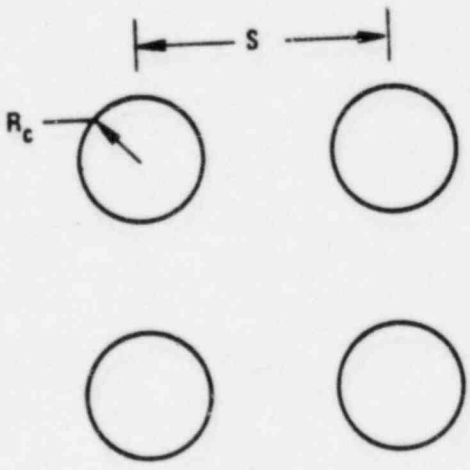
6.0 SIMULATION OF INTER- AND INTRA-SUBASSEMBLY FLOW AND HEAT REDISTRIBUTION

Coolant flow channels in the FØRE-2M program are not explicit duplications of the configuration of the geometry used in most fast-reactor designs. Rather, the actual flow area is represented by an equivalent annular flow passage as schematically shown on Figure 8. This simplified, one-dimensional representation is adequate for most situations and provides a reasonable approximation of the coolant flow characteristics surrounding a fuel rod.

Occasionally, however, situations arise in which the coolant flow adjacent to a fuel rod cannot be adequately characterized by one-dimensional axial flow. Intra-subassembly cross-flow and heat transfer between adjacent flow passages may result in a substantial deviation from the one-dimensional approximation. Such a condition may occur at very low flow rates and/or when there is a large nuclear or thermal gradient in the vicinity of the fuel rod. In order to approximate such conditions, two models have been included in the FØRE-2M program which simulate intra-assembly heat transfer and coolant flow redistribution. These models are only applied to Channel 3 in the program (i.e., the hot channel).



FLOW AREA: $A_f = \pi (R_{CH}^2 - R_c^2)$



EXAMPLE: EQUIVALENCE FOR SQUARE ARRAY

$A_f = S^2 - \pi R_c^2$

$\therefore R_{CH} = S/\sqrt{\pi}$

$D_H = 4 A_f / P$

$D_H = 4 (s^2 - \pi R_c^2) / (2 \pi R_c)$

$\therefore D_H = (2/R_c) [R_{CH}^2 - R_c^2]$

Figure 8 Schematic of Fuel Rod Coolant Channel

3487-8

6.1 INTRA-ASSEMBLY FLOW REDISTRIBUTION SIMULATION*

To simulate the channel cross-flow component, a parameter $(G/G_{in})_M$ has been introduced which represents the local flow rate in any axial section M relative to the inlet flow of Channel 3. The values of $(G/G_{in})_M$ are introduced via Input numbers 7860 to 7999. A set of up to twenty input values are supplied for each axial section. The input values correspond to the times specified by TIMEZ (Inputs 7800-7819).**

When this option is chosen (Input 31=1), the calculated inlet flow rate at any time in Channel 3 is multiplied by the value of $(G/G_{in})_M$ at that time to obtain the corresponding local flow rate in axial section M. The inlet flow rate in Channel 3 is calculated using any of the available pressure drop/flow redistribution options (Input 58) available.

The coolant enthalpy rise across the axial node is calculated using the local, rather than the inlet, flow rate. Thus, if the steady state value (i.e., the first value in the table) of $(G/G_{in})_M$ were, for example, 0.9 at axial section 4, the modified temperature rise across the node would approximately*** be related to the normal temperature rise as follows:

$$\Delta T_{MODIFIED} = \Delta T/(G/G_{in}) = 1.11\ \Delta T$$

A similar relationship exists for the transient analysis procedure where the calculated inlet velocity of Channel 3 at any point in the transient is modified by the appropriate value of $(G/G_{in})_M$ to obtain the local velocity

---

*Note that interassembly flow redistribution can be modeled by the Section 5.2 individual flow coastdown method or incorporated into the intra-assembly flow redistribution method of this section.

**Note that this is the same time table used for the individual flow coastdowns described in Section 5.2.

***Variations in the value of specific heat will alter the answer somewhat.

at that point in time. It should be noted that the tables for $(G/G_{in})_M$ do not have a scram delay or pump trip associated with them. For this option, the transient time and corresponding value of (G/G_{in}) are, therefore, taken directly from the input tables. It should also be noted that in case the user fails to define sufficient data for this variable, the values for $(G/G_{in})_M$ are defaulted to 1.0.

6.2 EXCESS ENERGY SIMULATION (INTER- AND INTRA-ASSEMBLY HEAT TRANSFER)

As part of the intra-assembly flow redistribution process, a certain amount of energy is removed or added as the cross-flow component enters or leaves the coolant node at a given axial position. In addition, heat may be transferred from one channel to an adjacent channel by conduction.

To address this problem using the present one-dimensional flow model in FØRE-2M, a term "excess energy" was defined which represents the radial heat conduction and/or radial mass transport energy transferred into or out of a particular coolant node. In this simulation model it is not important whether this energy was transferred by conduction or mass transport. It is only necessary to define the quantity of energy which enters (positive value) or leaves (negative value) the coolant node over any time interval.

The variables $QEXS_M$ (Inputs 8000 to 8139)* are supplied in a manner similar to that of the previously discussed variable $(G/G_{in})_M$. Up to twenty values are supplied for each axial node in Channel 3. Again, the values of this variable are chosen to correspond to the times specified in the TIMEZ table (Inputs 7800-7819).

During the steady-state calculations, the coolant temperature rise over any axial coolant node is modified by the excess energy term as follows:

$$\Delta T_{C,EXS} = \left[\Delta T_C + \frac{QEXS_M}{A_f \cdot C_p \cdot G_M} \right] \text{Steady State}$$

where:

$\Delta T_{C,EXS}$ is the coolant temperature rise including the excess energy term, (^oF)

*In units of Btu/sec

ΔT_C is the coolant temperature rise without the excess energy term, (^oF)

A_f is the coolant flow area, (ft^2)

C_p is the specific heat of the coolant evaluated at the mean temperature of the coolant node, ($\frac{Btu}{lb-^oF}$)

G_M is the local mass velocity including the $(G/G_{in})_M$ correction previously discussed, ($lb/sec-ft^2$)

$QEXS_M$ is the excess energy, (Btu/sec)

During the transient, a similar calculation is performed. The modification to the coolant nodal temperature is performed as follows:

$$\Delta T_{C,EXS} = \left[\Delta T_C + \frac{QEXS_M \, \Delta\tau}{\rho \cdot C_p \cdot A_f \cdot \Delta Z_M}\right] \text{ Transient}$$

where the previously undefined symbols are:

ρ is the coolant density evaluated at the mean temperature of the coolant node, (lb/ft^3)

ΔZ_M is the length of the coolant node at axial section M, (ft)

$\Delta\tau$ is the time interval over which the calculation is performed, (sec)

An excess energy ratio has been defined as:

$$\text{Ratio} = \frac{QEXS}{Q}$$

where

Q is the amount of heat transferred directly to the coolant from the fuel, cladding and other heat producing materials during steady state or over any time interval during the transient.

Values of this ratio are listed in the input at the same points in time as the other relevant data.

6.3 TYPICAL RESULTS OBTAINED BY INCLUDING INTER- AND INTRA-ASSEMBLY FLOW AND HEAT REDISTRIBUTION

A typical hot channel, axial coolant temperature distribution as calculated with and without the intra-assembly flow and heat redistribution techniques described in the previous sections is shown on Figure 9. For this analysis, input values for the $(G/G_{in})_M$ and $QEXS_M$ terms were obtained from a detailed subchannel analysis code. As can be noted, good agreement is obtained between the FØRE-2M model and the detailed subchannel analysis code predictions.

Also shown on Figure 9 is the typical FØRE-2M prediction if the Section 6.0 techniques are not applied. In this latter case, the intra-assembly flow maldistribution is set equal to a single value (spatially independent) which results in the FØRE-2M coolant temperature matching that of a detailed subchannel analysis code at the point of maximum cladding temperature position (approximately X/L=0.69 on Figure 9). As can be noted, this results in an overprediction of the coolant temperature above this axial position. The new techniques of Section 6.0 allow the designer to eliminate this overconservatism in the hot channel modeling.

An interface is currently being established with the transient subchannel analysis code, COBRA-WC,[11] to enable $(G/G_{in})_M$ and $QEXS_M$ data to be easily input to FØRE-2M on transient basis for low flow/high core temperature transients (e.g., natural convection cooling), where these effects are important. Since COBRA-WC is a whole core detailed subchannel analysis code, which models all of the core assemblies in parallel, the $QEXS_M$ term will account for both intra-assembly and inter-assembly heat transfer.

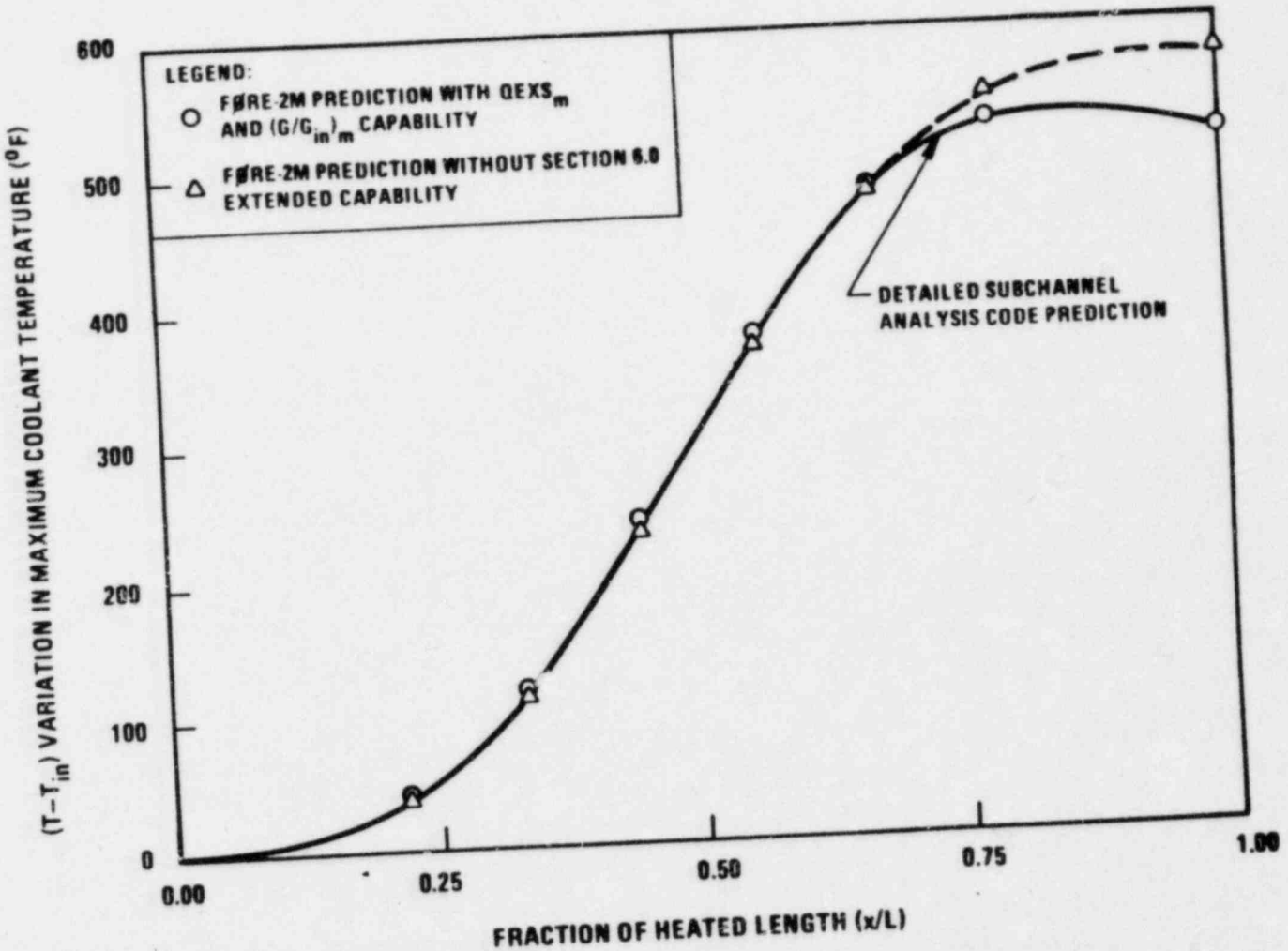


Figure 9 Comparison of FØRE-2M Coolant Axial Temperature Profile (With and Without Section 6.0 Modeling Capability) to that from Detailed Subchannel Analysis Code

7.0 REACTIVITY FEEDBACK AND DECAY HEAT MODIFICATIONS

Several changes have been made to the reactivity feedback and decay heat models in the FØRE-2M program. These modifications are all optional and can be used in place of the models which were originally programmed[1] into the code. A description of these options are contained in the following subsections of this report.

