

A MATHEMATICAL MODEL OF IODINE SPIKING

IN

PRESSURIZED WATER REACTORS

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(ABSTRACT)

When a pressurized water reactor is operated for a sufficiently long period of time, a small number of fuel rods will develop ruptures in their claddings. These defects will leak volatile fission products into the primary coolant, including radioactive iodine.

During steady-state operation of the reactor a low level iodine activity is thus present in the coolant. Initiation of a down-power or up-power transient will result in a rapid climb in the activity of the iodine which peaks at a level much higher than the initial activity. After this time the activity levels out and then slowly begins to decay back to a new steady-state level. This phenomenon is termed "iodine spiking."

A physical model of this process is sought for explanatory and predictive purposes. A FORTRAN code is developed that solves a system of differential equations which describe the production and removal of iodine in the fuel, gap region, and primary coolant. As much physics as possible is employed but some complicated diffusion processes have led to the utilization of certain parametric results obtained from empirical data. Actual PWR spiking data is also employed for comparison and adjustment of the model.

It is the goal of this project to be able to utilize the model for predictive analysis during actual PWR operation so that a better understanding of iodine spiking behavior can be obtained.

## ACKNOWLEDGEMENTS

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## TABLE OF CONTENTS

	Page
Acknowledgements.....	ii
Abstract.....	iii
List of Figures.....	vii
I. Introduction.....	1
A. Background and Purpose.....	1
B. PWR Iodine Production and Migration.....	2
C. Literature Search.....	3
II. Iodine Efflux and Leaching.....	6
A. Iodine Efflux Rate in UO <sub>2</sub> Fuel.....	6
B. Numerical solution.....	18
C. Enhanced Efflux in a Water Environment.....	18
D. Iodine Absorption in Cladding Material.....	20
E. Leaching Rate from a Failed Rod.....	21
III. Temperature Distribution in the Pin.....	24
A. Heat Conduction Equation.....	24
B. Thermal Conductivity.....	24
C. Specific Heat.....	25
D. Burnup Effects on UO <sub>2</sub> Fuel.....	25
E. Solution by Finite Difference.....	27
F. Boundary Conditions.....	31
IV. Iodine Balance Equations.....	36
A. Production and Removal in Pellet and Gap.....	36
B. Production and Removal in Primary Coolant.....	44

C.	Solution by the Runge-Kutta Method.....	48
V.	VEPCO Case Studies.....	53
A.	Sensitivity Analysis.....	53
B.	Comparison and Results.....	72
VI.	References.....	81
VII.	Appendices.....	84
A.	Appendix A. Time Step Analysis.....	84
B.	Appendix B. Operation and flow diagrams of the program..	91
C.	Appendix C. SPIKE Program Listing.....	123
VIII.	Vita .....	160

## LIST OF FIGURES

		Page
FIGURE 1	- Efflux for steady operation.....	15
FIGURE 2	- Efflux for a step change in power to 1.0%.....	16
FIGURE 3	- Efflux for an up-power ramp with a rise time of 900.0 seconds.....	17
FIGURE 4	- Leach rate for a step change in power to 1.0%.....	22
FIGURE 5	- Leach rate for an up-power ramp with a rise time of 900.0 seconds.....	23
FIGURE 6	- Nodal scheme for the finite difference temperature solution.....	29
FIGURE 7	- Steady state temperature distribution in the fuel pellet.....	33
FIGURE 8	- Temperature at the fuel center and half distance for a step change in power to 1.0%.....	34
FIGURE 9	- Temperature at the fuel center and half distance for an up-power ramp with a rise time of 15.0 seconds.....	35
FIGURE 10	- Isotopic decay chains.....	37
FIGURE 11	- Iodine-131 in the fuel for a step change in power to 1.0%, numerical solution.....	50
FIGURE 12	- Iodine-131 in the gap for a step change in power to 1.0%, numerical solution.....	51
FIGURE 13	- Iodine-131 in the coolant for a step change in power to 1.0%, numerical solution.....	52
FIGURE 14	- Peak to steady-state ratio as a function of the average fuel burnup.....	54
FIGURE 15	- Peak to steady-state ratio as a function of the average failure size.....	55
FIGURE 16	- Peak to steady-state ratio as a function of the fraction of iodine removed from the coolant loop.....	56

FIGURE 17	- Peak to steady-state ratio as a function of the number of failed fuel rods.....	57
FIGURE 18	- Peak to steady-state ratio as a function of the water enhancement factor.....	58
FIGURE 19	- Peak to steady-state ratio as a function of the iodine absorption factor.....	59
FIGURE 20	- Peak to steady-state ratio as a function of the antimony absorption factor.....	60
FIGURE 21	- Peak to steady-state ratio as a function of the tellurium absorption factor.....	61
FIGURE 22	- Peak to steady-state ratio as a function of the average coolant loop flow time.....	62
FIGURE 23	- Time to peak as a function of the average fuel burnup.....	63
FIGURE 24	- Time to peak as a function of the average failure size.....	64
FIGURE 25	- Time to peak as a function of the fraction of iodine removed from the coolant loop.....	65
FIGURE 26	- Time to peak as a function of the number of failed fuel rods.....	66
FIGURE 27	- Time to peak as a function of the water enhancement factor.....	67
FIGURE 28	- Time to peak as a function of the iodine absorption factor.....	68
FIGURE 29	- Time to peak as a function of the antimony absorption factor.....	69
FIGURE 30	- Time to peak as a function of the tellurium absorption factor.....	70
FIGURE 31	- Time to peak as a function of the average coolant loop flow time.....	71
FIGURE 32	- Dose equivalent of iodine-131 as a function of time. Experimental data.....	73

FIGURE 33	- Dose equivalent of iodine-131 as a function of time. Experimental data.....	74
FIGURE 34	- Down-power spike. Iodine-131 analytical and experimental data as a function of time.....	78
FIGURE 35	- Down-power spike. Iodine-132 analytical and experimental data as a function of time.....	79
FIGURE 36	- Down-power spike. Iodine-133 analytical and experimental data as a function of time.....	80
FIGURE 37	- Fuel temperature as a function of time step size.....	85
FIGURE 38	- Fuel temperature as a function of node size in the pellet.....	86
FIGURE 39	- Iodine-131 concentration in the fuel as a function of time step size.....	87
FIGURE 40	- Iodine-131 concentration in the gap as a function of time step size.....	88
FIGURE 41	- Iodine-131 concentration in the coolant as a function of time step size.....	89

## I. INTRODUCTION

### A. Background and purpose

Fuel rod defects in water cooled reactors statistically occur in relatively small numbers. Those that do occur are responsible for the entrance of volatile fission products into the primary coolant.

One of these fission products, radioactive iodine, reacts in a peculiar way during the transient operation of a pressurized water reactor. During steady-state operation there is a reasonably low iodine activity level in the primary coolant. Initiation of a power increase or decrease will result in a fairly rapid rise in this level by a factor of 50 to 100. This phenomenon is known as "iodine spiking" and is attributed to a release mechanism of the failed fuel rod. This iodine spike will generally tend to peak in two to four hours and then slowly decay back to a lower constant activity level.

Previous studies that have been carried out attribute this behavior not to the occurrence of new rod fissures during the transient, but to those failed rods which already exist [1]. The mechanism for release is directly traceable to the power transient.

The down-power spike is believed to initiate when the average core power dips below a level corresponding to the saturation temperature of the steam in the fuel rod gap region. The steam environment in the gap region will collapse to liquid causing a rapid dissolution of the iodine present in the gap. The iodine present in the gap is mostly combined with cesium to produce CsI. This salt will plate out on the internal surfaces of the gap and will rapidly dissolve when water is present

but will build up in the presence of steam. The hydraulic leaching of this substance into the primary coolant will manifest itself as an increase in the activity of the iodine.

The up-power spike will occur when the power rises to a sufficient level to cause the liquid environment in the gap to flash to steam. The difference in the mass will cause a rapid outward pulse of the dissolved iodine into the primary coolant, also causing a rapid rise in iodine activity levels.

There are two main reasons for developing a detailed model of the spiking mechanism. The temporary rise in the activity of the iodine can have adverse effects on the environment in the occurrence of a loss of coolant accident. Also the technical specification level can more reliably be set for the reactor coolant system if there is a working knowledge of how activity levels will change during transient conditions.

#### B. PWR Iodine Production and Migration

The iodine spiking mechanisms discussed previously are highly dependent on the initial inventory of iodine in the gap region and reactor coolant system prior to the initiation of the transient. A large portion of this research is dedicated to the determination of these quantities.

During a power transient the amount of iodine introduced into the rod gap from the fuel pellet surface is small, but the long term steady-state effect is of great importance. The concentration of iodine in the

gap is responsible for producing almost all of the iodine which will be leached into the primary coolant. Therefore it is necessarily important to have a detailed knowledge of the steady-state production and efflux of iodine into the rod gap from the fuel pellet as a function of the average fuel burnup and power level of the core. The initial concentrations, efflux rate, and hydraulic leach rate can be incorporated into a system of iodine balance equations. Solving this system will determine the characteristics of the iodine spike.

### C. Literature Search

Much of the previous work on iodine spiking concerns only a qualitative analysis of the phenomenon. Neeb and Schuster's [1] work is primarily concerned with understanding the phenomenon based on the physical and chemical properties of the radionuclides in question. This is the primary article on which the iodine spiking behavior has been based for this work. Many important results have been utilized in the modeling process.

For example, experimental evidence has shown that inert fission gas spiking is comparatively small in scale compared to long-lived volatile isotopes such as cesium and iodine. Also it has been observed that spiking of the iodine and cesium isotopes is practically identical. These two results tend to support the assumptions that cesium and iodine will plate out on the cladding as CsI causing a retaining effect during constant power operation.



Although the number of articles pertaining directly to iodine spiking are few, the number of articles describing fission gas release from uranium dioxide fuels are many. These papers contain both qualitative and analytical results.

Some fairly complicated computer codes have already been written to describe the release of volatile and non-volatile fission products from intact and failed fuel rods. Two of these codes are FASTGRASS and COMETHE; see Rest [2] and Vliet and Hoppe [3], respectively. Both of these models are based on bubble coalescence and diffusion along grain boundaries where diffusion to an external surface will take place through an interconnecting network of tunnels and cracks. These codes are exceedingly long and therefore too cumbersome to incorporate into an overall plant model in their present form.

An updated version of FASTGRASS called FRASS was developed by Gruber [4]. In this work, a parametric relationship for the release rate of fission products from uranium dioxide fuel is derived by calculating gas release rates for steady-state anneals and approximating each curve by a straight line. The intercepts of these lines are found to obey an Arrhenius relation. The result is a fairly straightforward analytical expression for the transient release rate of fission products.

Weissman, MacDonald, Miller, and Ferrari [5] have employed an "engineering approach" to determine the total fractional release of fission product gas for any time-varying power history of a reactor core. This has been adapted to produce an effective fission gas release rate during steady-state operation.

In order to calculate these release rates a detailed description of the fuel pellet temperature and thermal gradient is needed. A time and position-dependent heat conduction equation is solved. Useful relationships for the thermal conductivity and specific heat of  $\text{UO}_2$  fuel have been obtained from Rust [6] and Weisman [7]. Calculation of burnup-induced fuel expansion and redensification of  $\text{UO}_2$  have been obtained from Long [8] and Frost [9]. The above properties have all been incorporated in determination of the temperature distribution.

## II. IODINE EFFLUX AND LEACHING

### A. Iodine Efflux Rate in $UO_2$ Fuel

The iodine efflux  $e(t)$  is the fraction of iodine present in a fuel pellet which will exit the surface per unit time. It is similar in nature to a nuclear decay constant.

A mathematical definition of the efflux can be derived using a time and position-dependent differential equation [10]. The rate of change of iodine in the fuel equals the rate of production of iodine from fission less that which decays to a new species and that which diffuses through the pellet:

$$\frac{dI}{dt}(r,t) = y_I \sum_f \phi(t) - \lambda_I I(r,t) - \nabla \cdot \vec{J}(\hat{r},t) . \quad (2.1)$$

The iodine balance equation shown above describes the iodine distribution in the fuel pellet. The term  $\vec{J}(\hat{r},t)$  represents the mass flux vector in the fuel. For simplicity, the cumulative iodine yield  $y_I$  is presented above instead of including the direct yield plus production terms from the decay of the tellurium isotopes.

The average iodine concentration in the fuel,  $I(t)$  is

$$I(t) = \frac{1}{V_f} \int_{V_f} I(r,t) dV_f , \quad (2.2)$$

where  $V_f$  is the fuel volume.

The efflux is defined

$$e_I(t) = \frac{1}{V_f I(t)} \int_{V_f} \nabla \cdot \hat{J}(\hat{r}, t) dV_f, \quad (2.3)$$

where the units of  $e(t)$  are  $s^{-1}$ .

The mass flux vector  $\hat{J}(\hat{r}, t)$  for the  $UO_2$  is primarily a function of the iodine concentration gradient and the thermal gradient and is related to these through [11]

$$\hat{J}(\hat{r}, t) = -D_I \nabla \cdot I(\hat{r}, t) - D_{IT} \nabla \cdot T(\hat{r}, t). \quad (2.4)$$

Substitution into Eq. (2.3) yields

$$e_I(t) = \frac{1}{V_f I(t)} \int_{V_f} \nabla \cdot [-D_I \nabla \cdot I(r, t) - D_{IT} \nabla \cdot T(r, t)] dV_f. \quad (2.5)$$

A simplification can be made using Gauss' Divergence Theorem

$$e_I(t) = \frac{1}{V_f I(t)} \int_{A_f} [-D_I \nabla \cdot I(r, t) - D_{IT} \nabla \cdot T(r, t)] dA_f. \quad (2.6)$$

Assuming constant parameters in the  $z$  direction and using cylindrical coordinates gives

$$e_I(t) = \frac{1}{V_f I(t)} \int_{A_f} [-rD_I \frac{\partial I}{\partial r}(r, t) - rD_{IT} \frac{\partial T}{\partial r}(r, t)] dA_f. \quad (2.7)$$

Equation (2.7) can be further simplified using an experimental result noted by Peehs in Ref. [12]. Cesium and iodine doped  $UO_2$  powder was loaded into 11mm long molybdenum heating elements. Heating tests were

performed on the rods in order to determine the redistribution effects of a thermal gradient on the cesium and iodine. The results revealed that the thermal gradient contributes little to the diffusion process and that the concentration gradient is the controlling factor. Utilizing this result will simplify the previous expression to

$$e_I(t) = - \frac{1}{V_f I(t)} \int_{A_f} r D_I \frac{\partial I}{\partial r} (r, t) dA_f. \quad (2.8)$$

Equations (2.1) and (2.8) were first employed to try to determine the efflux. The results were inaccurate and predicted efflux rates that were entirely too low. A large proportion of the experimentation done to determine the diffusive properties of oxide fuels is performed on intact fuel and fuel-type substances. The major problem with this approach is that intact fuel acts nothing like fuel that has experienced burnup.

Uranium dioxide fuel in a commercial reactor quickly undergoes many significant changes. The knock-out effects of a neutron flux will cause an excess formation of vacancies in the  $UO_2$  matrix. These vacancies will migrate to internal defects and grain boundaries. Gas atoms and other fission products will become trapped in the vacancies as they coalesce to form bubbles. These bubbles will collect along the grain boundaries and cause swelling and redensification of the fuel. This "manufactured" porosity, along with the pressures exerted by thermal stress, will manifest itself as cracks and cavities within the pellet. These defects will join to form a network of interconnected tunnels

through which the fission gases will migrate to the fuel surface [13]. There is little simple diffusion taking place, except perhaps near the pellet surface. Since the diffusion coefficient  $D_I$  in Eq. (2.8) is defined for a simple diffusion process, the relationship must necessarily break down for this application.

Diffusion calculations done to describe fission gas behavior are performed using equivalent sphere models, which try to duplicate the bubble formation and migration process. Examples of these are the FASTGRASS [2] and COMETHE [3] models mentioned in the introduction.

Even though this haphazard diffusion explanation is complicated, there are some beneficial results which arise. A majority of the fission products produced will diffuse together trapped in the bubble formations. They will reach the internal tunnel-type defects and be flushed out of the fuel en masse. Therefore, if a model for fission gas diffusion can be obtained, it will be a good approximation to include iodine as one of the diffusing species.

Two different types of models for the efflux have been used in this research, one for the steady-state efflux and one for the efflux during a heating transient as a result of a power level change.

The steady-state efflux expression is adapted from Ref. [5], which describes an engineering approach and provides substantially improved predictions for the fission gas release process.

If  $K_1$  represents the proportion of fission gas that escapes from the grain boundaries and dislocations, then  $dm_1$ , the number of moles of gas released directly in time  $dt$ , is  $dm_1 = K_1 p dt$  where  $p$  is the gas

production rate. If the probability of trapped particle release per unit time is  $K_2$  and the number of moles trapped is  $C$ , then the trapped moles released is  $dm_2 = K_2 C dt$ . Only a fraction  $K_1$  of the gas released reaches the surface. Thus the total gas release is

$$dm = K_1 K_2 C dt + K_1 p dt . \quad (2.9)$$

Replacing  $C$  by  $(pt-m)$  and integrating yields,

$$m = \left\{ t - \frac{1 - K_1}{K_1 K_2} [1 - \exp(-K_1 K_2 t)] \right\} . \quad (2.10)$$

At constant power, the total fractional release is

$$F = \frac{m}{pt} = 1 - (1 - K_1) \left\{ \frac{1 - \exp(-K_1 K_2 t)}{K_1 K_2 t} \right\} . \quad (2.11)$$

The experimental values employed for  $K_1$  and  $K_2$  are taken from Ref. [14]. The values are found for 95% dense fuel to be

$$K_1 = \exp\left\{-\frac{6916.67}{T} + 1.84\right\} , \quad (2.12a)$$

and

$$K_1 K_2 = 0.25 \exp\left\{-\frac{11894.44}{T}\right\} , \quad (2.12b)$$

where temperature,  $T$ , is given in degrees Kelvin.

The time value  $t$  in Eq. (2.11) is the cumulative irradiation time of the fuel in the core in units of hours. In order to adapt this

expression to the purpose of this model the time variable is transformed to units of burnup,  $b$ . The resultant transformation is,

$$t(b) = (\text{fuel burnup}) \times \frac{(\text{fuel mass in core})}{(\text{avg. thermal power})} \times (24 \text{ hrs/day}) ,$$

(2.13)

or

$$t(b) = 0.6347b ,$$

where the units of burnup are MWd/MT. The values used in determining Eq. (2.13) are 90,200 kg for the fuel mass and 3411 MW for the average thermal power.

Substitution of Eq. (2.13) into Eq. (2.11) yields

$$F = 1 - (1 - K_1) \left\{ \frac{1 - \exp(-0.6347K_1K_2b)}{0.6347K_1K_2b} \right\} ,$$

(2.14)

In order to arrive at an expression for the efflux, Eq. (2.14) is differentiated with respect to burnup, resulting in the final equation

$$e_I(b) = \frac{dF}{db} = (1 - K_1) \left\{ \frac{1 - (1 + 0.6374K_1K_2b) \exp(-0.6374K_1K_2b)}{K_1K_2b} \right\} .$$

(2.15)

Equation (2.15) has also been multiplied by the appropriate units so that  $e(b)$  can be expressed in units of  $\text{hr}^{-1}$ .

It should be noted in the steady-state efflux solution that at zero burnup the equation takes the form of  $0/0$ . This difficulty is easily overcome by applying L'Hospital's Rule and taking the limit as  $b$  goes to zero, yielding



$$e(0) = 1 - K_1 . \quad (2.16)$$

Figure 1 represents the steady-state efflux as a function of the burnup. By inspection it is obvious that Eq. (2.15) breaks down for a small burnup level. At the beginning of the fuel life the efflux of fission products should be very low since burnup effects have not created extensive pellet cracking. This presents no problem in the modeling procedure because the time of fuel life under consideration will usually exceed 15000 MWd/MT. The failure of the fuel rod cladding is brought about by embrittlement of the metal with increased burnup, interacting with thermal stresses. Cladding failures of this type would occur during the later stages of the fuel cycle.

A transient gas release expression is employed which incorporates an entirely different solution scheme. Gruber [4] employs the results of a series of calculations carried out with the FRASS code. This is a long code which uses the bubble migration theory introduced earlier in Ref. [2]. The disadvantage of using the code directly is that it requires significant computer time and space and is not practical if a large number of fuel nodes is considered. Gruber derives a parametric relationship which overcomes this difficulty.

The relationship is derived by calculating gas release rates,  $e(t)$ , for steady-state anneals, in which the temperature and thermal gradient are considered constant. The results are plotted as  $\log e(t)$  versus  $t$ , and each curve is approximated by straight lines which are found to obey

an Arrhenius relation. The magnitude of release rate varies linearly with the thermal gradient, and in a more complicated way with the initial gas concentration  $C(0)$ .

The resulting expression for the transient efflux is,

$$e_I(t) = a_1 \sqrt{T} \exp\left\{-\frac{a_2}{T} - (a_3 + a_4 T)F\right\} \quad (2.17)$$

The initial values for  $F$  are taken from the steady-state efflux calculation. The constants in Eq. (2.17) are given by:

$$a_1 = 7.68 \times 10^{16} C_o^{-0.7654}, \quad (2.18a)$$

$$a_2 = 37800.0, \quad (2.18b)$$

$$a_3 = -1833.26 + 77.8269 \ln C_o - 0.823859 (\ln C_o)^2, \quad (2.18c)$$

$$a_4 = 0.0226916 - 4.89386 \times 10^{-4} \ln C_o, \quad (2.18d)$$

and

$$C_o = y_I \int_L \phi_o / (\lambda_I + e_{IO}) . \quad (2.18e)$$

The formulation of Eq. (2.17) provides a simple, rapid, and convenient method of calculating iodine release rates for transient situations.

The following figures 1, 2, and 3 show the response of the efflux solution for three different cases, one for steady-state release and the other two for transient heating.

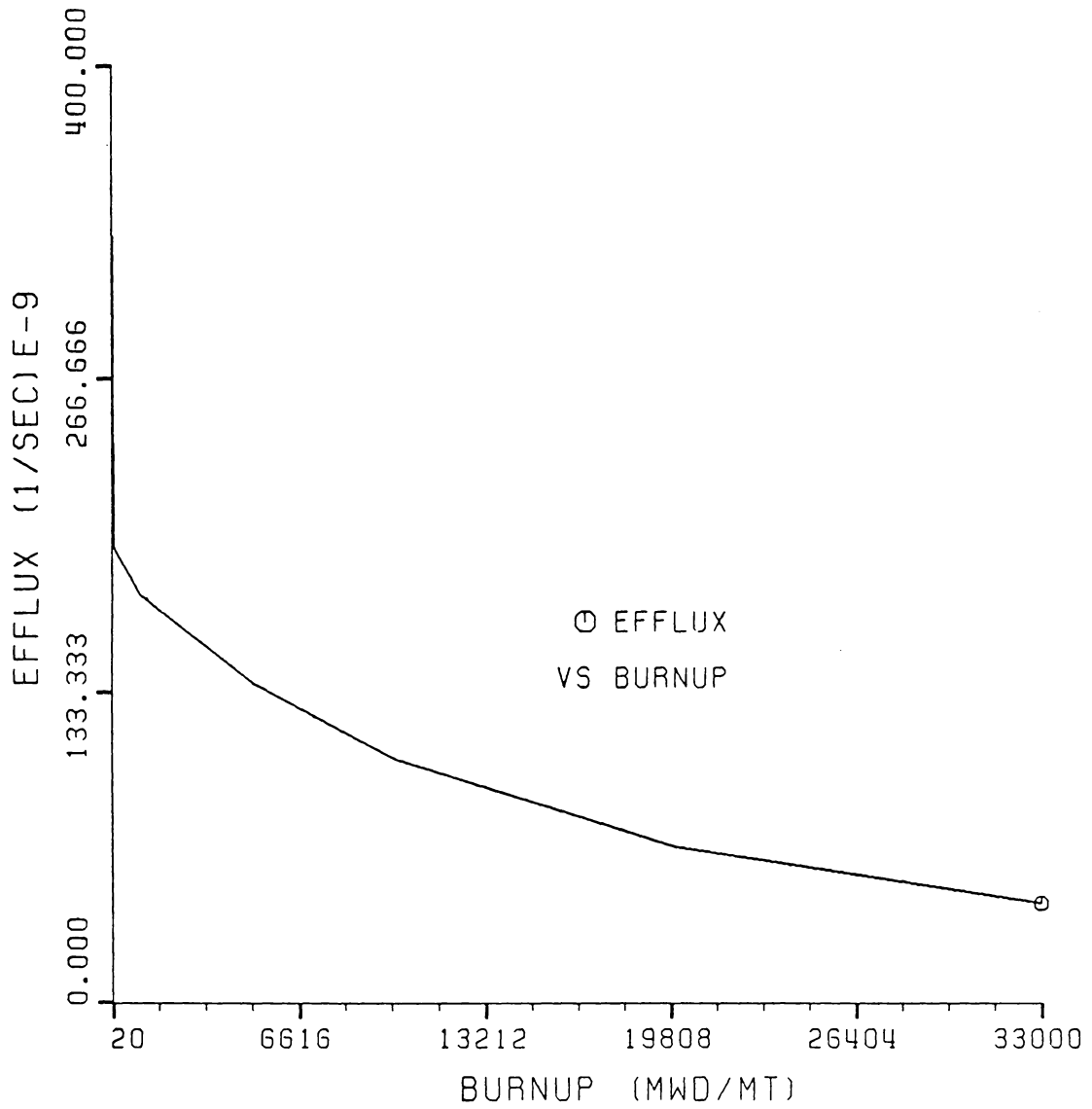


Figure 1. Efflux for steady operation.

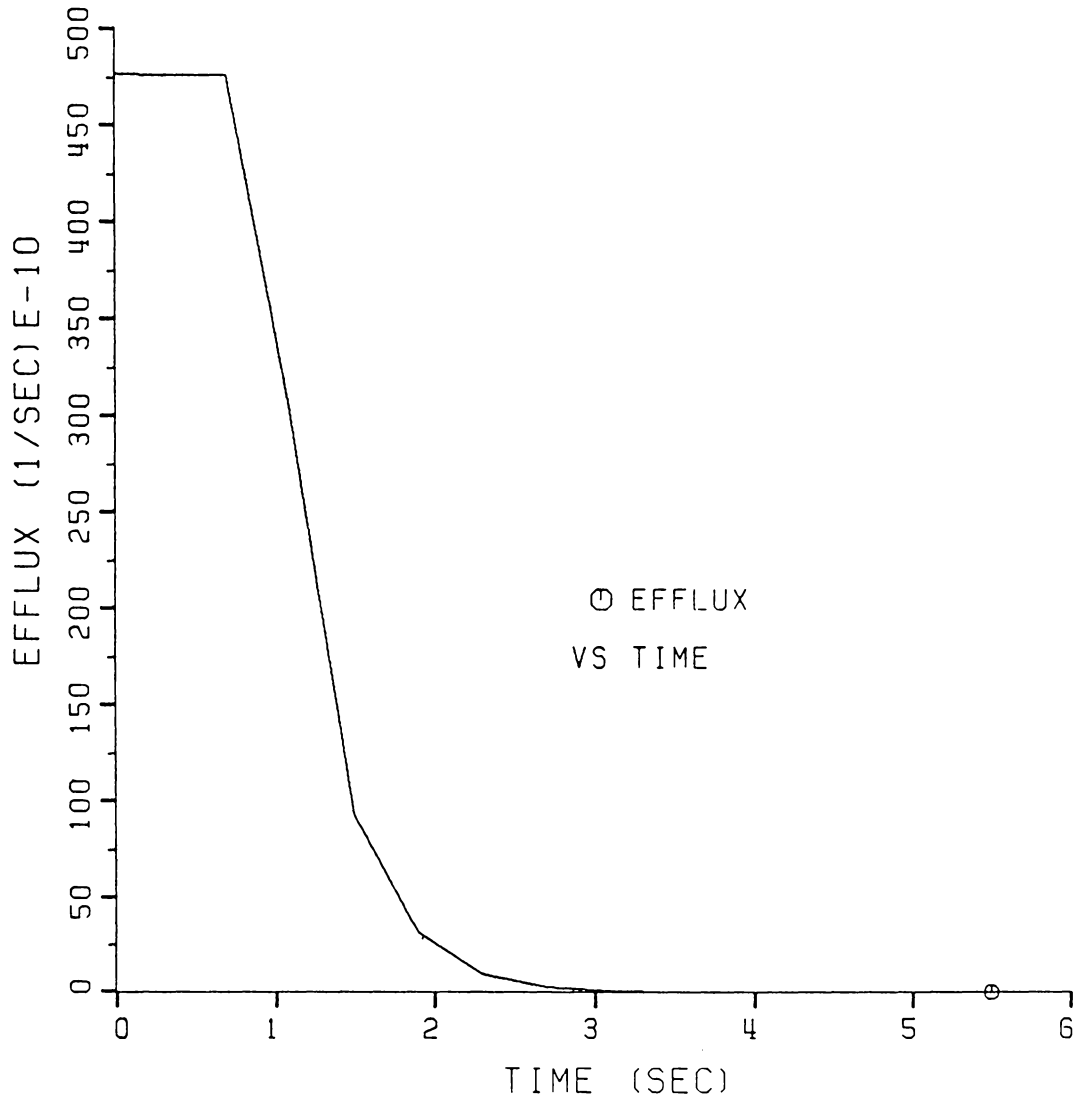


Figure 2. Efflux for a step change in power to 1.0%.

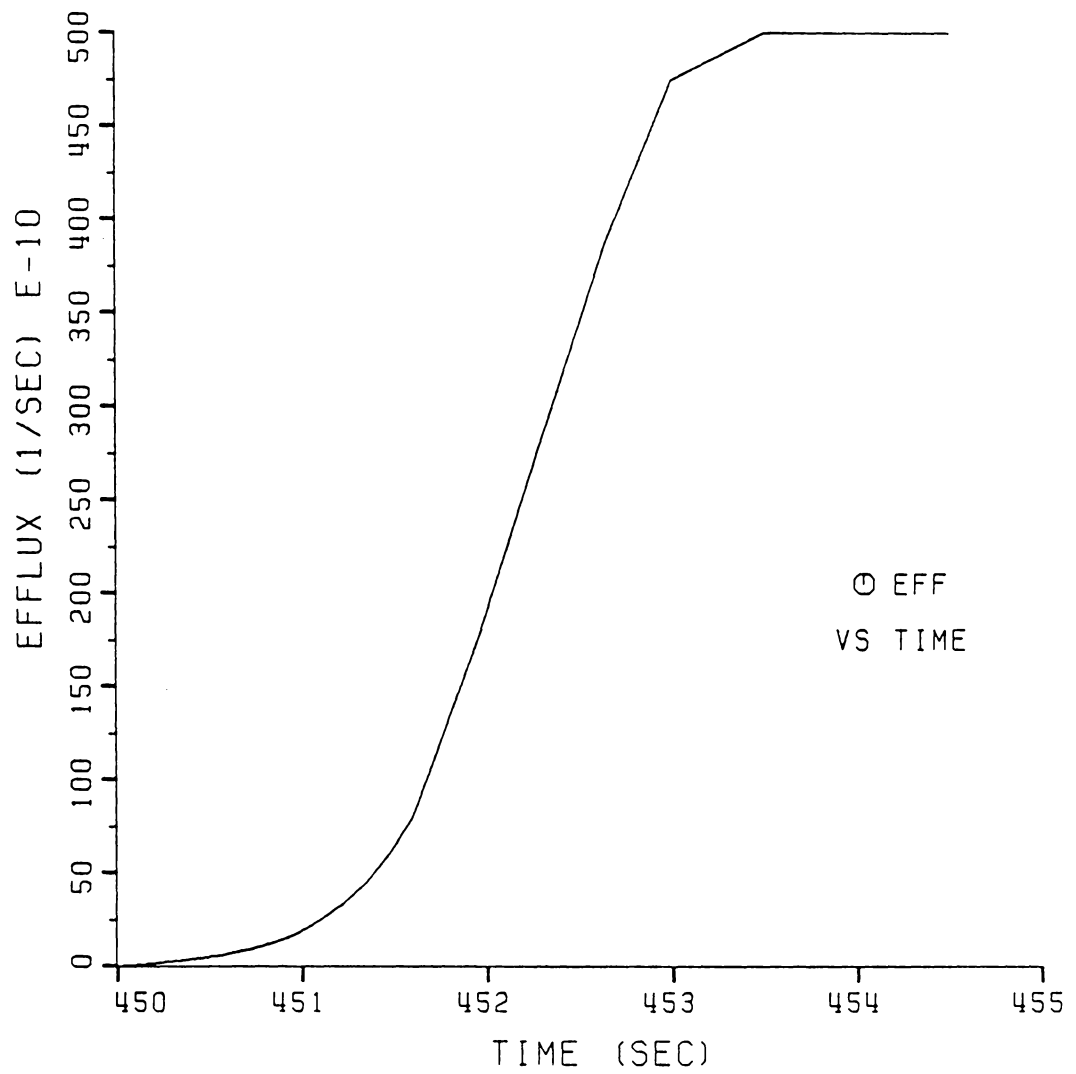


Figure 3. Efflux for an up-power ramp with a rise time of 900.0 seconds.

### B. Numerical Solution

The solutions described above correspond to a particular node in the fuel pellet. In order to obtain the value for the entire pellet, the efflux at each node must be integrated over the pellet volume to give the accumulated effect.

The method is the same for both the steady-state and transient cases. The calculation is performed by multiplying the efflux at a node by the fuel volume and then integrating over the interval  $r_{i-1/2}$  to  $r_{i+1/2}$ . The result is summed over the number of nodes and divided by the fuel radius,

$$\langle e \rangle^p = \frac{\sum_{i=1}^N \int_{i-1/2}^{i+1/2} e_i^p 2\pi r dr H}{\sum_{i=1}^N \int_{i-1/2}^{i+1/2} 2\pi r dr H} = \frac{1}{R_f} \sum_{i=1}^N \int_{i-1/2}^{i+1/2} e_i^p r dr . \quad (2.19)$$

The final result is

$$\langle e \rangle^p = \frac{1}{R_f} \sum_{i=1}^N e_i^p r_i , \quad (2.20)$$

where  $p$  is the time index and  $i$  is the radial index.

### C. Enhanced Efflux in a Water Environment

An important assumption being made is that the CsI salt, which plates out on the internal surfaces of the fuel rod, is readily soluble in water. This fact is important in the development of the leaching

model in that it is this dissolution of the CsI which causes the down-power iodine spike to occur. It is an equally important assumption in deriving the efflux rate of iodine from the fuel pellet.

The fuel pellet that has experienced a large burnup will have many new surfaces exposed to the inside of the cladding. These surfaces will be directly exposed to whatever environment exists in the gap region.

During full power operation of the core the steam environment in the gap will not affect the iodine efflux in the pellet since iodine is not readily dissolvable in steam. The relationships developed in Eqs. (2.15) and (2.17) should correspond well to this situation. Once a down-power transient occurs though, the steam will collapse to water and begin to penetrate the fuel pellet surface as temperatures begin to fall. This penetration will manifest itself as an increase in the efflux rate. Equations (2.15) and (2.17) do not take this into account.

A factor has been included in the efflux calculation which will increase  $\langle e \rangle^P$  if the temperature at a fuel node is less than the saturation temperature of the steam. Equation (2.20) can be written to relate the enhancement to both the steady state and transient efflux calculation,

$$\langle e \rangle^P = \frac{1}{R_f} \sum_{i=1}^N (e_i^P r_i) s, \quad (2.21)$$

where  $s = 1.0$  if the fuel temperature at node  $i$  exceeds the saturation temperature, or  $s = Q$  if the temperature at node  $i$  is below saturation temperature. The value of  $Q$  is determined by comparing the calculated



spike to actual plant data. Values used to correspond to data are discussed in Chapter V.

#### D. Iodine Absorption in Cladding Material

It has been experimentally found that, during the long term steady operation of a reactor, a significant proportion of the iodine plated onto the inner cladding surface will be absorbed by the oxide layer and effectively removed from the gap region [1].

The absorption takes place in the zirconium oxide layer on the cladding tube inner surface, possibly at oxygen vacancies, causing the formation of iodides. The observation made by Neeb and Schuster [1] is that about 30% of the iodine can be dissolved in boiling water from the zirconium oxide layer. The remainder is only obtained after dissolving the cladding tube section in hydrofluoric acid.

This implies that the steady-state concentration of iodine in the gap as a result of the efflux calculation is too large. The absorption effect must be accounted for. This is accomplished by incorporating a reduction factor into the steady-state calculation of the iodine for the gap region. By analogy, similar factors are applied to the isotopes of antimony and tellurium.

The assumption is also made that during a power transient there is no immediate absorption in the clad, i.e. the absorption process is a long term effect. Therefore during the transient calculation the reduction factor is removed.