7.1 ALTERNATE DOPPLER AND COOLANT DENSITY REACTIVITY FEEDBACKS

A new option for calculating the Doppler feedback and the coolant density feedback has been added to the program. If this option is selected (Input 7798=1), the local Doppler feedback $\Delta k\ (M,K)$ will be calculated using the following equation:

$$\Delta k(M,K) = F_{D\emptyset P}(M,K) \cdot \ln \left[\frac{\bar{T}_f(M,K) + 460.}{\bar{T}_f^o(M,K) + 460.} \right]$$

where:

$F_{D\emptyset P}(M,K)$ is the local Doppler feedback coefficient

$\bar{T}_f(M,K)$ is the local, average fuel temperature

$\bar{T}_f^o(M,K)$ is the local, steady state average fuel temperature

ln is the natural log

The local Doppler feedback coefficients (usually negative values) for each of the axial sections in the three channels are supplied using Inputs 8140 to 8146; 8147 to 8153; and 8154 to 8160.

The local coolant density feedback for this option is calculated from

$$\Delta k(M,K) = C_{FBK}(M,K) \cdot \left[T_c(M,K) - T_c^o(M,K) \right]$$

where:

$C_{FBK}(M,K)$ is the local coolant density feedback coefficient

$T_c(M,K)$ is the local coolant temperature

$T_c^o(M,K)$ is the local, steady state coolant temperature

The local coolant density feedback coefficients are supplied using Inputs 8161 to 8167; 8168 to 8174; and 8175 to 8181. Note that when this option is used it is advisable to set the normal coolant density feedback coefficients (Inputs 414-420) equal to zero to prevent duplication of feedback.*

The local Doppler feedback contributions and the local coolant density feedback contributions are summed to obtain the total reactivity feedback used in the kinetics calculations.

*The original Doppler feedback calculation is automatically bypassed to prevent such an occurrence.

7.2 REVISED CHANNEL INDEX ON ONE REACTIVITY FEEDBACK OPTION

Section 3.12 of Reference 2 describes two feedback mechanisms which had been previously incorporated into FORE-2M. These feedback mechanisms were originally programmed to use the temperatures of the average channel (i.e., Channel 1) in calculating the reactivity feedback. However, with the alternate geometry option now available (Section 8.1) it is possible that any one of the three channels may be the one of interest insofar as the radial and axial feedback mechanisms are concerned. Therefore, the equations in the program have been modified to allow the user to select which one of the three channels will be used for calculating these feedbacks.

The variable IREX (Input No. 8334) controls this selection process. Either Channel 1, Channel 2 or Channel 3 can be selected by setting IREX equal to 1, 2, or 3. If the user neglects to specify the channel, the option will default to Channel 1. A description of these feedback mechanisms and the equations used in the program are repeated here for completeness.

The two reactivity feedback mechanisms under discussion are an axial fuel expansion feedback and a core radial expansion feedback. Although other feedback mechanisms analogous to these are contained in the program, these two feedback options vary slightly in their method of application and require a more simplified input.

In the case of the axial fuel expansion feedback, the model uses the axially averaged fuel surface temperature (rather than the average fuel temperature) to compute the reactivity feedback. That is,

$$(\Delta k_{FE})^j = \alpha_{FE} \left[\frac{\sum_{m=1}^{MMAX} T_{s,m,k}^{(j)} \Delta Z_m - \sum_{m=1}^{MMAX} T_{s,m,k}^{(o)} \Delta Z_m}{\sum_{m=1}^{MMAX} \Delta Z_m} \right]$$

where:

α_{FE} is the axial fuel reactivity expansion coefficient ($\Delta k/^oF$) over the active core length (Input 320)

$T_{s,m,k}$ is the fuel surface temperature for axial increment m, Channel k

ΔZ_m is the length of axial increment m

and superscripts (j) refers to the jth time step and the superscript (o) refers to steady state. The channel subscript (k) is selected using the variable IREX (Input 8334).

This option, as opposed to other fuel expansion in the program, is a simplified estimate of the reactivity feedback associated with (for example) the case of a "dished fuel pellet" in which the outer edge of the pellet controls the stack length (for fresh fuel). If axial blankets are specified (Input numbers 55 and 56), only the active fuel length (axial sections 2 through 6) are considered in the equation. Note that a negative value of α_{FE} is required to produce a negative reactivity component for an expanding (increasing temperature) core.

In the case of core radial expansion, the model differs from others in the program in that the core expansion feedback is assumed to be proportional to the average outlet coolant temperature.* The reactivity change is given by

$$(\Delta k)_{RE}^j = \left[\alpha_{RE} \left(T_{c,out}^{(j)} - T_{c,out}^{(o)} \right) \right]_k$$

*The other model in the program utilizes a feedback mechanism which combines bowing, axial pressure differences, and changes in the radial temperature gradient across the core.

where

α_{RE} is the radial core expansion coefficient ($\Delta k/^{o}F$)

$T_{c,out}$ the channel outlet temperature (^{o}F)

and the superscripts (j and o) are the same as described previously. Again, the channel selection (subscript k) is controlled with Input 8334. A negative value of α_{RE} (Input 165) would give a negative reactivity feedback during a transient in which the core expanded due to an increase in temperature.

This feedback mechanism is particularly well suited for study of core expansion, core restraint, and similar reactivity effects which can be associated with changes in the average coolant outlet temperature. The magnitude of the reactivity coefficient (α_{RE}) would obviously be selected with consideration for the type of fuel element support involved (i.e., free radial expansion or fixed-end fuel element support).

7.3 ALTERNATE DECAY HEAT MODEL

The present method for determining the fraction of the reactor power which is attributed to decay heat is determined[1] using an empirical equation which contains several constants which are usually obtained from experimental data. Frequently, the relative power resulting from decay heat is available from another source. For example, such information may be available as a result of analyses performed for the purpose of establishing the nuclear characteristics of a reactor core.

To provide for this possibility, an optional decay heat model has been included in the FØRE-2M program. This option is activated using the variable IDECAY (Input No. 8207). When IDECAY is set equal to 1, the empirical decay heat model is bypassed and the decay heat fraction for the three individual channels is obtained from the following time versus decay fraction tables.

Inputs	Variable	Description
8212 to 8231	TDECAY(τ)	Times at which decay heat fractions are supplied. (The first value in the table is 0.0.)
8232-8251	PDECAY(τ,1)	Decay power fraction for Channel 1 corresponding to time values of TDECAY(τ)
8252-8271	PDECAY(τ,2)	As above, but for Channel 2.
8272-8291	PDECAY(τ,3)	As above, but for Channel 3.

The value of the time used to obtain the decay heat fraction can be referenced to the time of scram rather than the actual transient time.* Thus, if in a particular transient a scram were to have occurred at 0.1 seconds, the value of decay heat used at (for example) 1.0 seconds would be the decay heat value in the table corresponding to 0.9 seconds (i.e., $T' = T - TSCRAM = 1.0-0.1=0.9$).

*Using ISTART=1, Input number 8335.

If a transient were to proceed without any scram occurring, the steady state value of decay heat, corresponding to time-zero in the tables, would be used throughout the transient.

The relationship between the prompt neutron power at steady state and the total power for this model is given by:

$$P^* = P_o^o(1-f)/8.6 \times 10^{-10} \quad \frac{\text{FISSIONS}}{\text{cm}^3 \text{ sec}}$$

where P^* and P_o^o are respectively, the prompt fission rates and total power as previously defined by Equation (102) in Reference 1. The variable f represents the steady state decay heat fraction and is determined by one of the following methods:

1. If the "reactor power (Input 636)" and "total volume of fuel in core (Input 91)" are really representative of the total core, f is the weighted average of the decay heat fraction for Channels 1, 2 and 3.

$$f = \sum_{k=1}^{3} \text{PDECAY}(1,K) \cdot \text{FREG}(K)$$

where PDECAY(1,K) is the initial (steady state) decay heat fraction for Channel K and FREG(K) is the fraction of the total core power represented by Channel K.

The three values of FREG(K) are Inputs 8209, 8210, and 8211 and must be selected so that:

$$\sum_{k=1}^{3} FREG(K) = 1.0$$

Example: FREG(1) = 0.6
FREG(2) = 0.3
FREG(3) = 0.1
Total 1.0

2. If the program input for "reactor power" and "total fuel volume" are, in fact, only that associated with the "average" fuel rod (i.e., Channel 1), f is then given directly by the steady state decay heat fraction of the appropriate Channel.

f(k) = PDECAY (1,K)

The selection of which of the above methods is used is controlled by the variable IREG (Input 8208). If IREG=0, the weighted average method is used; if IREG≠0, the Channel K decay heat values are used. The value of IREG is also used to control the printout of the "prompt power" and "total power" during the transient as noted below:

IF IREG=0, Power printouts will be for Core Power
IF IREG=1, Power printouts will be Channel 1
IF IREG=2, Power printouts will be Channel 2
IF IREG=3, Power printouts will be Channel 3

For the "Channel" power printouts (i.e., IREG>0), the printout will correspond appropriately to that of either an individual fuel rod; a subassembly; or a region of the core depending on the magnitude of the fuel volume (Input 91) and power (Input 636) specified in the input.

Irrespective of which of the two methods are used, the individual decay heat fraction for each of the three rods is determined separately. The power generation rate in any one of the three fuel rods at the end of time step j is then given by:

$$P_j(K) = P_o \cdot PDECAY(\tau,K) + 8.6E\text{-}10 \cdot PSTR$$

where PSTR is the fission power which is determined using the kinetics equations programmed into the FØRE-2 program.[1]

The average power over the time step for the fuel rod is given by:

$$\bar{P}_j(K) = \frac{\int P_j(K)\, dt}{\int dt}$$

The value of $\bar{P}_j(K)$ is used to evaluate the local, transient heat generation rate for the appropriate channel.

7.4 SPECIAL SUBROUTINE FOR REACTIVITY FEEDBACK

Although FØRE-2M contains a variety of options related to reactivity feedback, there are occasions in the course of considering various design features when these standard feedback mechanisms are not sufficient to analyze a particular situation. The designer may, for example, wish to study the effect of providing some mechanically or thermally actuated feedback mechanism into the design.

To provide for this contingency, the FØRE-2M program has been "partially" modified by the inclusion of a special feedback subroutine (subroutine SPEC). At present, the subroutine is a dummy routine which, if this option were selected (Input 8333=1), would return with a zero value of reactivity feedback. However, the purpose of including the subroutine is to facilitate (if necessary) modifications of the code to accommodate a special feedback routine.

The subroutine SPEC has in CØMMØN all of the steady-state and transient temperatures which would probably be required for any conceivable reactivity feedback calculations. These temperatures are the coolant inlet temperature and the following temperatures for each axial position of each of the three channels:

1. Coolant nodal average;
2. Coolant nodal outlet;
3. Fuel surface;
4. Fuel average;
5. Cladding average;
6. Additional material.

The length (ΔZ_m) of each axial increment is also contained in the subroutine to allow for axial weighting. To use the model, it will obviously be necessary to program the equation(s) required to simulate the desired feedback mechanism(s). However, this task is simplified with the special subroutine and does not require any changes to the main program.