The magnitude of the reduction factor is determined experimentally

by comparison to actual iodine spiking data. The values employed are discussed in Chapter V.

#### E. Leaching Rate from a Failed Rod

The work done on computation of the iodine leaching rate was performed by L. M. Jones. For a detailed explanation and derivation of the expressions involved see Ref. [16].

Both up- and down-power transients were studied and several mathematical models were developed in order to model the leaching phenomenon. It was attempted to do this from basic thermal-hydraulic and chemical principles [16].

Figure 4 shows the results for a step change in power to zero and figure 5 for an up-power ramp with a rise time of 900.0 seconds. The ordinate in these figures represents the fraction of a given iodine isotope which leaches out per unit time.

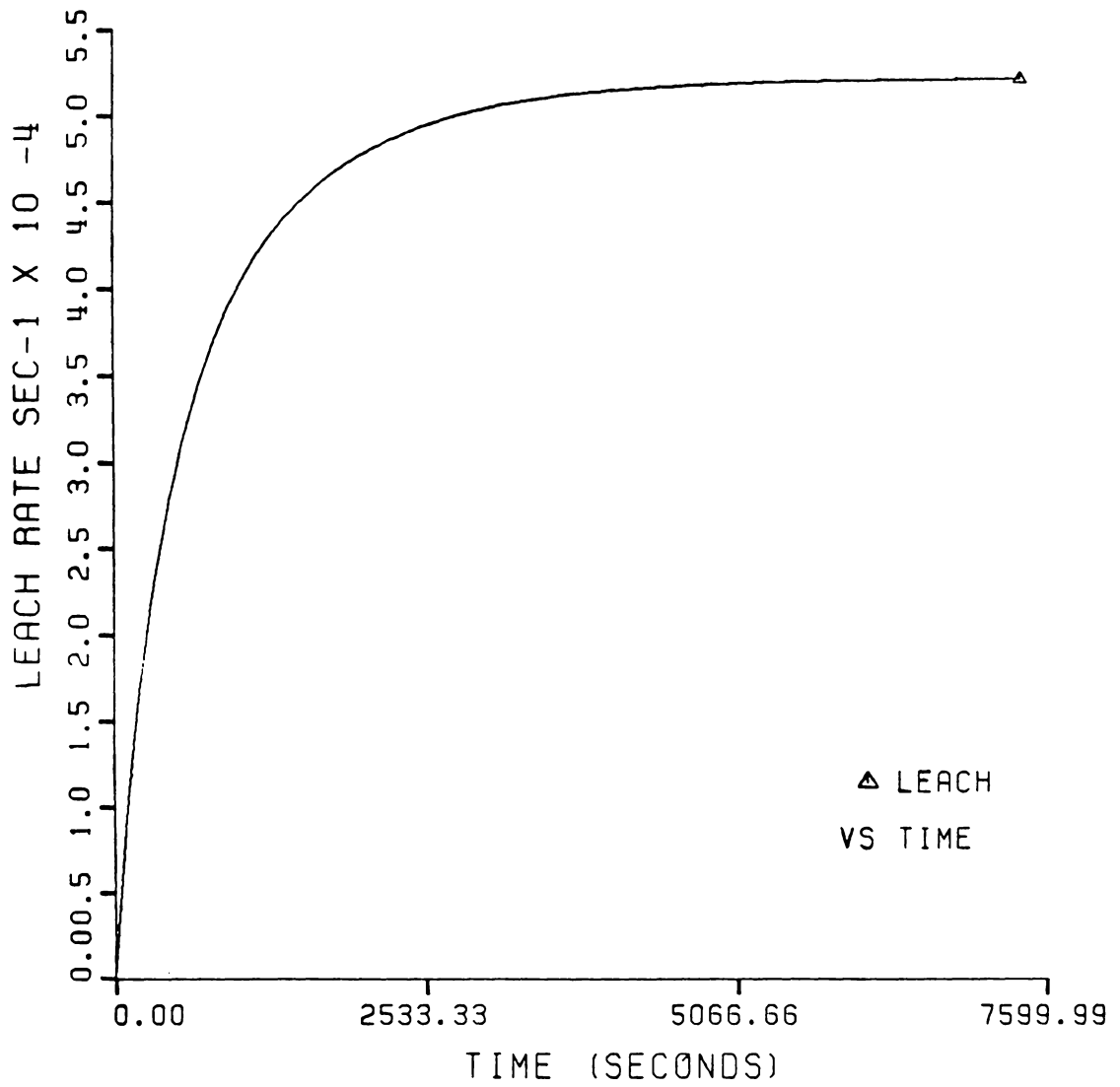


Figure 4. Leach rate for a step change in power to 1.0%.

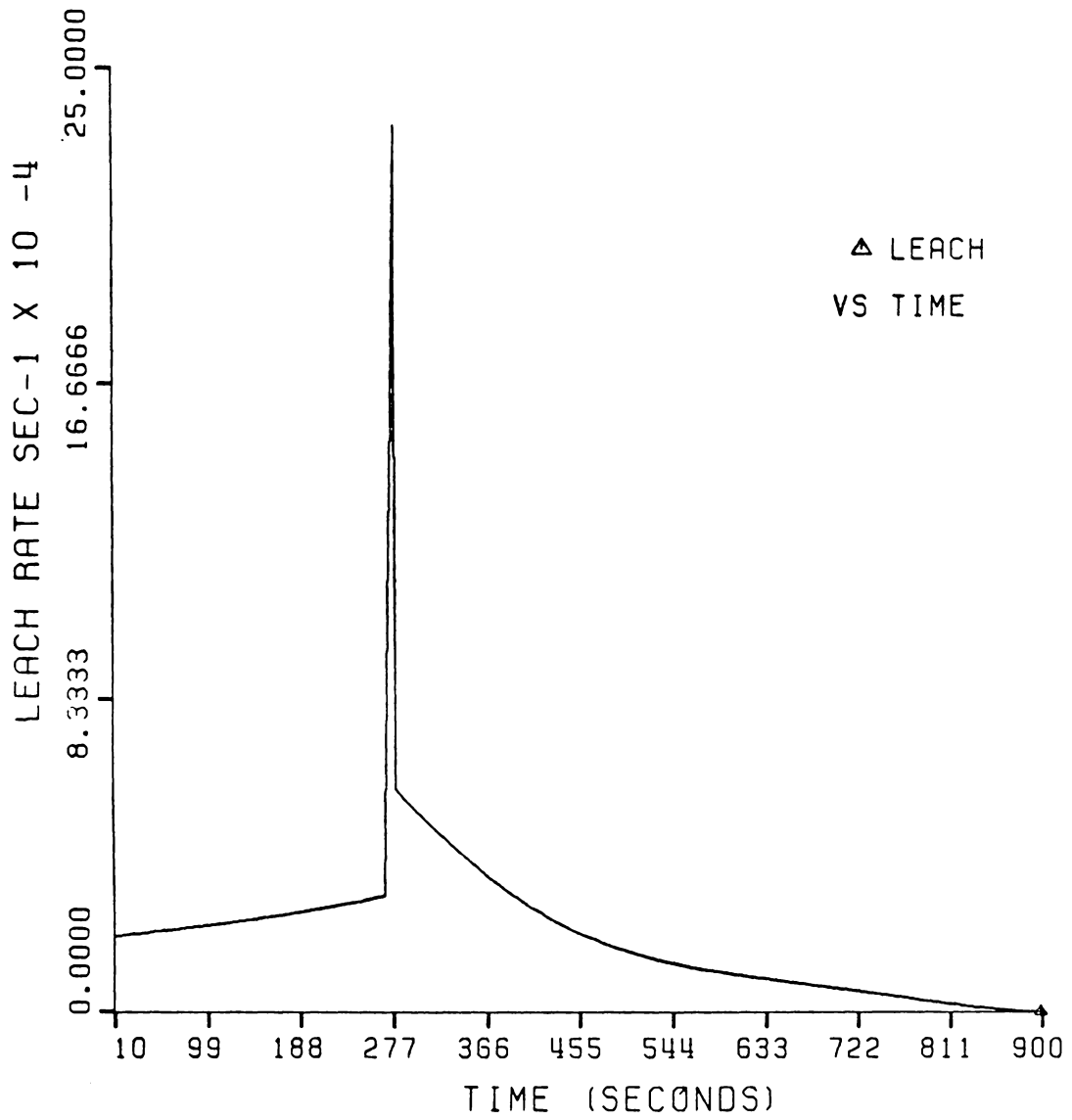


Figure 5. Leach rate for an up-power ramp with a rise time of 900.0 seconds

### III. TEMPERATURE DISTRIBUTION IN A FUEL PIN

#### A. Heat Conduction Equation

The efflux relationships developed in Chapter II are highly dependent on the temperature distribution in the fuel rod. Therefore a spatial and time-dependent heat conduction equation is solved. The rate of change of the temperature distribution in the fuel is equal to the heat production rate from fission less the diffusion rate of heat from the pellet [10]

$$\nabla \cdot (k\nabla T) + w_F \int_f \phi(t) = \rho_F C_F \frac{\partial T}{\partial t} . \quad (3.1)$$

Due to the geometry involved with the fuel rod, Eq. (3.1) is written in a cylindrical coordinate system. Two assumptions are made in doing this. Since the source term corresponds to the average power level of the core, the temperature distribution will be for an average fuel rod. Therefore there is no need to relate this to the axial position, and the z-dependence will be removed. Also since there is no preferred direction for heating in the pellet the angular dependence will also be removed. The result is

$$\frac{1}{r} \frac{\partial}{\partial r} [rk(T) \frac{\partial T}{\partial r}] + w_F \int_f \phi(t) = \rho_F C_F(T) \frac{\partial T}{\partial t} . \quad (3.2)$$

#### B. Thermal Conductivity

The thermal conductivity is treated as a temperature-dependent

quantity. The temperature in the fuel pin may vary as much as 500 degrees Celsius across a distance of no more than 5 mm. The conductive properties of uranium act in such a way that to use an average value for  $k(T)$  would not be accurate enough. Therefore the following expression from Ref. [6] has been employed,

$$k(T) = \frac{6882.113}{232.94 + 1.8T} + (1.04209 \times 10^{-11})(1.8T + 0.33)^3, \quad (3.3)$$

with  $k$  in W/m.K and  $T$  in K.

#### C. Specific Heat

The specific heat of Uranium oxide also varies significantly with the temperature. Therefore a temperature-dependent relationship is employed [7],

$$C_p(T) = \frac{(8.5057 \times 10^7)e^{\frac{535.285}{T}}}{\frac{535.285}{T} - 1)^2 T^2} + (2.4336 \times 10^{-2})T + \frac{(1.660 \times 10^{12})e^{\frac{-18970.6}{T}}}{T^2} \quad (3.4)$$

where the units of  $C_p$  are J/kg.K.

#### D. Burnup Effects on $UO_2$ Fuel

In order to represent the efflux and leach rate of the iodine in the most realistic manner, the burnup of the fuel has been incorporated into the temperature calculation.

The burnup will affect the distribution of temperatures in two important ways. There will be swelling of the fuel pellet and redensification. Both of these factors tend to increase the central temperature of the pellet. A larger temperature difference across the fuel will cause the steady-state efflux to rise. Also, when the diameter of the fuel increases, the volume of the gap decreases. A smaller gap region will mean that the initial inventory of iodine will be less. This means that the time it takes to leach the available iodine out of the fuel pin during a transient will be less. The result will be a shorter time to peak with increased burnup.

The radial expansion is determined by calculating the volume expansion of the  $UO_2$  and applying 1/3 of this to an increase in the fuel diameter [8],

$$\frac{\Delta D}{D_0} = \frac{1}{3} \frac{\Delta V}{V_0} \quad (3.5)$$

The change in the fuel volume is calculated using the expression [8]:

$$\frac{\Delta V}{V_0} = f\alpha[e^{-F} \frac{\Delta V}{V_0} - 1] + \beta(1 - \alpha)b \quad (3.6)$$

The constants are defined as

$$\alpha = \text{INITIAL UO}_2 \text{ POROSITY} \approx 0.07 , \quad (3.7a)$$

$$b = \text{FUEL BURNUP (MWd/MT)} , \quad (3.7b)$$

$$\beta = 1.6 \times 10^{-6} \quad (3.7c)$$

$$f = \text{DENSITY CORRECTION FACTOR} = 0.149\alpha^{-0.746} , \quad (3.7d)$$

and

$$F = \text{GEOMETRICAL FACTOR} = 100 . \quad (3.7e)$$

Note that in Eq. (3.6) the unknown  $\Delta V/V$  must be computed iteratively since it is implicit in the expression.

The redensification of uranium dioxide is experimentally found to vary logarithmically with respect to burnup and is expressed as [9],

$$\frac{\Delta \rho}{\rho_0} = m \ln b + c , \quad (3.8)$$

where  $m$  and  $c$  are constants.

Equation (3.8) applies only to the first 2000 MWd/MT of burnup, after which time the density of the fuel will remain essentially constant.

For 92% theoretically dense fuel the constants are [9]

$$m = 0.001846 \quad (3.9a)$$

and

$$c = 0.005529 . \quad (3.9b)$$

#### E. Solution by Finite Difference

There are two reasons for solving Eq. (3.2) using a finite differ-



ence method. The efflux equations are solved by breaking the fuel pellet into annular nodes, solving for  $e(t)$  in each node, and then integrating to obtain the accumulated effect. This means that a temperature solution giving values at discrete annular nodes in the pellet will correspond to the numerical solution used for the efflux. Also, the temperature-dependent quantities used for  $k(T)$  and  $C(T)$  make an analytical solution of the conduction equation a very formidable task.

Figure 6 shows the nodal scheme used to divide the fuel pellet.

Equation (3.2) is multiplied by  $2\pi r dr$ , the node area in  $dr$ . All the terms are then integrated over the nodal interval,  $r_{i-1/2}$  to  $r_{i+1/2}$ , i.e.

$$\rho_p C_p \frac{\partial}{\partial t} \left\{ \int_{i-1/2}^{i+1/2} T r dr \right\} = \rho_i C_{p_i} r_i \Delta r \frac{\partial T_i}{\partial t}, \quad (3.10a)$$

$$\begin{aligned} \int_{i-1/2}^{i+1/2} \partial [rk(T) \frac{\partial T}{\partial r}] &= (r_i + \frac{\Delta r}{2}) (k(T) \frac{\partial T}{\partial r})_{i+1/2} \\ &- (r_i - \frac{\Delta r}{2}) (k(t) \frac{\partial T}{\partial r})_{i-1/2}, \end{aligned} \quad (3.10b)$$

and

$$w_F \sum_f \int_{i-1/2}^{i+1/2} \phi(t) r dr = w_F \sum_f \phi(t) r_i \Delta r. \quad (3.10c)$$

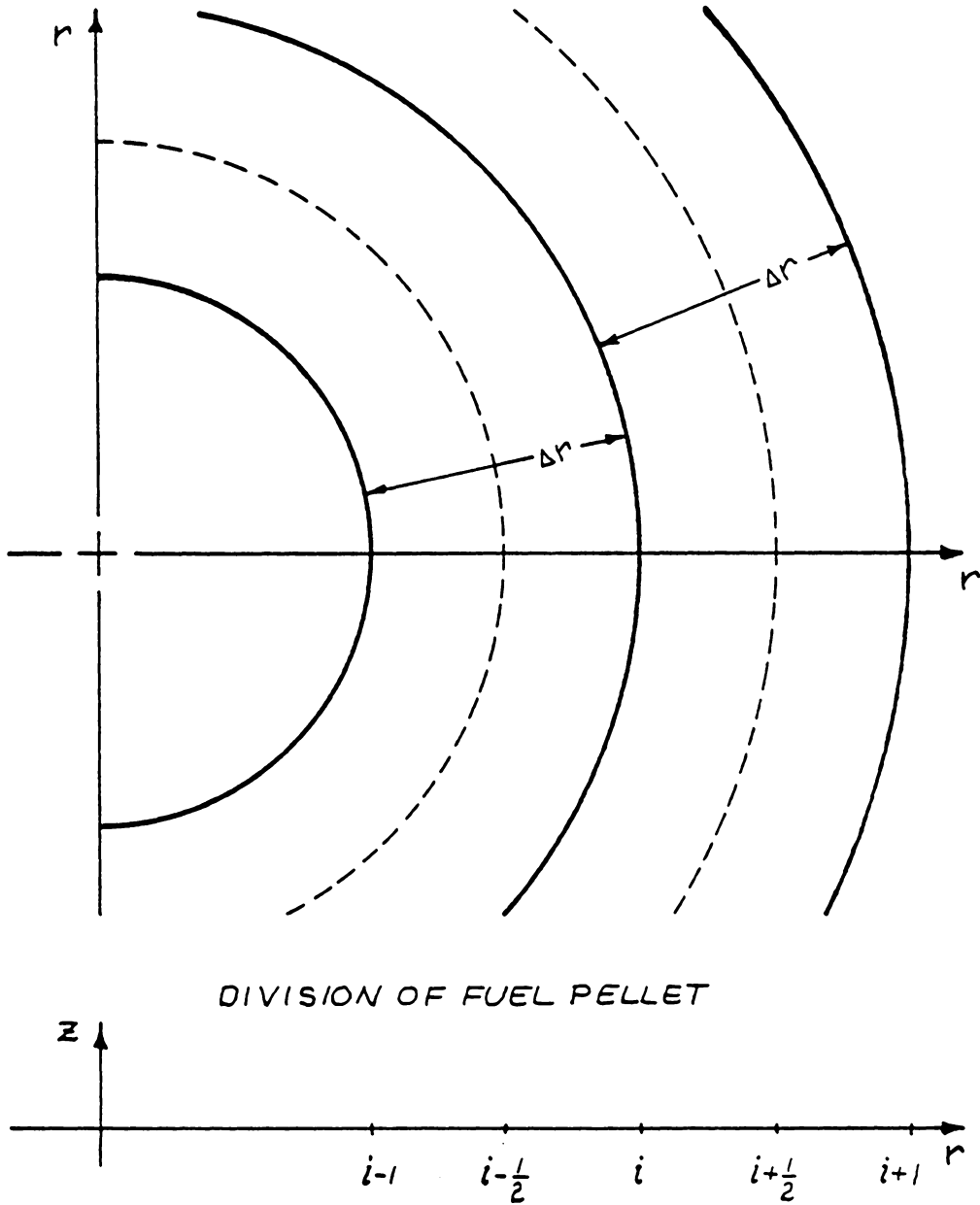


Figure 6. Nodal scheme for the finite difference temperature solution.

In order to be assured of a stable solution, an implicit method is used to describe the time dependence. The following backward difference approximation is used:

$$\frac{dT_i(t)}{dt} = \frac{T_i(t) - T_i(t - \Delta t)}{\Delta t} = \frac{T_i^P - T_i^{P-1}}{\Delta t}. \quad (3.11)$$

Equation (3.11) is substituted into Eq. (3.10). The result is the a system of linear equations each having the form

$$-a_i^P T_{i+1}^P + b_i^P T_i^P - c_i^P T_{i-1}^P = B_i^{P-1,P}, \quad (3.12)$$

with coefficients

$$a_i^P = \left( r_i + \frac{\Delta r}{2} \right) \frac{k_{i+1/2}^k}{\Delta r}, \quad (3.13a)$$

$$b_i^P = \left( r_i + \frac{\Delta r}{2} \right) \frac{k_{i+1/2}^k}{\Delta r} + \rho_i C_i r_i \frac{\Delta r}{\Delta t} + \left( r_i - \frac{\Delta r}{2} \right) \frac{k_{i-1/2}^k}{\Delta r}, \quad (3.13b)$$

$$c_i^P = \left( r_i - \frac{\Delta r}{2} \right) \frac{k_{i-1/2}^k}{\Delta r} \quad (3.13c)$$

and

$$B_i^{P-1,P} = w_F \int_f \phi^P r_i \Delta r + \rho_i C_i r_i \frac{\Delta r}{\Delta t} T_i^{P-1}. \quad (3.13d)$$

In matrix form, Eq. (3.12) can be written as  $[A][T] = [B]$ . The matrix  $[A]$  is of tridiagonal form and therefore the equation can be solved in a straight-forward manner using Gaussian elimination since  $[A]$  can be stored as three independent vectors, each containing one diagonal of the matrix.

## F. Boundary Conditions

There are two boundary conditions which Eq. (3.12) must satisfy, one for the center of the pellet and one for the outer edge.

At the center of the pellet the slope of the temperature distribution must be zero. This is accomplished by setting the temperature in the second position of the [T] vector equal to the first one. The result is a separate linear equation for the center node,

$$-a_2 T_3^P + (b_2 - c_2) T_2^P = B_2^{P-1,P} . \quad (3.14)$$

The coefficients in Eq. (3.14) will be slightly different as well. Since the center node is being included in the derivation of the above a multiplier of 3/2 must be included to account for the mass, so

$$a_i^P = (r_2 + \frac{\Delta r}{2}) \frac{k_2}{\Delta r} \quad (3.15a)$$

$$b_2^P = (r_2 + \frac{\Delta r}{2}) \frac{k_2}{\Delta r} + \rho_2 C_{p_2} r_2 \frac{\Delta r}{\Delta t} \left(\frac{3}{2}\right) + (r_2 - \frac{\Delta r}{2}) \frac{k_1}{\Delta r} , \quad (3.15b)$$

$$c_2^P = (r_2 - \frac{\Delta r}{2}) \frac{k_1}{\Delta r} , \quad (3.15c)$$

and

$$B_2^{P-1,P} = \frac{3}{2} \{ w_F \int_{\phi}^P r_2 \Delta r + \rho_2 C_{p_2} r_2 \frac{\Delta r}{\Delta t} T_2^{P-1} \} . \quad (3.15d)$$

At the outer edge of the fuel pellet the surface temperature of the pellet is known. Application of this will remove the bottom row in the  $[A][T] = [B]$  equation. A known term will also be added to the last term in  $[B]$ ,  $B_N + a_N T_{N+1}$ . The  $N+1$  term represents the outermost node.

By applying both boundary conditions a system composed of  $N$  nodes will have  $N-2$  equations.

An expression needs to be derived in order to evaluate the terms  $k_{i+1/2}$  and  $k_{i-1/2}$ . The finite difference solution is formulated such that the temperatures are calculated at the nodal points  $i=1,2,3,\dots,N$ , not at their midpoints. Therefore the following results from Ref. [14] are used in order to relate the  $k$  values to the nodal points:

$$k_{i+1/2} = \frac{2k_i k_{i+1}}{k_i + k_{i+1}} \quad (3.16a)$$

and

$$k_{i-1/2} = \frac{2k_{i-1} k_i}{k_{i-1} + k_i} \quad (3.16b)$$

Figures 7, 8, and 9 show the results of this calculation for the steady-state and two transient conditions.

For an analysis of time step and nodal size determination see Appendix A.

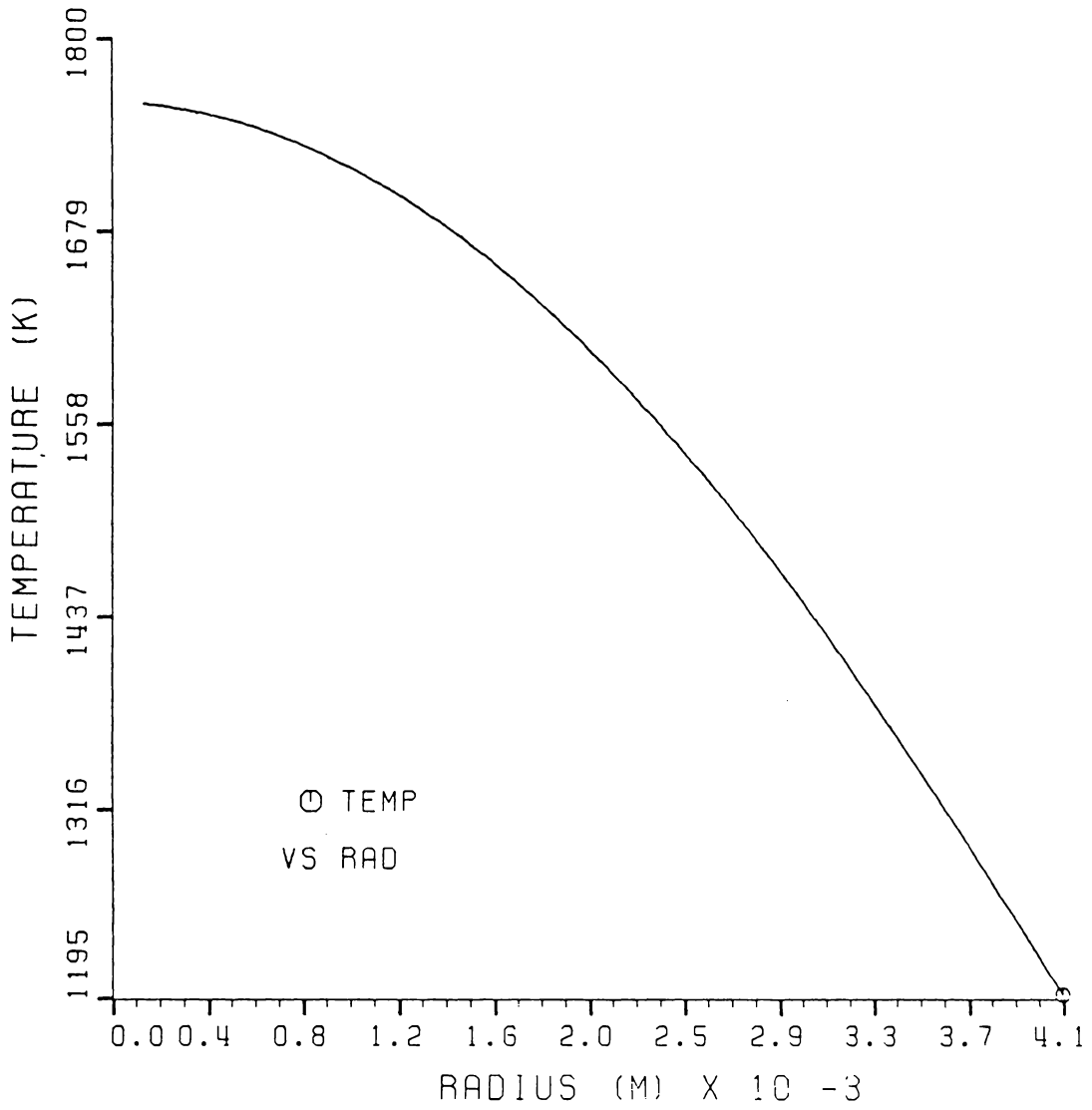


Figure 7. Steady state temperature distribution in the fuel pellet.

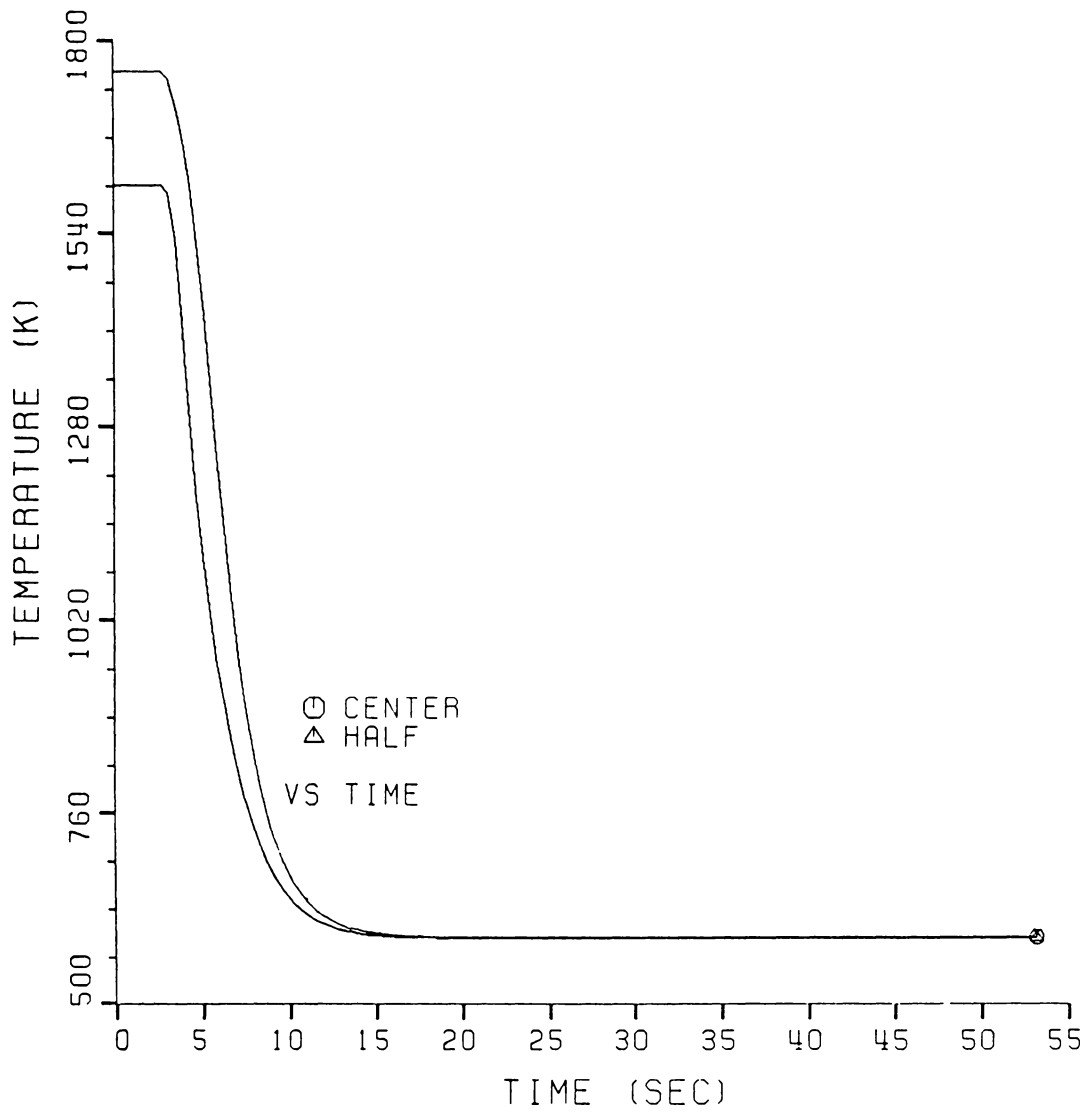


Figure 8. Temperature at the fuel center and half distance for a step change in power to 1.0%.

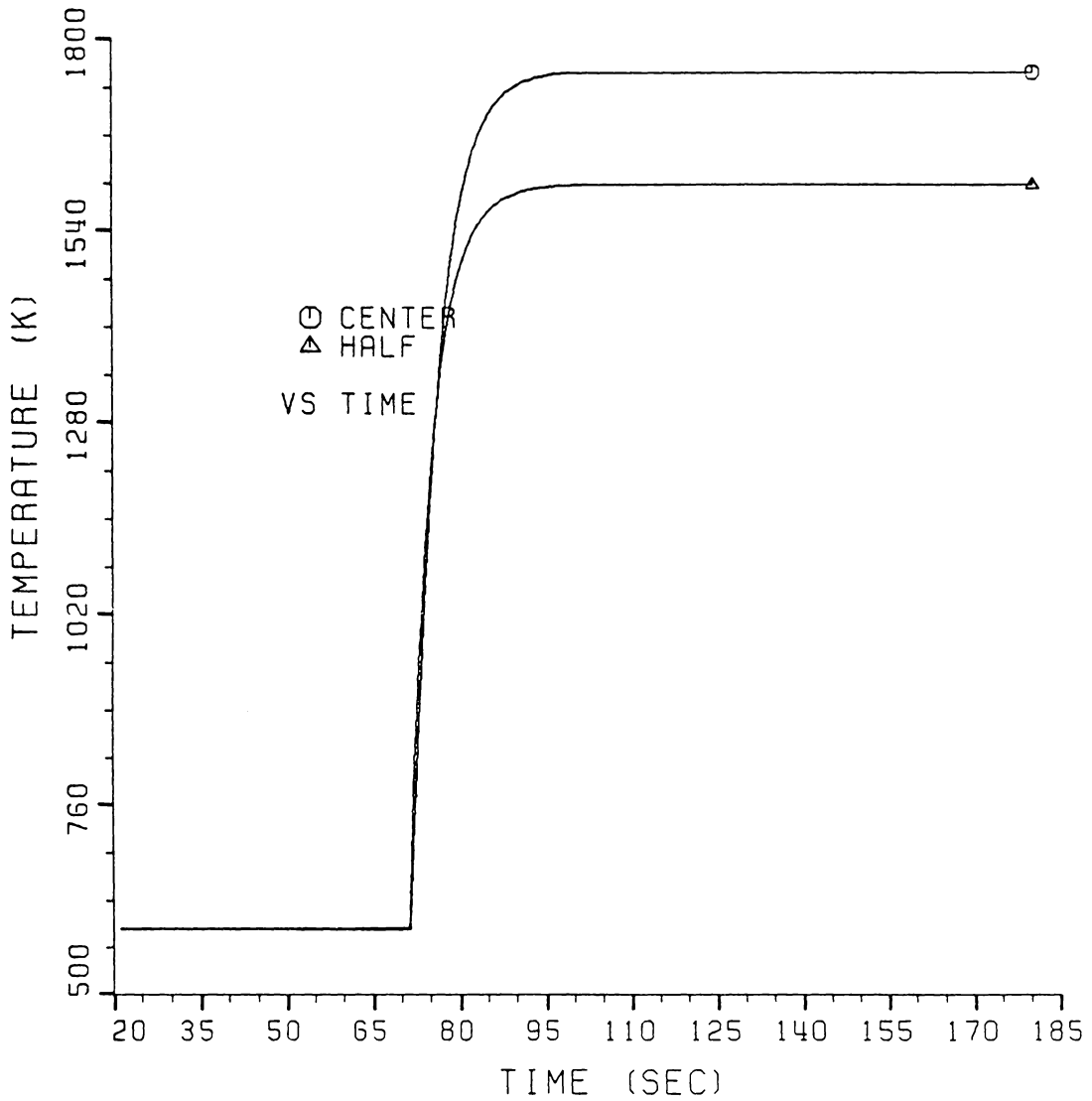


Figure 9. Temperature at the fuel center and half distance for an up-power ramp with a rise time of 15.0 seconds.



#### IV. IODINE BALANCE EQUATIONS

##### A. Production and Removal in Pellet and Gap

The differential equations governing the iodine concentration in the fuel pellet and gap region are similar in nature. Both equations represent a lumped model for iodine production and removal based on the production and decays of their precursors and are therefore functions of time only.

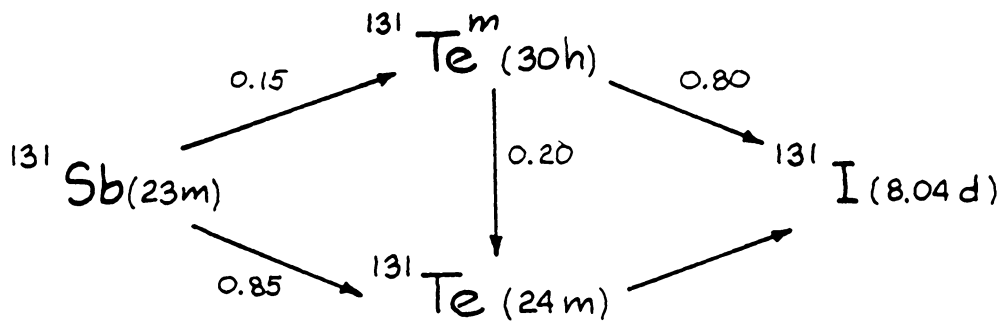
Figure 10 shows the decay chains of the iodine fission products and precursors. With the exception of iodine-132 the isotopic production of iodine is a four-stage process. Antimony is produced directly from the fission process and subsequently decays into two unstable states of tellurium. The tellurium isotopes will then decay to produce iodine.

From the decay chains presented here two systems of generalized equations are developed, one for the fuel pellet and the other for the gap region.