8.0 MODEL CHANGES TO ALLOW FOR ALTERNATE FUEL ROD CHARACTERISTICS

This section discusses a group of changes made to the program to permit the user to specify an alternate set of characteristics for one or more of the three fuel rods analyzed by the FØRE-2M program. In general, these changes will allow several of the specified characteristics (e.g., geometry) of the Channel 3 (hot channel) fuel rod to be significantly different than the characteristics of the other two fuel rods. Previously, many of these parameters had to be identical for all three fuel rods.

The addition of these modifications now allows for the simultaneous analysis of two entirely different types of fuel rods in the same study. Such a situation could arise, for example, in the study of a fast breeder reactor which had driver fuel rods and blanket rods with different characteristics.

The modifications discussed in this section and in other sections do not have to be used at the same time but can, in fact, be used individually. For example, the alternate decay heat model (Section 7.3) can be used regardless of whether or not the alternate fuel rod geometry model is selected.

8.1 ALTERNATE FUEL GEOMETRY OPTION

In the original version of the FØRE-2 computer program, the equations were all directed at obtaining the solution of a fuel rod transient involving three identical fuel rods. These three fuel rods were identified as an average rod (Channel 1), the peak rod (Channel 2) and the hot rod (Channel 3). And while the heat generation rates and heat transfer characteristics of the three rods could be different, the geometry of all three fuel rods were the same.

Recently, it has been observed that with certain fast reactor core geometries the feedback contribution of the blanket rods becomes a non-trivial portion of the overall feedback. And since the geometry of the fuel rods and blanket rods are not necessarily the same, the simultaneous treatment of more than one fuel rod geometry becomes desirable. This feature has, therefore, been included in these latest modifications to the FØRE-2M program.

To activate this option, it is merely necessary to set the option trigger (Input No. 7768=1) and supply a second set of geometric input variables (Inputs 7769 to 7790 and 8190 to 8206). This alternate geometry will then be assigned to the fuel rod in Channel 3 (i.e., the "hot rod"). Channels 1 and 2 (i.e., the average and peak rods) will use the values of the geometry normally supplied in any problem.* Note that with this option, either two blanket rods and one fuel rod, or two fuel rods and one blanket rod may be analyzed in the same transient. The only restriction is that the geometry of the Channel 1 and Channel 2 fuel rods is identical while that of Channel 3 is different.

The relative heat generation rates in Channels 2 and 3 are controlled using Inputs 179 and 180. Since the geometry of Channel 2 is the same as for Channel 1, the heat generation of Channel 2 is related to the heat generation of Channel 1 by the ratio of the power (P_k) in the respective channels. Thus, for the peak channel (Channel 2),

---

*Other information which has been explicitly defined for Channel 3 in the original code version (Ref. 2) is also automatically carried over for the alternate geometry (e.g., axial variation in central void size; Inputs 915-921).

$$P_r \text{ (Input 180)} = (P_2/P_1)$$

For Channel 3, the differences in geometry must also be considered so that the correction factor on heat generation becomes:

$$P_H \text{ (Input 179)} = (P_3/P_1)(R_{f,1}/R_{f,3})^2$$

where

P_k is the rod power of Channel K
$R_{f,k}$ is the fuel radius of Channel K

8.2 ALTERNATE AXIAL POWER SHAPE

Frequently, the axial power shape of the fuel rods and blanket rods also differ enough to warrant consideration. An alternate axial power shape is therefore available to supplement the alternate fuel rod option discussed in the previous section. However, the alternate axial power shape can be used even if the alternate geometry option is not used.

The option trigger for the alternate axial power shape is Input 32 (i.e., Input 32=1). Up to seven relative values, corresponding to the number of axial sections (Input 8) are then supplied using Inputs 8182 to 8188. As in the case of the regular axial power shape (Inputs 171 to 177), the values should be normalized so that:

$$\frac{\sum_{m=1}^{MMAX} F_z \cdot \Delta Z}{\sum_{m=1}^{MMAX} \Delta Z} = 1.0$$

The alternate axial power shape will be applied to Channel 3 if this option is chosen. The normal axial power distribution will be assigned to Channels 1 and 2.

Note that this alternate power shape option is entirely different that the option described in Section 10.1 (Inputs 849 to 855). With that option, the axial power shape (Inputs 171 to 177) can be modified at one point in the transient. Since this transient alteration would apply equally to all three channels (i.e., as a percentage change from the original shape), it is suggested that both of these power shape options not be used simultaneously in order to avoid the possible introduction of an unwanted change in the power shape.

8.3 AXIAL VARIATION IN HEAT GENERATION HOT SPOT FACTOR

To provide an additional degree of flexibility to the program user, a spatial variation in the factor on heat generation for the "hot rod" (i.e., Channel 3) is now available. This feature can only be used in conjunction with the alternate power shape option (Inputs 32 and 8182-8188).

If the user wishes to use this feature, the axial variation in the hot spot factor is supplied via inputs 7791 to 7797. If these inputs are supplied, this axial variation in hot spot factor will be used in place of the normal hot spot factor (INPUT 179) in computing the local heat generation rate in the Channel 3 fuel rod.

The local heat generation rate in each of the three fuel rods is then computed in the following manner:

Channel 1 (The Average Channel)

$$Q_1'''(M) = 948.05 \cdot PIN \cdot A_m \cdot FRFL/V\emptyset LFL$$

where:

$Q_1'''(M)$ is the average heat generation in the fuel of Channel 1 at axial section M, Btu/sec-ft^3

PIN is the input power (INPUT 636), Mw

A_m is the ratio of local power to average power at axial section M (INPUTS 171-177)

FRFL is the fraction of power produced in the fuel

VØLFL is the volume of fuel in the core (INPUT 91), ft^3

Channel 2 (The Peak Channel)

$$Q_2'''(M) = Q_1'''(M) \cdot P_r$$

where:

P_r is the radial peak-to-average power density in the core (INPUT 180)

Channel 3 (The Hot Channel)

a) If INPUT 32 is equal to zero:

$$Q_3'''(M) = Q_1'''(M) \cdot P_H$$

where:

P_h is the hot spot factor used in calculating heat generation in the hot channel (INPUT 179)

b) If INPUT 32 is equal to 1 and INPUTS 7791 to 7797 are not specified:

$$Q_3'''(M) = Q_1'''(M) \cdot P_H \cdot XPØWR(M)/A_m$$

where:

XPØWR(M) is the ratio of local power to average power for the alternate power shape (INPUTS 8182-8188)

c) If INPUT 32 is equal to 1 and INPUTS 7791 to 7797 are specified:

$$Q_3'''(M) = Q_1'''(M) \cdot PS_m \cdot XPØWR(M)/A_m$$

where:

PS_m is the local hot spot factor on heat generation at axial section M (INPUTS 7791-7797) for the alternate power shape in the hot channel (INPUTS 8182-8188)

The addition of this feature permits the user to easily account for any spatial variation in heat generation uncertainties which may occur.

9.0 PROGRAM REVISIONS

During the course of updating the FØRE-2M program, several minor errors were uncovered. These errors were either a result of an incorrect derivation of an equation or were caused by a programming error. In general, the errors resulted in either conservative predictions or had little or no effect upon the overall results.

9.1 REVISION TO THE CALCULATION OF AVERAGE FUEL TEMPERATURE

One of the model changes made to the original FØRE-2 program[1] was changing the location at which the temperature calculations were performed within a fuel node. If the original program, this location corresponded to the volume weighted center of the fuel node. In the earlier revision to the model[2], it was shown that by changing the location a more accurate temperature calculation could be obtained.

Figure 10 is a schematic representation of the fuel node network for a four region fuel rod (up to 10 regions can be specified). Shown on the figure schematically are three sets of radii:

1. the radii describing the fuel node boundaries (user specified)

2. the location of the volume weighted nodal centers

3. the radii at which temperatures are calculated using the improved location discussed above.

The relationship between the boundary radii and the radii at which the temperatures are calculated was derived by comparing an exact solution with a solution obtained using a finite element approximation. The resulting relationship was shown[2] to be:

$$r_m^2 = \frac{R_{n+1}^2 - R_n^2}{2 \log(R_{n+1}/R_n)}$$

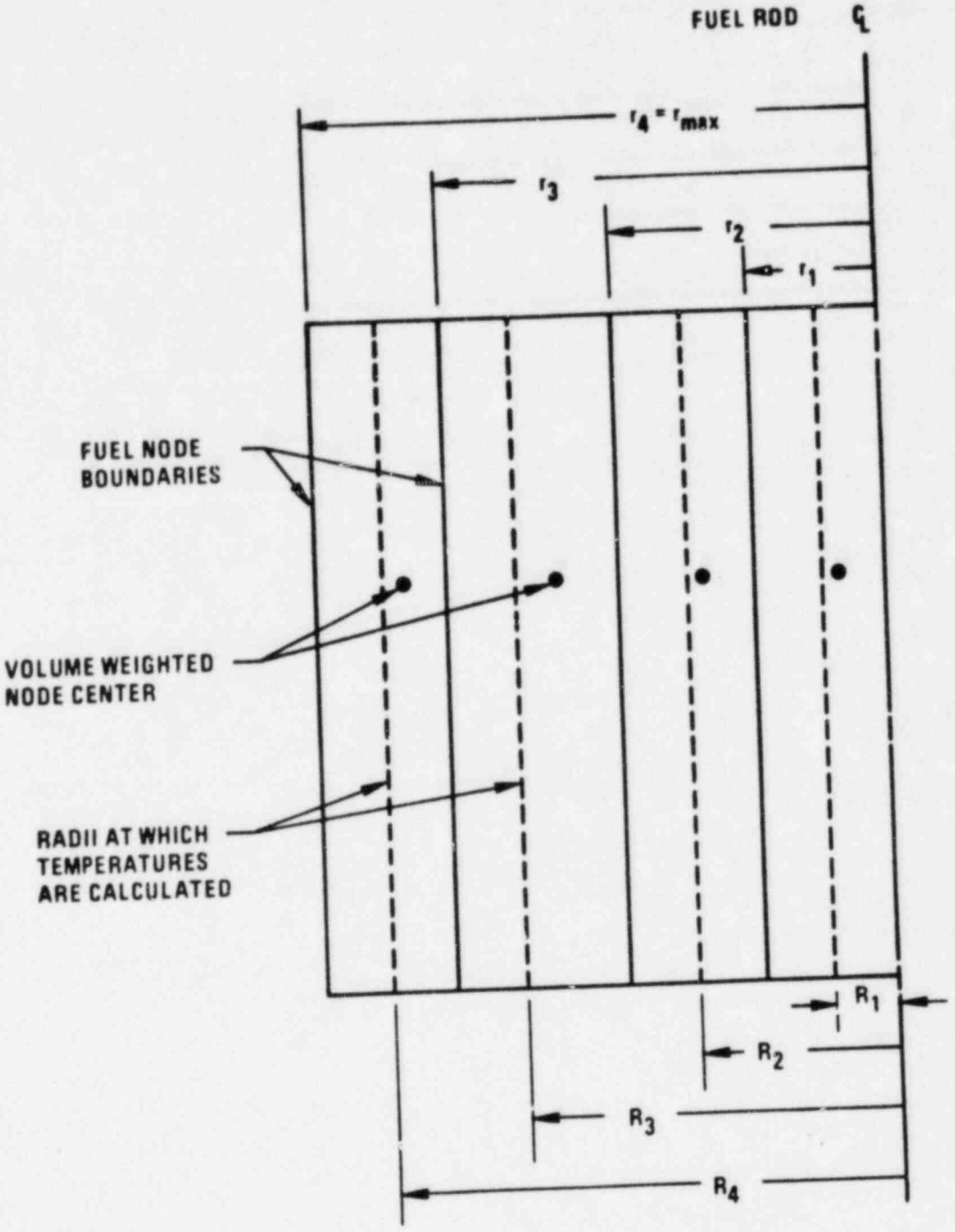


Figure 10 Schematic of Fuel Node Network in FØRE-2M

3487-10

While this modification to the program improved the temperature calculations, it introduced an error in the average temperature calculation since the average node temperature is associated with the volume weighted node center. While this error did not significantly change the overall results obtained from the program,* the value of the average temperature listed in the FØRE-2M output was in error. To correct this deficiency, the average temperature of each fuel node was determined by a parabolic interpolation of the two adjacent fuel temperatures. For the example shown on Figure 10, for example, the average fuel temperature of node 2 would be given by:

$$T_2 = T_1 - (T_1 - T_2) \left[\frac{a_2^2 - R_1^2}{R_2^2 - R_1^2} \right]$$

where:

T_1 and T_2 are the temperatures calculated at R_1 and R_2

and a_2 is the radius at the location corresponding to the volume weighted node center and is defined by

$$a_2 = \sqrt{\frac{r_2^2 + r_1^2}{2}}$$

*Since the Doppler calculation uses a transient temperature change rather than an absolute value, the difference between the values obtained at the two locations is quite small so that the calculated feedback resulting from a change in the fuel temperature was not affected appreciably.

9.2 REVISION IN DERIVATION OF A GAP CONDUCTANCE EQUATION

In performing the recent program modifications, it was noted that one of the equations in the original FØRE-2 version of the variable gap conductance model contained a minor derivation error. This equation was related to the decrease in gap dimension resulting from fuel melting if the volume of molten fuel exceeded the central void volume. The equation* was given in the form

$$\Delta R_{melting} = \left[\frac{\Delta V_{melt} \, R_f}{2} \quad \frac{(\Delta V_{melt} + 1) R_o^2}{2R_f} \right] \frac{1}{A_f} \sum_{m=1}^{N} A_{m(melt)}$$

where:

A_f	is the total fuel volume
A_m	is the area of molten fuel
R_f	is the fuel radius
R_o	is the radius of the central void
$\Delta R_{melting}$	is the change in radius due to fuel melting
ΔV_{melt}	is the fractional change in fuel volume associated with melting
N	is the number of fuel rings which have melted

The equation is derived by comparing the change in fuel volume associated with melting with the amount of molten fuel that can be accommodated by the central void. The excess molten fuel volume is then assumed to contribute to a change in the radial expansion of the fuel rod.

Letting $f = \frac{1}{A_f} \sum_{m=1}^{N} A_m$, we have for a unit length of fuel

$$\pi(R_f^2 - R_o^2) f \cdot \Delta V_{melt} = \pi R_o^2 + 2\pi R_f \Delta R$$

$$\Delta R_{melting} = \left[\frac{\Delta V_{melt} \, R_f}{2} \quad \frac{(\Delta V_{melt} + 1) R_o^2}{2R_f} \right] \frac{1}{A_f} \sum_{m=1}^{N} A_{m(melt)}$$

*Equation 34 of Reference 1.

Comparison of this equation with the previous equation shows that the multiplier on R_o^2 now contains a term 1/f rather than the value of unity contained in the original equation. This error would have resulted in a slight underprediction of the expansion characteristics of the fuel if the following four conditions existed:

1. The original variable gap conductance model (Input 20=+1) was used.

2. A central void was specified or occurred as a result of sintering.

3. Fuel melting occurred.

and 4. The molten fuel volume exceeded the volume of the central void.

In the event that all of the above conditions existed, the result would have been that the calculated fuel temperatures would have been overpredicted. This error has been corrected in the modified version of the computer program.

10.0 PROGRAM MODIFICATIONS TO PROVIDE USER FLEXIBILITY

In addition to the changes made to obtain model improvements, several features have been added to the FØRE-2M program which do not affect the basic calculations but which were added to provide some additional flexibility for the user. The use of these additional features allows the user to either obtain specific information or to have the ability to manipulate the output without having to stop and RESTART a problem. These features have been included as options since it may not be necessary nor desirable to use them for many cases.

10.1 MODIFY THE AXIAL POWER SHAPE DURING THE TRANSIENT

Certain types of analyses require that the axial power shape be changed at some point in the transient. For example, for a control rod insertion transient, the axial power shape changes when the rod is inserted from an initially withdrawn position.

The analysis of this type of transient has previously been performed using the RESTART option in the computer program. The insertion phase of the transient is run. Then the program is stopped, the axial shape appropriately modified, and the remainder of the transient analyzed.

To provide more flexibility for the user, a new option has been added which allows the axial power shape to be modified without stopping the problem. Input number 848 is a new variable (TSWAP) that defines the time at which the alternate power shape will become effective. The alternate axial power shape (Inputs 849-855) is defined by the variable ALTPØW(M)*.

After the time TSWAP has been reached, the local heat generation is corrected by multiplying by the ratio of the alternate shape factor to the original shape factors (PØWRAT(M), Inputs 171-177) as shown below.

for $\tau \leq$ TWSAP,

$$Q'''_{(\text{modified})} = Q''' \cdot \text{ALTPØW}(M)/\text{PØWRAT}(M)$$

*where $1 \leq M \leq$ MMAX

10.2 PRINTOUT INTERVAL VARIATION DURING THE TRANSIENT

Printout intervals (i.e., the period of time between printouts) can be controlled by several different input variables in FØRE-2M. However, once these variables are selected, the printout interval is fixed and is either a function of the number of timesteps (Input 34) or a specified time between printouts (Input 71).

In many transients, there may be a period of time during which the parameters change quite rapidly while during the remainder of the transient changes occur more slowly. Thus, while it may be important to have frequent printouts during the one portion of the problem, the same printout interval might produce a needless amount of output during the slower portion of the transient.

A new option has therefore been added which permits the user to change the printout interval during the problem. If a non-zero value is input to location 856, it will represent the point in time, specified in seconds, at which a new printout interval will becomd effective. This new printout interval is specified as Input 857 and will override Input 71 once the problem time exceeds the value of Input 856.

10.3 OPTION FOR SEARCHING FOR PEAK VALUES OF CERTAIN CRITICAL PARAMETERS

In order to reduce the amount of output data, the user of FØRE-2M usually does not print out the results from each calculation. Rather, he selects a printout interval (INPUT 71) which will result in a reasonable quantity of output data. Frequently however, particularly for transients in which the values of the parameters change rapidly (e.g., rapid reactivity transients), this procedure will fail to specifically print out the maximum value of certain critical parameters.* The user must then attempt to estimate the magnitude and time at which the maximum values of these parameters could occur.

To avoid the possibility of errors in this procedure, an option has been added (INPUT 8338) which will key the FØRE-2M program to search for and record the time of occurrence and maximum values of: 1) reactor power; 2) maximum fuel centerline temperature; 3) maximum cladding I.D. temperature; and 4) maximum channel coolant temperature. The user can select either Channel 1 (INPUT 8338=1), Channel 2 (INPUT 8338=2) or Channel 3 (INPUT 8338=3) as the channel on which the search for maximum temperatures will be performed. The program will then identify the time and axial location at which the maximum values of these parameters occur.

Since this option will increase the computer execution time slightly (<0.5%), it is recommended that this option be bypassed (INPUT 8338=0) for slow transients were interpolation will usually produce satisfactory results.

*Such a condition usually occurs in the first few seconds of a transient.

10.4 STORAGE OF DATA FOR SUBSEQUENT RETRIEVAL FOR A PLOTTING PACKAGE

An option has been included in the latest version of FØRE-2M which allows for storage of selected parameters for possible use in a subsequent plotting package. The original FØRE-2 program (1) did have a plotting package in it, but this was later removed because it was somewhat incompatible with the Westinghouse computer facility.

The present version of FØRE-2M stores 169 selected variables (Tables 4 and 5) on TAPE 2. This storage is initiated by setting option IPLØT (INPUT 8337) equal to 1; if the option is not desired, this variable should be set equal to zero (INPUT 8337=0).

Once the option is selected, the user must then save the data tape for subsequent use by specifying the appropriate "CATALOG TAPE 2" command. Rather than write a generalized plotting routine (which may not be compatible with every computer facility), it is suggested that each facility write its own plotting program, retrieving the data stored on TAPE 2 and manipulating it as required. The 169 variables are stored on TAPE 2 in a series of strings, indexed according to the index numbers shown on Tables 4 and 5. There will be "N" strings (each 169 words in length) where "N" corresponds to the number of computer printouts that were obtained during the problem. The dimension of this "dummy" array is therefore given by DUMMY (N, 169) where N can vary between 1 (steady state) and the maximum number of printouts (NMAX) in a given problem. The following method (for example) could then be used to retrieve the data:

```
      DO 100 N=1, NMAX

100   READ (2) (DUMMY (N,I),I=1,169)
```

TABLE 4

VARIABLES STORED ON TAPE 2 FROM FØRE-2M RUN
CORE DEPENDENT PARAMETERS

Index Number	Parameter
1	TIME (sec)
2	Total Core Power (Mw)
3	Prompt Core Power (Mw)
4	Channel 1, Coolant Mass Velocity (lb/sec-ft^2)
5	Channel 2, Coolant Mass Velocity (lb/sec-ft^2)
6	Channel 3, Coolant Mass Velocity (lb/sec-ft^2)
7	Channel 1, Coolant Outlet Temperature (^{o}F)
8	Channel 2, Coolant Outlet Temperature (^{o}F)
9	Channel 3, Coolant Outlet Temperature (^{o}F)
10	Maximum* Cladding Temperature (^{o}F)
158	Total Core Reactivity (Δk)
159	Programmed Reactivity (Δk)
160	Total Feedback (Δk)
161	Doppler Feedback (Δk)
162	Cladding OD Temp. (°F), Channel 3, Axial Node #1
163	Cladding OD Temp. (°F), Channel 3, Axial Node #2
164	Cladding OD Temp. (°F), Channel 3, Axial Node #3
165	Cladding OD Temp. (°F), Channel 3, Axial Node #4
166	Cladding OD Temp. (°F), Channel 3, Axial Node #5
167	Cladding OD Temp. (°F), Channel 3, Axial Node #6
168	Cladding OD Temp. (°F), Channel 3, Axial Node #7
169	Coolant Inlet Temperature

TABLE 5

VARIABLES STORED ON TAPE 2 FROM FORE-2M RUN

CHANNEL DEPENDENT PARAMETERS

Parameter	Channel	Index Number Axial Sections 1 to 7						
		1	2	3	4	5	6	7
Fuel Centerline Temperature (°F)	1	11	12	13	14	15	16	17
	2	60	61	62	63	64	65	66
	3	109	110	111	112	113	114	115
Average Fuel Temperature (°F)	1	18	19	20	21	22	23	24
	2	67	68	69	70	71	72	73
	3	116	117	118	119	120	121	122
Fuel Surface Temperature (°F)	1	25	26	27	28	29	30	31
	2	74	75	76	77	78	79	80
	3	123	124	125	126	127	128	129
Cladding I.D. Temperature(°F)	1	32	33	34	35	36	37	38
	2	81	82	83	84	85	86	87
	3	130	131	132	133	134	135	136
Average Coolant Temperature (°F)	1	39	40	41	42	43	44	45
	2	88	89	90	91	92	93	94
	3	137	138	139	140	141	142	143
Outlet Coolant Temperature (°F)	1	46	47	48	49	50	51	52
	2	95	96	97	98	99	100	101
	3	144	145	146	147	148	149	150
Surface Heat Flux (Btu/hr-ft^2)	1	53	54	55	56	57	58	59
	2	102	103	104	105	106	107	108
	3	151	152	153	154	155	156	157
Cladding O.D. Temperature (°F)	3	162	163	164	165	166	167	168

11.0 REFERENCES

1. J. N. Fox, B. E. Lawler and H. R. Butz, "FØRE-II, A Computational Program for the Analysis of Steady-State and Transient Reactor Performance," GEAP-5273, September 1966.

2. J. V. Miller and R. D. Coffield, "FØRE-2M: Modified Version of the FORE-II Computer Program for the Analysis of LMFBR Transients," CRBRP-ARD-0142, November 1976.

3. "Nuclear Systems Materials Handbook," Vol. I, TID-26666, 1975.