In the fuel the iodine balance was initially to be determined using a time and space-dependent equation with the cumulative yield as the source term [10],

$$\frac{\partial I_F}{\partial t}(r, t) = y_{I\Sigma_f}\Phi(t) - \lambda_{I}I_F(r, t) - \nabla \cdot \vec{J}(\hat{r}, t) \quad (4.1)$$

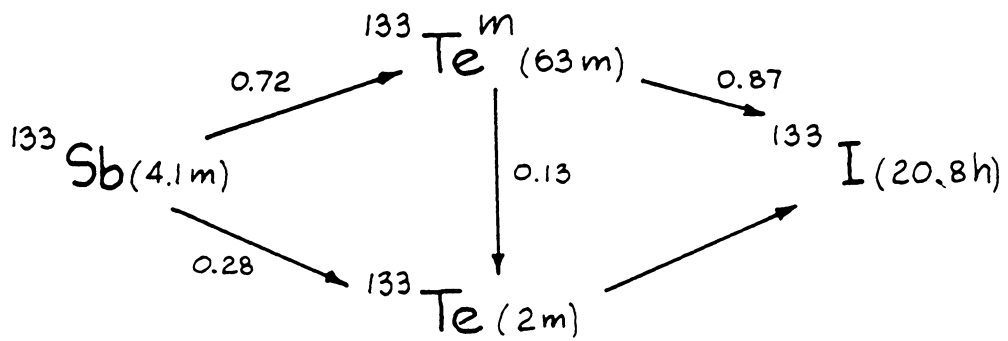
Since the efflux of fission products from the fuel is a known function, independent of the mass flux vector, the following approximation is made:



IODINE-131 ISOTOPE CHAIN



IODINE-132 ISOTOPE CHAIN



IODINE-133 ISOTOPE CHAIN

Figure 10. Isotopic decay chains.

$$\nabla \cdot \hat{\mathbf{J}}(\hat{\mathbf{r}}, t) \approx e_I(t)I_F(t) \quad (4.2)$$

This represents an effective removal of iodine from the fuel pellet and no radial dependence is needed. Therefore, Eq. (4.1) can be written as

$$\frac{dI_F}{dt}(t) = y_I \Sigma_f \Phi(t) - \lambda_I I_F(t) - e_I(t)I_F(t) \quad (4.3)$$

On the right-hand side of the equation, the first term represents the production of iodine from the fission process, the middle term is the removal of iodine by radioactive decay and the last term is the removal by diffusion out of the pellet.

This form of the iodine balance equation was to initially be employed for the model but it was decided that the decay chain equations should also be incorporated in order to formulate a better prediction. The average time-to-peak of a typical iodine spike is on the order of three to five hours. The half-life of tellurium-131 is 30 hours and tellurium-133 is 63 minutes (the metastable states), therefore an appreciable time lag will exist between the production of antimony and its eventual decay to iodine. Using a cumulative yield model for the iodine will essentially ignore this time lag and therefore shift the spiking characteristics in an unrealistic manner.

A set of equations are developed for the 131 isotopes in the fuel and then generalized to the three isotopes. The same method is employed for the gap region and primary coolant.

From Fig. 10, the  $^{131}\text{I}$  decay chain begins with the direct production from fission of antimony. The antimony will decay and diffuse out of the pellet simultaneously,

$$\frac{dS_F^1}{dt}(t) = y_{S1}\Sigma_f\Phi(t) - [\lambda_{S1} + e(t)]S_F^1(t) . \quad (4.4)$$

Fifteen percent of the antimony atoms will decay to the metastable state of tellurium. There is also direct production of tellurium by fission. This will decay radioactively to iodine and the non-metastable state of tellurium. There is also diffusion out of the pellet,

$$\frac{dT_F^{m1}}{dt}(t) = y_{Tm1}\Sigma_f\Phi(t) + 0.15\lambda_{S1}S_F^1(t) - [\lambda_{Tm1} + e(t)]T_F^{m1}(t) . \quad (4.5)$$

The non-metastable tellurium will be produced by 85% of the antimony decays and 20% of the metastable tellurium decays. There is also direct production from fission. All of the tellurium will decay to iodine and will also migrate to the pellet surface,

$$\frac{dT_F^1}{dt}(t) = y_{T1}\Sigma_f\Phi(t) + 0.2\lambda_{Tm1}T_F^{m1} + 0.85\lambda_{S1}S_F^1(t) - [\lambda_{Tn} + e(t)]T_F^1(t) \quad (4.7)$$

The last isotope in the decay chain of interest is the iodine. This will come from the decays of the two states of tellurium and a small amount will come directly from fission. The iodine will also decay radioactively and diffuse out of the fuel,

$$\frac{dI_F^1}{dt}(t) = y_{I1\Sigma_f}\Phi(t) + \lambda_{Tn}T_F^1(t) + 0.8\lambda_{Tm1}T_F^{m1} - [\lambda_{I1} + e(t)]I_F^1(t) \quad (4.7)$$

The general set of equations for the fuel pellet are similar in development and are as follows:

$$\frac{dS_F^n}{dt}(t) = y_{sn\Sigma_f}\Phi(t) - [\lambda_{sn} + e(t)]S_F^n(t) , \quad (4.8)$$

$$\frac{dT_F^{mn}}{dt}(t) = y_{Tmn\Sigma_f}\Phi(t) + \gamma_1^n\lambda_{sn}S_F^n(t) - [\lambda_{Tmn} + e(t)]T_F^{mn}(t) , \quad (4.9)$$

$$\begin{aligned} \frac{dT_F^n}{dt}(t) = & y_{Tn\Sigma_f}\Phi(t) + \gamma_2^n\lambda_{Tmn}T_F^{mn}(t) + \gamma_3^n\lambda_{Sn}S_F^n(t) \\ & - [\lambda_{Tn} + e(t)]T_F^n(t) , \end{aligned} \quad (4.10)$$

$$\begin{aligned} \frac{dI_F^n}{dt}(t) = & y_{In\Sigma_f}\Phi(t) + \gamma_4^n\lambda_{Tn}T_F^n(t) + \gamma_5^n\lambda_{Tmn}T_F^{mn}(t) \\ & - [\lambda_{In} + e(t)]I_F^n(t) . \end{aligned} \quad (4.11)$$

The subscripts and superscripts are defined in table I.

The initial conditions for Eqs. (4.8-11) above are readily obtainable by equating the d/dt operator to zero. The results are,

$$S_F^n(0) = \frac{y_{Sn} \Sigma_f \Phi_o}{\lambda_{Sn} + e_o}, \quad (4.12)$$

$$T_F^{mn}(0) = \frac{y_{Tmn} \Sigma_f \Phi_o + \gamma_1^n \lambda_{Sn} S_{FO}^n}{\lambda_{Tmn} + e_o}, \quad (4.13)$$

$$T_F^n(0) = \frac{y_{Tmn} \Sigma_f \Phi_o + \gamma_2^n \lambda_{Tmn} T_{FO}^{mn} + \gamma_3^n \lambda_{Sn} S_{FO}^n}{\lambda_{Tn} + e_o}, \quad (4.14)$$

and

$$I_F^n(0) = \frac{y_{In} \Sigma_f \Phi_o + \gamma_4^n \lambda_{Tn} T_{FO}^n + \gamma_5^n \lambda_{mn} T_{FO}^{mn}}{\lambda_{In} + e_o}, \quad (4.15)$$

TABLE I

Numerical values of the production fractions used in the decay chain equations.

Note: These values are applicable to the three regions of the core considered by the model, the fuel pellet, gap region, and the primary coolant.

	n=1	n=2	n=3
$\gamma_1$	0.15	0.0	0.72
$\gamma_2$	0.2	0.0	0.13
$\gamma_3$	0.85	0.0	0.28
$\gamma_4$	1.0	1.0	1.0
$\gamma_5$	0.8	0.0	0.87

#### Definitions:

##### Superscripts

n=1, corresponds to the 131 isotopes.

n=2, corresponds to the 132 isotopes.

n=3, corresponds to the 133 isotopes.

m, metastable state of the isotope.

##### Subscripts

Tm, metastable state of tellurium.

S, antimony.

I, iodine.

F, fuel region.

G, gap region.

C, primary coolant.

The decay chain equations in the gap are developed in the same way as those in the fuel pellet. The major differences are that there is production by diffusion into the gap and no direct yield production, and there is removal from the gap by leaching into the primary coolant.

The following general set of equations describes the iodine balance and removal in the gap:

$$\frac{dS_G^n}{dt}(t) = \frac{V_F}{V_G} e(t)S_F^n(t) - [\lambda_{Sn} + R(t)]S_G^n(t) , \quad (4.16)$$

$$\frac{dT_G^{mn}}{dt}(t) = \frac{V_F}{V_G} e(t)T_F^{mn}(t) + \gamma_1^n S_G^n(t) - [\lambda_{Tmn} + R(t)]T_G^{mn}(t) , \quad (4.17)$$

$$\begin{aligned} \frac{dT_G^n}{dt}(t) &= \frac{V_F}{V_G} e(t)T_F^n(t) + \gamma_2^n \lambda_{Tmn} T_G^{mn}(t) + \gamma_3^n \lambda_{Sn} S_G^n(t) \\ &- [\lambda_{Tn} + R(t)]T_G^n(t) , \end{aligned} \quad (4.18)$$

and

$$\begin{aligned} \frac{dI_G^n}{dt}(t) &= \frac{V_F}{V_G} e(t)I_F^n(t) + \gamma_4^n \lambda_{Tn} T_G^n(t) + \gamma_5^n \lambda_{Tmn} T_G^{mn}(t) \\ &- [\lambda_{In} + R(t)]I_G^n(t) . \end{aligned} \quad (4.19)$$

The initial conditions for the gap are found by setting the  $d/dt$  operator to zero. The results are,

$$S_G^n(0) = \frac{(V_F/V_G)e_o S_{Fo}^n}{\lambda_{Sn} + R_o} \quad (4.20)$$

$$T_G^{mn}(0) = \frac{(V_F/V_G)e_o T_{Fo}^n + \gamma_2^n \lambda_{Sn} S_{Go}^n}{\lambda_{Tmn} + R_o} , \quad (4.21)$$



$$T_G^n(0) = \frac{(V_F/V_G)e_o T_{Fo}^n + \gamma_2^n \lambda_{Tmn} T_{Go}^{mn} + \gamma_3^n \lambda_{Sn} S_{Go}^n}{\lambda_{Tn} + R_o}, \quad (4.22)$$

and

$$I_G^n(0) = \frac{(V_F/V_G)e_o I_{Fo}^n + \gamma_4^n \lambda_{Tn} T_{Go}^n + \gamma_5^n \lambda_{Tmn} T_{Go}^{mn}}{\lambda_{In} + R_o}. \quad (4.23)$$

#### B. Production and Removal in the Primary Coolant

The balance equations for the primary coolant are not only dependent on diffusion from the fuel pin, but also on the transit time around the coolant loop and through the core. During the transit a percentage of the coolant is directed through a filtration system to remove the radionuclides and this removal process is also incorporated.

An approximation is employed for the coolant equation, therefore the iodine balance is developed assuming that production is dependent only on leaching from the failed rod. This allows for a general understanding of the assumptions made in the derivation. The results are then expanded to account for production by decay of the precursor isotopes.

The rate of change of iodine in the primary coolant equals the production from leaching in the gap, plus that which returns from a transit around the coolant loop, less that which leaves the core in transit around the coolant loop, and that which decays radioactively:

$$\begin{aligned} V_c \frac{dI_c}{dt}(t) = & NV_G R(t) I_G(t) + \left(\frac{dV_c}{dt}\right)_{in} I_c(t - T_L) f_I e^{-\lambda T_L} \\ & - \left(\frac{dV_c}{dt}\right)_{out} I_c(t) - \lambda_I V_c I_c(t) \end{aligned} \quad (4.24)$$

where  $T_L$  is the average loop transit time.

Equation (4.24) can be simplified by noting that the terms  $(dV/dt)_{in}$  and  $(dV/dt)_{out}$  can be taken to be constant and rewritten as  $V/T_c$  where  $T_c$  is the average core transit time. The result is

$$\begin{aligned} \frac{dI_c}{dt}(t) = & \frac{NV_G}{V_c} R(t)I_G(t) + I_c(t - T_L) \frac{f_I e^{-g_I T_L}}{T_c} \\ & - \frac{I_c}{T_c}(t) - g_I I_c(t) \end{aligned} \quad (4.25)$$

A further simplification is also noted in the delay term  $I_c(t - T_L)$ . The average loop transit time for a commercial power reactor is about ten seconds. The rate of change of iodine concentration in the coolant takes place over a long period of time. Therefore the approximation is made that  $I_c(t - T_L) \approx I_c(t)$ . A numerical example for both methods is tabulated in table II which demonstrates the validity of this approximation. Equation (4.24) is written in its final form as

$$\frac{dI_c}{dt}(t) = N \frac{V_G}{V_c} R(t)I_G(t) + \left( \frac{f_I e^{-g_I T_L}}{T_c} - \frac{1}{T_c} + g_I \right) I_c(t) . \quad (4.26)$$

The approximations used in Eq. (4.26) are extrapolated to the general form of the decay equations in the coolant where production of iodine is also a function of the rate of decay of precursors. The coolant equations are

$$\frac{dS_c^n}{dt}(t) = N \frac{V_G}{V_c} R(t) S_G^n(t) + \left[ \frac{f e^{-\lambda_{Sn} T_L}}{T_c} - \frac{1}{T_c} - \lambda_{Sn} \right] S_c^n(t) , \quad (4.27)$$

$$\begin{aligned} \frac{dT_c^{mn}}{dt}(t) &= N \frac{V_G}{V_c} R(t) T_G^{mn}(t) + \gamma_1^n \lambda_{Sn} S_c^n(t) \\ &+ \left[ \frac{f e^{-\lambda_{Tmn} T_L}}{T_c} - \frac{1}{T_c} - \lambda_{Tn} \right] T_c^n(t) , \end{aligned} \quad (4.28)$$

$$\begin{aligned} \frac{dT_c^n}{dt}(t) &= N \frac{V_G}{V_c} R(t) T_G^n(t) + \gamma_2^n \lambda_{Tmn} T_c^{mn}(t) + \gamma_3^n \lambda_{Sn} S_c^n(t) \\ &+ \left[ \frac{f e^{-\lambda_{Tn} T_L}}{T_c} - \frac{1}{T_c} - \lambda_{Tn} \right] T_c^n(t) , \end{aligned} \quad (4.29)$$

and

$$\begin{aligned} \frac{dI_c^n}{dt}(t) &= N \frac{V_G}{V_c} R(t) I_G^n(t) + \gamma_4^n T_c^n(t) + \gamma_5^n \lambda_{Tmn} T_c^{mn}(t) \\ &+ \left[ \frac{f e^{-\lambda_{In} T_L}}{T_c} - \frac{1}{T_c} - \lambda_{In} \right] I_c^n(t) . \end{aligned}$$

TABLE II

Comparison for  $I(t)$  for approximation used in the Runge-Kutta solution for iodine concentration in the primary coolant.

$I_p(t-T_L)$	$I_p(t)$	time (sec)
0.4076E 14	0.4076E 14	0.000
0.2509E 15	0.2703E 15	20.599
0.1015E 16	0.9898E 15	62.599
0.2019E 16	0.2020E 16	132.599
0.3047E 16	0.3049E 16	202.599
0.4018E 16	0.4022E 16	272.599
0.4937E 16	0.4942E 16	342.599
0.5805E 16	0.5812E 16	412.599
0.6627E 16	0.6635E 16	482.599
0.7405E 16	0.7414E 16	552.599
0.8069E 16	0.8079E 16	615.599
0.8771E 16	0.8781E 16	685.599
0.9434E 16	0.9445E 16	755.599
0.1006E 17	0.1007E 17	825.599
0.1066E 17	0.1067E 17	895.599
0.1122E 17	0.1123E 17	965.599
0.1170E 17	0.1171E 17	1028.599

The initial conditions for Eq. (4.27-30) are obtained by equating the d/dt operator to zero, resulting in:

$$S_c^n(0) = -N\left(\frac{V_G}{V_c}\right)R_o S_{Go}^n / \left[ \frac{f e^{-\lambda_{Sn} T_L}}{T_c} - \frac{1}{T_c} - \lambda_{Sn} \right], \quad (4.31)$$

$$T_c^{mn}(0) = - \frac{N(V_G/V_c)R_o T_{Go}^{mn} + \gamma_1^n \lambda_{Sn} S_{co}^n}{\frac{f e^{-\lambda_{Tmn} T_L}}{T_c} - \frac{1}{T_c} - \lambda_{Tmn}}, \quad (4.32)$$

$$T_c^n(0) = - \frac{N(V_G/V_c)R_o T_G^o + \gamma_2^n T_{co}^{mn} + \gamma_3^n \lambda_{Sn} S_{co}^n}{\frac{f e^{-\lambda_{Tn} T_L}}{T_c} - \frac{1}{T_c} - \lambda_{Tn}}, \quad (4.33)$$

$$I_c^n(0) = - \frac{N(V_G/V_c)R_o I_{Go}^n + \gamma_4^n \lambda_{Tn} T_{co}^n + \gamma_5^n \lambda_{Tmn} T_{co}^{mn}}{\frac{f e^{-\lambda_{In} T_L}}{T_c} - \frac{1}{T_c} \lambda_{In}}. \quad (4.34)$$

### C. Solution by the Runge-Kutta Method

A numerical method is employed to solve the differential equations of the fuel, gap, and coolant because they contain time-dependent coefficients which are themselves either numerically derived or complicated. A Runge-Kutta method is used because it offers a reasonably stable time-dependent solution for a wide range of time-step sizes.

For all equations the solution form can be written as [15]

$$I_{p+1} = I_p + \Delta t(C_1 + 2C_2 + 2C_3 + C_4)/6 \quad (4.35)$$

where the C terms are defined as

$$C_1 = f(I_p) , \quad (4.36a)$$

$$C_2 = f(I_p + C_1/2) , \quad (4.36b)$$

$$C_3 = f(I_p + C_2/2) , \quad (4.36c)$$

and

$$C_4 = f(I_p + C_3) . \quad (4.36d)$$

The function  $f$  simply represents the right-hand side of the equation being solved.

Examples of the results are shown in figures 11 through 13 for a typical down-power transient where the power level drops to zero.

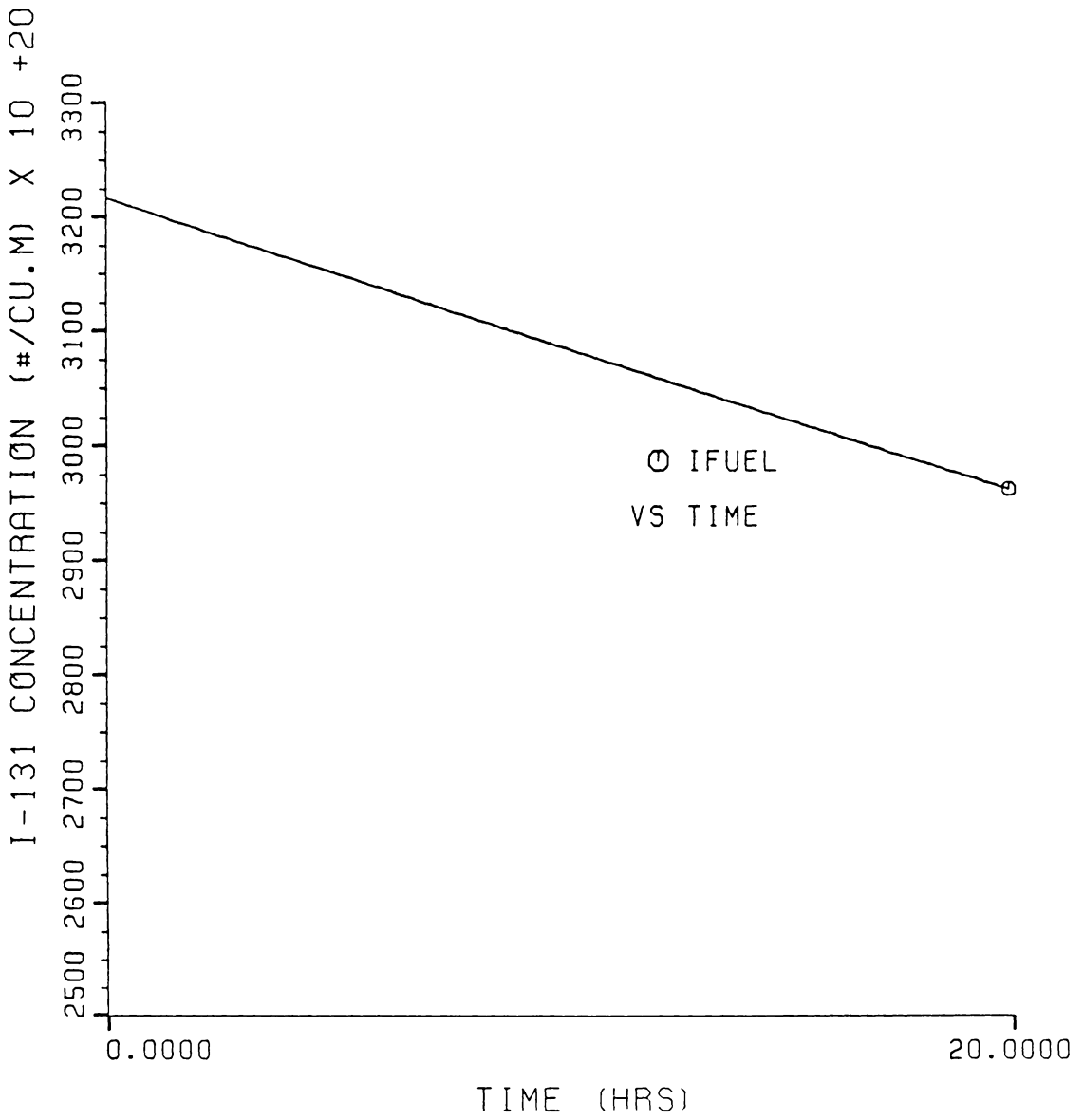


Figure 11. Iodine-131 in the fuel for a step change in power to 1.0%, numerical solution.

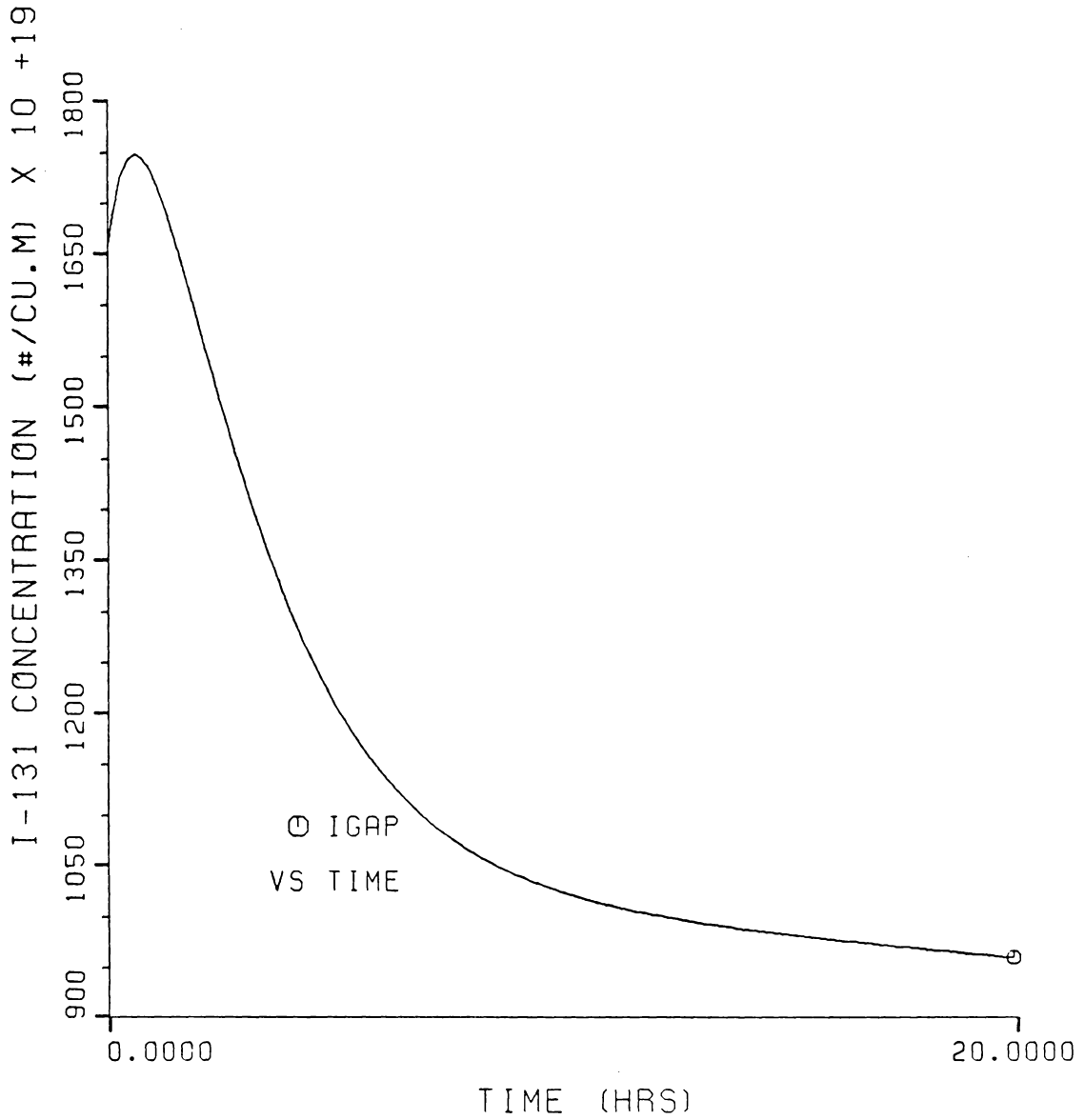


Figure 12. Iodine-131 in the gap for a step change in power to 1.0%, numerical solution.



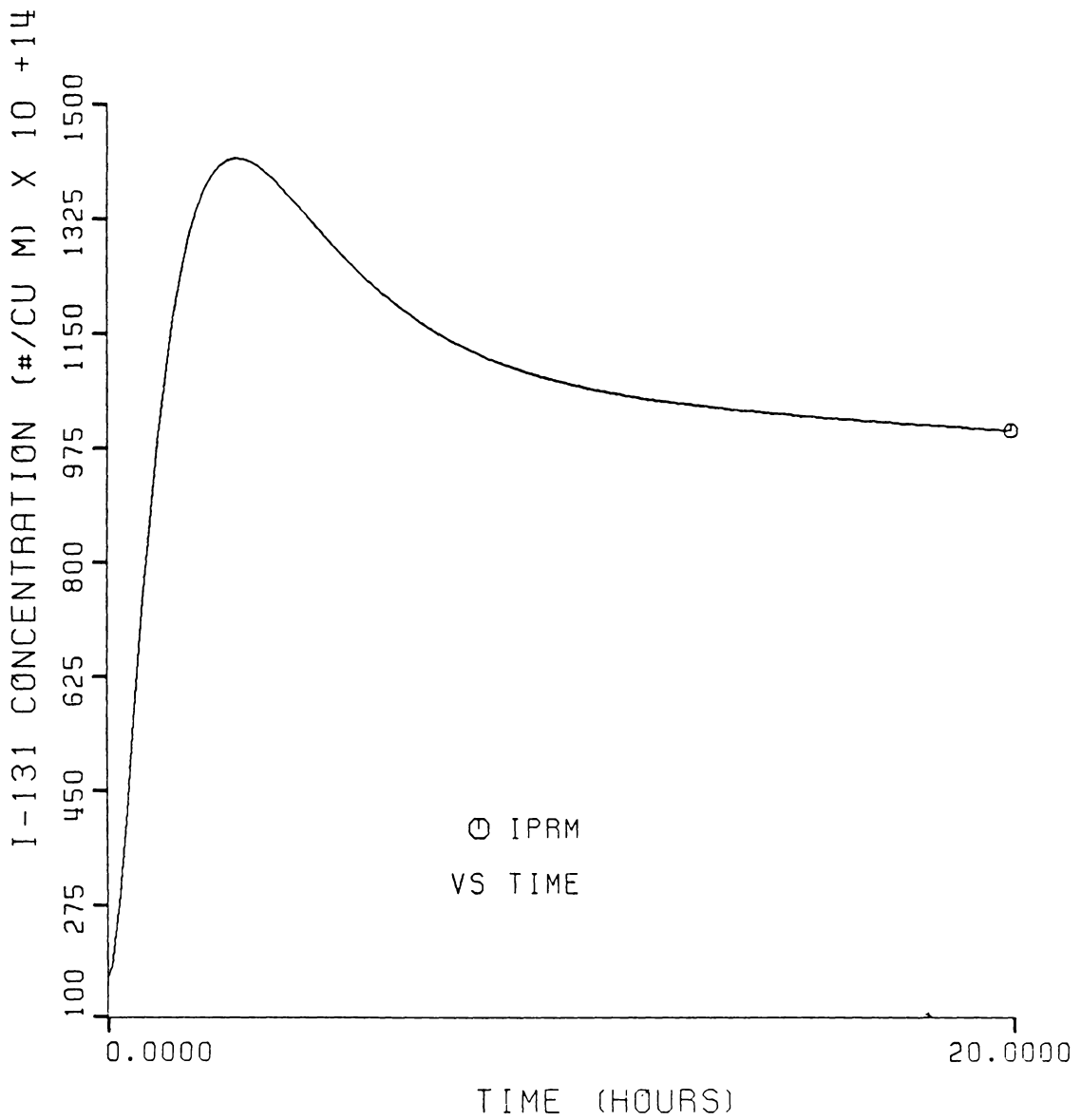


Figure 13. Iodine-131 in the coolant for a step change in power to 1.0%, numerical solution.

## V. VEPCO CASE STUDIES

### A. Sensitivity Analysis

A sensitivity analysis has been performed incorporating the variable properties of the code. Two parameters have been used for the comparison medium, the time-to-peak of the iodine spike, and the ratio of the peak iodine activity to the steady-state activity.

The variable properties are,

1. the average burnup of the fuel,
  2. the average failure size in a fuel rod cladding,
  3. the fraction of iodine removed in transit around the coolant loop,
  4. the number of failed rods in the core,
  5. the water enhancement factor for the efflux rate,
  6. the iodine absorption factor for the cladding,
  7. the average flow time for the coolant loop,
  8. the antimony absorption factor for the cladding,
- and
9. the average flow time for the coolant loop.

Figures 14 through 22 show the above properties for the peak to steady-state ratio as a function of each of these parameters, while figures 23 and 31 show the properties for the time-to-peak as a function of these same parameters.

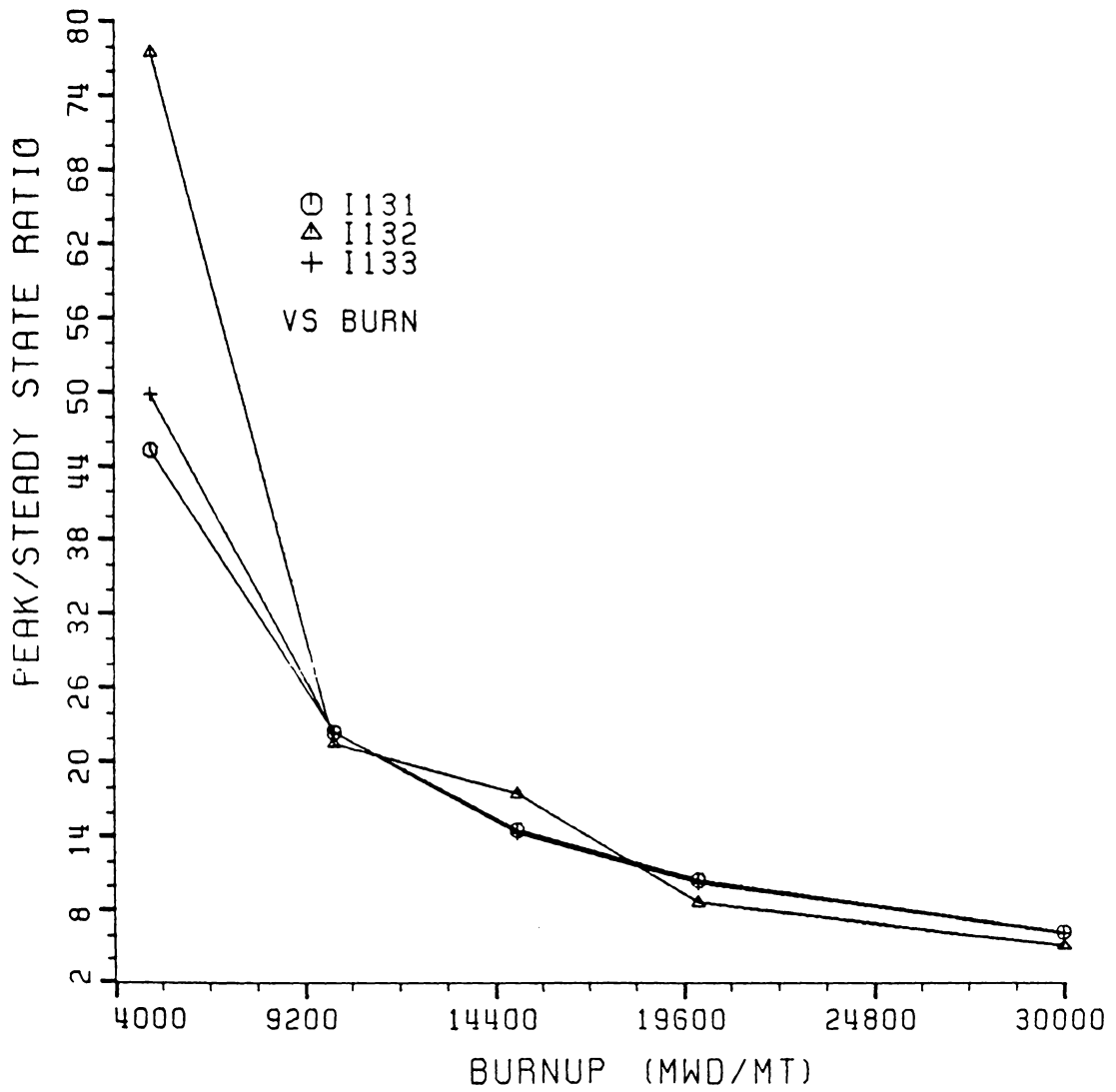


Figure 14. Peak to steady-state ratio as a function of the average fuel burnup.

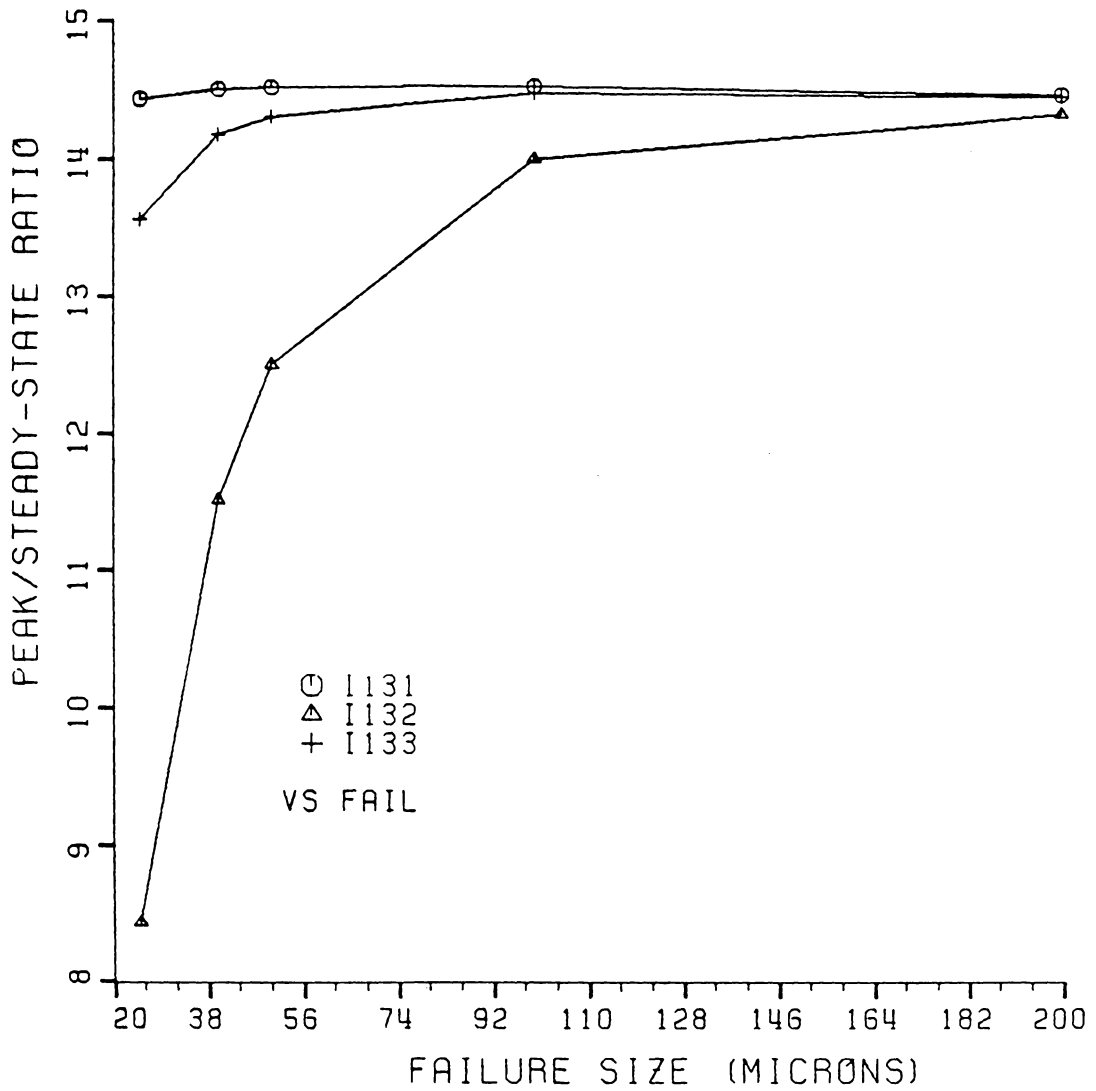


Figure 15. Peak to steady-state ratio as a function of the average failure size.

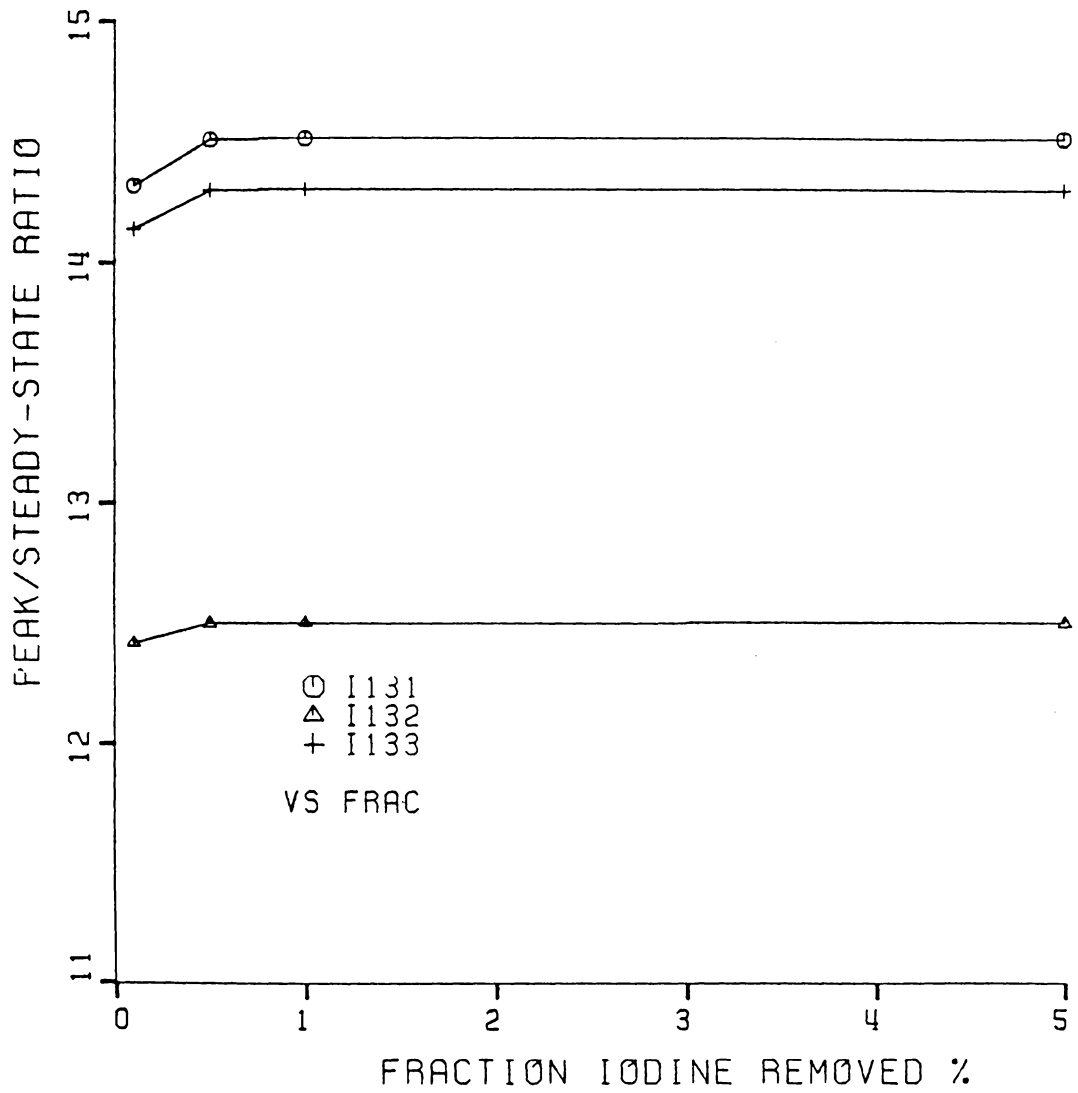


Figure 16. Peak to steady-state ratio as a function of the fraction of iodine removed from the coolant loop.

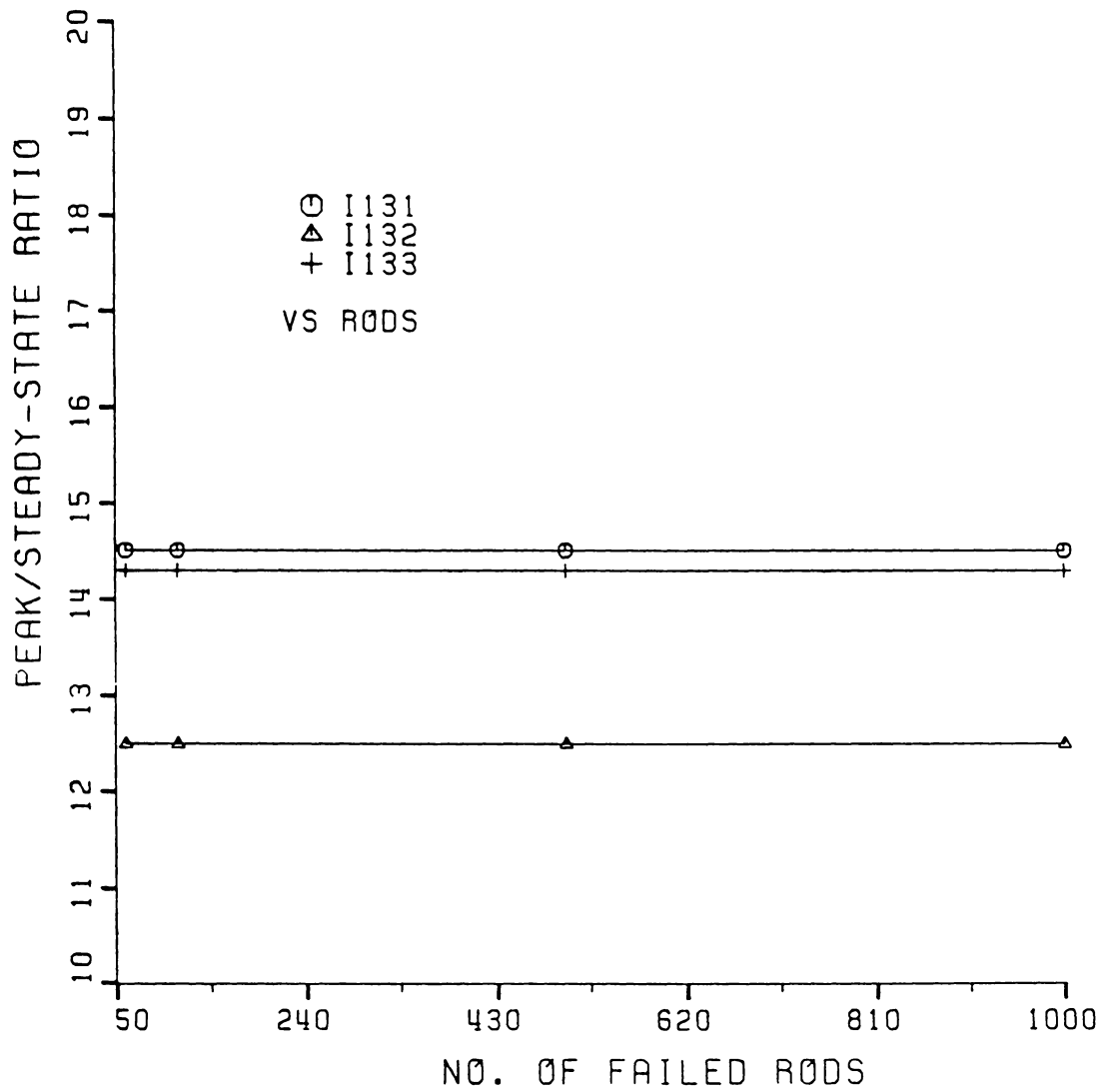


Figure 17. Peak to steady-state ratio as a function of the number of failed fuel rods.

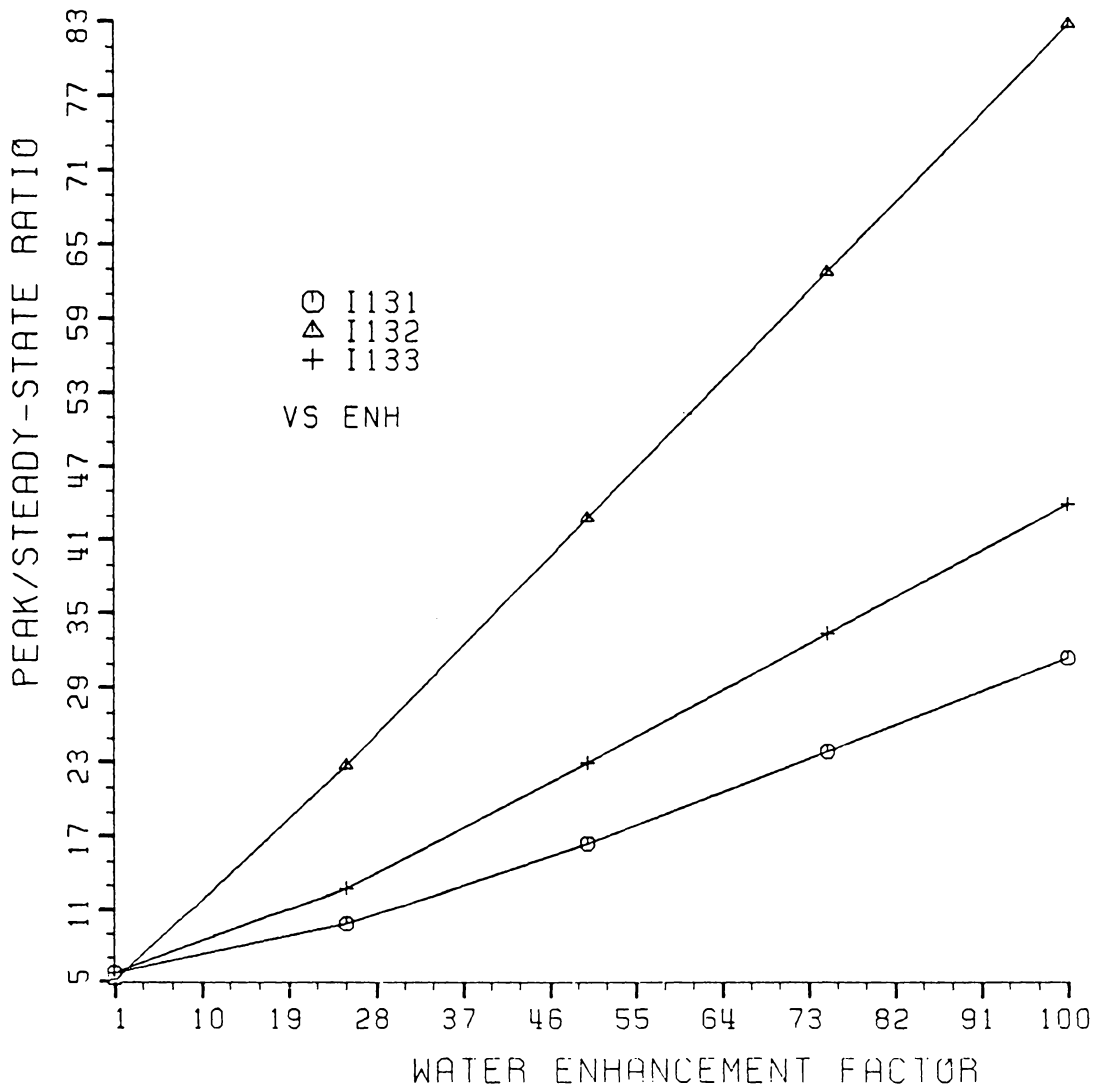


Figure 18. Peak to steady-state ratio as a function of the water enhancement factor.

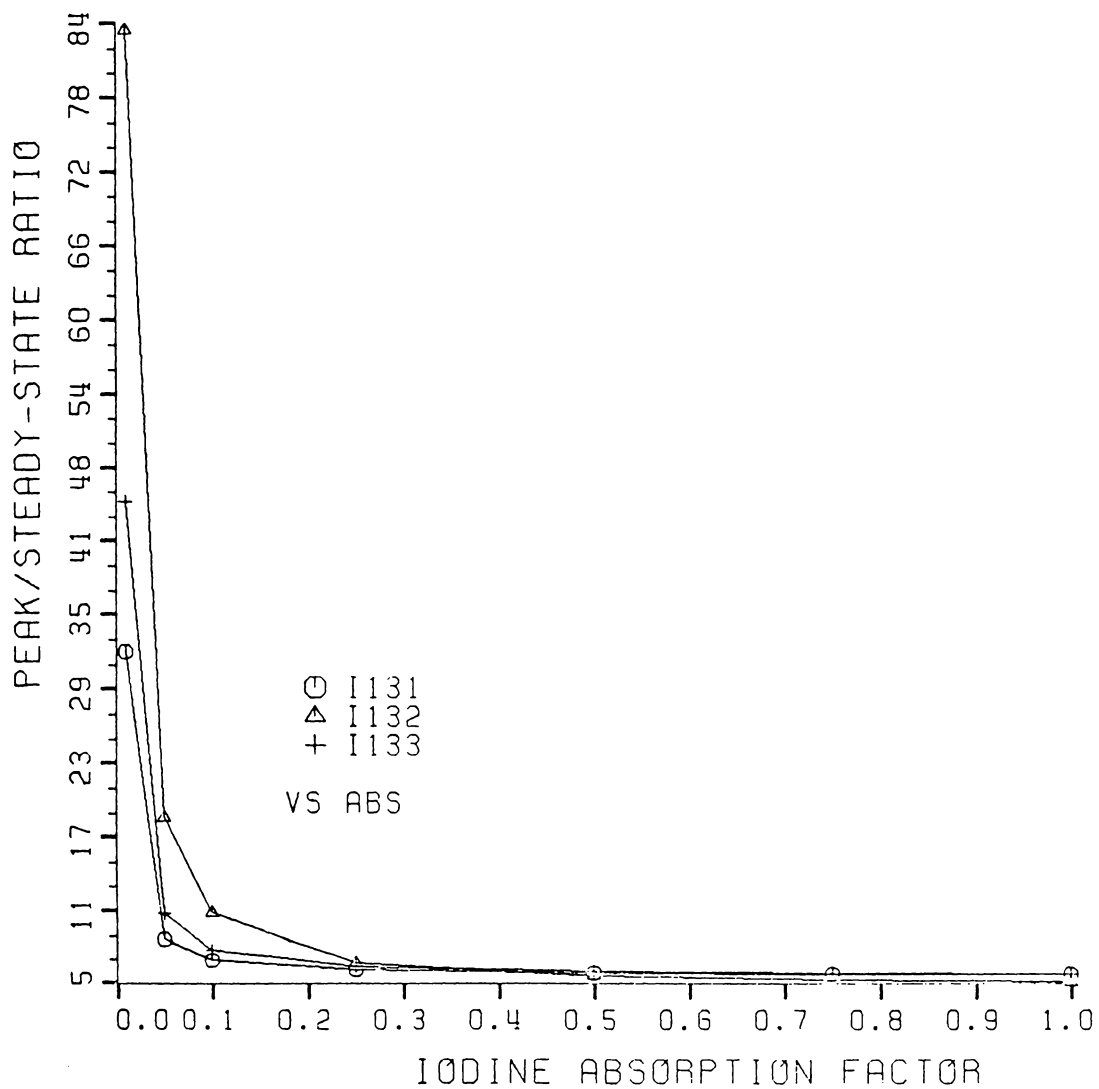


Figure 19. Peak to steady-state ratio as a function of the cladding absorption factor.



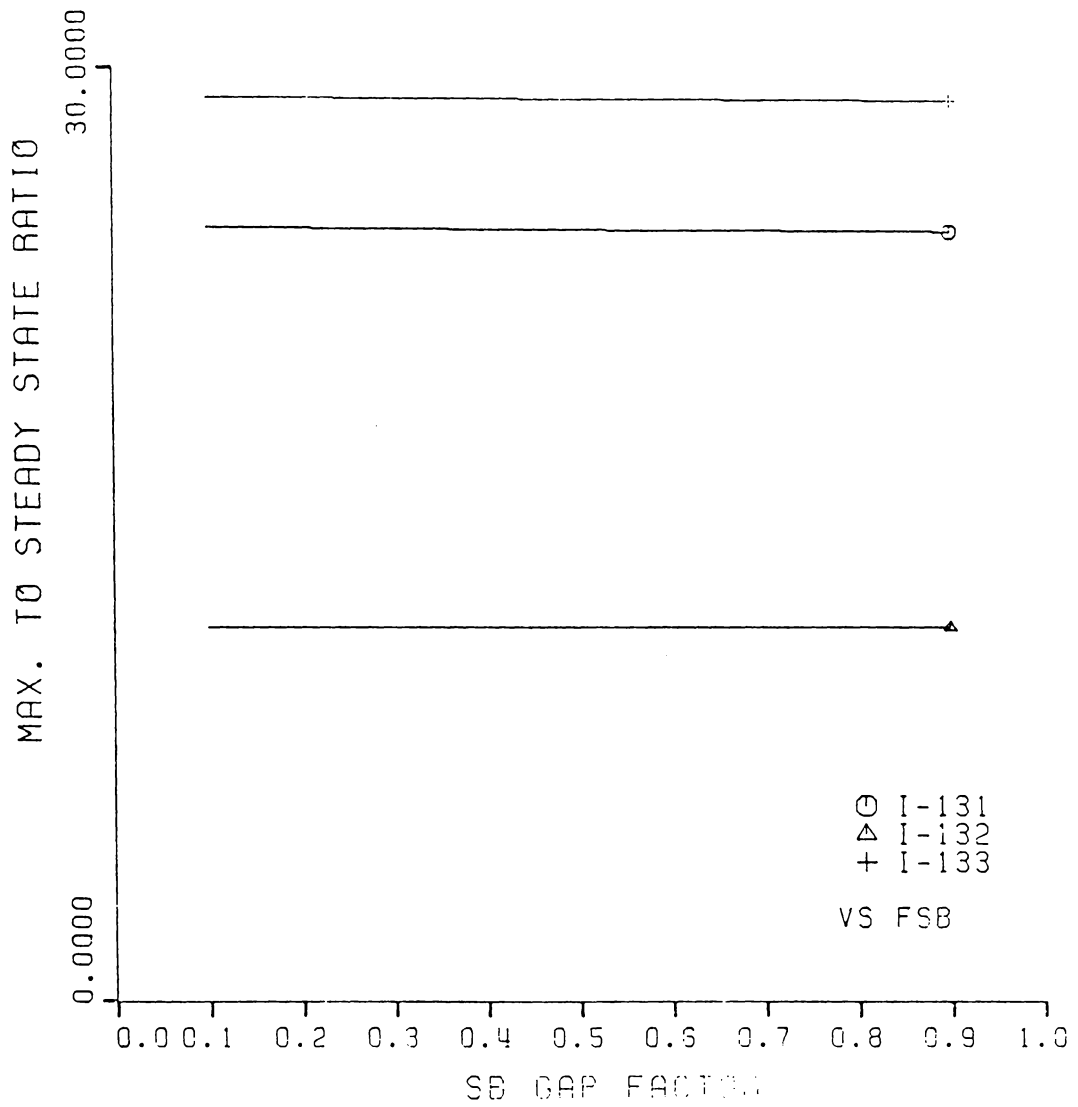


Figure 20. Peak to steady-state ratio as a function of the antimony absorption factor.

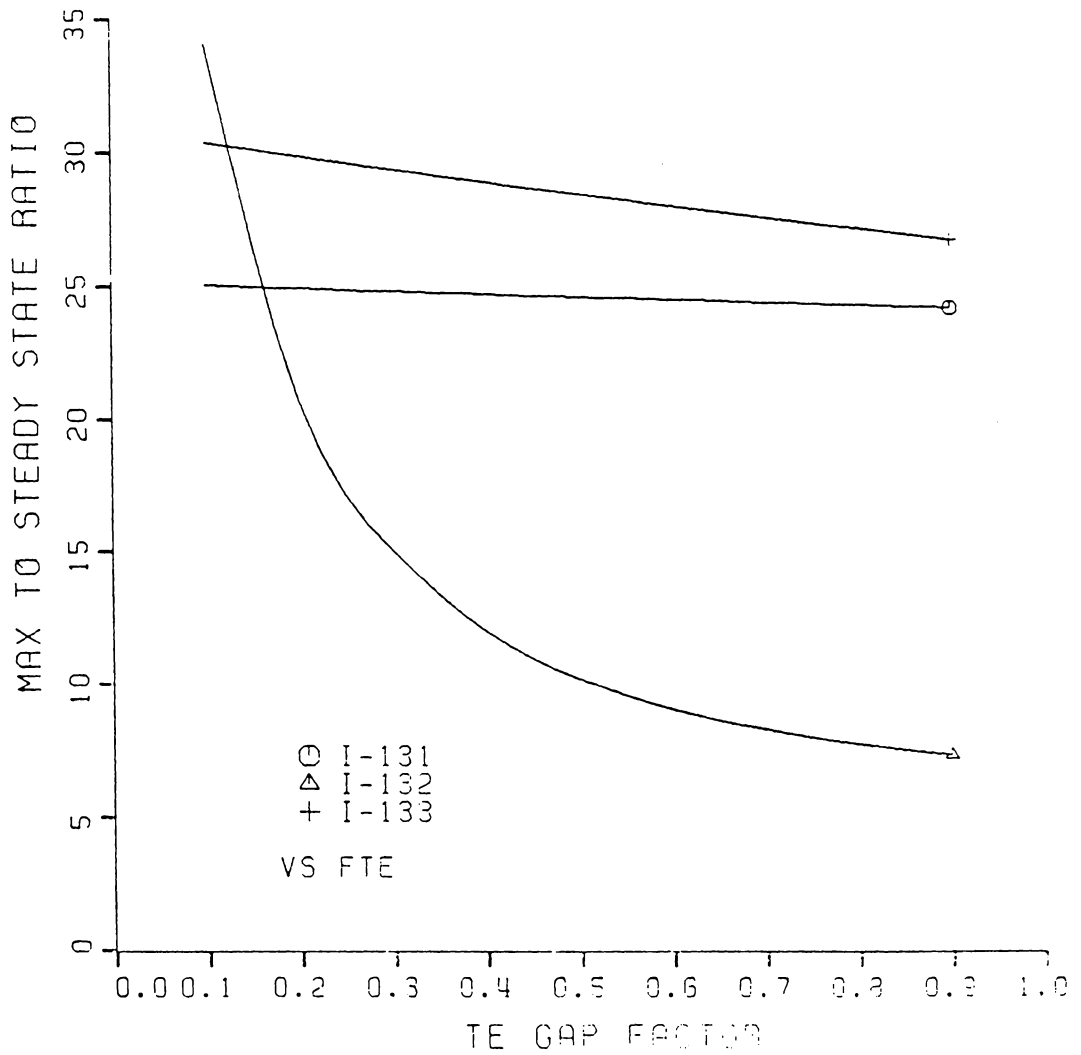


Figure 21. Peak to steady-state ratio as a function of the tellurium absorption factor.

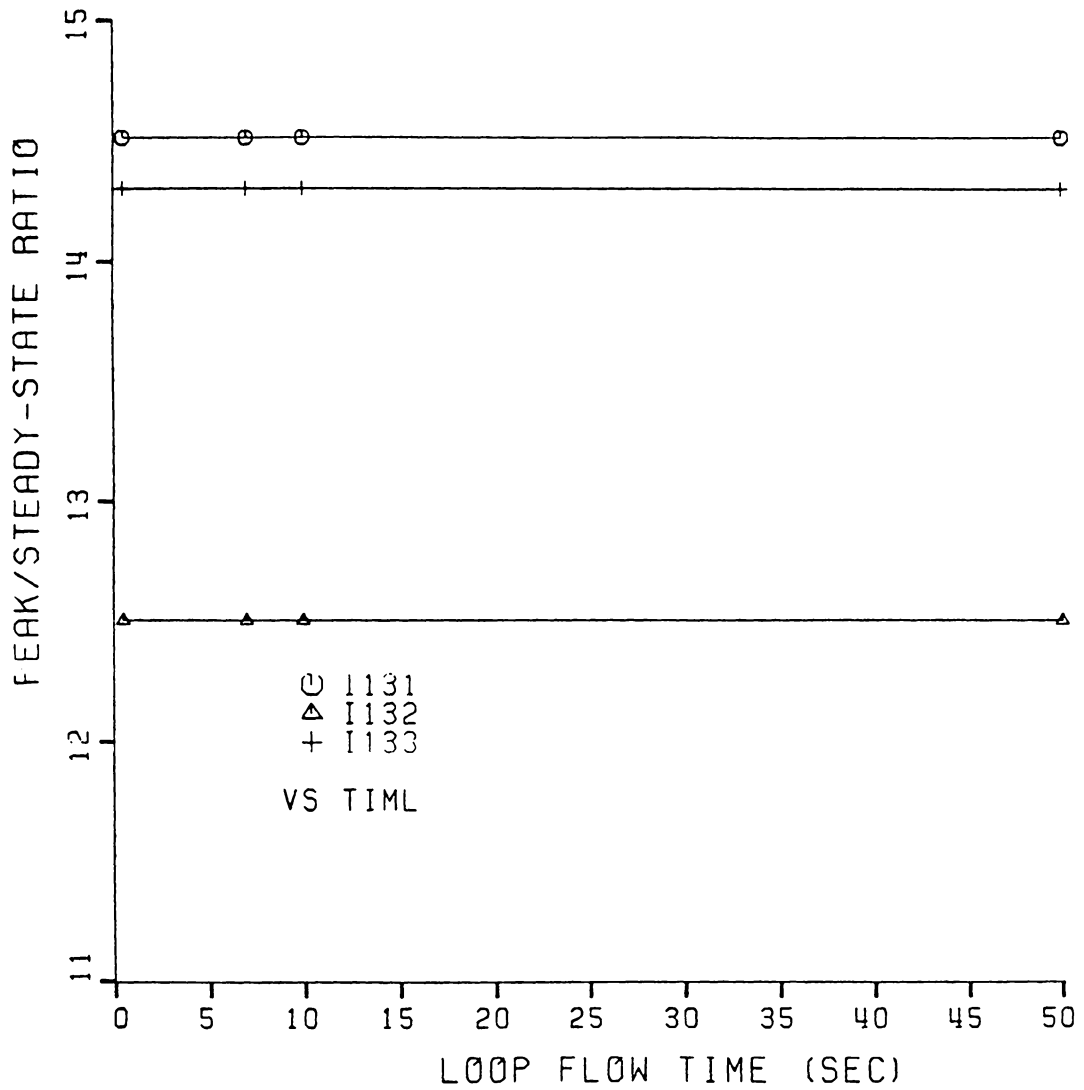


Figure 22. Peak to steady-state ratio as a function of the average coolant loop flow time.

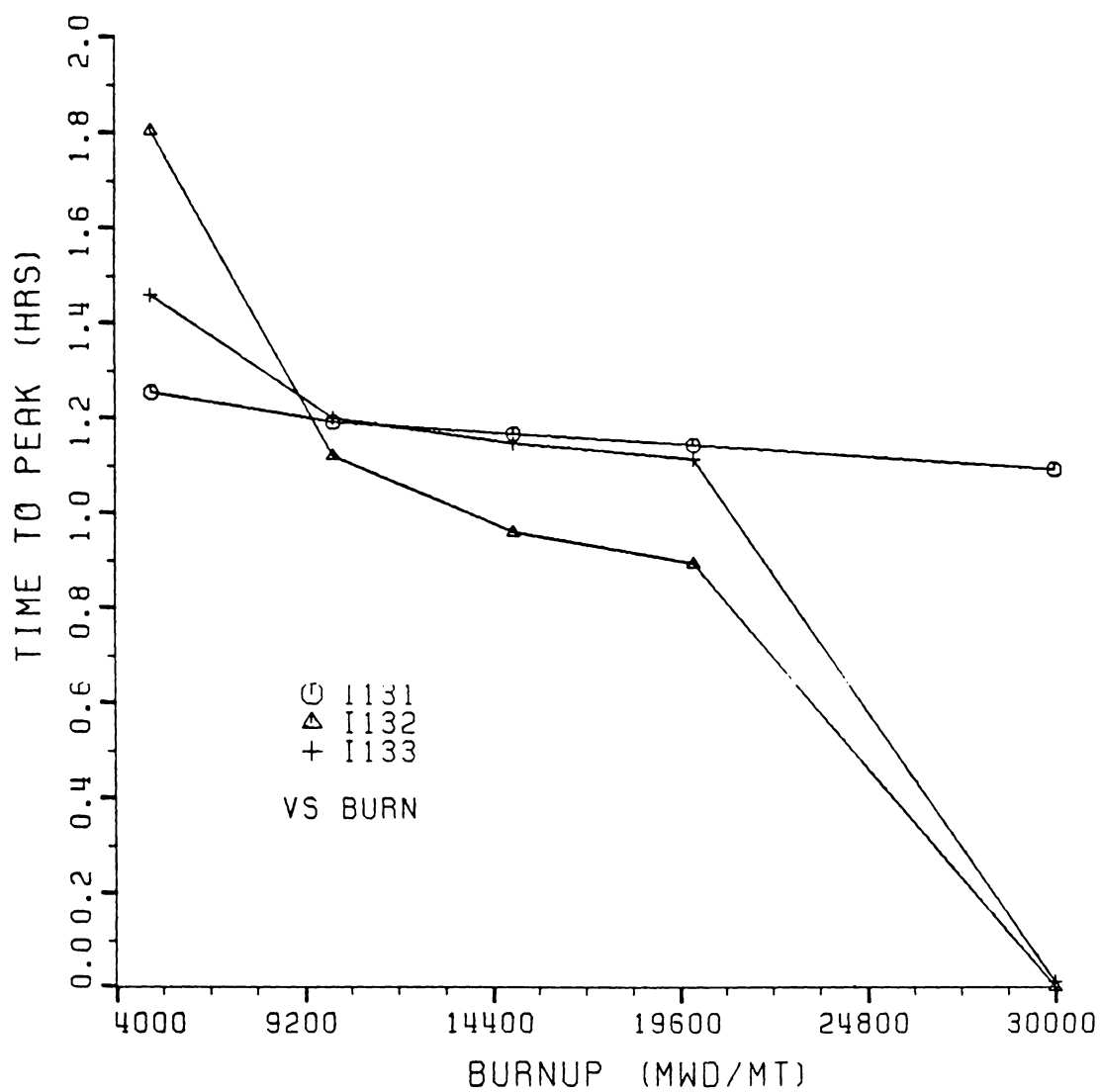


Figure 23. Time to peak as a function of the average fuel burnup.

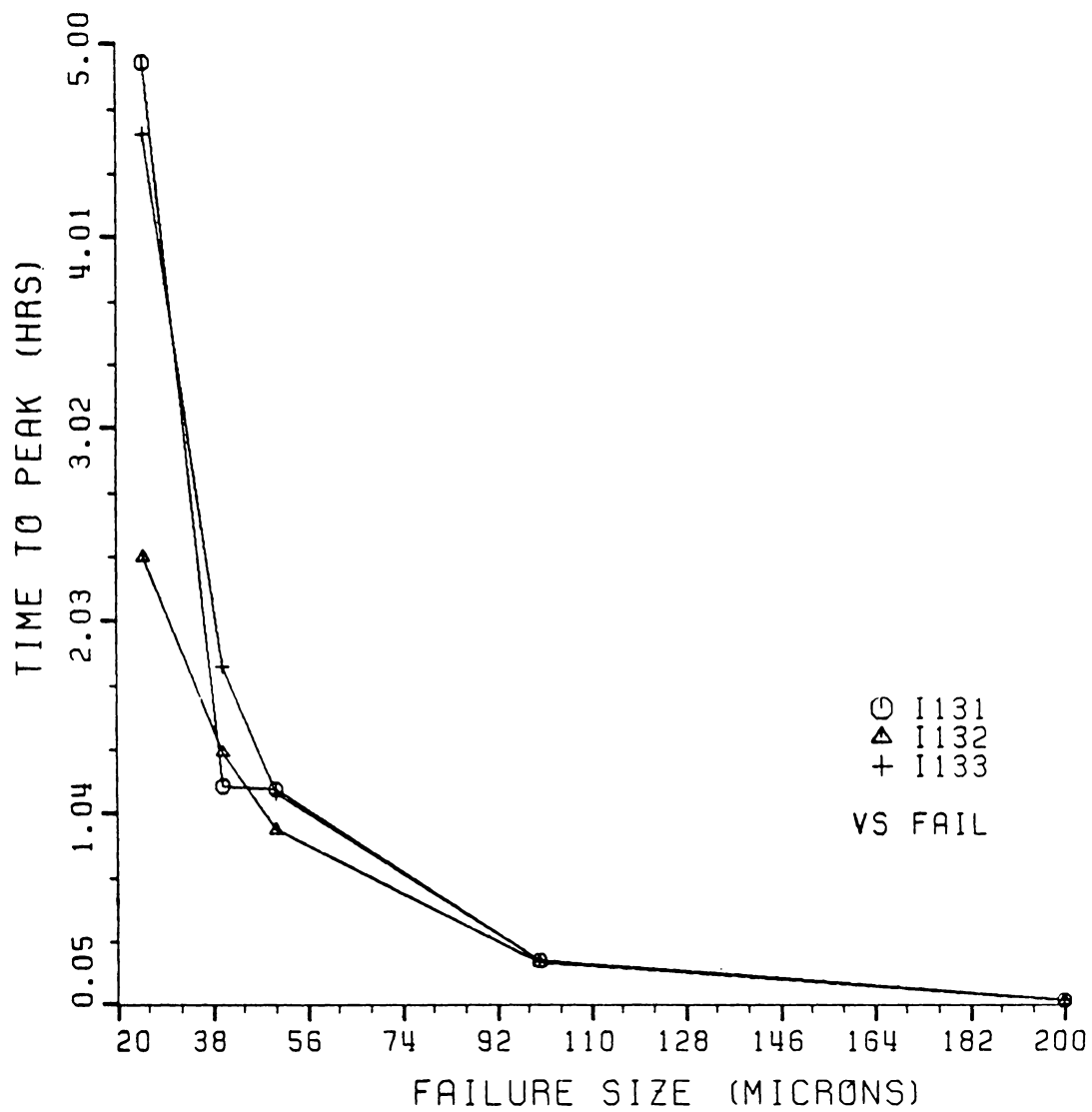


Figure 24. Time to peak as a function of the average failure size.

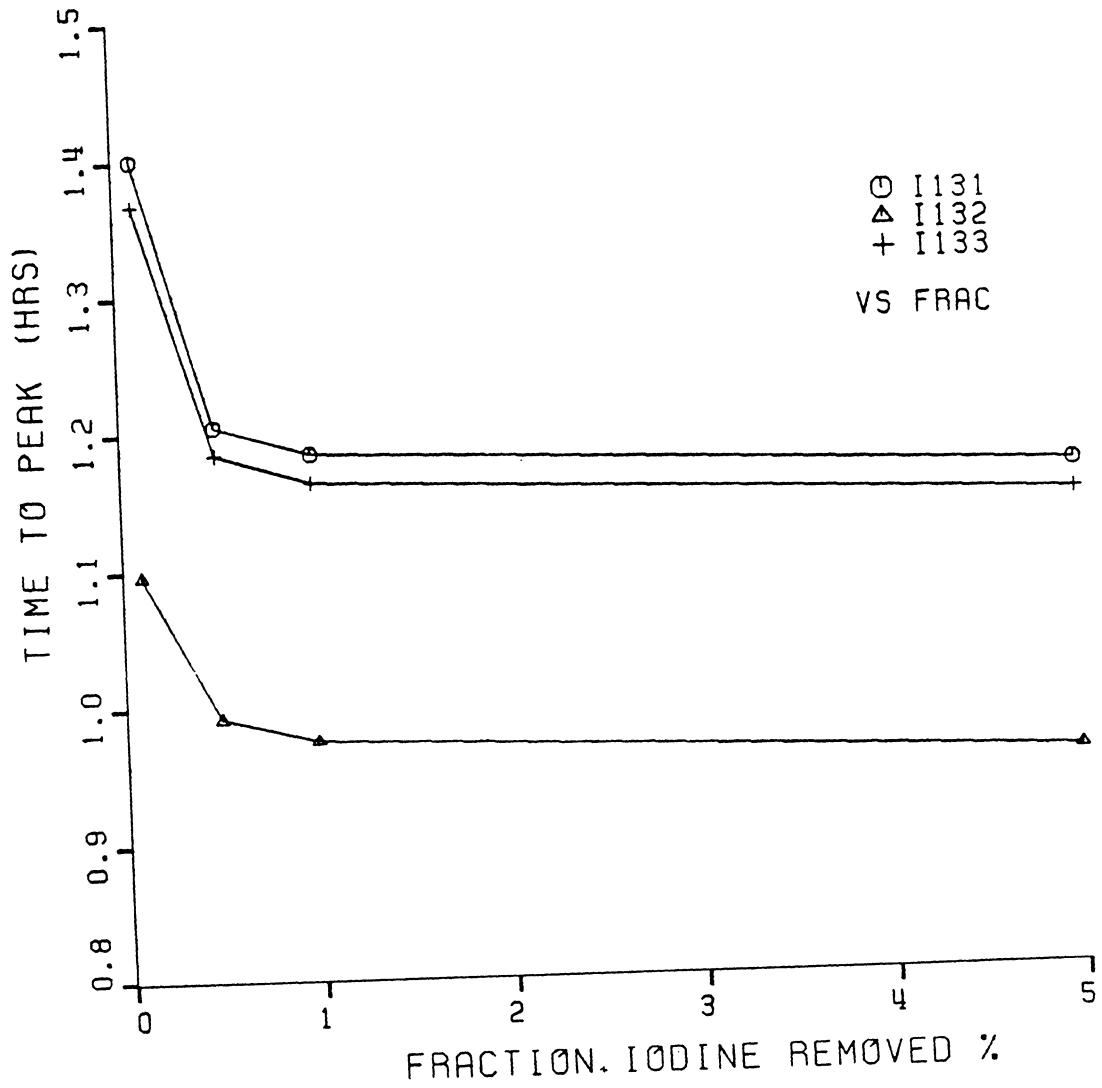


Figure 25. Time to peak as a function of the fraction of iodine removed from the coolant loop.