4. A. M. Ross and R. L. Stoute, "Heat Transfer Coefficient Between UO_2 and Zircaloy-2," AECL-1552 (CRFD-1075), June 1962.

5. R. B. Baker, "Calibration of a Fuel-to-Cladding Gap Conductance Model for Fast Reactor Fuel Pins," HEDL-TME-77-86, May 1978.

6. G. G. Gubareff, J. E. Janssen and R. H. Torborg, Thermal Radiation Properties Survey, Second Edition, Honeywell Research Center, Minneapolis, Minnesota, 1960.

7. W. H. McAdams, Heat Transmission, McGraw-Hill Book Company, New York, 1939, pp. 54-55.

8. "LIFE-III Fuel Element Performance Code," ERDA-77-56, July 1977.

9. "Compilation of Boron Carbide Design Support Data for LMFBR Control Elements," HEDL-TME-75-19, 1975.

10. G. H. Golden and J. V. Tokar, "Thermophysical Properties of Sodium," ANL-7323, August 1967.

11. T. L. George, R. A. Masterson and K. L. Baseshore, "A Modified Version of COBRA for Whole-Core LMFBR Transient Analysis," Trans. Am. Nucl. Soc. 32, pp. 531-532 (1979).

12. R. L. Gibby, L. Liebowitz, J. F. Kerrisk, et al., "Analytical Expressions for Enthalpy and Heat Capacity for Uranium-Plutonium Oxide," HEDL-TME-73-60, June 1973.

APPENDIX A

INPUT DATA

A.1 INPUT DATA

The particular input for the data cards is discussed in Subsection A-3. The format for the other cards are:

Case Card:

Column	Contents	
1	) independent case designation (dependent case designation	
2-6	FØRE*	
7-9	User's initials	Column 2-34 are Optional
10	*	
11-14	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	Columns 6-9 are Optional
9	*	

Because of tape-handling difficulties when a wrapup is requested, only single cases can be run in this version of the code.

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 spaces 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 locations beyond 60 must be external fixed point (F Field) or floating point (E Field) numbers: that is, a decimal point must be used.*

Repeat and skip options offer additional input flexibility. The expression 1.0 ΔRnΔ, for example, assigns 1.0 to n consecutive locations. The Δ is to typographically 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 B contains a listing of the input for a 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. The last card of a given input variable overrides previous data.

A.2 RESTART

The user has the option in FØRE-2M for a final and two intermediate wrapups, and for a restart with changes in input from any of these wrapups. Table A-1 contains a list of input values that cannot be changed on restart.

Because of the restart capability, the flexibility of FØRE-II has been greatly extended. A typical use might be the coefficients of reactivity terms which are single value input. For the particular transient

*Inputs 7768, 7798, 7799, 8207, 8208, 8292, 8333 to 8335, and 8336 to 8339 are exceptions to this rule.

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.

The input deck for a restart is as follows:

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

A.3 DESCRIPTION OF INPUT DATA

Table A-2 describes the input data for the FØRE-2M program. Not all of the variables are required for any given problem. The actual amount of input data required depends upon the options selected for a particular case. It should be noted that core flow and inlet temperature as a function of time must be input to the code. These data are typically calculated with a plant simulation model which analyzes the coupled thermal/hydraulics of the primary, intermediate and steam loops.

TABLE A-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

TABLE 2:

INTEGER VARIABLES, LOCATIONS 1 to 60 INPUT FOR FØRE-2M

Nodal and Tabular Options

Input Number	Variable	Range	Units	Remarks
1	IMAX	$1 \leq IMAX \leq 6$	-	Number of delay groups
2	IMMAX	$1 \leq IMMAX \leq 3$	-	Number of terms in empirical fit to fission product decay [see Equation (102) of Ref. 1]
3	INUM	$2 \leq INUM \leq 30$	-	Number of mass velocity entries
4	ISMAX	$2 \leq ISMAX \leq 30$	-	Number of effective multiplication factor entries (if this is input)
5	JMAX		-	Maximum number of time steps
6	KNUM	$2 \leq KNUM \leq 30$	-	Number of T_c^{in} entries
7	LMAX	$2 \leq L \leq 7$ ($L \neq 0,1$)	-	Number of radial core regions
8	MMAX	$1 \leq M \leq 7$	-	Number of vertical core sections
9	NMAX	$1 \leq N \leq 10$	-	Number of radii at which fuel temperatures are calculated
10	NUMPWR	$2 \leq NUMPWR \leq 30$	-	Number of power entires (if this is input)
11	NMVØID	$2 \leq NMVØID \leq 30$	-	Number of entries due to sodium voiding (if this is an input)
12	NMSCRM	$2 \leq NMSCRM \leq 30$	-	Number of Δk points due to scram (if this is an input)
13	NMCØØL	$2 \leq NMCØØL \leq 30$	-	Number of bulk coolant boiling entries (if this is an input)
14	NMCLAD	$2 \leq NMCLAD \leq 20$	-	Number of cladding burnout entries (if this is an input)
15	NMTERM		-	Channel to which temperature limits should be applied (1, 2 or 3). If 0, average channel will be used (including coolant temperature scram).

Nodal and Tabular Options

Input Number	Variable	Range	Units	Remarks
16	δ_f	0	-	Equals 0 means use calculated w_ℓ which assumes parabolic profile
		1		Equals 1 means use input values for w_ℓ (locations 820 - 826)
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_g	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)	±(1 or 2)		For variable conductance from fuel to cladding
		0		Constant conductance (see location 341)

(1) If δ_{gap}=1, the Ross and Stoute model, modified to include radiant heat transfer, is used.

If δ_{gap}=2, axial variations in conductances and radial gap dimensions are specified for each of the three channels using Inputs 827 to 847 and 948 to 968 (see Reference 3 for a description of the model used with this option).

If δ_{gap} = -1 or -2, the Ross and Stoute model (including radiant heat transfer) is used. Inputs 948 to 968 are used to specify either the cold (δ_{gap} = -1) or hot (δ_{gap} = -2) radial gap dimension.

Nodal and Tabular Options

Input Number	Variable	Range	Units	Remarks
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)	0		Use curve fit for fuel conductivity (Input No. 118-120)
		1		Uses table (Input No. 861-900)
		2		Uses original TID-26666 Pu-UO_2 conductivity
		3		Uses irradiated B_4C conductivity from HEDL-TME-75-19
		4		Uses TID-26666 (Rev. 1, 8/1/77) Pu-UO_2 conductivity
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

(1) If δ_k = 2 or 4 is used, Inputs 858 and 859 must be specified. If alternate geometry option (Input 7768) is used, Inputs 8205 and 8206 must also be specified.

Code Options

Input Number	Variable	Range	Units	Remarks
26	δ_{step}	1 0		If user has specified step size For calculation of step size
27	δ_u	1 0		If additional material is used Otherwise (if $\delta_u = 0$, G_u must be 0.0)
28	δ_{cof}	1 0		If $h^{(j)}_{c,m,k} = 3$ should be calculated at time of void (set to 1 if no voiding table) Otherwise
29	$\delta_{restart}$	1 0		If this is a restart Otherwise
30	δ_{ave}	0 1		If average fuel temperature is based on core only If average fuel temperature is based on core plus blankets
31	δ_s	0 1		Option on coolant cross-flow component and excess energy. If δ_s=1, Inputs 7860 to 7999 and 8000 to 8140 must be supplied
32	N_s	0 1		Number of axial power shapes. If N_s=0, only one shape supplied (Inputs 171-177). If N_s=1, an alternate shape must be supplied for Channel 3 (Inputs 8182-8188)

Edit Options

Input Number	Variable	Range	Units	Remarks
33	δ_{long}	1 0		Print the long edit Do not print the long edit
34	NMLØNG			Number of steps/printout (long edit)
35	$\delta_{\emptyset p1}$	1 0		Print section D (precursor concentrations) Do not print section D
36	$\delta_{\emptyset p2}$	1 2 3 0		Edit average channel only, sections E and F (Fuel and Radial Temperatures) Edit average and peak channels Edit average, peak, and hot-spot channels Edit all channels calculated
37	δ_{temp}	1 0		Print fuel Equivalents Print fuel Temperatures
38	MSKIP	<MMAX		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	$\delta_{\emptyset p3}$	1 0		Print out section G (Coolant Temperature and Velocity) Do not print section G
47	$\delta_{\emptyset p4}$	1 0		Print section H (Cladding surface heat flux) Do not print section H
48	$\delta_{\emptyset p5}$	1 0		Print section I (Coefficients and Gap Conductance) Do not print section I

Edit Options

Input Number	Variable	Range	Unit	Remarks
49	δ_{wrapup}	0 1 2 3		No Wrapup Final wrapup only One additional wrapup Two additional wrapups
50-51	JRAPUP	<JMAX		Time step where wrapup is desired (if δ_{wrapup} = 2, specify one value) (if δ_{wrapup} = 3, specify two values)

Other Options

Input Number	Variable	Range	Units	Remarks
52	KNTNV	0 1 2		If your case is a restart: means continue problem where original one left off Means continue problem from first wrapup Means continue problem from second wrapup
53	IVARY(1)			Option for variable void } See Section 3.2
54	ISINTR(1)			Option for fuel sintering } Reference 2
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 1		High-density coolant (liquid metal) Low-density coolant (gas or steam)
58	$\delta_{\Delta P}$	-2 to +6		Option for pressure drop(2)
59	δ_{AFW}	0 1		Option for axial flux weighting Axial weighting per Input 171-177 Axial weighting per Input 941-948
60	δ_{melt}	1 0		Option for melt routine: Calculates percentage molten fuel No calculation

(1) To obtain correct heat balance for core of non-uniform axial hole size in pellet (prescribed but not calculated by code, e.g., "cored pellets"), a proper heat balance requires using [53] and [54] = 1.

(2) See Section 2.2 of this addendum and Section 3.9 of Reference 2 for a description of the pressure drop/flow redistribution options.

Times and Termination Controls

Input No.	Variable	Range	Units	Remarks
61	DELP		-	Maximum fractional power change per step
62	DELT		sec	Initial step size (must always be input)
63	HMAX		sec	User's maximum step size (input only if $\delta_{step} = 1$)
64	TMAX (1)		sec	Maximum running time of transient
65	T_1^{Max}		°F	Upper limit for temperature of fuel node 1
66	T_1^{Min}		°F	Lower limit for temperature of fuel node 1
67	T_N^{Max}		°F	Upper limit for fuel boundary node
68	T_N^{Min}		°F	Lower limit for fuel boundary node
69	T_c^{Max}		°F	Upper limit for coolant temperatures
70	T_c^{Min}		°F	Lower limit for coolant temperatures
71	p^{Max}		sec	Maximum time between printouts
72	TS_{Min}		sec	Minimum time step size (recommend 10^{-5})
73	-			Blank
74	-			Blank

(1) NOTE: An additional time limit on computer running time is established with the control cards which precede the FØRE-2M input deck. The program has a built-in 10-second delay on this specified value to permit the printing of the output. For short running problem (TMAX < 30_8 seconds), the delay is reduced to 3 seconds.