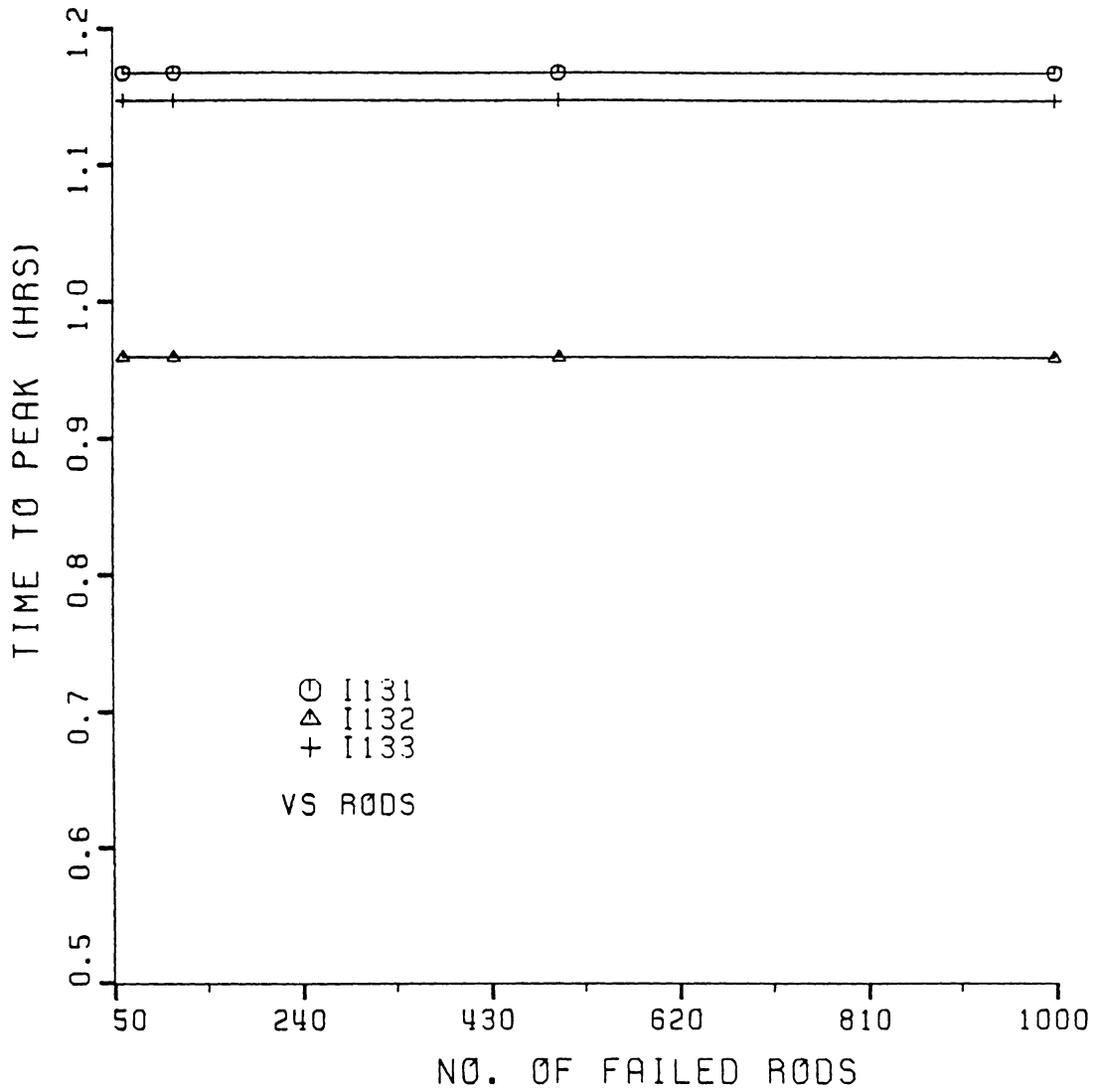


Figure 26. Time to peak as a function of the number of failed fuel rods.

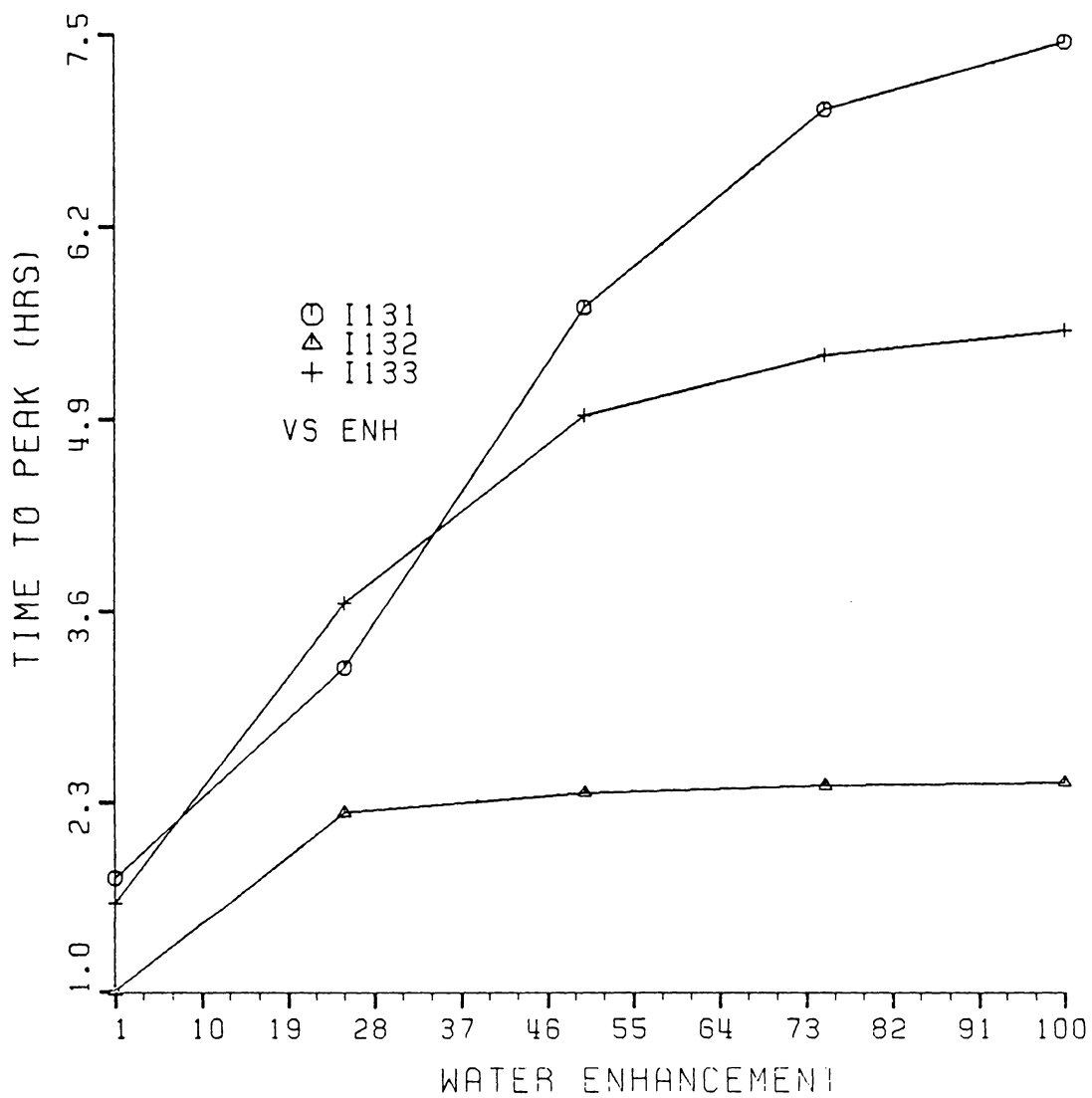


Figure 27. Time to peak as a function of the water enhancement factor.



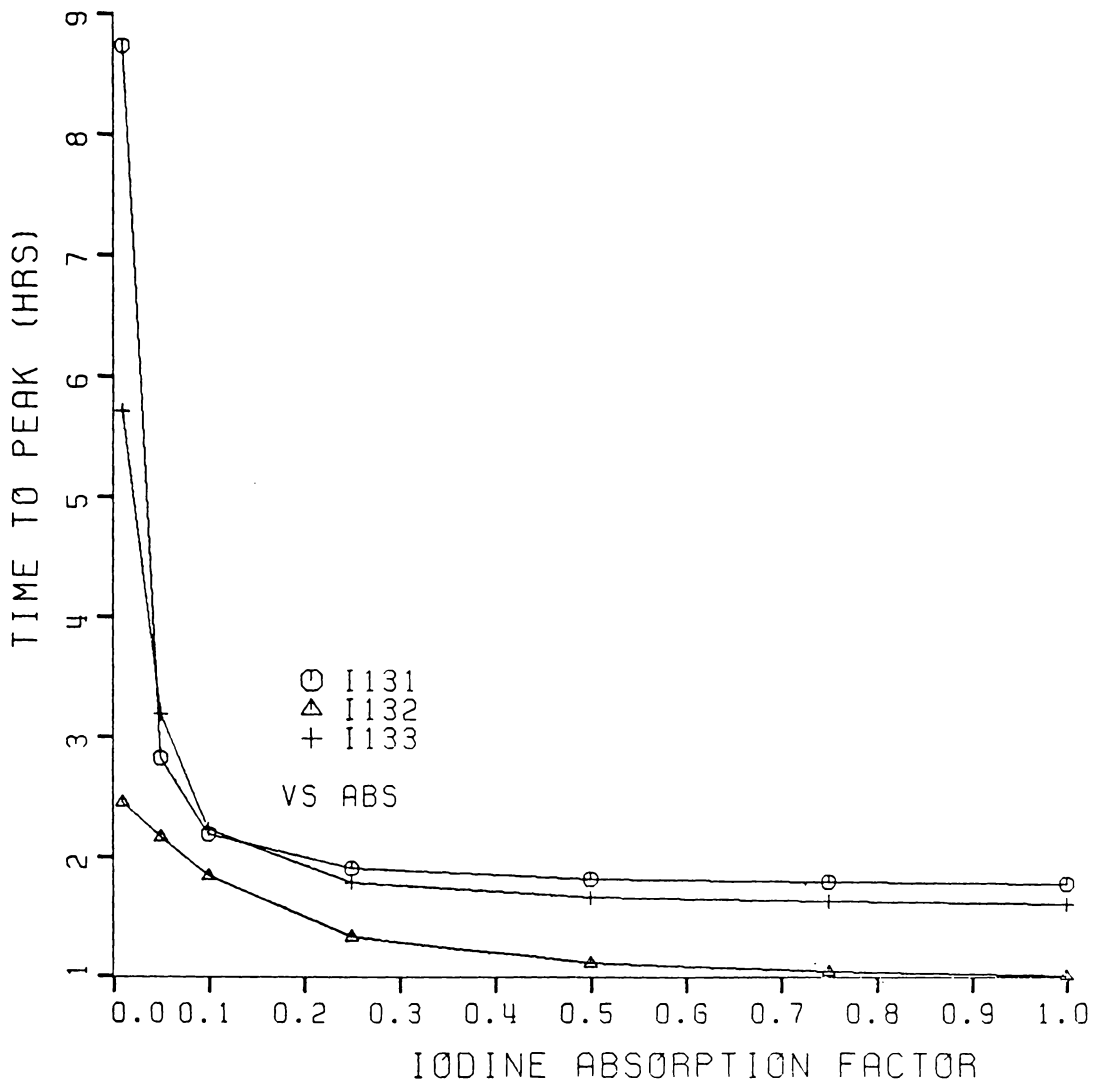


Figure 28. Time to peak as a function of the iodine absorption factor.

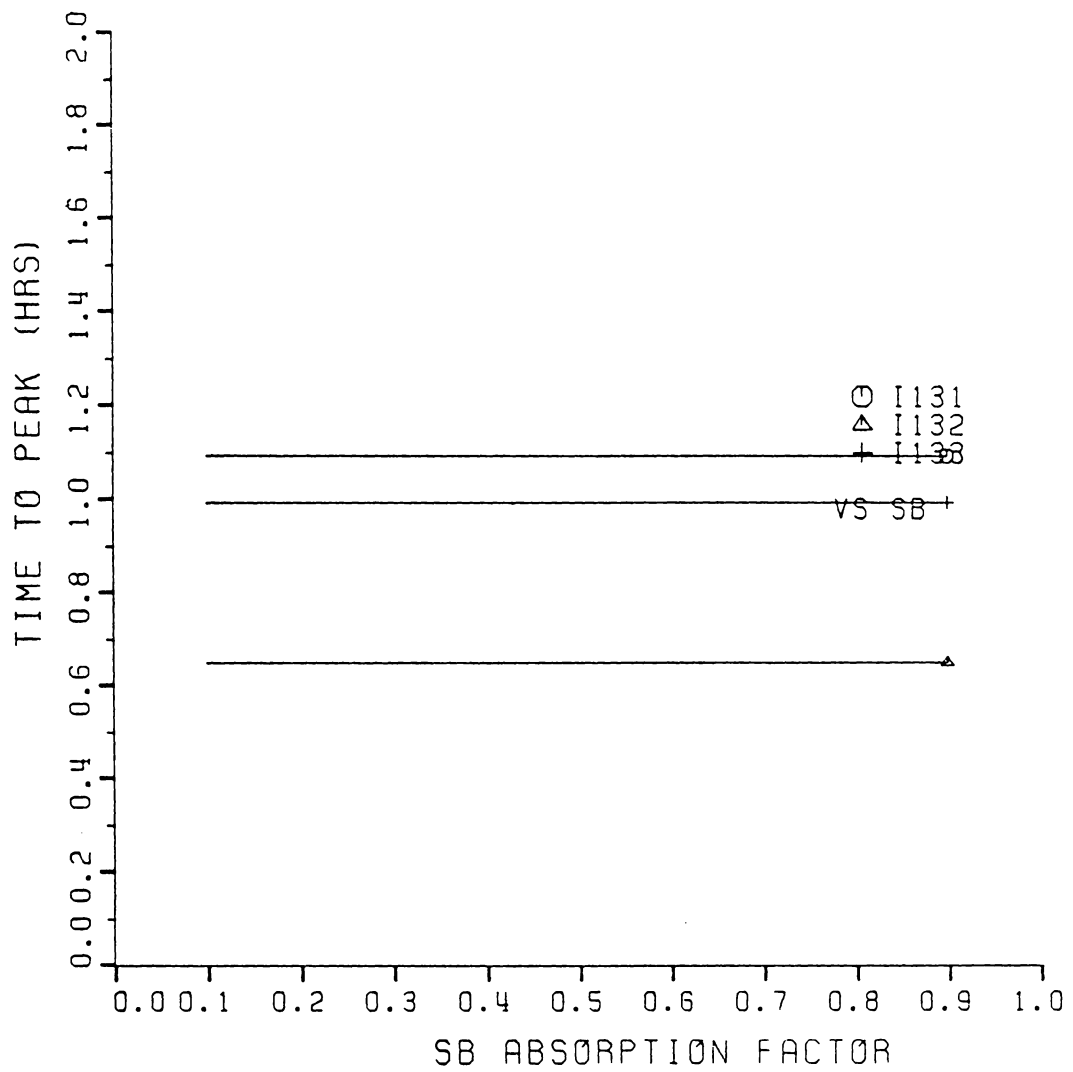


Figure 29. Time to peak as a function of the antimony absorption factor.

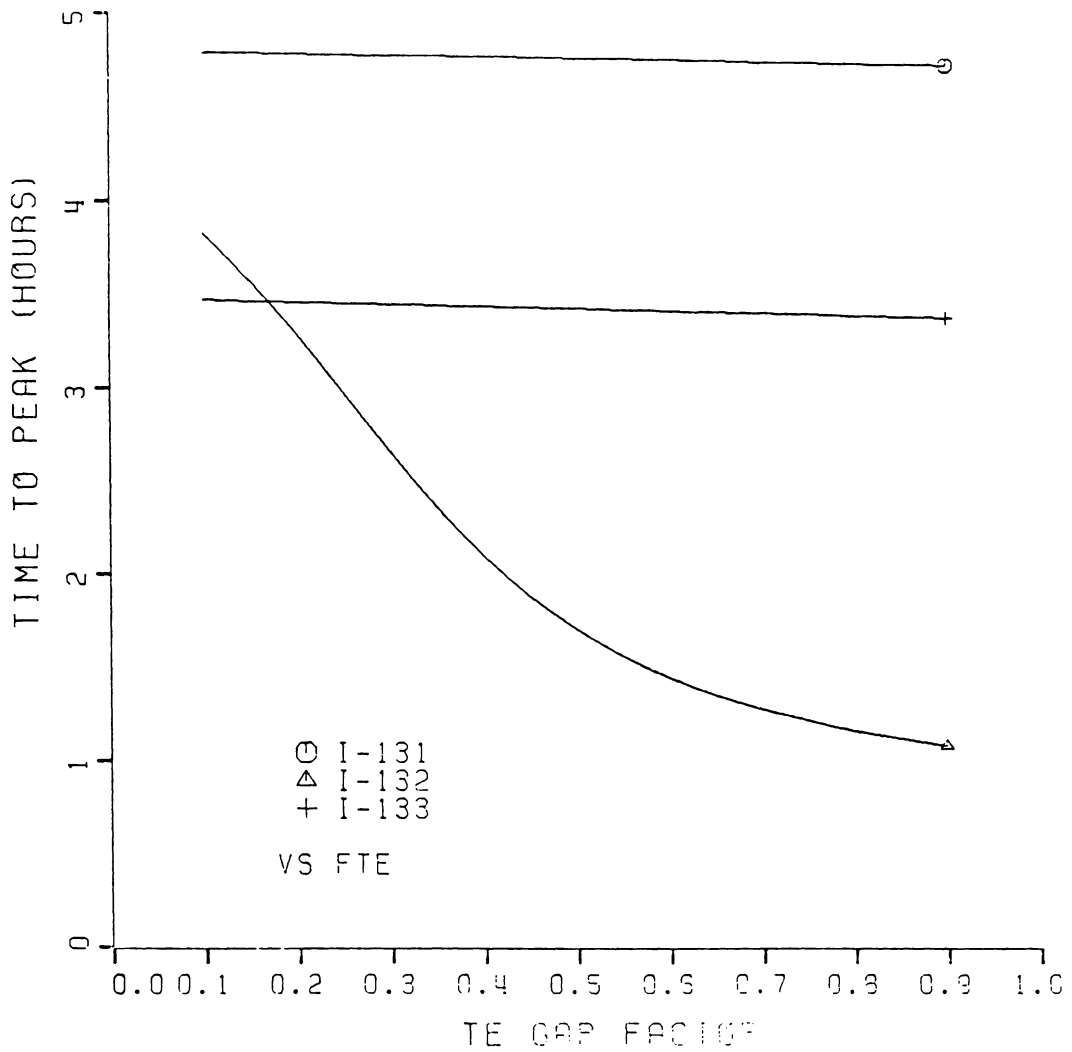


Figure 30. Time to peak as a function of the tellurium absorption factor.

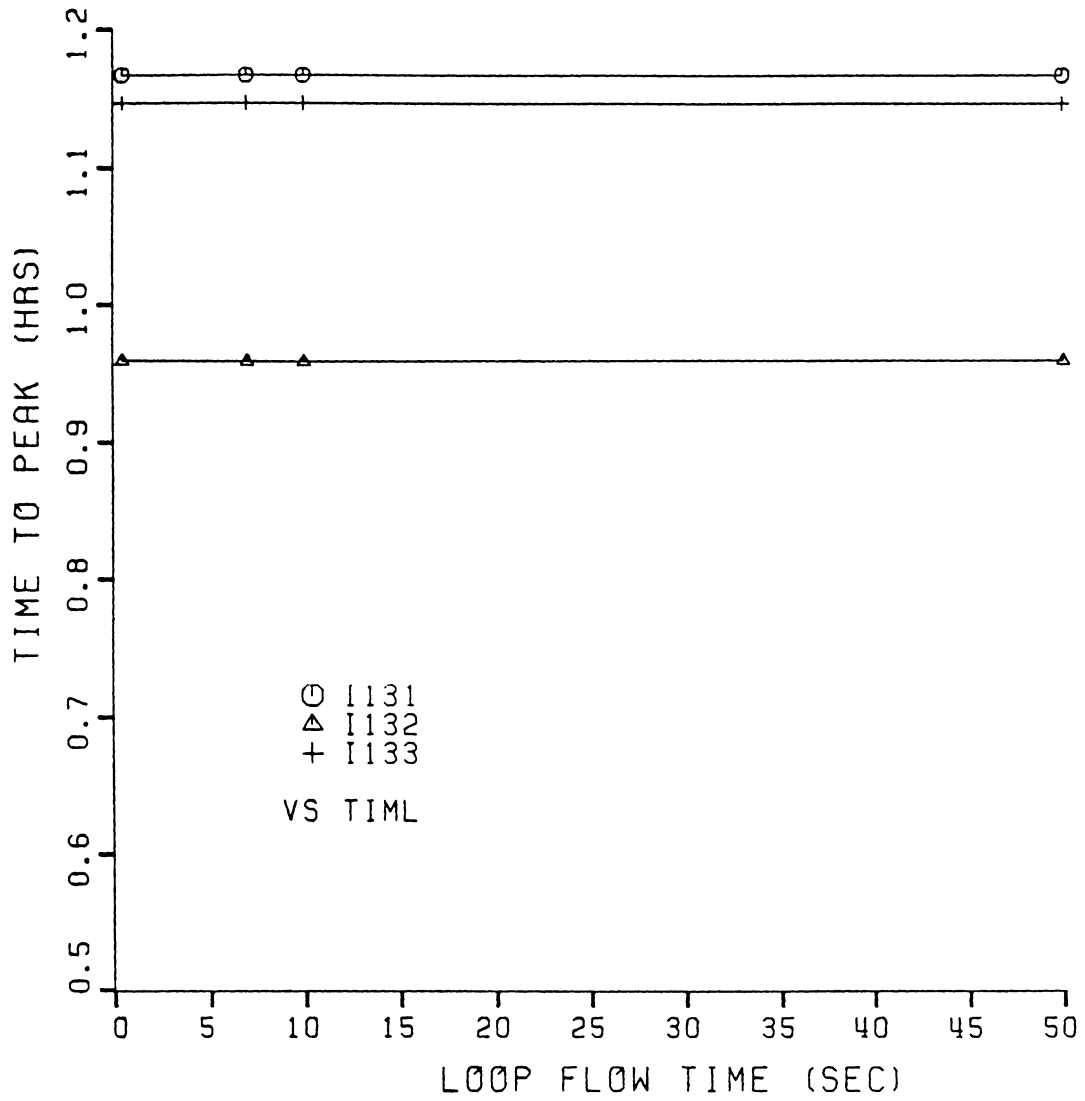


Figure 31. Time to peak as a function of the average coolant loop flow time.

## B. Comparison and Results

Figures 32 and 33 show spiking phenomena for two different Westinghouse PWR cores over a fifteen month time interval for iodine-131. The associated power traces reveal how the core iodine activity level reacts to the standard down-power transient on a large number of occasions. The data related to two different cores also reveals how the spiking phenomenon can vary greatly from one core to the next.

In order to adjust the model to the experimental data one particular spike is focused upon and its associated core geometry, power level, filter efficiency, and fuel burnup become constants of the calculation.

There are six variable parameters that can be adjusted so that a fit can be made,

1. NDEF, the number of failed rods in the core. Typical Westinghouse data reveals that this value will be on the order of 3% of the total fuel rod inventory.
2. FS, the average failure size in a fuel rod. Various sources have produced failure size data ranging from 50 microns to several millimeters. Caution must be exercised in the choosing of this parameter. Failure sizes larger than 200 microns may lead to gross inaccuracies in the generated data due to assumptions used in the derivation of the leach rate calculation. See Refs. [1] and [16].
3. STEAM, water enhancement in the fuel during a down-power transient. From Neeb and Schuster [1] this variable should be on

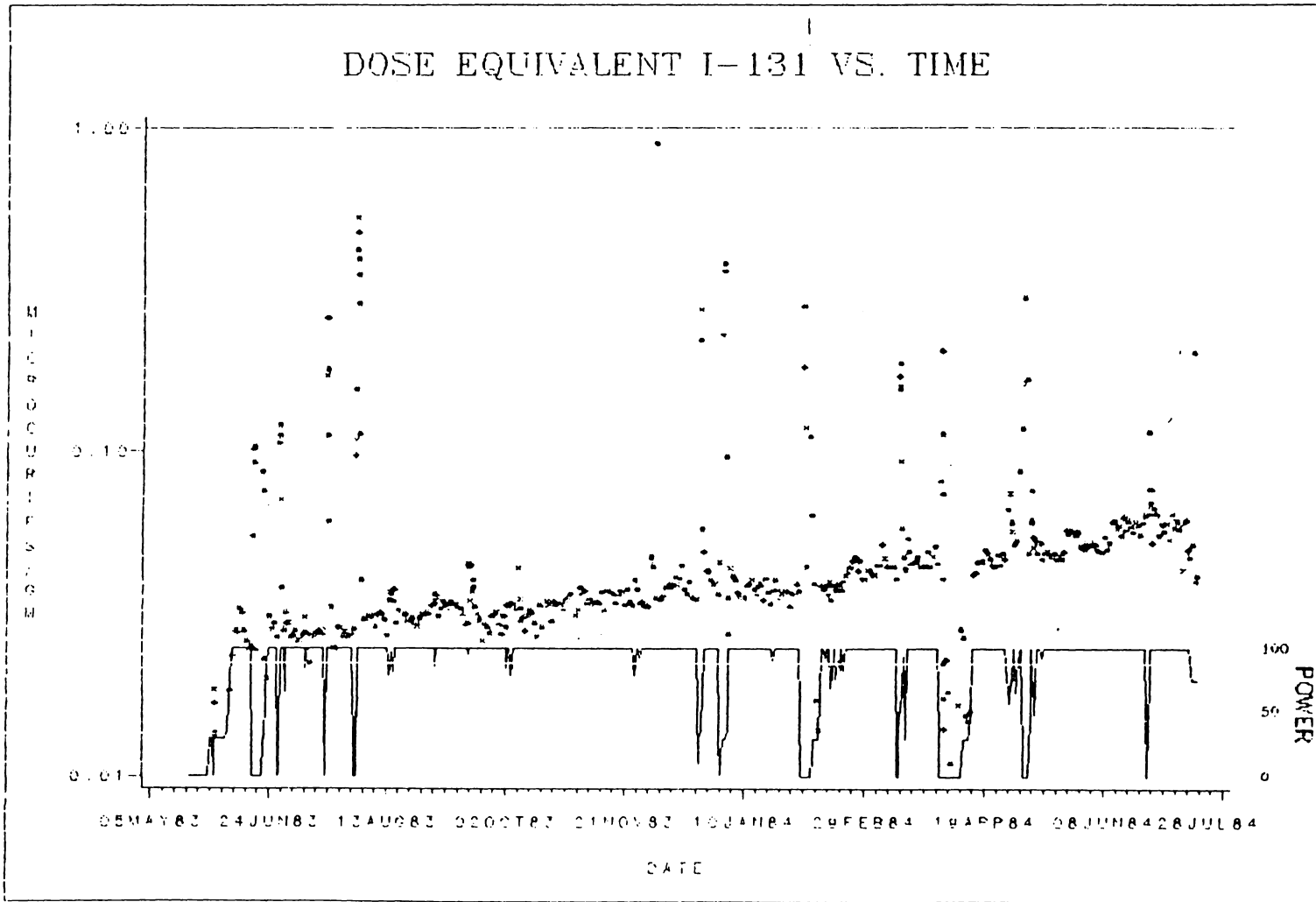


Figure 32. Dose equivalent of iodine-131 as a function of time. Experimental data.

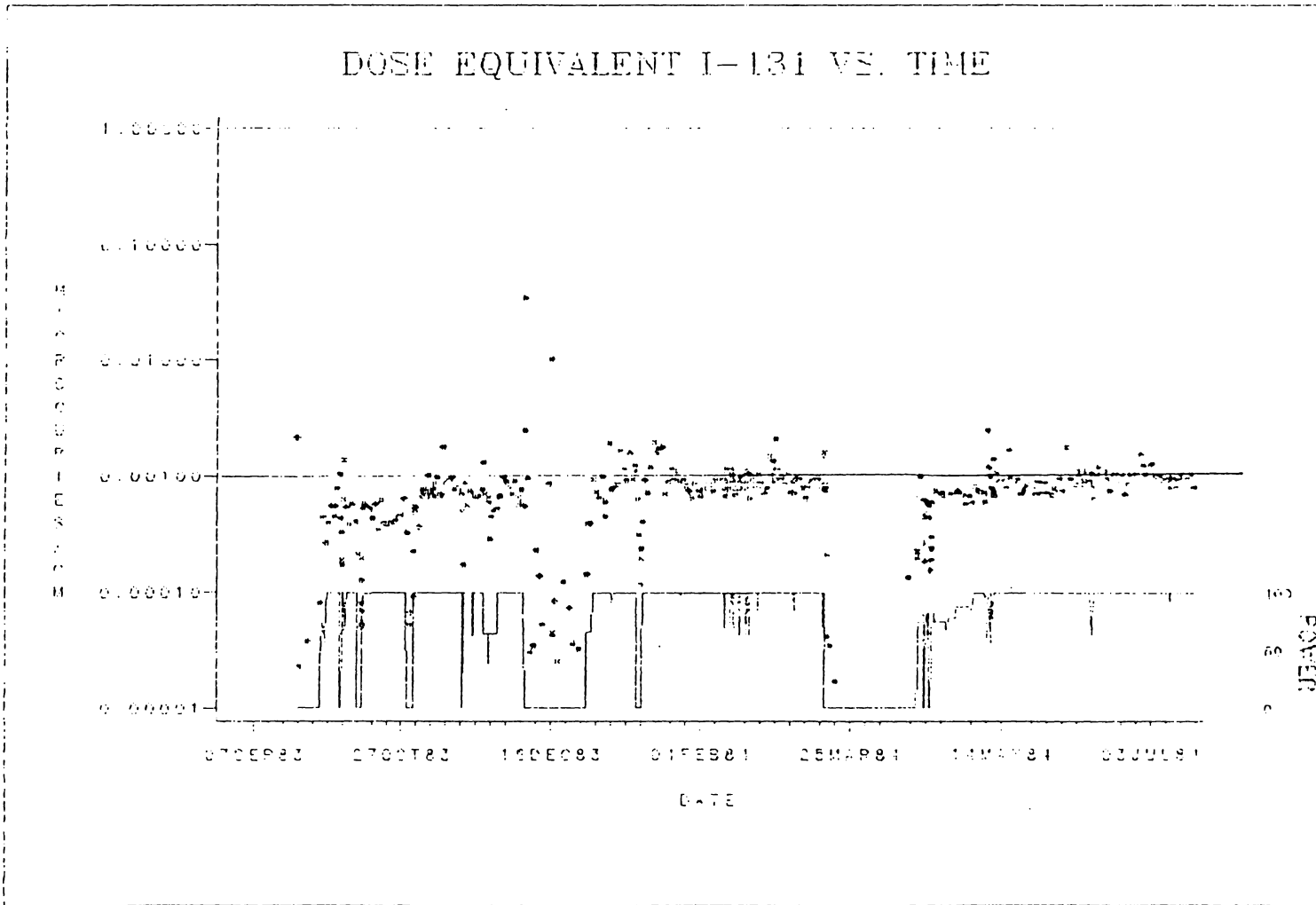


Figure 33. Dose equivalent of iodine-131 as a function of time. Experimental data.

the order of 40 (i.e. 1.4% increase in the efflux rate during a transient).

4-6. ABSI, ABSTE, ABSSB, the cladding absorption factors for iodine, tellurium, and antimony. The absorption of iodine in the oxide layer is expected to effectively remove up to 30% (i.e.  $ABSI = 1.0 - 0.30 = 0.70$  or 70%) of the element from the spiking process [1]. Values of this absorption factor for tellurium and antimony are not well known and may even be negligible.

In the following figures a typical spike taken from the data represented by Fig. 32 is compared to the predicted concentrations of the iodine-131, 132, and 133 isotopes.

The data for the iodine-131 isotope is the most comprehensive of the three isotopes and therefore the model adjustment is made to fit this data (see Fig. 34). Figures 35 and 36 show the results for the same transient case applied directly to the iodine-132 and 133 isotopes.

The input data corresponding to the result is:

```
4.095E-3 8.2E-5 5.72E-4 1.32 1.25E-2 0.94E-2 3.37 55777 3.66
21.3 0.71 11.0
0.99965 33 0.73E-4 16.0 0.20 0.80 0.40
30000.0 589.0
5.090E17
1.0 0.01 42000.0
015.0 00150.0
1
```

For explanation of the terms and the order in which they appear see Appendix B.

The result generated by the model for the given transient is as follows:



CASE1: DOWN POWER TRANSIENT

WATER ENHANCEMENT = 16.0000 I GAP FACTOR = .20000

SB GAP FACTOR = .80000 TE GAP FACTOR = .40000

	IODINE-131	IODINE-132	IODINE-133	
	0.1889E+16	0.2001E+14	0.2827E+15	NO./CU.M
	0.0750	0.670	0.1042	UCI/G
MAX/SS	24.7765	12.0664	28.9670	
PEAK TIME	4.7751	2.1112	3.44451	HRS

NUMBER OF FAILED RODS = 33

AVERAGE FAILURE SIZE = 0.7300E-04 M

FILTER SYSTEM = 99.9650%

AVERAGE FUEL BURN UP = 30000.0000 MWD/MT

The resulting fit is fairly good for the iodine-131 isotope but the corresponding results for the 132, and 133 isotopes are not as sound.

The model that was initially developed to describe the spiking phenomenon was based upon a failure mechanism in the fuel cladding brought about by thermal stress and neutron embrittlement. The resulting fit falls well within the confines of the phenomenon as described in the literature (i.e. Ref. [1]) but does not correspond well to the VEPCO on-line data.

A failure mechanism in the cladding material of the Westinghouse cores used by VEPCO was later discerned that is significantly different from that envisioned earlier. The resulting failure sizes are much larger than anticipated thus rendering the leaching model not as effective as it could be.

The VEPCO data used in the comparison also has some discrepancies

associated with it. The steady-state ratios of the iodine isotopes should, at any time during the core life, always remain constant, but in fact the data reveals varying activity ratios. This fact tends to discredit the validity of the data, possibly rendering it unsound as a comparison medium.

Another possible cause of the discrepancy between the different isotopes of iodine is that a detailed knowledge of the chemical properties of antimony and tellurium are not well understood for this application. The effective production and removal of the precursor isotopes may be largely in error within the model. An attempt to correct for this has been made by including a gap "hold-up" factor similar to that for iodine (see Ch. II), but the chemical properties of tellurium and antimony may be totally unrelated therefore rendering the hold-up factor unsound or incomplete as an approximation.

The generated data can be made to fit any one of the three iodine isotopes extremely well with the other results only approximating the experimental data, the error arising only in the chemical take-up of the precursors in the fuel or gap. This success tends to support the theory involved in the modeling of the down-power transient spike.

The results of the up-power transient model do not fit the experimental data with as much success. The shape of the iodine spike is strongly dependent on the leach rate calculation for the given transient. Figure 5 represents the leach rate for a ramp increase in power. The steep spike in the leach rate curve represents the instant when the liquid environment of the gap region flashes to steam. For

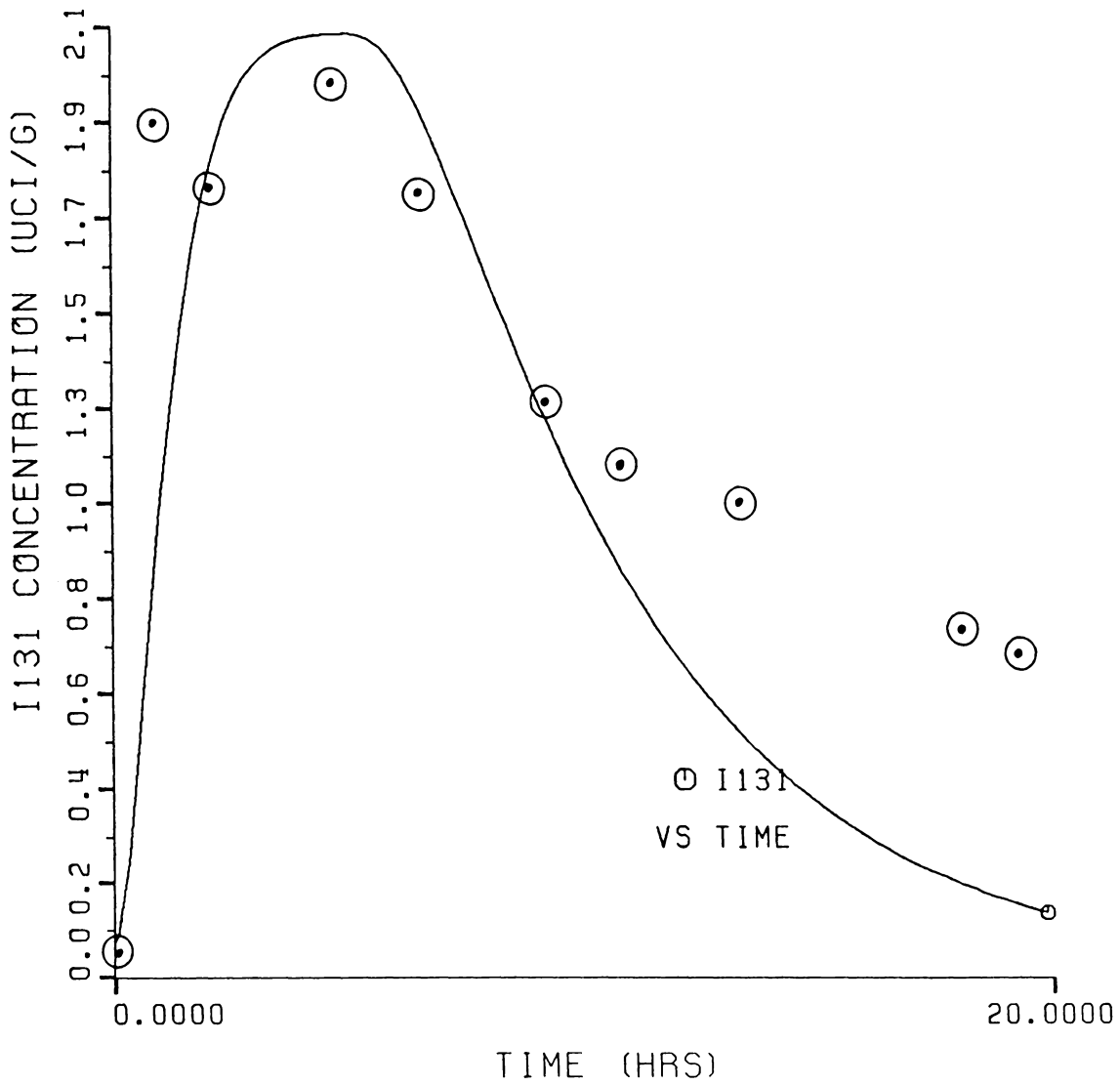


Figure 34. Down-power spike. Iodine-131 analytical and experimental data as a function of time.

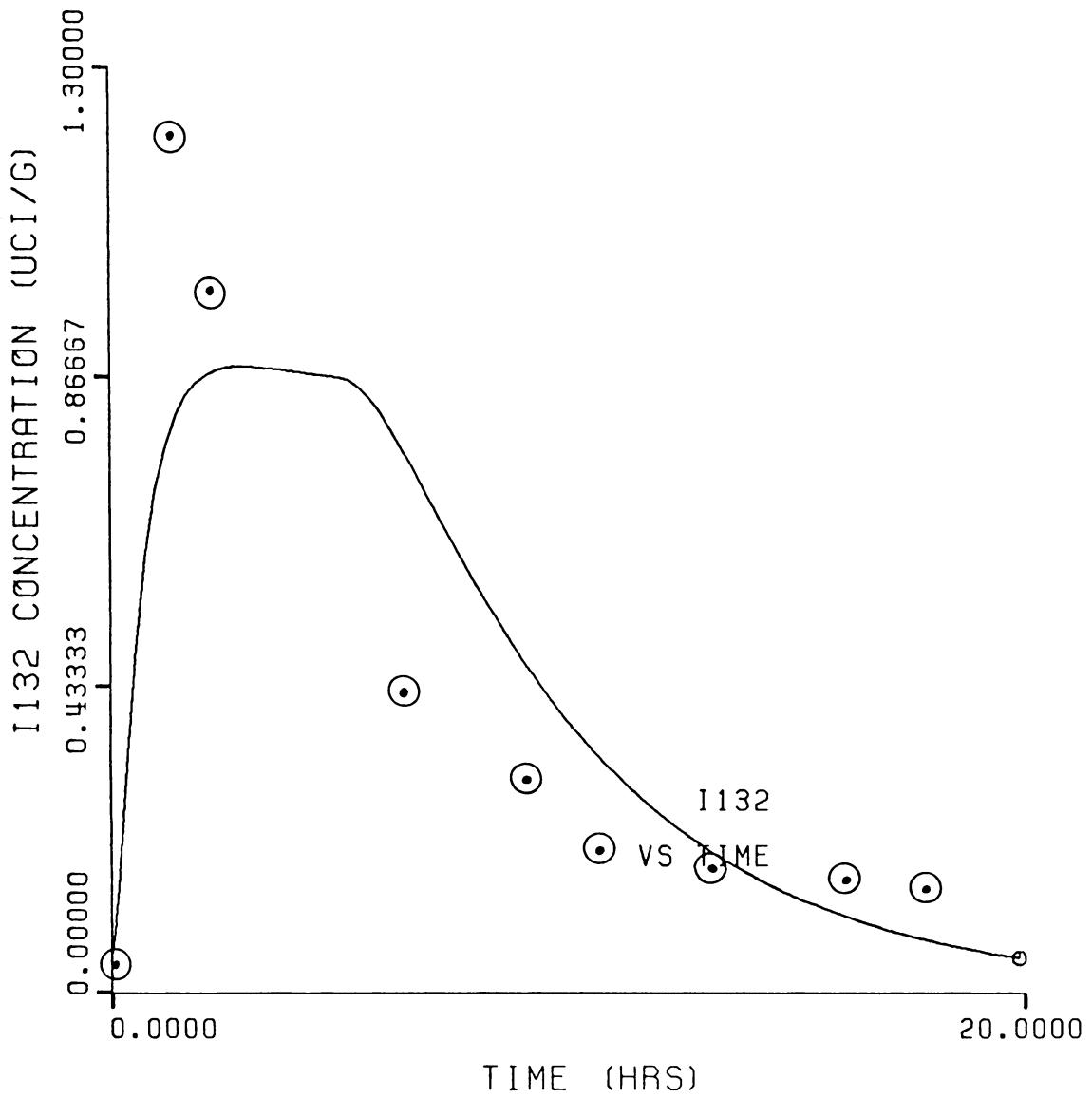


Figure 35. Down-power spike. Iodine-132 analytical and experimental data as a function of time.

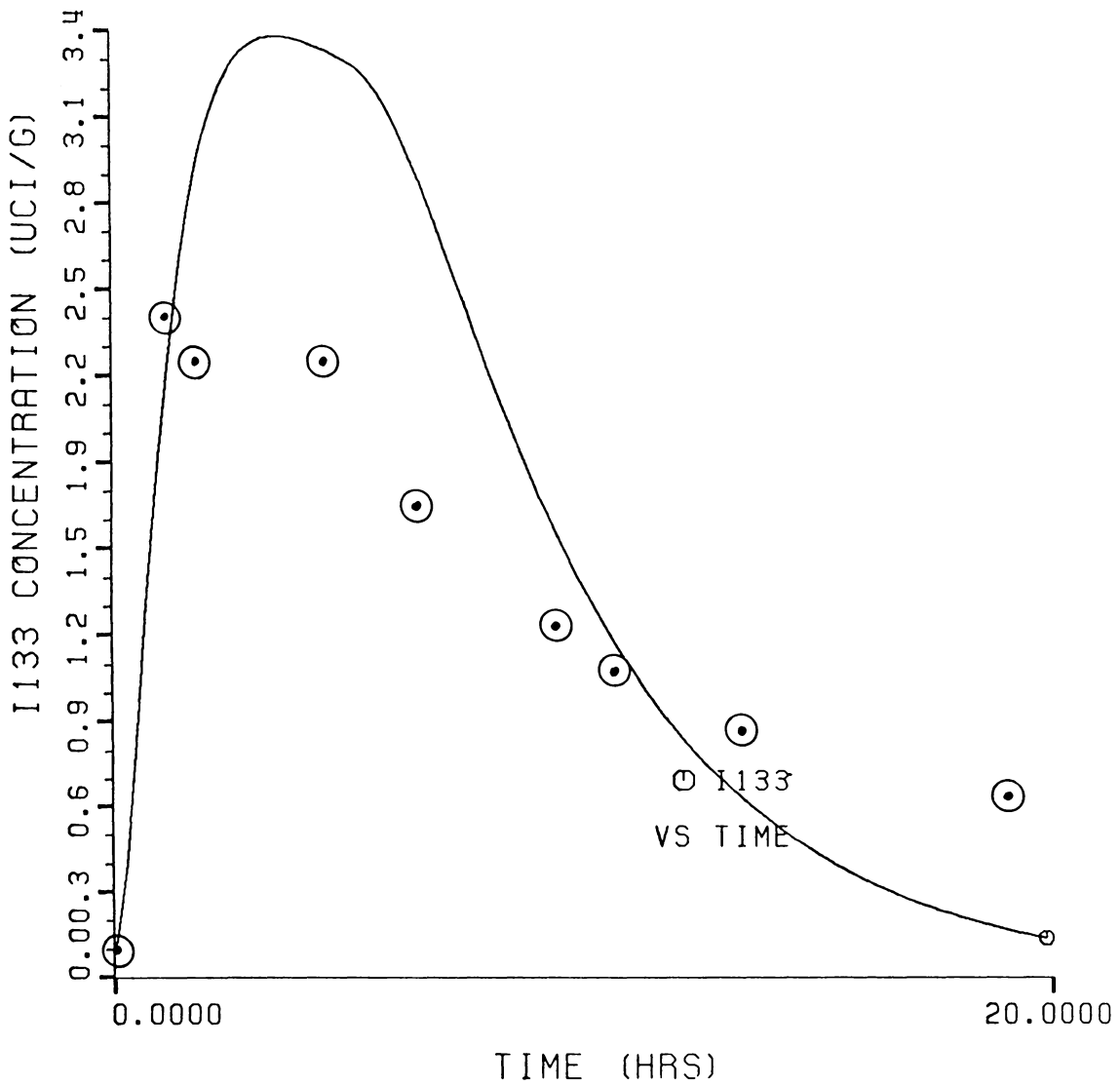


Figure 36. Down-power spike. Iodine-133 analytical and experimental data as a function of time.

purposes of the model it is this mechanism which generates the major production of iodine in the primary coolant. The dissolved iodine is forced out of the gap as the expanding water vapor creates a pressure difference between the gap region and the primary coolant. The iodine spike that is produced in the primary coolant is exceedingly steep and short-lived. This is contrary to the experimental data which shows the spike to be very similar in shape to the down-power curve. It can be concluded from this that there may be some basic mechanism for the hydraulic leaching of material into the coolant that has been neglected.

In conclusion, a successful model of iodine spiking for a down-power transient has been developed which gives physical significance to the mechanisms involved with the process. Further understanding of the up-power spiking mechanism needs to be developed.

## VIII. REFERENCES

1. Neeb, K. H. and Schuster, E., "Origin and General Behavior of Fission Iodine from Defective Fuel Rods upon Shutdown of a Pressurized-Water Reactor," Siemens Research and Development Reports, Vol. 8, n. 2, pp. 92-97, May 1979.
2. Rest, J., "An Improved Model for Fission Product Behavior in Nuclear Fuel Under Normal and Accident Conditions," Materials Science and Technology Division, Argonne National Laboratory, Nov. 1983.
3. Vliet, J. and Hoppe, N., "Oxide Behavior Modelling Progress in COMETHE," BN-1050, February 1982.
4. Gruber, E. E., "Transient Fission Gas Release from Oxide Fuels," Trans. Am. Nucl. Soc., 22, 418, 1975.
5. Weisman, J., McDonald, P. E., Miller, A. I., and Ferrari, H., "Fission Gas Release from  $UO_2$  Fuel Rods with Time Varying Power Histories," Trans. Am. Nucl. Soc., 12, 900, 1969.
6. Rust, James H., Nuclear Power Plant Design, Haralson Publishing Co., 1979, Library of Congress Catalog Number: 79-88918.
7. Weisman, Joel, Eckart, Leroy, "Fuel Rod design Educational Module," sponsored by The National Science Foundation, Contract Number SED75-04822 A02 in conjunction with The United States Energy Research & Development Administration, September 1977.
8. Long, L. S., Weisman, J., Thermal Analysis of Pressurized Water Reactors, 2nd ed., published by The American Nuclear Society, 1979.
9. Frost, R. T., Nuclear Fuel Elements, p. 61.
10. Onega, R. J., Parkinson, T. F., "VEPCO Report (Phase I)," VPI&SU Project No. 801374-1, December 1982.
11. Slattery, J. C., "Momentum, Energy and Mass Transfer in Continua," Robert E. Kreiger Publishing Company, Huntington, New York, 1981.
12. Peehs, M., Schweighofer, W., Haas, E. and Wurtz, R., "On the Behavior of Cesium and Iodine in Light Water Reactor Fuel Rods," September 1980, pp. 157-164.
13. Olander, D. R., "Fundamental Aspects of Nuclear Fuel Elements," Technical Information Center, Energy Research and Development Administration, TID-26711-P1, May 1983.

14. Patankar, S. V., Numerical Heat Transfer and Fluid Flow, McGraw Hill Publishing Co., 1980, p. 44.
15. Carnahan, Brice, Luther, H. A., James, O., Applied Numerical Methods, John Wiley & Sons, Inc., 1969, Library of Congress Catalog Number: 67-27555.
16. Jones, L. M., "A Mathematical Model for the Leaching of Fission Product Iodine from Failed Reactor Fuel Rods," Masters Thesis, Virginia Polytechnic Institute and State University, August 1984.



## APPENDIX A

### Time Step Analysis

The numerical solutions to the differential equations involved in the model have different ranges of time step sizes that can be used in the determination of concentrations and temperatures. The finite difference and Runge-Kutta methods employed will give stable solutions, but the size of the time steps used can greatly affect the accuracy of the results.

Figure 37 shows the fuel temperature as a function of the time step size for a down-power transient. The temperature values begin to level off for a time step of less than 0.1 seconds. Therefore, a time step value of 0.1 seconds should be the upper limit for the temperature solution.

A similar method is employed to determine the most correct node size for the spatial division of the fuel pellet. Figure 38 shows the result of the fuel temperature as a function of the number of nodes. A leveling of the curve occurs at approximately 20 nodes and therefore this should be the minimum number of nodes.

For the Runge-Kutta solutions the time step sizes are shown to be variable for times greater than 10.0 seconds. Figures 39, 40, and 41 show the iodine solutions as a function of time step size for the fuel pellet, gap region, and primary coolant respectively. All three figures are representative of a down-power transient.

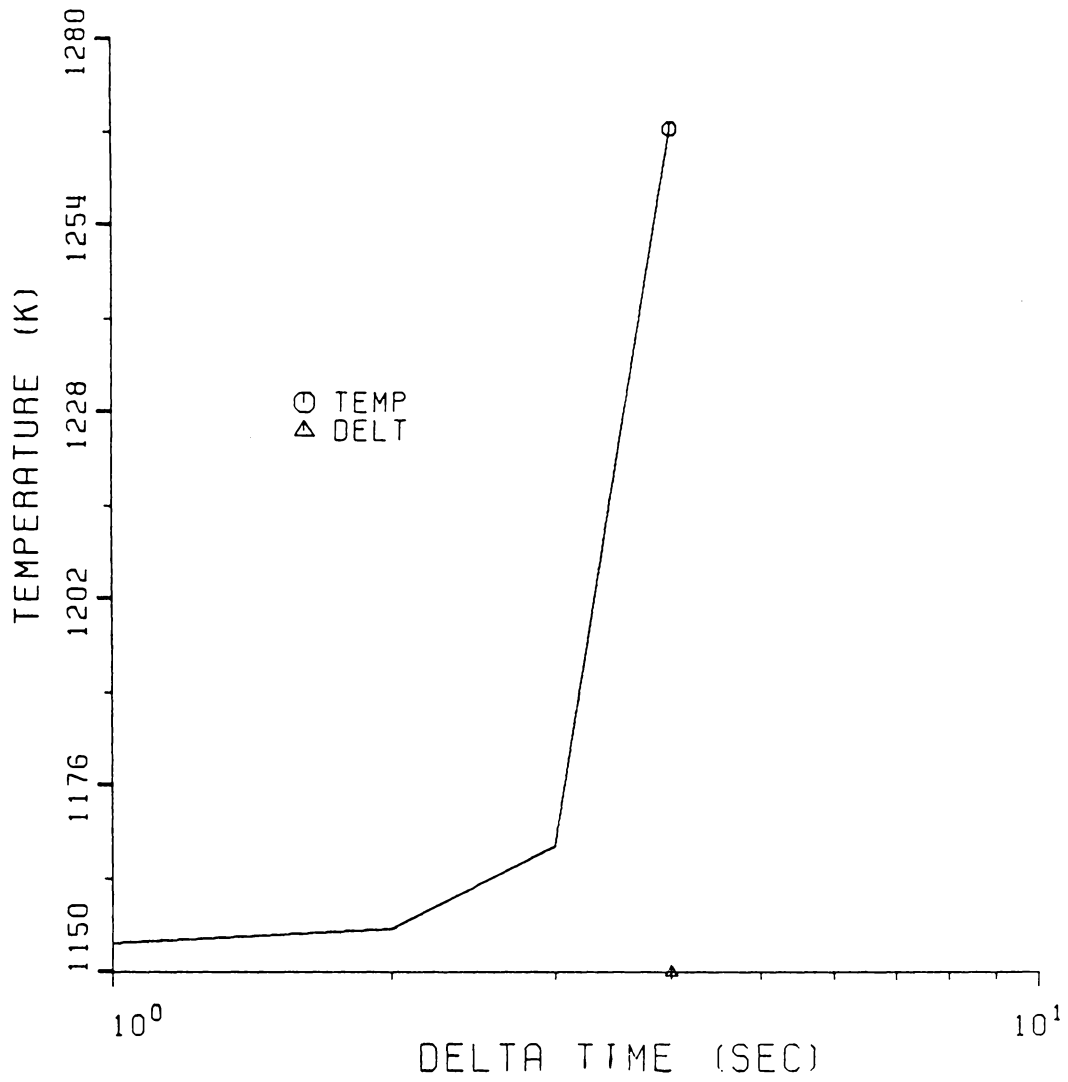


Figure 37. Fuel temperature as a function of time step size.

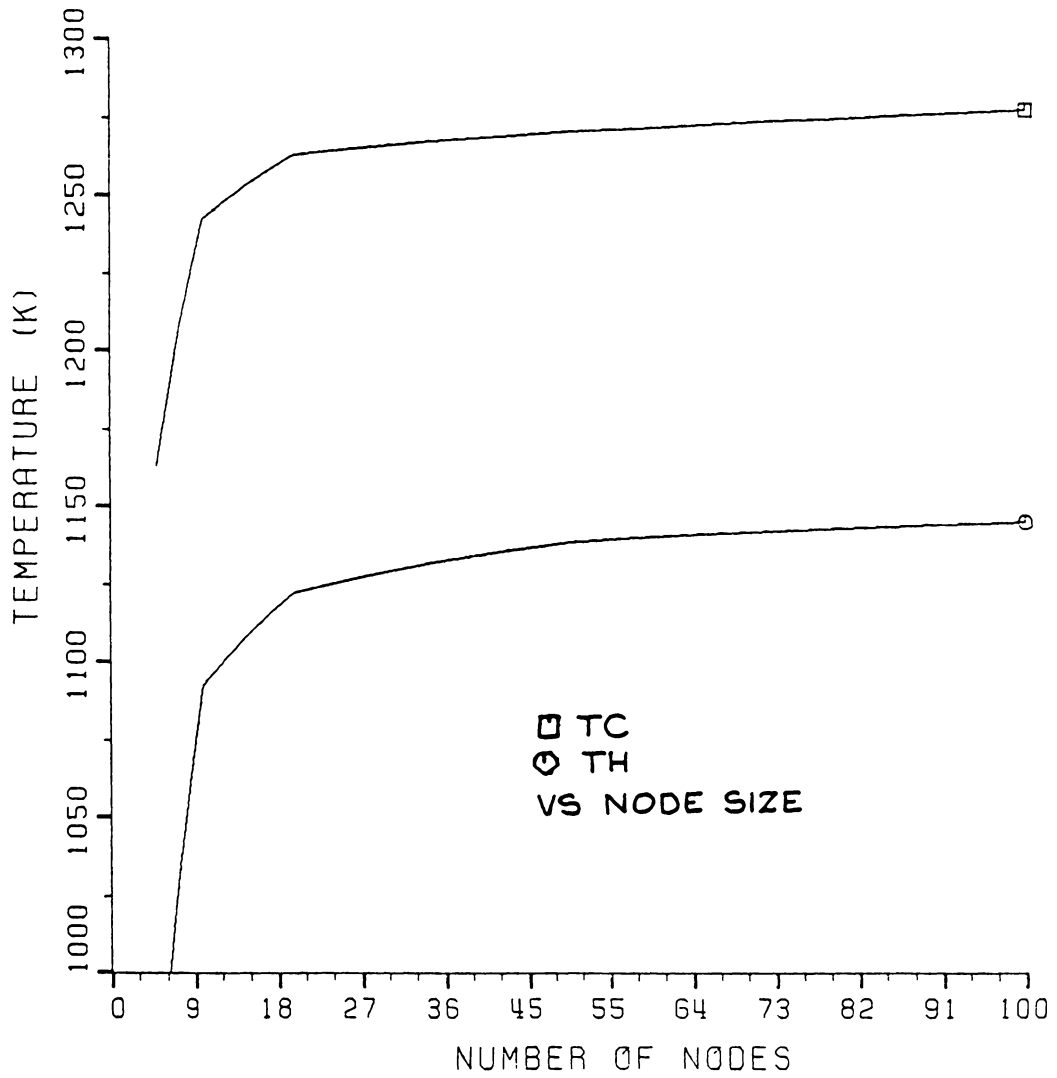


Figure 38. Fuel temperature as a function of node size in the pellet.

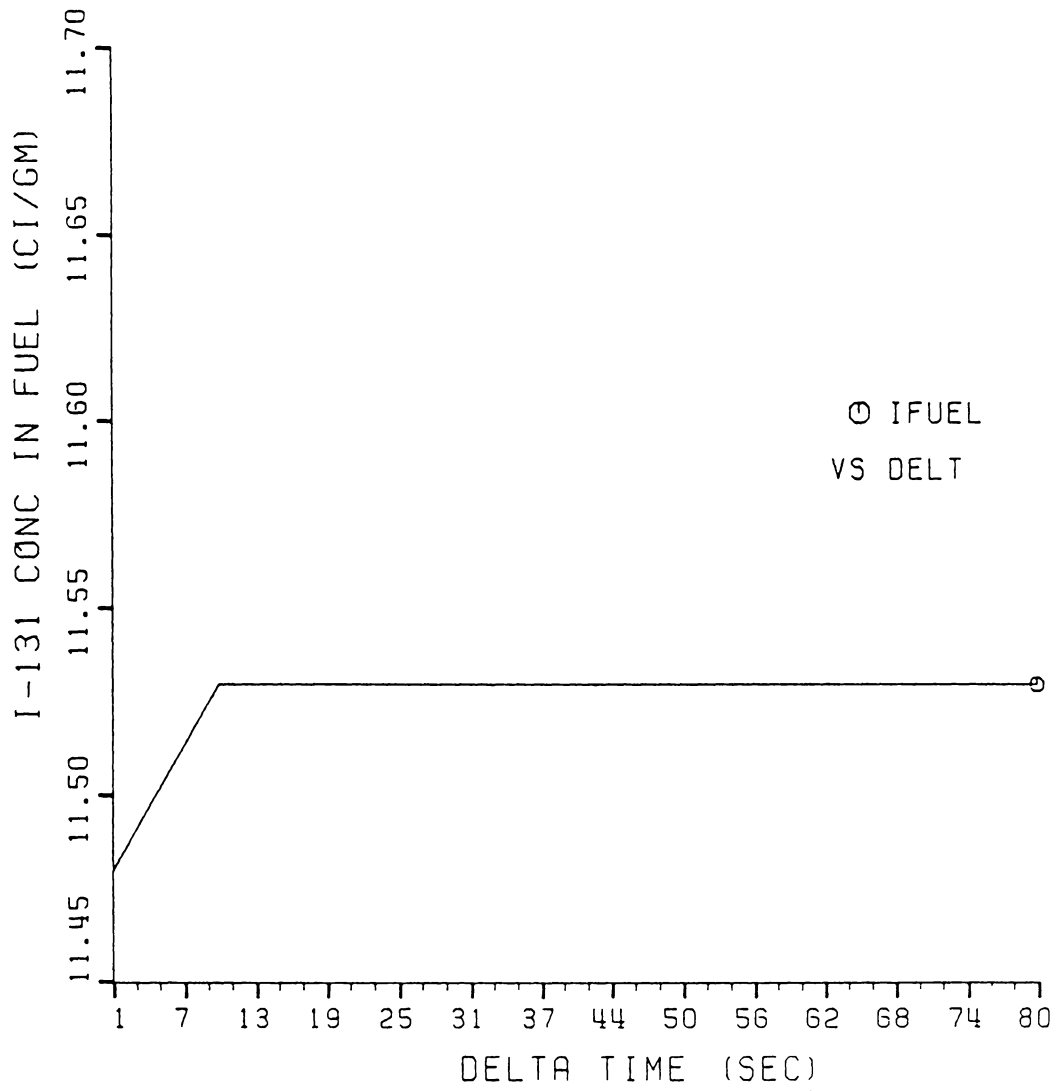


Figure 39. Iodine-131 concentration in the fuel as a function of time step size.

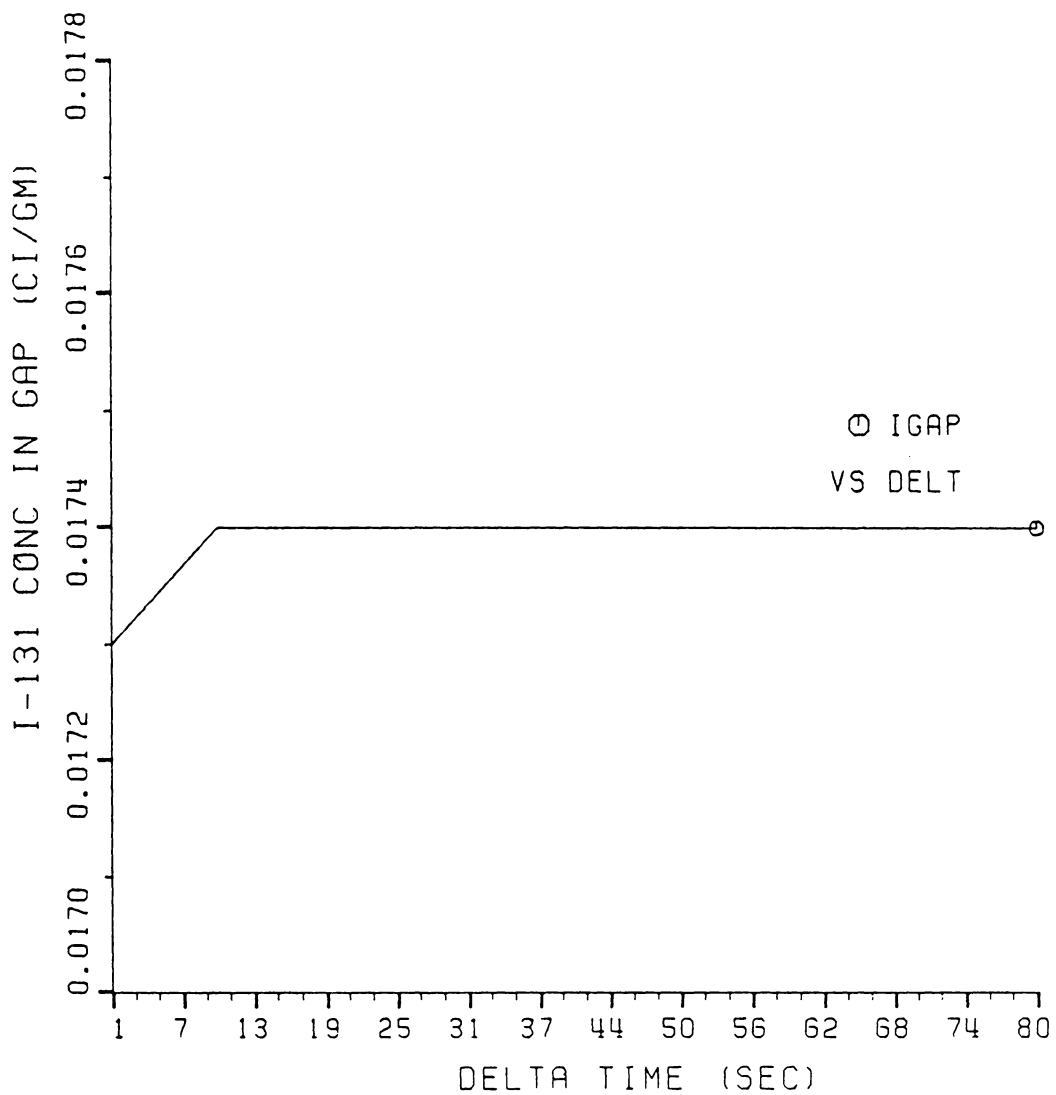


Figure 40. Iodine-131 concentration in the gap as a function of time step size.

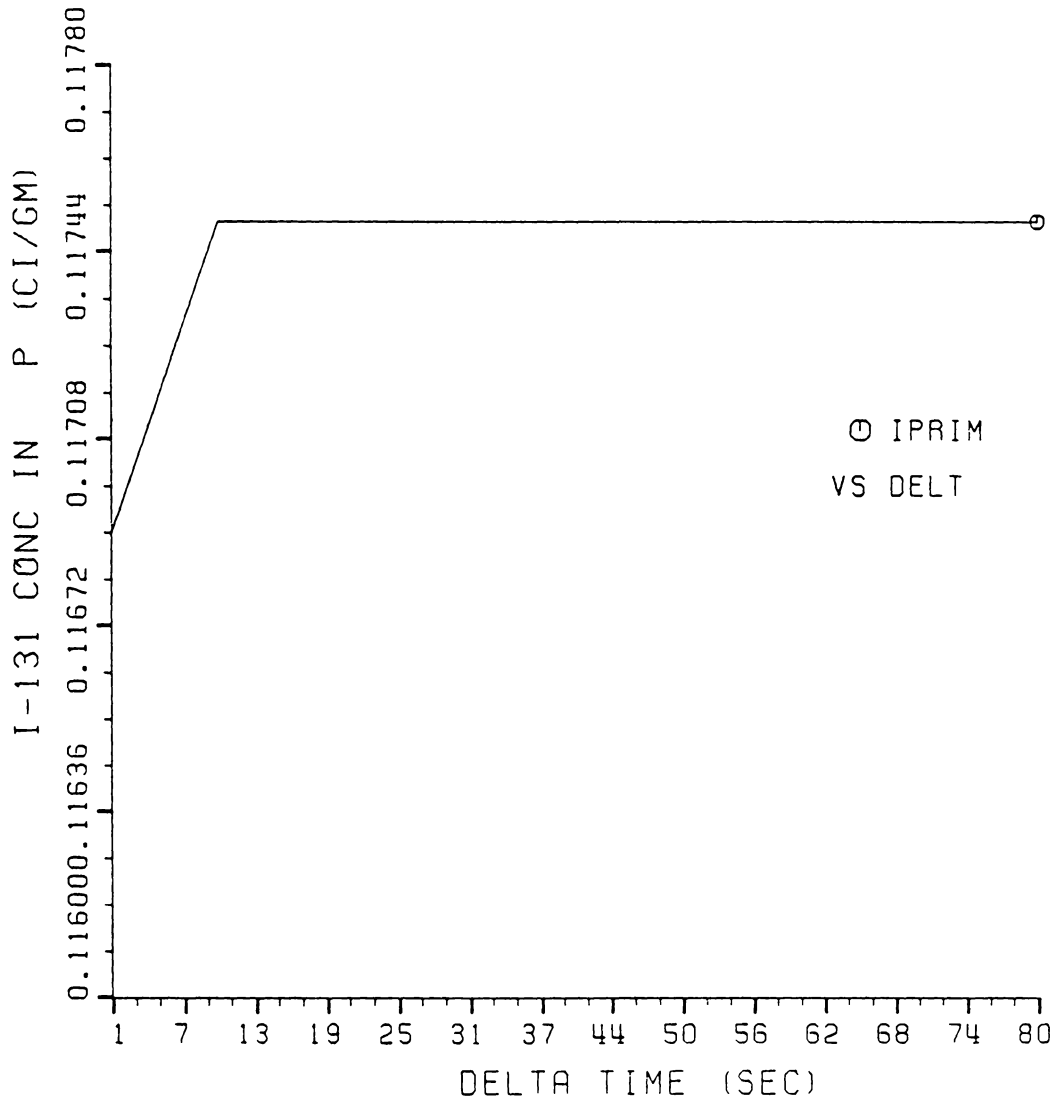


Figure 41. Iodine-131 concentration in the coolant as a function of time step size.

As noted above, the time step for the temperature solution should not exceed 0.1 seconds. If this limitation is employed throughout the program execution then the time to execute the program will approach the real time of the spiking phenomenon. This difficulty is avoided by changing time steps during the calculation. The fuel temperatures will become steady within a 20 second period after initiation of a down-power transient. A simple test is run to compare temperatures at previous times. Once the level can be considered constant, a new larger time step is employed and the last calculated temperature distribution is maintained. This time step does not exceed 15.0 seconds.

If an up-power transient spike is also to be calculated then the time step is reduced to the initial value of less than 0.1 seconds in order to accommodate a rise in temperature.

## APPENDIX B

## Operation and Flow Diagrams of the Program

The FORTRAN code for the iodine spiking model is written as a long series of subroutines. The major subroutines are called from the main routine. The principal function of the main routine and major subroutines are listed below. Any minor subroutines will be discussed later.

## 10. MAIN

- a. Read geometry and power transient data.
- b. Initialize nuclear decay constants and cumulative fission yields for iodine-131, 132, and 133.
- c. Call various subroutines and exercise control.

## 11. TIMVAL

- a. Define and initialize time step variables.

## 12. RADFB

- a. Compute the new fuel pellet radius with increased burnup.
- b. Compute the new gap thickness.

## 13. SETVAL

- a. Initialize the time index to zero.
- b. Initialize test flags.
- c. Define the conversion factor from neutron flux to power ( $n/m^2 \cdot s$  to W).

## 14. RHOF

Calculate the densification of the uranium dioxide fuel with increased burnup.



## 15. FLUXCA

Calculate the power level at the present time interval.

## 16. TESTT

Controls the change of time steps to accommodate the power transient condition.

## 17. TEMPFR

Calculates the temperature distribution in the fuel pellet at the present time interval and power level.

## 18. EFSTDY

Calculate the steady-state iodine efflux rate for the present burnup interval and temperature distribution.

## 19. EFTRAN

Calculate the transient iodine efflux rate at the present time interval and temperature distribution.

## 20. RCAL

Calculate the leach rate for the failed fuel rod at the present time interval.