Geometry

Input Numb..	Variable	Range	Units	Remarks
75	D_B		ft	Diameter of the fuel channel (see Equation 67 of Reference 1)
76	R_c		ft	Equivalent radius of the coolant
77	R_e		ft	Cladding inner radius
78	R_E		ft	Cladding outer radius
79-88	R_n		ft	Outer radius of fuel node n; $1 \leq n \leq$ NMAX
89	R_o		ft	Radius of the void (fuel pin center)
90	R_T		ft	Core outer radius
91	V_f		ft^3	Total volume of fuel in core
92	V_s		ft^2	Volume of structure per unit length of fuel
93	V_u		ft^2	Volume of additional material per unit length of fuel
94-100	$(\Delta Z)_m$		ft	Length of core axial section m; $1 \leq m \leq$ MMAX
101	Z_T		ft	Total distance from channel inlet to outlet
102	B	≥ 0	Btu/Ft-Sec-°F^2	Constant multiplier on temperature for cladding thermal conductivity
103	P/F Ratio			Power-to-flow scram
104	Period		sec	Reactor period scram
105	$\Delta\tau$		sec	Time interval over which reactor period is averaged (if zero, average is over one time step)

Material Properties

Input Number	Variable	Range	Units	Remarks
106*	Fe		-	Hot spot factor for thermal conductivity of the cladding - multiplier Input 107 for Channel 3
107	Ke (or A)		Btu/Sec-Ft-°F	Thermal conductivity of the cladding
108	K_s		Btu/Sec-Ft-°F	Thermal conductivity of the structure (must be non-zero)
109	K_u		Btu/Sec-Ft-°F	Thermal conductivity of the additional material (must be non-zero)
110	C_e		Btu/lb-°F	Specific heat of the cladding
111	C_s		Btu/lb-°F	Specific heat of the structure
112	C_u		Btu/lb-°F	Specific heat of the additional material
113	ρ_f		lb/ft^3	Fuel density
114	ρ_e		lb/ft^3	Cladding density
115	ρ_s		lb/ft^3	Structure density
116	ρ_u		lb/ft^3	Density of additional material
117	T_f^{MELT}		°F	Fuel melting temperature (see note on pg. 37)
118	K^0		Btu/Sec-Ft-°F	Constants used in calculating thermal conductivity of the fuel (only if quadratic fit selected input 22=0)
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

*Indicates hot spot factor.

Material Properties

Input Number	Variable	Range	Units	Remarks
122	B_K		Btu/Sec-Ft-°F^2	Constants used in calculating fuel conductivity at melting (only if quadratic fit selected Input 22=0)
123	C_K		Btu/Sec-Ft-°F^3	
124	B^{MELT}		Btu/Ft^3	Fuel heat of fusion
125-144	C'		Btu/lb-°F	Specific heat of fuel versus Temperature
145-164	T'		°F	
165	α_{RE}		Δk/°F	Core radial expansion coefficient
166	G_o		Lb/Sec-Ft^2	Initial flow rate in average channel(1)
167	M	1.0 to 7.0		Channel 3 axial cladding section for which Input 168-170 apply
168	F_3	>0		HCF of cladding at 167 axial section(2)
169	F_2	>0		HCF of film at 167 axial section(2)
170	F_1	>0		Ratio of flux at exit to flux at midpoint of 167 axial section(2)

(1) If G_o = 0, absolute flow rates as a function of time must be specified using Input 196-225.

(2) Internally set to 0.0 if not specified.

Power and Flow Factors

Input Number	Variable	Range	Units	Remarks
171-177	A_m	$1 \leq m \leq$ MAX	-	Ratio of peak power to average power for axial section m
178	F_Y		-	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	$\sum_{n=1}^{N} Y_n A_n = A_f$	-	Ratio of heat generation rate in fuel node n to fuel average heat generation rate
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	TSØLID		°F	Solidus temperature of fuel
194	TLIQ		°F	Liquidus temperature of fuel
195	TPLAS		°F	Temperature at which fuel becomes plastic

Coolant Flow Characteristics

Input Number	Variable	Range	Units	Remarks
196-225	G_c'		$Lb/Ft^2\text{-}Sec$ (1)	Coolant mass velocity for average channel versus Time
226-255	T'		sec	
256-285	$T_c'^{Inlet}$		°F	Coolant inlet temperature versus Time
286-315	T'		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 Suggested values: C = 0.316 e = 0.25
318	e		-	
319	D_H		ft	Hydraulic diameter of coolant passage
320	α_{FE}		$\Delta k/°F$	Axial fuel expansion coefficient

(1) If Input 166 is specified, a normalized flow rate (G/G_o) should be used.

Coolant Heat Transfer Coefficient Inputs

Input Number	Variable	Range	Units	Remarks
321	A_H			Constants used in coolant heat transfer coefficient equation $1 \leq m \leq M$ Max. (See Equation 15 of Ref. 1)
322	B_H			
323-329	$C_{H,m}$			
330	M_H			
331	N_H			
332	R_H			
333	D_{HT}		ft	Appropriate diameter for use in calculating the coolant heat transfer coefficient
334*	F_h		-	Hot spot factor for calculating coolant heat transfer coefficient
335	d_s		ft	Characteristic structure dimension (see Subsection 3.4.4 of Reference 1)
336	d_u		ft	Characteristic dimension of the additional material (see Subsection 3.4.4 of Ref. 1)
337	G_s		ft^{-1}	Structure surface-to-volume ratio
338	G_u		ft^{-1}	Additional material surface-to-volume ratio (if $\delta_u = 0$, G_u must be 0.0)-(see Subsection 3.4.4 of Reference 1)
339	$h_{c,3}$		Btu/Sec-Ft^2-°F	Coolant heat transfer coefficient for hot spot channel at time of void (used only if $\delta_{cof} = 0$)
340	DECØUP			Option for decoupling additional material DECØUP = 1.0 Decouples 1, 2, 3 DECØUP = 2.0 Decouples 2, 3 DECØUP = 3.0 Decouples 3

*Indicates hot spot factor.

Gap Conductivity Inputs

Input Number	Variable	Range	Units	Remarks
341	h_f		Btu/Sec-Ft^2-°F	Heat transfer coefficient of fuel cladding gap (if location 20 is 0, only locations 341, 355, and 359 need be considered in this section)
342	A_g		Btu/Sec-Ft-°F	Constants used in equation for calculating thermal conductivity of the gap (see Equation 38 of Reference 1)
343	B_g		Btu/Sec-Ft-°F^2	
344	C_g		Btu/Sec-Ft-°F^3	
345	a_o		ft^2	Constant used in gap conductivity equation (see Equation 37 of Reference 1)
346	B_o		-	Constant used in gap conductivity equation (see Equations 39 and 40 of Reference 1)
347	E_e		lb/in^2	Modulus of elasticity of the cladding
348	g_c		ft	Average jump distances for the fission gas at the cladding and fuel surfaces, respectively
349	g_f		ft	
350	$(R_e-R_f)^{cold}$		ft	Cold cladding radius minus cold fuel radius
351	δ_c		ft	Arithmetic mean roughness heights of cladding and fuel, respectively
352	δ_f		ft	
353	ℓ		lb/ft^2	Meyer hardness of material (use hardness value for the softer of the two materials)
354	ΔV^{MELT}		-	Volume increase of fuel due to melting
355*	F_g		-	Hot spot factor to calculate gap coefficient

* Indicates hot spot factor.

Gap Conductivity Inputs

Input Number	Variable	Range	Units	Remarks
356	$\sigma_{y.p.}$		lb/in^2	Elastic yield point of cladding
357	EMISF	0 - 1.0		Emissivity of the fuel surface
358	EMISC	0 - 1.0		Emissivity of the clad inner surface
359*	$F_{g,p}$			Peaking factor for gap coefficient for peak channel

*Indicates peaking factor.

Feedback Inputs

Input Number	Variable	Range	Units	Remarks
360	C_f		-	Relative worth of axial fuel expansion (see Equation 90 of Reference 1)
361	α_s		$°F^{-1}$	Linear thermal expansion coefficient of structure in the radial direction
362	α_s'		$°F^{-1}$	Effective coefficient of thermal expansion used in calculation of increase in core radius
363	α_s''		$°F^{-1}$	Structure coefficient of thermal expansion (see Subsection 3.5.3 of Reference 1)
364	$\alpha_{s,ax}$		$°F^{-1}$	Linear thermal expansion coefficient of structure in the axial direction (see Equation 97 of Reference 1)
365 366 367	E_{e0} E_{e1} E_{e2}		- $°F^{-1}$ $°F^{-2}$	Fit coefficients for fractional expansion of cladding from 70°F. Of the form $\frac{\Delta L}{L} = E_{e0} + E_{e1} T + E_{e2} T^2$
368 369 370	E_{f0} E_{f1} E_{f2}		- $°F^{-1}$ $°F^{-2}$	Fit coefficients for fractional expansion of fuel from 70°F. Do not include discontinuity due to melting in this fit
371 372 373	E_{u0} E_{u1} E_{u2}		- $°F^{-1}$ $°F^{-2}$	Fit coefficients for fractional expansion of additional material from 70°F

Feedback Inputs

Input Number	Variable	Range	Units	Remarks
374-404				Blank
405	$R_T \frac{\delta k}{\delta R_T}$		-	Core radius coefficient
406	$H_t \frac{\delta k}{\delta H_t}$	$1 \leq m \leq MMAX$	-	Core height coefficient
407-413	$(\rho_e \frac{\delta k}{\delta \rho_e})_m$	$1 \leq m \leq MMAX$	-	Density coefficient of reactivity of the cladding for section m
414-420	$(\rho_c \frac{\delta k}{\delta \rho_c})_m$	$1 \leq m \leq MMAX$	-	Density coefficient of reactivity of the coolant for section m
421-427	$(\rho_f \frac{\delta k}{\delta \rho_f})_m$	$1 \leq m \leq MMAX$	-	Density coefficient of reactivity of the fuel for section m
428-434	$(\rho_u \frac{\delta k}{\delta \rho_u})_m$	$1 \leq m \leq MMAX$	-	Density coefficient of reactivity of the additional material for section m
435-441	$(\rho_s \frac{\delta k}{\delta \rho_s})_m$	$1 \leq m \leq MMAX$	-	Density coefficient of reactivity of the structure for section m
442-471 472-501	$k_{p,s}$ T_s		- sec	Table for effective multiplication versus Time
502-531 532-561	$\Delta k'_{void}$ T'_{void}		- sec	Δk due to sodium voiding versus Time since initiation
562-591 592-621	$\Delta k'_{scram}$ T'_{scram}		- sec	Δk due to scram versus Time since initiation
622	H		ft	Distance between core inlet and exit support plates

Feedback Inputs

Input Number	Variable	Range	Units	Remarks
623	Ψ_o		Radians	Measurement of the core lower support plate's angular deflection from the horizontal (at steady state)
624	Z_o		ft	Distance from core inlet support to actual core inlet
625	A_{Dop}		-	Input constants used in Doppler feedback equations
626	B_{Dop}		-	
627	b			
628-634	P_ℓ	$1 \leq \ell \leq LMAX$	-	Spatial power weighting factor, radial direction
635	C_D		-	Doppler correction for temperature profile

Power Inputs

Input Number	Variable	Range	Units	Remarks
636	P_{in}		MW	Input power
637-666 667-696	P' T'_p		- sec	Normalized Power Versus Time
697-699	A_{im}	$1 \leq im \leq IMMAX$	t^{α}	Terms used in empirical expression for decay of fission products
700-702	α_{im}	$1 \leq im \leq IMMAX$	t^{α}	Terms used in empirical expression for decay of fission products (cannot be equal to 0.1)
703-705	a_{im}	$1 \leq im \leq IMMAX$	sec	Terms used in empirical expression for decay of fission products
706	S		fissions/cc-sec	Source
707	T_o		sec	Length of time prior to start of problem for which the reactor operated at the constant power, P_o
708-713	β_i	$1 \leq i \leq IMAX$		Delayed neutron fraction, i^{th} group
714-719	γ_i	$1 \leq i \leq IMAX$	sec^{-1}	Decay constants of i^{th} group
720	ν		-	Neutrons per fission
721	ℓ		sec	Neutron lifetime
722-727	C_i	$1 \leq i \leq IMAX$	cc^{-1}	Delayed neutron precursor concentration for i^{th} group
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

Input Number	Variable	Range	Units	Remarks
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}		°F	Scram initiation temperature
733	ϵ_{Scram}		-	Scram constant to determine start of scram reactivity
734-753	$T_c^{'Boil}$		°F	Coolant's bulk boiling temperature versus absolute pressure
754-773	P_c'		lb/in^2	
774-793	$T_e^{'Burnout}$		°F	Cladding burnout temperature versus absolute pressure
794-813	P_e'		lb/in^2	
814	f_Z		-	Fraction of channel frictional pressure drop inlet to void
815	P_{St}		lb/in^2	Static head pressure at channel inlet
816	P_{Pump}		lb/in^2	Pump head pressure at channel inlet
817	T_f^{Vapor}		°F	Fuel temperature at which vaporization occurs
818	W_f	typically 10^{-4}		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 $\delta_f = 1$)

Miscellaneous

Input Number	Variable	Range	Units	Remarks
827-833	$(F_h)_1$	$1 \leq m \leq$ MMAX	If Input 20 = 2 these values are BTU/HR-FT^2-^{o}F If Input 20 = 0 these are correction factors	Axial correction for gap coefficient, Channel 1, M = 1, 7
834-840	$(F_h)_2$	$1 \leq m \leq$ MMAX		Axial correction for gap coefficient, Channel 2, M = 1, 7
841-847	$(F_h)_3$	$1 \leq m \leq$ MMAX		Axial correction for gap coefficient, Channel 3, M = 1, 7
848	TSWAP	≥ 0.0	seconds	If TSWAP > 0.0, this is time at which alternate power shape (849-855) becomes effective
849-855	ALTPØW(M)	$1 \leq m \leq$ MMAX	-	Alternate axial power shape factor to use with TSWAP
856	TJACK	≥ 0.0	seconds	If TJACK > 0.0, this is time at which Input 857 becomes effective
857	PJACK		seconds	Alternate printout interval; overrides Input 71 when time is greater than TJACK
858	ρ_i	0 - 1.0	Fractional % of Theoretical	Initial density
859	ρ_s	0 - 1.0	Fractional % of Theoretical	Sintered density
860	T_s		^{o}F	Sintering temperature
861-880	K'_f		BTU/FT-Sec-^{o}F	Table for fuel conductivity versus temperature (input only if δ_k equals 1)
881-900	T'_{fuel}		^{o}F	

Miscellaneous

Input Number	Variable	Range	Units	Remarks
901-907	R_{Hole-1} (2)	$0 \leq r \leq r_1$	ft	Axial variation in central void for Channel 1; M = 1, 7
908-914	R_{Hole-2} (2)	$0 \leq r \leq r_1$	ft	Axial variation in central void for Channel 2; M = 1, 7
915-921	R_{Hole-3} (2)	$0 \leq r \leq r_1$	ft	Axial variation in central void for Channel 3; M = 1, 7
922	Fraction of power generated in the cladding.			Note: Not an input variable; calculated by the code
923-925	$F_{G(1,2,3)}$	>0		Velocity correction factor for ΔP calculation, for Channels 1, 2, and 3
926-928	$F_{fr(1,2,3)}$	>0		Friction factor correction for Channels 1, 2 and 3
929-931	$K_{exit(1,2,3)}$	>0		Exit loss coefficient for Channels 1, 2 and 3
932-934	$\sigma_{in(1,2,3)}$	0 - 1.0		Area ratio for inlet of Channels 1, 2 and 3
935-937	$\sigma_{out(1,2,3)}$	0 - 1.0		Area ratio for exit of Channels 1, 2 and 3
938-940	$Z_{H(1,2,3)}$		ft	Height of fluid above active core for Channels 1, 2, and 3
941-947	$AFFIT_m$	$1 \leq m \leq MMAX$		Axial flux weighting factors for input No. 59 = 1

(2) NOTE: If the specified hole size exceeds the radius (R_1) at which the temperature of the first node is calculated, a warning message will be printed out at the beginning of the transient output.

Miscellaneous

948-954(1)	RGAP(M,1)	$1 \leq m \leq$ MMAX	inches	Hot radial gap dimensions for variable gap conductance option 2 (Input 20 = ±2)
955-961(1)	RGAP(M,2)	$1 \leq m \leq$ MMAX	inches	Hot radial gap dimensions for variable gap conductance option 2 (Input 20 = ±2)
962-968(1)	RGAP(M,3)	$1 \leq m \leq$ MMAX	inches	Hot radial gap dimensions for variable gap conductance option 2 (Input 20 = ±2)
969	ØE(69)	>0.0	-	If value greater than 0.0, axial variation in fuel conductivity factors need be specified [FCØN(M,K)]
970-976(2)	FCØN(M,1)	$1 \leq m \leq$ MMAX		Axial variation in fuel conductivity correction for Channel 1 [if ØE(69)>0.0]
977-980				(Not Currently Used)

(1) If Input 20 = -1, the cold gap dimension is specified in inches.

(2) Default values for Inputs 970-976, 1181-1187 and 1188-1194 are 1.0.

Built-in Tables

Input Number	Variable	Range	Units	Remarks
981-1000 1001-1020	K_c T_c		Btu/Sec-Ft °F	Thermal conductivity of coolant versus temperature
1021-1040 1041-1060	α_c T_c		$°F^{-1}$ °F	Coolant coefficient of expansion versus temperature
1061-1080 1081-1100	μ_c T_c		lb/ft-sec °F	Dynamic viscosity of coolant versus temperature
1101-1120 1121-1140	C_c T_c		Btu/lb-°F °F	Specific heat of coolant versus temperature
1141-1160 1161-1180	P_c T_c		lb/ft^3 °F	Density of coolant versus temperature
1181-1187	FCØN(M,2)	$1 \leq m \leq$ MMAX		Axial variation in fuel conductivity correction for Channel 2 [if ØE(69)>0.0]
1188-1194	FCØN(M,3)	$1 \leq m \leq$ MMAX		Axial variation in fuel conductivity correction for Channel 3 [if ØE(69)>0.0]

Alternate Geometry

Input Number	Variable	Range	Units	Remarks
7768	IXIND	0 or 1	-	Alternate geometry option. If IXIND=1, Inputs 7769-7790 and 8190-8206 must be supplied
7769	XRACL		ft	Equivalent radius of coolant for alternate geometry
7770	XRACD		ft	Cladding inner radius, alternate geometry
7771	XRACS		ft	Cladding outer radius, alternate geometry
7772-7781	XRAND		ft	Outer radius of fuel node, alternate geometry, $1 \leq n \leq NMAX$
7782	XRADVØ		ft	Radius of central void, alternate geometry
7783	XVØST		ft^2	Volume of structure per unit length of fuel
7784	XVØMT		ft^2	Volume of additional material per unit length of fuel
7785	XDIHY		ft	Hydraulic diameter for alternate geometry

Alternate Geometry

Input Number	Variable	Range	Units	Remarks
7786	XDHT		ft	Appropriate hydraulic diameter for calculating heat transfer for alternate geometry
7787	XDIST		ft	Characteristic structural dimension for alternate geometry
7788	XDIMT		ft	Characteristic dimension of additional material for alternate geometry
7789	XGST		ft^{-1}	Structure surface-to-volume ratio of alternate geometry
7790	XGMT		ft^{-1}	Additional material surface-to-volume ratio for alternate geometry
7791-7797	PS_m*			Hot spot factor on heat generation for the alternate power shape in Channel 3; $1 \leq M \leq MMAX$

*If any value of PS_m is equal to zero, the normal hot spot factor (Input 179) will be used.

Alternate Feedback and Flow Parameters

Input Number	Variable	Range	Units	Remarks
7798	IFEEB	0 or 1	-	If IFEEB=1, alternate feedbacks 8140 to 8181 must be supplied
7799	IPUMP	0 or 1	-	Option on pump trip. If IPUMP=1, pump coastdown begins at scram
7800-7819	TIMEZ		seconds	Table of times for Inputs 7820 to 8139
7820-7839	GPEAK(τ)	$\leq$1.0		Normalized flow coastdown for Channel 2 (use TIMEZ)
7840-7859	GHØT(τ)	$\leq$1.0		As above for Channel 3
7860-7879	$(G/G_{in})_{M=1}$			Values of local flow rate in Axial Section 1 of Channel 3 relative to the inlet flow of Channel 3 (use TIMEZ)
7880-7899	$(G/G_{in})_{M=2}$			As above for Axial Section 2
7900-7919	$(G/G_{in})_{M=3}$			As above for Axial Section 3

Alternate Feedback and Flow Parameters

Input Number	Variable	Range	Units	Remarks
7920-7939	$(G/G_{in})_{M=4}$			Values of local flow rate in Axial Section 4 of Channel 3 relative to the inlet flow of Channel 3 (use TIMEZ)
7940-7959	$(G/G_{in})_{M=5}$			As above for Axial Section 5
7960-7979	$(G/G_{in})_{M=6}$			As above for Axial Section 6
7980-7999	$(G/G_{in})_{M=7}$			As above for Axial Section 7
8000-8019	QEXS(M=1)		BTU/sec	Excess energy supplied to Axial Section 1 of Channel 3
8020-8039	QEXS(M=2)		BTU/sec	Same as above for Axial Section 2
8040-8059	QEXS(M=3)		BTU/sec	Same as above for Axial Section 3
8060-8079	QEXS(M=4)		BTU/sec	Same as above for Axial Section 4
8080-8099	QEXS(M=5)		BTU/sec	Same as above for Axial Section 5

Alternate Feedback and Flow Parameters

Input Number	Variable	Range	Units	Remarks
8100-8119	QEXS(M=6)		BTU/sec	Excess energy supplied to Axial Section 6 of Channel 3
8120-8139	QEXS(M=7)		BTU/sec	Same as above for Axial Section 7
8140-8146	FDØP(M,1)		ΔK	Alternate Doppler coefficient for Channel 1, Axial Sections 1 to 7
8147-8153	FDØP(M,2)		ΔK	Alternate Doppler coefficient for Channel 2, Axial Sections 1 to 7
8154-8160	FDØP(M,3)		ΔK	Alternate Doppler coefficient for Channel 3, Axial Sections 1 to 7
8161-8167	CØFBK(M,1)		ΔK/°F	Alternate coolant density reactivity coefficient for Channel 1, Axial Sections 1 to 7
8168-8174	CØFBK(M,2)		ΔK/°F	As above for Channel 2
8175-8181	CØFBK(M,3)		ΔK/°F	As above for Channel 3
8182-8188	XPØWR(M)			Alternate axial power shape for Channel 3 ($1 \leq M \leq MMAX$)
8189	TPUMP		seconds	Pump trip delay if IPUMP=1

Alternate Geometry

Input Number	Variable	Range	Units	Remarks
8190	XRHØFL		lbs/ft^3	Alternate density of fuel for Channel 3
8191	XLIQ		^oF	Liquidus temperature of fuel for alternate geometry
8192	XSØLID		^oF	Solidus temperature of fuel for alternate geometry
8193	XCAH			Constants used in coolant heat transfer coefficients equation of alternate geometry $1 \leq m \leq MMAX$ (see Equation 15 of Ref. 1)
8194	XCBH			
8195-8201	XCCH(M)			
8202	XCMH			
8203	XCNH			
8204	XCRH			
8205	XRHØ1		<1.0	Fractional density of as-manufactured fuel for alternate geometry
8206	XRHØ2		<1.0	Fractional density of sintered fuel for alternate geometry

Alternate Decay Heat

Input Number	Variable	Range	Units	Remarks
8207	IDECAY	0 or 1		Option for alternate decay heat model
8208	IREG	0, 1, 2 or 3		Option on using core or Channel K as reactor indicator for the IDECAY=1 option. If IREG=0, average core power is used; if IREG=K, Channel K power is used. (see footnote)
8209-8211	FREG(K)	$\sum_{K=1}^{3}$ FREG=1.0		Fractional power of reactor associated with regions corresponding to Channels 1, 2 and 3 for determining average core power for the IDECAY=1 option.
8212-8231	TDECAY		Second	Table of time for alternate decay heat values
8232-8251	PDECAY(1)			Fraction of power attributed to decay heat in Channel 1
8252-8271	PDECAY(2)			As above, but for Channel 2
8272-8291	PDECAY(3)			As above, but for Channel 3

FOOTNOTE: IREG also is used to control printout of transient power (see Section 7.3) if the IDECAY=1 option is used.