## 21. CONC

- a. Calculate the steady-state and transient iodine-131, 132, and 133 concentrations in the fuel pellet and gap region.
- b. Calculate the steady-state and transient concentrations in the gap region.

## 22. PRIM

Calculate the steady-state and transient iodine-131, 132, and 133 concentrations in the primary coolant. This is the actual iodine spike calculation.

## 23. OUTPUT

- a. Print numerical values for the iodine-131, 132, and 133 concentrations in the fuel, gap, and primary coolant.
- b. Print the numerical values for the efflux and leach rate.

- c. Print the numerical values for the fuel temperature and power level.

#### 24. RUNDAT

Print output data for the up or down power transient. Includes the time to peak, steady-state concentrations, max to steady-state ratios, and the average cladding failure size.

#### 25. QUIT

Compares current program time step to a predetermined value in order to halt program execution.

A more detailed description of these routines follows. When applicable, a flow diagram is also given and minor subroutines are described.

#### 1. MAIN

##### A. Variable list

ABSFAC		Iodine absorption factor in the clad.
AL(I)	$\lambda_I$	Radioactive decay constants, 1/sec.
BULK	$T_b$	Average bulk coolant temperature, K.
CY(I)	$y_I$	Cumulative fission yields.
DCORE	$D_c$	Active core diameter, m.
DELT	$\Delta t$	Time step size, s.
DROD	$D_R$	Fuel Rod Diameter, m.
FLUXO	$\phi_o$	Initial steady-state flux level, $n/m^2 \cdot sec.$
FRACT	$f_I$	Fraction of iodine not removed by the filtration system.
FS		Average cladding failure size, m.
HT	$H_c$	Active core height, m.
NDEF	N	Number of defective fuel rods in the core.
NRODS		Total number of fuel rods in the core.

P		Time index.
PCNTDP	$\phi_{\text{new}}/\phi_0$	New down-power level, i.e., percent of initial steady-state power.
PITCH	p	Fuel rod pitch, m.
POND	$p/D_R$	Pitch/diameter ratio.
RF	$R_F$	Fuel radius, m.
RT		Rise time for up-power transient.
SIGF	$\sum_f$	Average macroscopic fission cross section for the core fuel, l/m.
THC	$t_c$	Cladding thickness, m.
THG	$t_g$	Gap thickness, m.
TI	t	Time, sec.
TIMC	$T_c$	Average core transit time for coolant, sec.
TIML	$T_L$	Average loop transit time for coolant, sec.
TOFDP		Time of down-power occurrence, sec.
TOTDP		Total down power time under consideration, sec.
TOTUP		Total up-power time under consideration, sec.
TSTEP		Total for time index P.

B. FLOW diagram, Figure A1.

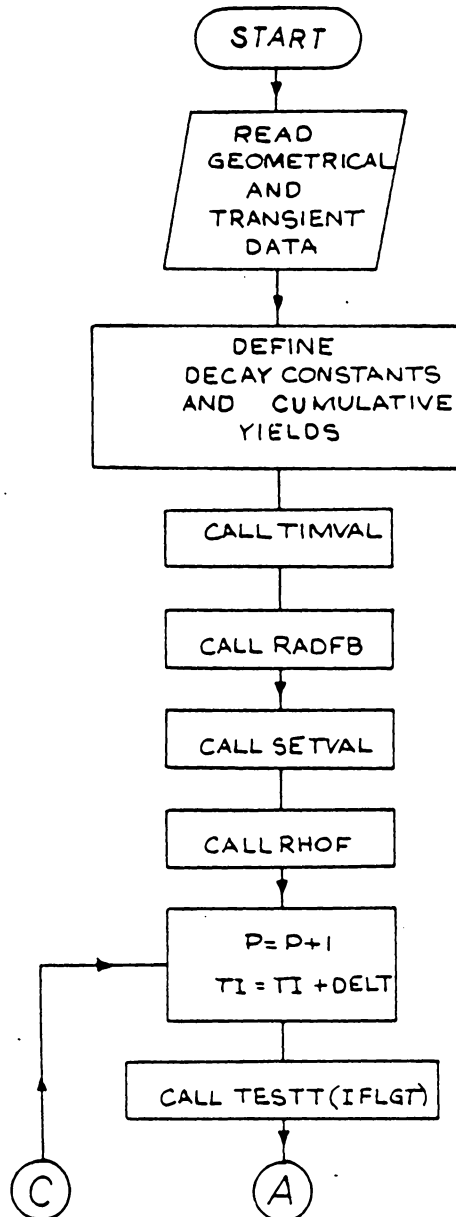
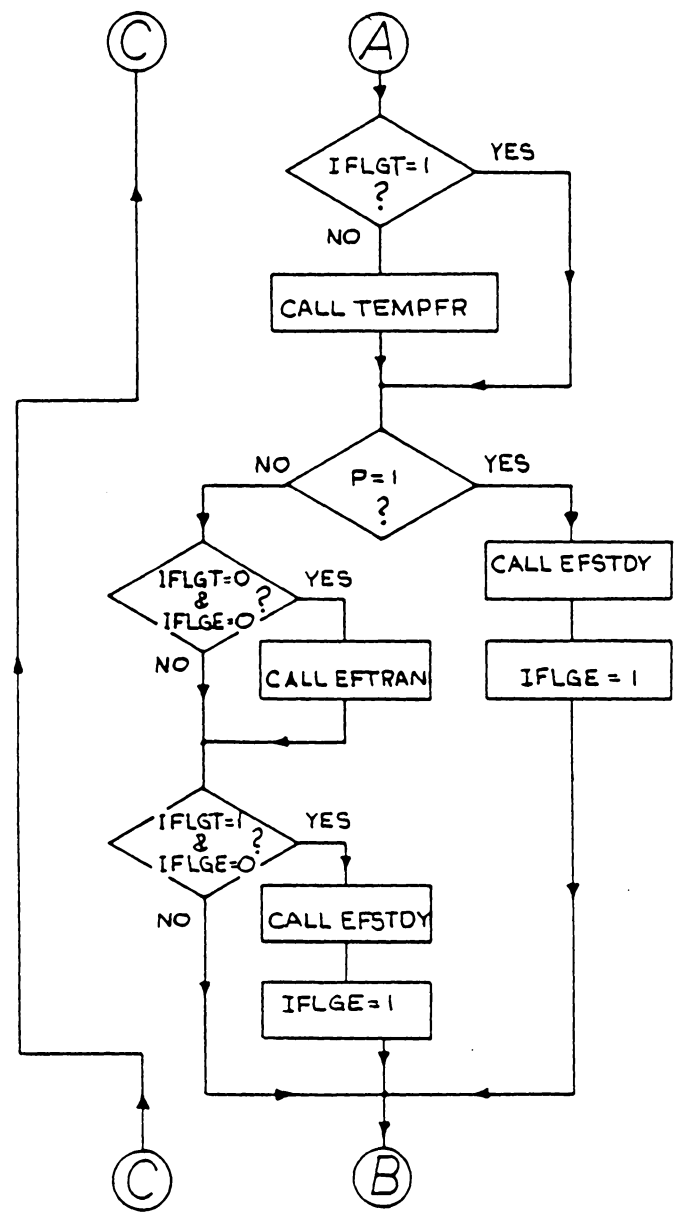
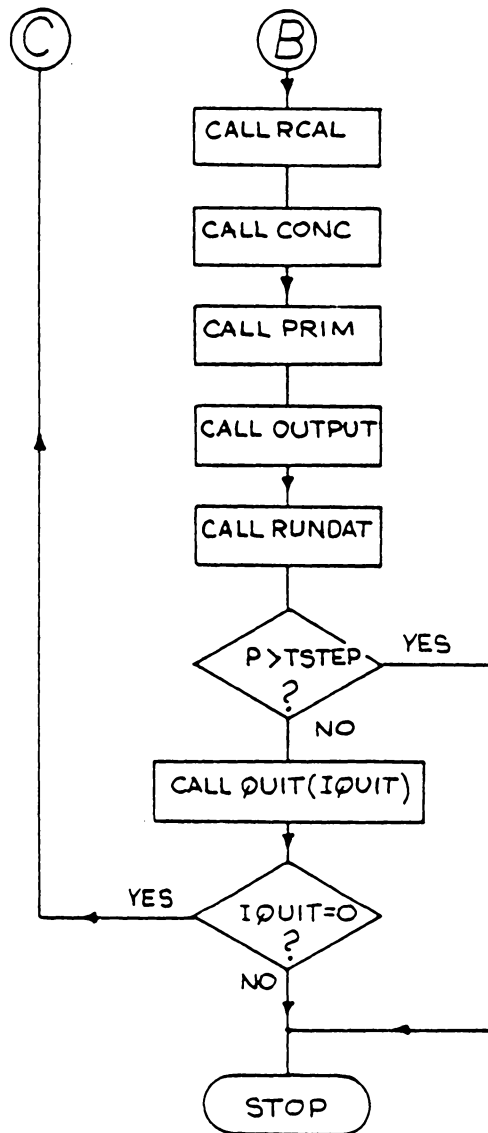


Figure A1. Main Routine





## 2. TIMVAL

## Variable List

DELTT	$\Delta t$	Alternate, longer, time step. Replaces DELT when temperature solution becomes stable, sec.
NP		Transient Type. NP=0 corresponds to a down-power. NP=1 corresponds to an up-power.
NSTEP	N	Number of nodes in the fuel pellet.

## 3. RADFB

## A. Variable list

DELD	$\Delta D$	The change in diameter of the fuel pellet, m.
DELR	$\Delta r$	Nodal width in the fuel pellet, m.
DELV	$\Delta v$	The change in volume of the fuel pellet, $m^3$ .
SAVRF	$R_{F_0}$	Original fuel pellet radius, m.
SAVTHG	$t_{g_0}$	Original gap thickness, m.

## B. Minor Subroutines

SOLVE	Solves a function with an implicit variable for the variable.
F(X)	Contains the function to calculate the volume change of the fuel.

## C. Flow diagram, Figure A2.

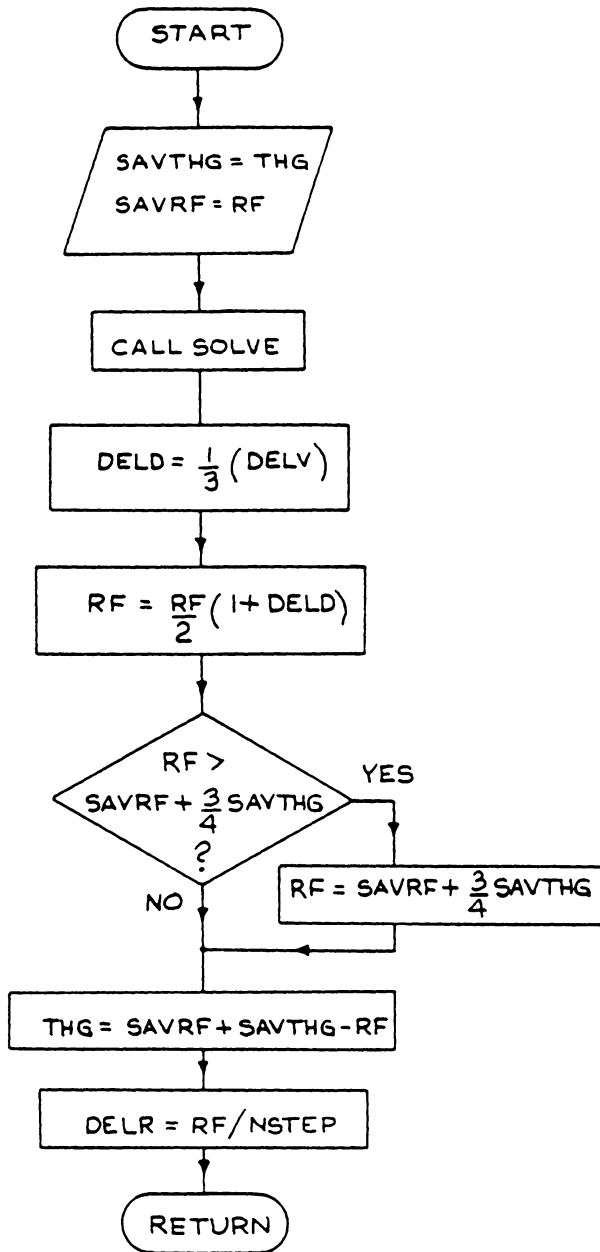


Figure A2. Subroutine RADFB



## 4. SETVAL

## Variable List

IFLG		Flag used in transient efflux calculation.
IK2		Flag to initialize the temperature matrix for the thermal conductivity calculation.
KCOND		Flag to initialize the convergence calculation for the thermal conductivity.
NSUB		Number of nodes in the fuel less one.
WF	$W_f$	Conversion factor.

## 5. RHOF

## Variable List

BURN	b	Average burnup of the fuel, MWd/MT.
DRHO	$\Delta\rho$	Change in the uranium dioxide density, $\text{kg/m}^3$ .
RHO	$\rho$	Uranium dioxide density, $\text{kg/m}^3$ .

## 6. FLUXCA

## A. Variable List

FLUX	$\phi(t)$	Flux level in the core, $\text{n/sec/m}^2$ .
TIME1	t	Time, same as TI, sec.

## B. Flow diagram, Figure A3.

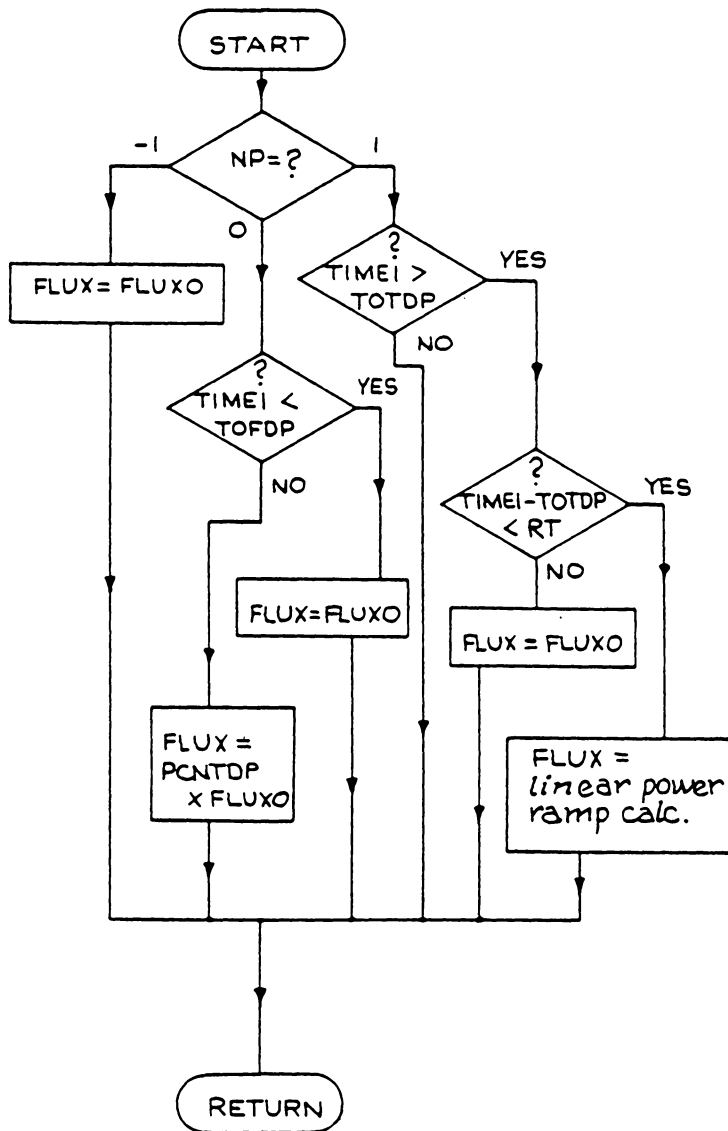


Figure A3. Subroutine FLUXCA

## 7. TESTT

## Variable List

DELSAV		Retains the smallest time increment for later use, sec.
IFLGT		Flag which turns on and off the temperature distribution calculation in the fuel.
ITIM		Flag which initializes the test for constant temperatures.
TIM	t	Time variable used in the temperature convergence test, sec.

## 8. TEMPFR

## A. Variable List

L		Initialize indices for temperature coefficient matrix to zero.
RI	$r_i$	Radial position in the fuel pellet, m.
TMAT(I,2)	$T(r,t)$	Temperature vector. Stores previous and old time step values of the temperature distribution, K.

## B. Minor subroutines

BOUND		Sets up boundary condition factors in the fuel for the temperature solution.
KFUEL		Calculates the thermal conductivity of the fuel.
SPHF		Calculates the specific heat of the fuel.
COEFFT		Calculates the coefficients of the linear temperature equation at the present node.
SETUP		Places the temperature coefficients in the [A] matrix.
CALCT		Solves the equation $[A][T] = [B]$ for the temperature vector [T].

TESTKF

Tests for the convergence of the thermal conductivity at time equal zero.

C. Flow diagram, Figure A4.

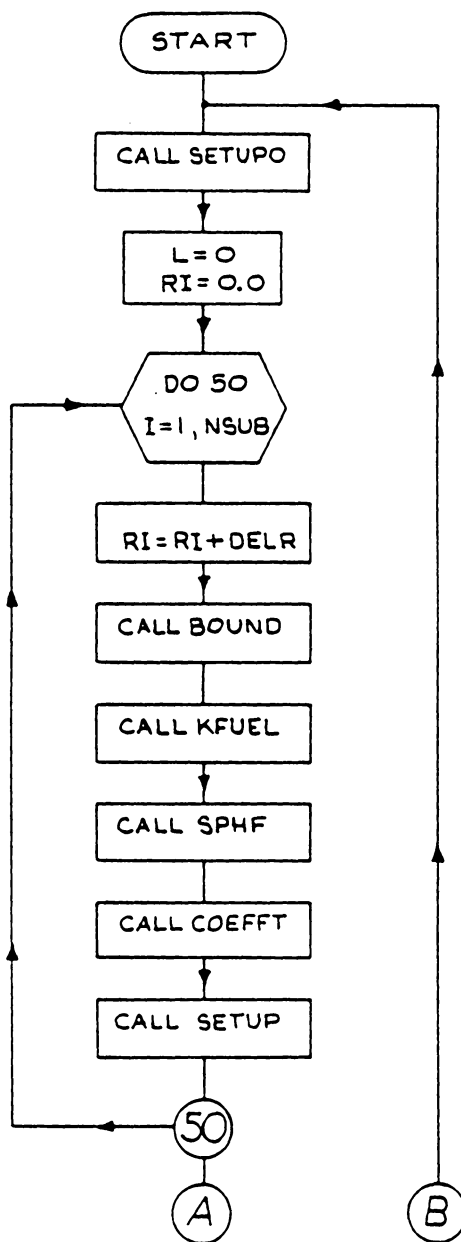
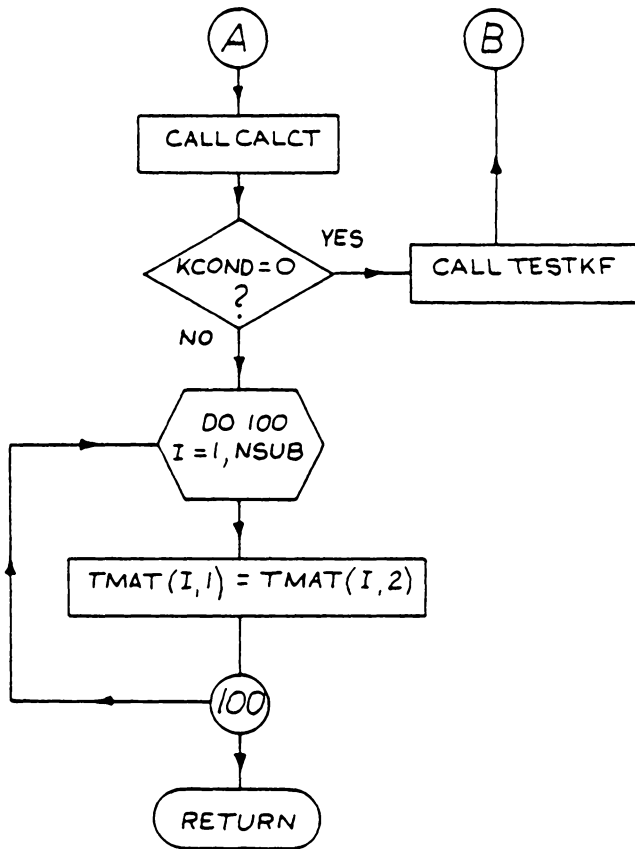


Figure A4. Subroutine TEMPFR



## 9. EFSTDY

## A. Variable List

EI	$e_I(t)$	Efflux variable, $s^{-1}$ .
EIO	$e_{I_0}$	Initial efflux ( $t=0$ ), $s^{-1}$ .
ENHANC		Water enhancement variable for the efflux.
FRAC		Fraction of fission gas released.
FDOT(I)	$\frac{dF}{dt}$	Efflux calculation at each node in the fuel, $1/s$ .
FGAS(I)		Fractional gas release at each node in the fuel.
SUM1		Summing variable to total up the efflux of the fuel.
SUM2		Summing variable to total up the fractional gas release of the fuel.

## B. Minor subroutines

FVAL		Routine to calculate the efflux and fractional gas release at each nodal point in the fuel.
------	--	---

## C. Flow diagram, Figure A5

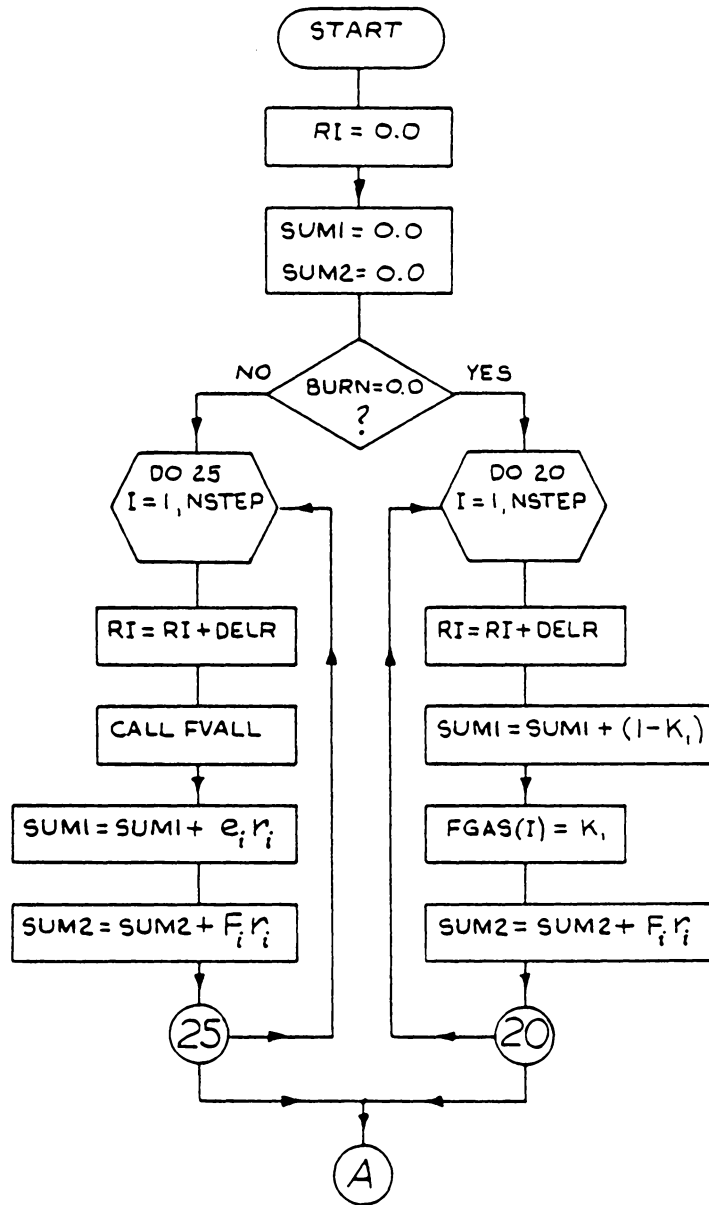
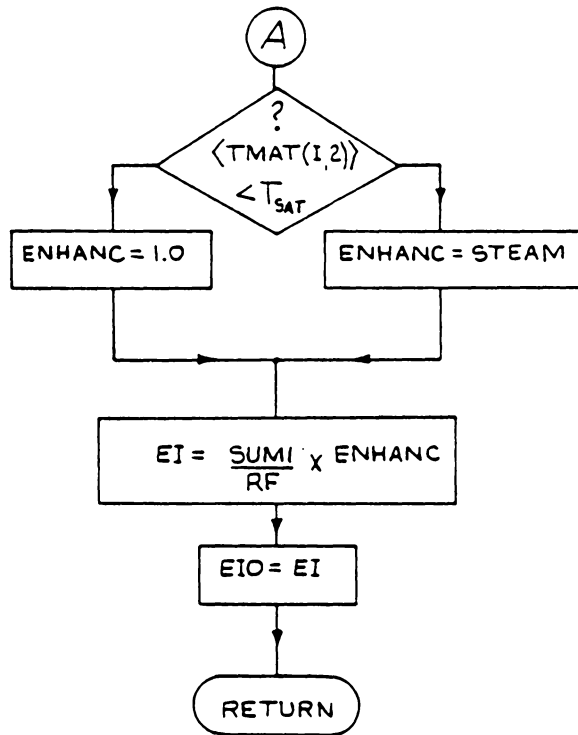


Figure A5. Subroutine EFSTDY





## 10. EFTRAN

## A. Variable List

A1,2,3,4		Coefficients in the transient efflux expression.
CA		Initial concentration of iodine-131 in the fuel.
CB		Initial concentration of iodine-132 in the fuel.
CC		Initial concentration of iodine-133 in the fuel.
GRADT	VT	The temperature gradient at a nodal point in the fuel.
CON1(I)		Mesh constant to bind the steady-state and transient solutions together.

## B. Flow diagram, Figure A6.

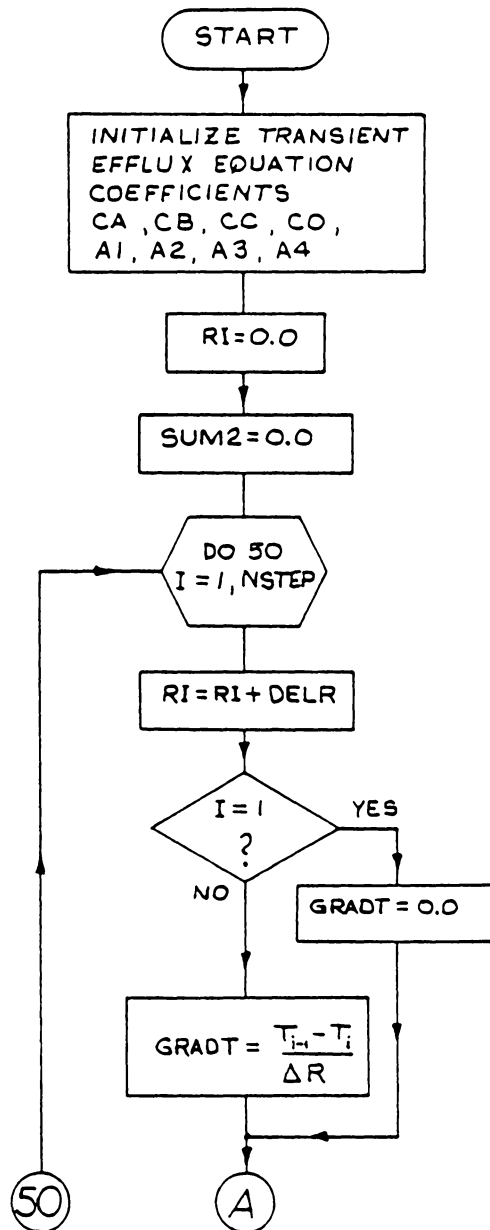
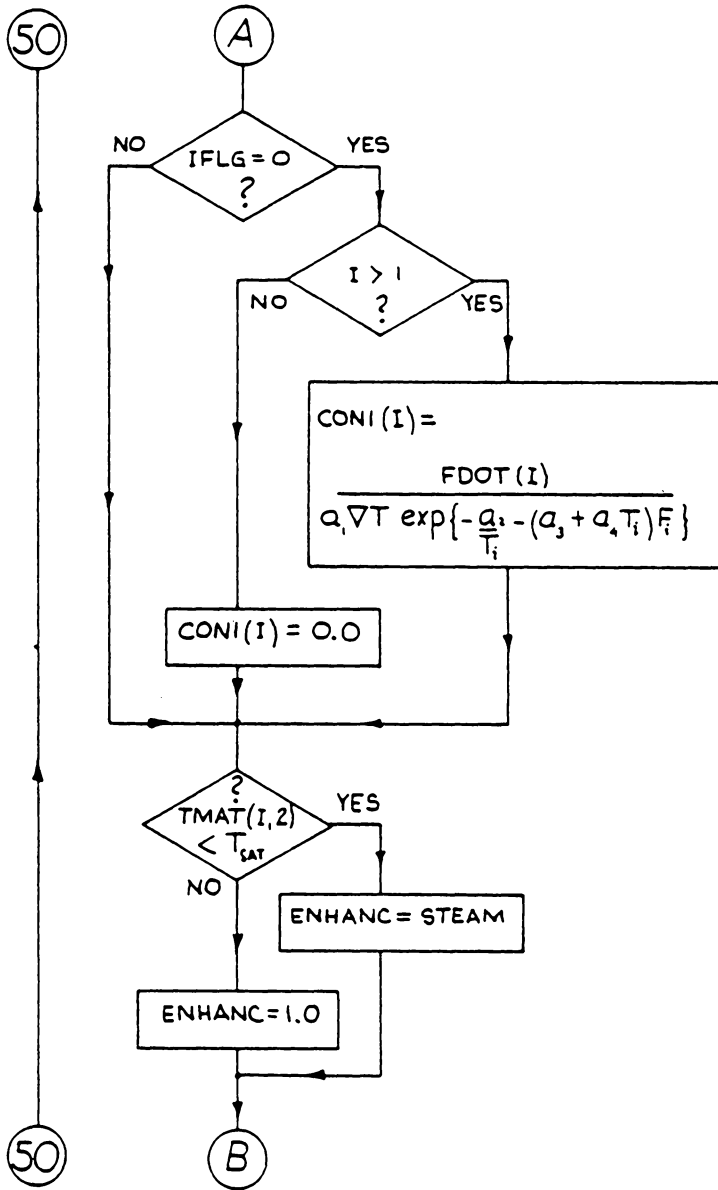
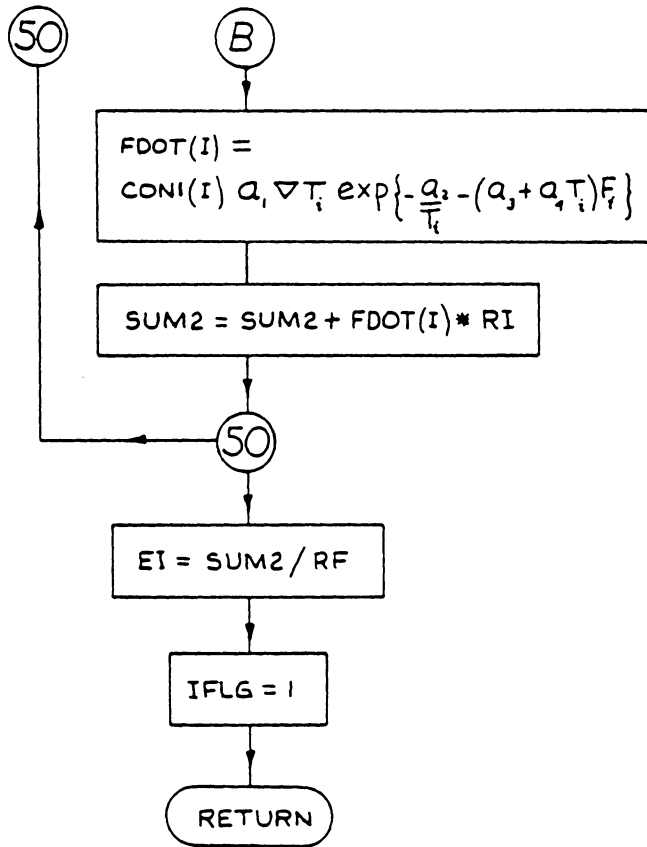


Figure A6. Subroutine EFTRAN





## 11. RCAL

## Minor subroutines

SPOWER	Steady power leach rate calculation as the result of a failed rod. The routine is not yet developed.
DPOWER	Down power leach rate calculation.
UPOWER	Upower leach rate calculation.

For more detail on the RCAL calculation see reference [16].

## 12. CONC

## A. Variable List

CONCR(I)	$I_F(t)$	Concentration in the fuel pellet for iodine-131, 132, 133.
CONCG(I)	$I_G(t)$	Concentration in the gap region for iodine-131, 132 and 133.
SB(I)		Concentration in the fuel pellet for antimony-131, 132, 133.
SBG(I)		Concentration in the gap region for antimony-131, 132, 133.
TEM(I)		Concentration in the fuel pellet for tellurium(m)-131, 132, 133.
TEMG(I)		Concentration in the gap region for tellurium(m)-131, 132, 133.
TE(I)		Concentration in the fuel pellet for tellurium-131, 132, 133.
TEG(I)		Concentration in the gap region for tellurium-131, 132, 133.
GMI,2,3,4,5	$\gamma^n$	Isotopic production fractions.
CR1,2,3,4		Coefficients in the Runge-Kutta solution for the fuel.
CG1,2,3,4		Coefficients in the Runge-Kutta solution for the gap.

R	R(t)	Leaching rate, s <sup>-1</sup> .
VFVG	$\frac{V_F}{V_G}$	Ratio of fuel volume to gap volume.
B. Minor subroutines		
FIR(X)		Function to calculate the differential equation in the fuel for the Runge-Kutta solution.
FIG(X)		Function to calculate the differential equation in the gap for the Runge-Kutta solution.
C. Flow diagram, Figure A7.		

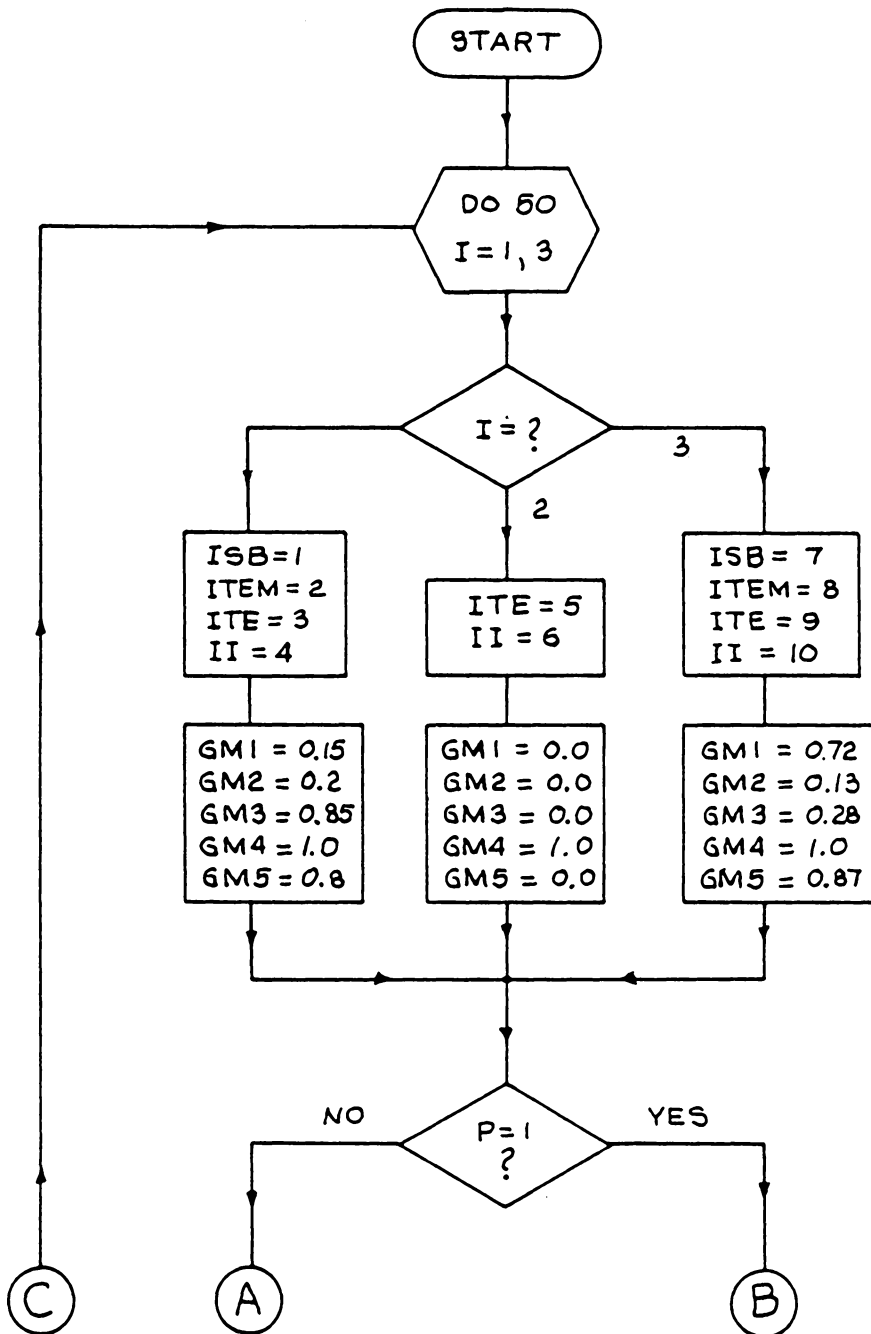


Figure A7. Subroutine CONC





## 13. PRIM

## A. Variable List

CONCP(I) Concentration in the primary coolant of iodine-131, 132, 133.