Alternate Fuel Specific Heat Table and Other Miscellaneous Items

Input Number	Variable	Range	Units	Remarks
8292	IXCP	0, 1, 2 or 3		Channel to which alternate fuel specific heat applies
8293-8312	XCPFIT		BTU/lb-^{o}F	Alternate fuel specific heat
8313-8332	XTEMP		^{o}F	Temperatures corresponding to alternate specific heat
8333	ISPEC			Option for selecting special reactivity feedback subroutine
8334	IREX	1, 2 or 3		Channel to which Inputs 165 and 320 apply
8335	ISTART			Indicator for start of decay heat curves (Inputs 8232 to 8291). If ISTART=0, time is measured from steady state (τ=0). If ISTART=1, time is measured from point of scram.
8336	IPRØP	0 or 1		IPRØP=0; tabular sodium properties will be used. IPRØP=1; built-in curve fit of Appendix C sodium properties will be used.

Alternate Fuel Specific Heat Table and Other Miscellaneous Items

Input Number	Variable	Range	Units	Remarks
8337	IPLØT	0 or 1		IPLØT=0 bypasses this option. IPLØT=1, selected transient results will be written onto TAPE 2 for subsequent use in plotting package
8338	ITMAX	0, 1, 2, or 3		ITMAX=0 bypasses this option. ITMAX=1, 2, or 3: program will print out time of occurrence and maximum value of reactor power and maximum values of fuel cladding and coolant temperatures for either Channel 1, 2 or 3.
8339	ICP_f	0 or 1		ICP_f=0; tabular specific heat of fuel is used (INPUTS 125 to 164). ICP_f=1; curve fit of specific heat of fuel will be used (INPUTS 193, 194 and 8340 to 8343 must be specified).
8340	$A(C_p)_f$		BTU/lb-°F	Constants for curve fit of specific heat of fuel $C_p = A + B \cdot T + C \cdot T^2 + D \cdot T^3 + E \cdot T^4$
8341	$B(C_p)_f$		BTU/lb-°F^2	
8342	$C(C_p)_f$		BTU/lb-°F^3	
8343	$D(C_p)_f$		BTU/lb-°F^4	
8344	$E(C_p)_f$		BTU/lb-°F^5	
8345	$F(C_p)_f$		BTU/lb-°F	Effective specific heat of mixed-oxide fuel between the solidus and liquidus temperatures

APPENDIX B

MISCELLANEOUS INFORMATION

AND

SAMPLE DECK STRUCTURE FØRMATS

B.1 MISCELLANEOUS INFORMATION

The purpose of this section is to assist the user in the preparation of input for running the modified version of the FØRE-II computer program.

The present program includes a restart option which allows for possible restarts at three distinct points (user specified) in the transient. This option can be used to either study a parametric variation in some variable (for example, scram reactivity rates) from some point in the transient or it can be used to continue a problem from the final timestep of a previous run. This latter usage is quite effective for long running problems (for example, a continuous rod withdrawal from "zero" power). The problem can be run for a short time to see if it is progressing properly, and then can be restarted and run to completion. The WRAPUP-RESTART option can also be used in long running problems to assure that a set of restart variables are available in case of an inadvertent problem termination (e.g., "time estimate exceeded"). The restart variables are stored on TAPE 1 and read from TAPE 4 if a restart is desired.

In FØRE-2M, the "hot channel factors" are used to decrease the value of a variable rather than to directly increase the temperature rise associated with that factor. For example, the hot channel factor on enthalpy rise is used to decrease the flow in the hot channel rather than to directly increase the temperature rise of the coolant in the hot channel. Likewise, the hot channel factors on film, gap and thermal conductivities are used to decrease the nominal value of these variables. Therefore, because of the manner in which they are applied, the hot channel factors used in FØRE-2M are the reciprocals on the normal hot channel factors. The exceptions to this rule are the factors on heat generation (INPUT 179 and 180) which are applied directly.

Another point to consider in running a FØRE-2M transient is that the hot channel is treated as a complete and separate channel and that some factors will affect more than one variable. The factor on heat generation in the fuel will, for example, also affect the enthalpy rise since the excess heat due to the increased heat generation will be transferred to the coolant. Care must be exercised that a duplication of such factors is avoided. As an example, since the normal hot channel factor on enthalpy rise ($F_{\Delta H}$) includes the factor on heat generation ($F_{\Delta Q}$), the appropriate factor to include in the FØRE-2M program (F_V, Input number 192) would be

$$F_V = \frac{F_{\Delta Q}}{F_{\Delta H}}$$

A list of the hot channel factors available in FORE-2 is given below and noted by an asterick in the input listing (Appendix A).

Input Number	Symbol	Definition
106	F_e	Hot-spot factor for thermal conductivity of clad
121	F_k	Hot-spot factor for fuel conductivity
179	P_H	Hot-spot factor used in calculating heat generation rates in hot channel (normally $F_R \times F_{\Delta Q}$)
180	P_r	Radial peak-to-average power density ratio in core (i.e. F_R)
191	F_r	Peak* channel factor used in calculating flow rate in peak channel
192	F_v	Hot-spot factor used in calculating flow rate in hot channel
334	F_h	Hot-spot factor for calculating coolant heat transfer coefficient
355	F_g	Hot-spot factor for gap coefficient
359	$F_{g,p}$	Peaking factor for gap coefficient in peak channel

*In FØRE-2M, Channel 1 = Average Channel; Channel 2 = Peak Channel; and Channel 3 = Hot Channel.

B.2 INPUT DECK STRUCTURE

The binary tape of the modified FØRE-II program is cataloged at the Advanced Reactor Division as WMFØRE2M. Tables B.1 through B.5 show the structure of input decks for various options of the program. The "control cards" listed before the input deck are required for a specific computer system and could therefore differ from site-to-site.

TABLE B-1

STRUCTURE OF A REGULAR PROBLEM (NO RESTART)

```
ATTACH (A, WMFØRE2M, ID = SARDC, MF = MFA)
SETCØRE (ZERØ)
A.
789
)FØRE*XYZ*1234                                    12-15-75
     (Data)
       :
       :                                          (See Table B-5)
       :
     (Data)
9999
)LAST  *
```

TABLE B-2

STRUCTURE OF A WRAPUP PROBLEM (PREPARATION FOR RESTART)

```
ATTACH (A, WMFØRE2M, ID = SARDC, MF = MFA)
SETCØRE (ZERØ)
A.
CATALØG (TAPE1,WMNAMEIT,CN=CASE, ID=USER, SC=S)
7
8
9
)FØRE*XYZ*5678                                    12-15-75
     (Data)
       :                                  (Input 49 = 1, 2 or 3)
       :                                  (Input 50 and 51
       :                                   Specify Timesteps for
       :                                   Wrapups)
     (Data)
9999
)LAST  *
```

TABLE B-3

STRUCTURE OF A RESTART PROBLEM

```
ATTACH (A, WMFØRE2M, ID = SARDC, MF = MFA)
ATTACH (TAPE4, WMNAMEIT, ID=USER, MF=MFA)**
SETCØRE (ZERØ)
A.
789
)FØRE*XYZ*6942                                  12-15-75
     29
     52                                         See input for restart - Appendix A
9999
(FØRE*XYZ*6942                                  12-15-75
     (Data)
       :
       :
       :                                        (Only data which is to be changed
       :                                         need be specified)
       :
     (Data)
9999
)LAST  *
```

**WMNAMEIT must correspond to tape name previously reserved from WRAPUP

TABLE B-4

STRUCTURE OF A RESTART PROBLEM WITH ADDITIONAL WRAPUP

```
ATTACH (A, WMFØRE2M, ID = SARDC, MF = MFA)
ATTACH (TAPE4, WMNAMEIT, ID=USER, MF=MFA)
SETCØRE (ZERØ)
A.
CATALØG (TAPE1,WMNEWNAME, CN=NEWCASE, ID=USER, SC=S)
7
8
9
)FØRE*XYZ*7865                                    12-15-75
     29
     52              Restart data input
9999
(FØRE*XYZ*7865                                    12-15-75
     (Data)
       :
       :
       :                          (For additional wrapups, inputs
       :                           49, 50 and 51 must be specified)
       :
     (Data)
9999
)LAST  *
```

(1) The name of the new restart tape may be the same as old restart tape provided a PURGE (,WMNAMEIT, ID=USER, PW=CASE) preceeds the statement.

TABLE B-5

INPUT DECK STRUCTURE FOR FØRE-2M

(See Appendix A)

A) Regular Problem - no restart

1) Independent Case Card
2) (Data)
   ⋮
3) 9999 (Sentinel Card)
4))LAST * (Last Card)

B) RESTART Problem

1) Independent Case Card
2) Input 29 } Restart variables
3) Input 52 }
4) 9999 (Sentinel Card)
5) Dependent Case Card
6) (Data)
   ⋮ } Data which is being changed
7) 9999 (Sentinel Card)
8))LAST * (Last Card)

APPENDIX C

BUILT-IN TABLES

OF

SODIUM PROPERTIES

From

G. H. Golden and J. V. Tokar, "Thermophysical Properties of Sodium," ANL-7323, Argonne National Laboratory, August, 1967

NOTE: These values may be over-ridden by using all or part of INPUT values numbers 981 through 1180.

BUILT-IN TABLES
OF
SODIUM PROPERTIES

Thermal Conductivity of Sodium, K'_c	vs.	Temperature, T'_c
.014055 BTU/sec-ft-°F		200°F
.013572		300
.013089		400
.012619		500
.012164		600
.011717		700
.011497		750
.011283		800
.011069		850
.010858		900
.010447		1000
.010247		1050
.010047		1100
.009661		1200
.00928		1300
.00892		1400
.008567		1500
.008225		1600
.007894		1700
.007575		1800

NOTE: These values may be over-ridden by using all or part of INPUT values numbers 981 through 1020.

BUILT-IN TABLES
OF
SODIUM PROPERTIES

Thermal Expansion Coefficient of Sodium, α'_c		vs.	Temperature, T'_c
46.34×10^{-6}	$°F^{-1}$		200 °F
47.28			300
48.22			400
49.18			500
50.15			600
51.12			700
51.62			750
52.11			800
52.61			850
53.11			900
54.12			1000
54.63			1050
55.14			1100
56.18			1200
57.23			1300
58.28			1400
59.36			1500
60.44			1600
61.54			1700
62.66			1800

NOTE: These values may be over-ridden by using all or part of INPUT vlaues numbers 1021 through 1060.

BUILT-IN TABLES
OF
SODIUM PROPERTIES

Dynamic Viscosity of Sodium, μ'_c	vs.	Temperature, T'_c
0 .0004753 #/ft-sec		200°F
.0003699		300
.0003026		400
.0002565		500
.0002233		600
.0001983		700
.000188		750
.0001788		800
.0001706		850
.0001632		900
.0001505		1000
.000145		1050
.00014		1100
.000131		1200
.0001234		1300
.0001168		1400
.000111		1500
.0001059		1600
.0001013		1700
.0000972		1800

NOTE: These values may be over-ridden by using all or part of INPUT values numbers 1061 through 1100.

BUILT-IN TABLES
OF
SODIUM PROPERTIES

Specific Heat of Sodium, C'_c	vs.	Temperature, T'_c
0.3311 BTU/#-°F		200°F
.3250		300
.3194		400
.3146		500
.3105		600
.307		700
.3055		750
.3042		800
.3030		850
.3020		900
.3006		1000
.3001		1050
.2998		1100
.2998		1200
.3004		1300
.3017		1400
.3036		1500
.3063		1600
.3096		1700
.3136		1800

NOTE: These values may be over-ridden by using all or part of INPUT values numbers 1101 through 1140.

BUILT-IN TABLES
OF
SODIUM PROPERTIES

Density of Sodium ρ'_c	vs.	Temperature, T'_c
57.965 #/FT^3		200°F
57.157		300
56.344		400
55.527		500
54.705		600
53.881		700
53.467		750
53.053		800
52.638		850
52.222		900
51.389		1000
50.971		1050
50.533		1100
49.716		1200
48.878		1300
48.038		1400
47.198		1500
46.357		1600
45.517		1700
44.677		1800

NOTE: These values may be over-ridden by using all or part of INPUT values numbers 1141 through 1180.