SBC(I) Concentration in the primary coolant of antimony-131, 132, 133.

TEMC(I) Concentration in the primary coolant of tellurium(m)-131, 132, 133.

TEC(I) Concentration in the primary coolant of tellurium-131, 132, 133.

REMI(I) Removal term for iodine-131, 132, 133.

REMSB(I) Removal term for antimony-131, 132, 133.

REMTEM(I) Removal term for tellurium(m)-131, 132, 133.

REMTE(I) Removal term for tellurium-131, 132, 133.

## B. Minor subroutines

FP(X) Function to calculate the differential equation in the coolant for the Runge-Kutta solution.

## C. Flow diagram, Figure A8.

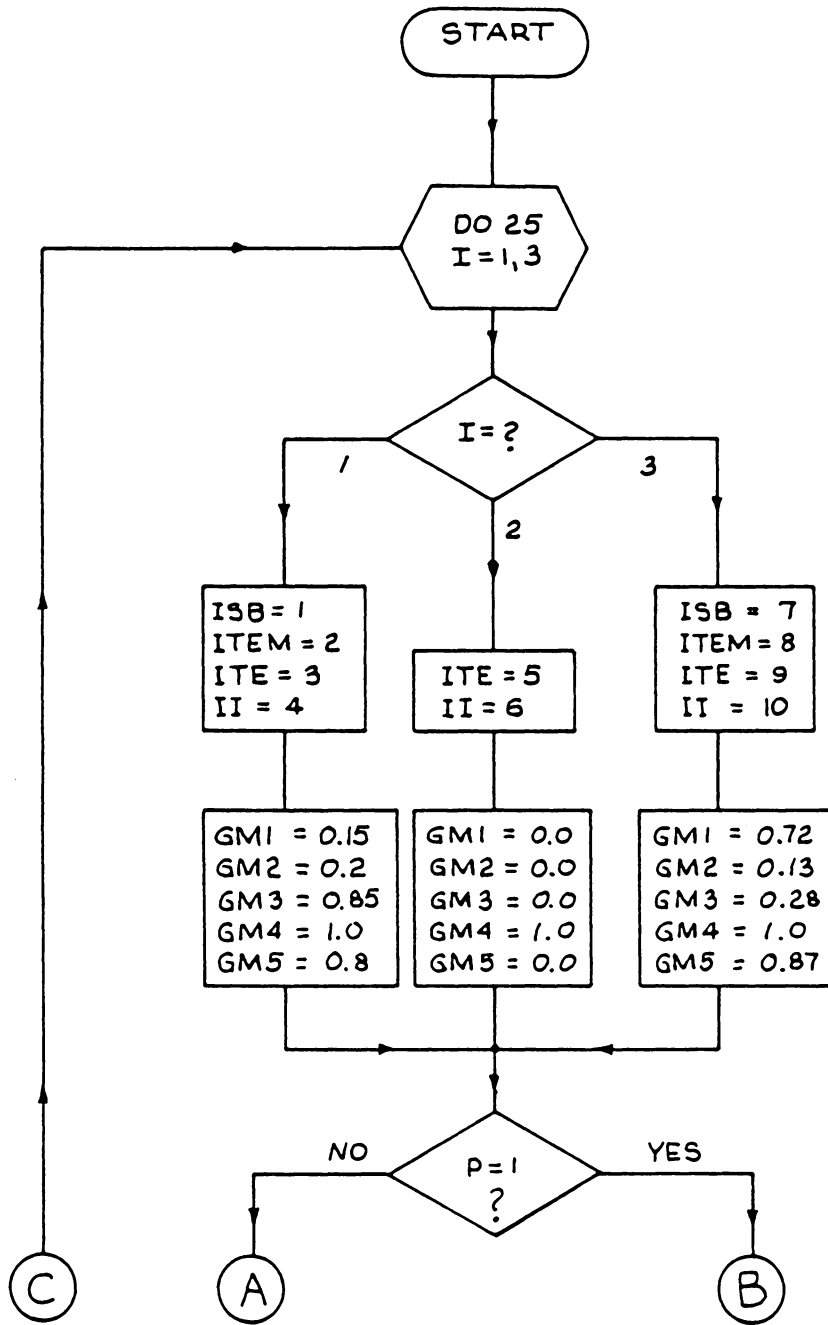
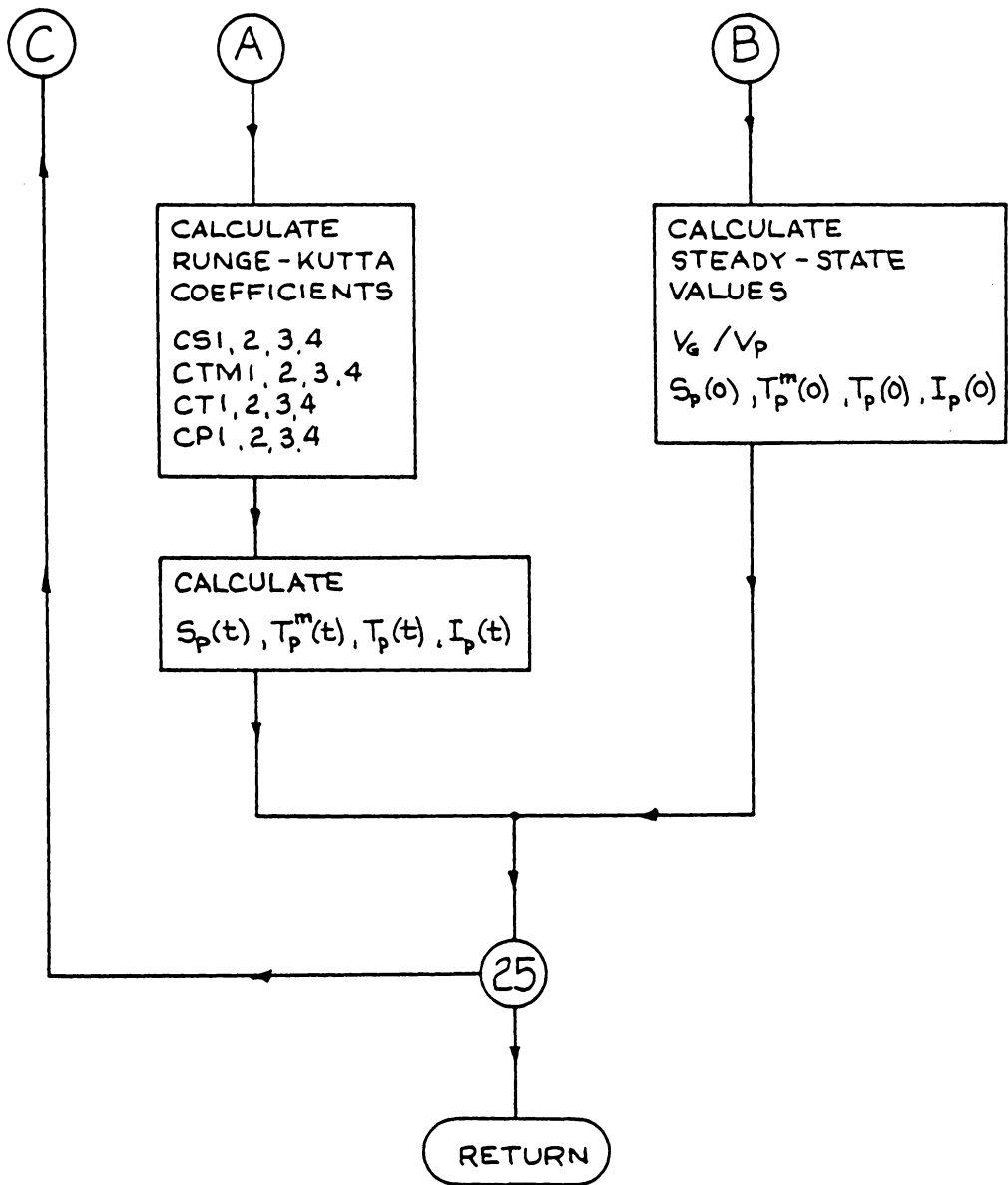


Figure A8. Subroutine PRIM



## 14. QUIT

## Variable List

ICASE	Flag to initiate which transient case to calculate.
IQUIT	Flag to end execution if all time comparison criterion are met.

## Input Data File

The input data for the code is inserted at the bottom of the listing or in a separate file. The input is format-free and only needs to be placed on the proper line. The following is a description of the data.

There are eight lines of input data,

## 1. Core geometry data,

RF THG THC POND PITCH DROD DCORE NRODS HT

Example

4.095E-3 8.2E-5 5.72E-4 1.32 1.25E-2 0.94E-2 3.37 55777 3.66

## 2. Average core parameters,

SIGF TIMC TIML

Example

21.3 0.71 11.0

## 3. Failure parameters,

FRACT NDEF FS STEAM ABSI ABSSB ABSTE

Example

0.95 112 5.00E-5 50.0 0.20 0.80 0.40

## 4. Average fuel and coolant conditions,

BURN BULK

Example

30000,0 589.0

## 5. Initial average power level,

FLUXO

Example

5.09E17

## 6. Down power transient data,

TOFDP PCNTDP TOTDP

Example

1.0 0.01 43200.0

## 7. Upower transient data,

RT TOTUP

Example

900.0 1000.0

8. Transient case flag,

ICASE

Example

1

An example of the input data appended to the FORTRAN listing of the code is given in Appendix C.

APPENDIX C

ISPIKE PROGRAM LISTING

\*\*\*

```

C$JOB      WATFIV,TIME=600,PAGES=50
C*****
C  PURPOSE:  CALCULATION OF AN IODINE SPIKE FOR THE TRANSIENT  *
C            OPERATION OF A PRESSURIZED WATER REACTOR.        *
C                                                    *
C  SPONSOR:  VIRGINIA ELECTRIC POWER COMPANY.                *
C                                                    *
C  PROGRAMMING DONE BY:  K. W. TOBIN                        *
C                       L. M. JONES                        *
C                                                    *
C*****
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
COMMON/TIMES1/TOTUP,ICASE
COMMON/VOLS/VOLF,VOLG,VOLC
COMMON/DEFECT/NDEF,FS
COMMON/CONTRL/NSTEP,NP
C
COMMON/GAS0/KCOND,IK2
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE
COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
C
REAL KF1,KF2
INTEGER P,TSTEP
C
C..... INPUT OF CORE PARAMETERS AND FAILURE DATA .....
C
READ(5,*)RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
READ(5,*)SIGF,TIMC,TIML
READ(5,*)FRACT,NDEF,FS,STEAM,ABSFAC,ABSSB,ABSTE
READ(5,*)BURN,BULK
READ(5,*)FLUXO
READ(5,*)TOFDP,PCNTDP,TOTDP
READ(5,*)RT,TOTUP
READ(5,*)ICASE
C
C..... NUCLEAR DECAY CONSTANTS FOR ANTIMONY, TELLURIUM, AND IODINE.
C
AL(1)=5.02E-4
AL(2)=6.42E-6
AL(3)=4.62E-4

```



```

AL(4)=9.97E-7
AL(5)=2.47E-6
AL(6)=8.41E-5
AL(7)=4.66E-3
AL(8)=2.09E-4
AL(9)=9.24E-4
AL(10)=9.26E-6
C
C..... DIRECT YIELDS FOR ANTIMONY, TELLURIUM, AND IODINE .....
C
DY(1)=0.026
DY(2)=0.0015
DY(3)=0.0009
DY(4)=0.0003
DY(5)=0.047
DY(6)=0.00044
DY(7)=0.04
DY(8)=0.0202
DY(9)=0.00066
DY(10)=0.00033
C
C..... CUMULATIVE YIELDS OF I-131, I-132, I-133 .....
C
CY(1)=0.031
CY(2)=0.047
CY(3)=0.069
C
C..... SETUP OF INITIAL FUEL AND TIME PARAMETERS .....
C
CALL TIMVAL
C
CALL RADFB
CALL SETVAL
CALL RHOF
C
C..... BEGINNING OF TIME LOOP: P = TIME INDEX, TI= TIME VARIABLE.
C
20 P=P+1
TI=TI+DELT
C
CALL FLUXCA(TI)
C
C..... CALCULATION OF TEMPERATURE DISTRIBUTION IN A FUEL PELLETT .....
C
CALL TESTT(IFLGT)
IF(IFLGT.EQ.1)GO TO 50
CALL TEMPFR
50 CONTINUE
C
C..... CALCULATION OF STEADY-STATE AND TRANSIENT FISSION PRODUCT

```

```

C          EFFLUX FROM A FUEL PELLETT .....
C
      IF(P.EQ.1)CALL EFSTDY
      IF(P.EQ.1)IFLGE=0
      IF(P.GT.1)THEN
        IF(IFLGT.EQ.0.AND.IFLGE.EQ.0)CALL EFTRAN
        IF(IFLGT.EQ.1.AND.IFLGE.EQ.0)THEN
          CALL EFSTDY
          IFLGE=1
        END IF
      END IF

C
C..... CALCULATION OF THE LEACHING RATE FROM A CLADDING FAILURE .....
C
      CALL RCAL

C
C..... CALCULATION OF IODINE CONCENTRATIONS IN THE DIFFERENT REGIONS.
C
      CALL CONC

C
      CALL PRIM

C
C..... OUTPUT ROUTINES FOR THE TRANSIENT DATA .....
C
      IF(P.EQ.1)THEN
        IFLG3=0
        CALL OUTPUT
      END IF
      IF(IFLG3.EQ.60)THEN
        CALL OUTPUT
        IFLG3=0
      ELSE
        IFLG3=IFLG3+1
      END IF
      CALL RUNDAT

C
      IF(P.GE.TSTEP)GO TO 100
      CALL QUIT(IQUIT)
      IF(IQUIT.EQ.0)GO TO 20

C
100 STOP
      END

C
C*****SUBROUTINES*****
C
C..... CONTROLS THE TIME STEP CHANGE FOR THE TRANSIENT .....
C
      SUBROUTINE TESTT(IFLGT)
      COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,PCWO,SIGF,FLUX,POW,WF
      COMMON/TIMES/TINC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
      COMMON/CONTRL/NSSTEP,NP

```

```

COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
COMMON/GAS2/AMAT(50, 50), TMAT(50, 2), BVEC(50), A, B1, C, B2, TOUT, JN, JO
COMMON/GAS3/BURN, IORF, BULK, IFLG, STEAM, ABSFAC, ABSSB, ABSTE
C
INTEGER P
C
IF(P.EQ.1)THEN
IFLGT=0
ITIM=0
DELSAV=DELT
ELSE
IF(NP.EQ.0.AND.FLUX.NE.FLUXO)THEN
IF(ITIM.EQ.0)TIM=TI
ITIM=1
IF(TI-TIM.LT.20.0)IFLGT=0
IF(TI-TIM.GE.20.0)IFLGT=1
IF(TI-TIM.GE.20.0)DELT=DELTT
END IF
IF(NP.EQ.1.AND.FLUX.GE.PCNTDP*FLUXO)THEN
IF(FLUX.LT.FLUXO)THEN
DELT=DELSAV
IFLGT=0
ELSE
IF(ITIM.EQ.1)TIM=TI
ITIM=0
IF(TI-TIM.LT.25.0)IFLGT=0
IF(TI-TIM.GE.25.0)IFLGT=1
IF(TI-TIM.GE.25.0)DELT=DELTT
END IF
END IF
END IF
C
RETURN
END
C
C-----
C..... CALCULATES TEMPERATURE DISTRIBUTION IN THE FUEL PELLETT .....
C
SUBROUTINE TEMPFR
C
COMMON/NUCDA/AL(10), CY(10), DY(10), FLUXO, POWO, SIGF, FLUX, POW, WF
COMMON/GEOM/RF, THG, THC, POND, PITCH, DROD, DCORE, NRODS, HT
COMMON/TIMES/TIMC, TIML, DELT, DELTT, TOFDP, PCNTDP, TOTDP, RT
COMMON/CONTRL/NSTEP, NP
COMMON/GASO/KCOND, IK2
COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
COMMON/GAS2/AMAT(50, 50), TMAT(50, 2), BVEC(50), A, B1, C, B2, TOUT, JN, JO
COMMON/GAS3/BURN, IORF, BULK, IFLG, STEAM, ABSFAC, ABSSB, ABSTE
C
25 CALL SETUPO
C

```

```

L=0
RI=0.0
C
DO 50 I=1,NSUB
C
RI=RI+DELR
C
CALL BOUND
CALL KFUEL
CALL SPHF
CALL COEFFT
CALL SETUP
C
50 CONTINUE
C
CALL CALCT
C
IF(KCOND.EQ.0)THEN
CALL TESTKF
GO TO 25
END IF
C
DO 100 I=1,NSUB
TMAT(I,1)=TMAT(I,2)
100 CONTINUE
C
RETURN
END
C
C-----
C..... COMPUTES NEW FUEL PELLETT AND GAP DIMENSIONS .....
C
SUBROUTINE RADFB
C
COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
COMMON/VOLS/VOLF,VOLG,VOLC
COMMON/CONTRL/NSTEP,NP
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE
COMMON/SUBRAD/DELV
C
SAVTHG=THG
SAVRF=RF
CALL SOLVE
DELD=0.5*DELV/3.0
RF=RF*(1.0+DELD)
C
IF(RF.GT.SAVRF+0.75*SAVTHG)RF=SAVRF+0.75*SAVTHG
THG=SAVRF+SAVTHG-RF

```

```

      DELR=RF/NSTEP
C
      RETURN
      END
C
      SUBROUTINE SOLVE
      COMMON/GAS3/BURN, IORF, BULK, IFLG, STEAM, ABSFAC, ABSSB, ABSTE
      COMMON/SUBRAD/DELV
      IF(BURN.GE.10.0)GO TO 5
      DELV=0.0
      GO TO 150
5 XL=0.000001
      YL=F(XL)
10 XR=XL+0.00001
      YR=F(XR)
      IF(YL*YR)20,30,40
40 XL=XR
      YL=YR
      GO TO 10
30 IF(YL.EQ.0.0)THEN
      DELV=YL
      ELSE
      DELV=XR
      END IF
      GO TO 150
20 X=(XL+XR)/2.0
      Y=F(X)
      IF(YL*Y)60,70,80
70 DELV=X
      GO TO 150
60 XR=X
      YR=Y
      GO TO 90
80 XL=X
      YL=Y
90 IF(XR-XL.LT.0.00001)GO TO 100
      GO TO 20
100 DELV=(XL+XR)/2.0
150 RETURN
      END
C
      FUNCTION F(X)
      COMMON/GAS3/BURN, IORF, BULK, IFLG, STEAM, ABSFAC, ABSSB, ABSTE
      COMMON/SUBRAD/DELV
      POR=0.07
      B=1.6E-6
      F=(0.149*POR**0.254)*(EXP(-100.0*X)-1.0)+B*(1.0-POR)*BURN-X
      RETURN
      END
C
C-----

```

C..... CALCULATES THE DENSIFICATION OF THE FUEL .....

C

SUBROUTINE RHOF

COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF

COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT

COMMON/VOLS/VOLF,VOLG,VOLC

COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L

COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE

C

IF(BURN.LT.20)DRHO=0.0

IF(BURN.GE.20.AND.BURN.LE.2000)DRHO=0.001846\*ALOG(BURN)-0.005529

IF(BURN.GT.2000)DRHO=0.0085

C

RHO=10956.57\*(DRHO+1)

C

RETURN

END

C

C-----

C..... INITIALIZATION ROUTINE FOR TIME INDEX, FLAGS, ETC .....

C

SUBROUTINE SETVAL

C

COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF

COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R

COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT

COMMON/CONTRL/NSTEP,NP

COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT

COMMON/GAS0/KCOND,IK2

COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L

COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE

C

INTEGER P,TSTEP

C

WF=3.204E-11

P=0

TI=-DELT

KCOND=0

IK2=0

IFLG=0

NSUB=NSTEP-1

C

RETURN

END

C

C-----

SUBROUTINE SETUPO

COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L

COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO

C

DO 20 NC=1,NSUB

```

      DO 10 NR=1,NSUB
      AMAT(NR,NC)=0.0
10 CONTINUE
20 CONTINUE
C
      RETURN
      END
C
C-----
      SUBROUTINE BOUND
C
      COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
C
      REAL BCF
      INTEGER ICF, P, I
C
      IF(P.EQ.1)THEN
        ICF=0
      ELSE
        ICF=1
      END IF
C
      IF(I.EQ.1)THEN
        BCF=1.5
      ELSE
        IF(I.EQ.NSUB)THEN
          BCF=0.5
        ELSE
          BCF=1.0
        END IF
      END IF
      RETURN
      END
C
C-----
      SUBROUTINE KFUEL
C
      COMMON/GAS0/KCOND, IK2
      COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
      COMMON/GAS2/AMAT(50,50), TMAT(50,2), BVEC(50), A, B1, C, B2, TOUT, JN, JO
C
      INTEGER I, P, ICF
      REAL BCF, KF1, KF2, KIM1, KIP1, KI
C
      IF(P.EQ.1)THEN
        IF(IK2.EQ.0)THEN
          KF1=2.28
          KF2=2.28
        ELSE
          IF(I.EQ.1)THEN
            KIM1=KF1
          
```

```

        ELSE
            KIM1=KI
        END IF
        KI=6882.113/(232.94+1.8*TMAT(I,2))+(1.04209E-11)*(1.8*TMAT(I,2)+0.
&33)**3
C
        IF(I.EQ.NSUB)THEN
            KF1=2.0*KIM1*KI/(KIM1+KI)
        ELSE
            KIP1=6882.113/(232.94+1.8*TMAT(I+1,2))+(1.04209E-11)*(1.8*TMAT
&(I+1,2)+0.33)**3
            KF1=2.0*KIM1*KI/(KIM1+KI)
            KF2=2.0*KIP1*KI/(KIP1+KI)
        END IF
        END IF
    ELSE
        IF(I.EQ.1)THEN
            KIM1=KF1
        ELSE
            KIM1=KI
        END IF
        KI=6882.113/(232.94+1.8*TMAT(I,1))+(1.04209E-11)*(1.8*TMAT(I,1)
&+0.33)**3
C
        IF(I.EQ.NSUB)THEN
            KF1=2.0*KIM1*KI/(KIM1+KI)
        ELSE
            KIP1=6882.113/(232.94+1.8*TMAT(I+1,1))+(1.04209E-11)*(1.8*T
&MAT(I+1,1)+0.33)**3
            KF1=2.0*KIM1*KI/(KIM1+KI)
            KF2=2.0*KIP1*KI/(KIP1+KI)
        END IF
        END IF
C
    RETURN
    END
C
C-----
    SUBROUTINE SPHF
C
    COMMON/GASO/KCOND, IK2
    COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
    COMMON/GAS2/AMAT(50, 50), TMAT(50, 2), BVEC(50), A, B1, C, B2, TOUT, JN, JO
    INTEGER I, P
C
    IF(P.EQ.1)THEN
        SPH=322.22
    ELSE
        S1=(8.5057E7)*EXP(535.285/TMAT(I,1))/((EXP(535.285/TMAT(I,1))-
&1)**2*TMAT(I,1)**2)
        S2=(2.4336E-2)*TMAT(I,1)

```



```

S3=(1.660E12)*EXP(-18970.6/TMAT(I,1))/TMAT(I,1)**2
SPH=S1+S2+S3
END IF
C
RETURN
END
C
C-----
SUBROUTINE COEFFT
C
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
COMMON/CONTRL/NSTEP,NP
COMMON/GASO/KCOND,IK2
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
C
REAL KF1,KF2,BCF
INTEGER ICF,I,P
C
A=-(RI+DELR/2.0)*KF2/DELR
C=-(RI-DELR/2.0)*KF1/DELR
B1=-A-C+RHO*SPH*RI*DELR*BCF*ICF/DELT
C
CALL FLUXCA(TI)
C
CALL TEMPR
IF(P.EQ.1)THEN
  IF(I.EQ.NSUB)THEN
    B2=BCF*RI*DELR*(WF*SIGF*FLUX+RHO*SPH*ICF/DELT)-A*TOUT
  ELSE
    B2=BCF*RI*DELR*(WF*SIGF*FLUX+RHO*SPH*ICF/DELT)
  END IF
ELSE
  IF(I.EQ.NSUB)THEN
    B2=BCF*RI*DELR*(WF*SIGF*FLUX+RHO*SPH*ICF*TMAT(I,1)/DELT)-A*TOU
&T
  ELSE
    B2=BCF*RI*DELR*(WF*SIGF*FLUX+RHO*SPH*ICF*TMAT(I,1)/DELT)
  END IF
END IF
C
RETURN
END
C
C-----
SUBROUTINE SETUP
C
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
C

```

```

      INTEGER L,I
C
      IF(I.EQ.1)THEN
        AMAT(1,1)=B1+C
        AMAT(1,2)=A
        BVEC(1)=B2
      ELSE
        L=L+1
        AMAT(I,L)=C
        AMAT(I,L+1)=B1
        IF(I.NE.NSUB)AMAT(I,L+2)=A
        BVEC(I)=B2
      END IF
C
      RETURN
      END
C
C-----
      SUBROUTINE CALCT
C
      COMMON/CONTRL/NSSTEP,NP
      COMMON/GAS0/KCOND,IK2
      COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
      COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
C
      REAL WK(150)
      INTEGER P,TSTEP
C
      MM=1
      IJOB=0
      IA=50
      IB=50
      CALL LEQIF(AMAT,IA,NSUB,NSUB,BVEC,IB,MM,IJOB,WK,IER)
C
      DO 40 J=1,NSUB
        TMAT(J,2)=BVEC(J)
40  CONTINUE
C
      TMAT(NSUB+1,2)=TOUT
C
      RETURN
      END
C
C-----
      SUBROUTINE TESTKF
C
      COMMON/GAS0/KCOND,IK2
      COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
      COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
C
      IF(IK2.EQ.0)THEN

```

```

DO 25 J=1,NSUB
  TMAT(J,1)=0.0
  TMAT(J,2)=1000.0
25 CONTINUE
  IK2=1
  END IF
C
DO 50 J=1,NSUB
  EPS=ABS((TMAT(J,2)-TMAT(J,1))/TMAT(J,2))
  IF(EPS.GT.0.0001)GO TO 75
50 CONTINUE
  KCOND=1
  GO TO 110
C
75 DO 100 J=1,NSUB
  TMAT(J,1)=TMAT(J,2)
100 CONTINUE
C
110 RETURN
  END
C
C-----
C..... OUTPUTS THE NUMERICAL DATA TO A SPECIFIED DEVICE .....
C
SUBROUTINE OUTPUT
C
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/TIMES/TIMC,TIML,DELT,DELT',TOFDP,PCNTDP,TOTDP,RT
COMMON/TIMES1/TOTUP,ICASE
COMMON/VOLS/VOLF,VOLG,VOLC
COMMON/DEFECT/NDEF,FS
COMMON/CONTRL/NSTEP,NP
COMMON/GASO/KCOND,IK2
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE
COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
C
INTEGER I,P,TSTEP
REAL KF1,KF2
C
C
C DO 25 I=1,NSTEP
C RI=DELR*I
C WRITE(3,50)TMAT(1,2),TMAT(15,2),TI
C 25 CONTINUE
C 50 FORMAT(1X,2F10.3,F17.5)
C
WRITE(2,60)FLUX*1.0E-14,TI/3600.0

```

```

60 FORMAT(1X,F10.4,F17.5)
C
  WRITE(8,75)EI(1)*1.0E00,TI
75 FORMAT(1X,E17.4,F17.5)
C
  WRITE(11,85)R*1.0E00,TI/3600.0
85 FORMAT(1X,E17.4,F17.5)
C
  I=1
C
  WRITE(4,100)CONCR(I)*1.0E-20,TI/3600.0
100 FORMAT(1X,F12.4,F17.5)
C
  WRITE(10,125)CONCG(I)*1.0E-19,TI/3600.0
125 FORMAT(1X,F12.4,F17.5)
C
  WRITE(12,150)CONCP(I)*1.0E-14,TI/3600.0
150 FORMAT(1X,F12.4,F17.5)
C
  RETURN
  END
C
C-----
C..... OUTPUTS RUN CHARACTERISTICS TO A SPECIFIED DEVICE .....
C
  SUBROUTINE RUNDAT
C
  COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
  COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
  COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
  COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
  COMMON/TIMES1/TOTUP,ICASE
  COMMON/VOLS/VOLF,VOLG,VOLC
  COMMON/DEFECT/NDEF,FS
  COMMON/CONTRL/NSTEP,NP
  COMMON/GAS0/KCOND,IK2
  COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
  COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
  COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE
  COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
C
  INTEGER P
C
  IF(ICASE.EQ.1.AND.P.EQ.1)THEN
  CSS1=CONCP(1)
  CSS2=CONCP(2)
  CSS3=CONCP(3)
  CT1=CSS1
  CT2=CSS2
  CT3=CSS3
  IWRITE=0

```

```

IWRIT1=0
END IF
C
IF(ICASE.EQ.1)THEN
IF(CONCP(1).GT.CT1)THEN
CT1=CONCP(1)
TIM1=(TI-TOFDP)/3600.0
END IF
IF(CONCP(2).GT.CT2)THEN
CT2=CONCP(2)
TIM2=(TI-TOFDP)/3600.0
END IF
IF(CONCP(3).GT.CT3)THEN
CT3=CONCP(3)
TIM3=(TI-TOFDP)/3600.0
END IF
END IF
C
IF(ICASE.EQ.2.AND.NP.EQ.0)THEN
CUP1I=CONCP(1)
CUP2I=CONCP(2)
CUP3I=CONCP(3)
CUP1T=CUP1I
CUP2T=CUP2I
CUP3T=CUP3I
IWRITE=0
IWRIT1=0
END IF
C
IF(ICASE.EQ.2.AND.NP.EQ.1)THEN
IF(CONCP(1).GT.CUP1T)THEN
CUP1T=CONCP(1)
TIM1=(TI-TOTDP)/3600.0
END IF
IF(CONCP(2).GT.CUP2T)THEN
CUP2T=CONCP(2)
TIM2=(TI-TOTDP)/3600.0
END IF
IF(CONCP(3).GT.CUP3T)THEN
CUP3T=CONCP(3)
TIM3=(TI-TOTDP)/3600.0
END IF
END IF
C
IF(ICASE.EQ.2)THEN
CSS1=CUP1I
CSS2=CUP2I
CSS3=CUP3I
CT1=CUP1T
CT2=CUP2T
CT3=CUP3T

```

```

      END IF
C
      IF(IWRIT1.EQ.0)THEN
      IF(CONCP(1).LT.CT1.AND.CONCP(2).LT.CT2.AND.CONCP(3).LT.CT3)THEN
      IWRITE=1
      END IF
      IF(IWRITE.EQ.1)THEN
      IWRIT1=1
      CMCS1=CT1/CSS1
      CMCS2=CT2/CSS2
      CMCS3=CT3/CSS3
      AO1=CSS1*AL(4)/(2.5123E10)
      AO2=CSS2*AL(6)/(2.5123E10)
      AO3=CSS3*AL(10)/(2.5123E10)
      IF(ICASE.EQ.1)WRITE(14,145)
      IF(ICASE.EQ.2)WRITE(14,150)
      WRITE(14,*)
      WRITE(14,153)STEAM,ABSFAC
      WRITE(14,157)ABSSB,ABSTE
      WRITE(14,*)
      WRITE(14,*)
      WRITE(14,175)
      WRITE(14,*)
      WRITE(14,200)CSS1,CSS2,CSS3
      WRITE(14,225)AO1,AO2,AO3
      WRITE(14,*)
      WRITE(14,*)
      WRITE(14,250)CMCS1,CMCS2,CMCS3
      WRITE(14,*)
      WRITE(14,260)TIM1,TIM2,TIM3
      WRITE(14,*)
      WRITE(14,270)NDEF
      WRITE(14,*)
      WRITE(14,280)FS
      WRITE(14,*)
      WRITE(14,290)FRACT*100.0
      WRITE(14,*)
      WRITE(14,300)BURN
      END IF
      END IF *
C
145 FORMAT(1X,'CASE 1: DOWN POWER TRANSIENT')
150 FORMAT(1X,'CASE 2: UP POWER TRANSIENT')
153 FORMAT(1X,'WATER ENHANCEMENT = ',F9.4,' I GAP FACTOR = ',F6.5)
157 FORMAT(1X,'SB GAP FACTOR = ',F6.5,' TE GAP FACTOR = ',F6.5)
175 FORMAT(1X,'          IODINE-131 IODINE-132 IODINE-133')
200 FORMAT(10X,3E12.4,'    NO./CU.M')
225 FORMAT(10X,3F12.4,'    UCI/G')
250 FORMAT(4X,'MAX/SS',3F12.4)
260 FORMAT(1X,'PEAK TIME',3F12.4,'.    HRS')
270 FORMAT(1X,'NUMBER OF FAILED RODS =.',I5)

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280 FORMAT(1X,'AVERAGE FAILURE SIZE = ',E12.4,' M')
290 FORMAT(1X,'FILTER SYSTEM = ',F10.4,' %')
300 FORMAT(1X,'AVERAGE FUEL BURN UP = ',F10.4,' MWD/MT')
RETURN
END
C-----
C..... CALCULATES THE POWER LEVEL DURING THE TRANSIENT .....
C
C      SUBROUTINE FLUXCA(TIME1)
C
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/CONTRL/NSTEP,NP
COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE
C
C      INTEGER I,P
C      REAL KF1,KF2
C
C      IF(NP)10,20,30
10    FLUX=FLUXO
      GO TO 40
20    IF(TIME1.LE.TOFPD)FLUX=FLUXO
      IF(TIME1.GT.TOFPD)FLUX=PCNTDP*FLUXO
      GO TO 40
30    IF(TIME1.GE.TOTDP)THEN
      IF(TIME1-TOTDP.LE.RT)THEN
      FLUX=PCNTDP*FLUXO+(TIME1-TOTDP)/RT*(FLUXO-PCNTDP*FLUXO)
      ELSE
      FLUX=FLUXO
      END IF
      END IF
40    CONTINUE
      RETURN
      END
C
C-----
C      SUBROUTINE TEMPR
C
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
COMMON/CONTRL/NSTEP,NP
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE
C
C      INTEGER P
C      IORF=1
C
C      CALL FLUXCA(TI)
C

```

```

PCNT=FLUX/FLUXO
C
  IF (IORF.EQ.0) THEN
    HC=3441.708-619.2136*PCNT
  ELSE
    IF (PCNT.LE.0.11) HC=1016189.3-9200762.8*PCNT
    IF (PCNT.GT.0.11) HC=938.01+231.54*PCNT
  END IF
  TOUT=(WF*SIGF*FLUX*RF/(2.0*HC))+BULK
C
  RETURN
  END
C
C-----
C..... CALCULATES THE STEADY-STATE EFFLUX .....
C
  SUBROUTINE EFSTDY
C
  COMMON/GEOM/RF, THG, THC, POND, PITCH, DROD, DCORE, NRODS, HT
  COMMON/EFFLUX/EI(3), EIO(3), FRAC(3), FGAS(50), FDOT(50), FI(3), R
  COMMON/CONTRL/NSTEP, NP
  COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
  COMMON/GAS2/AMAT(50,50), TMAT(50,2), BVEC(50), A, B1, C, B2, TOUT, JN, JO
  COMMON/GAS3/BURN, IORF, BULK, IFLG, STEAM, ABSFAC, ABSSB, ABSTE
C
  RI=0.0
  SUM1=0.0
  SUM2=0.0
C
  IF (BURN.EQ.0) THEN
    DO 20 I=1, NSTEP
      RI=RI+DELR
      SUM1=SUM1+(1-EXP(-(6916.67/TMAT(I,2))+1.84))*RI
      FGAS(I)=EXP(-(6916.67/TMAT(I,2))+1.84)
      SUM2=SUM2+FGAS(I)*RI
20  CONTINUE
      GO TO 40
    END IF
C
    DO 25 I=1, NSTEP
      RI=RI+DELR
      CALL FVAL(TMAT(I,2), BURN, RATE, F)
      FGAS(I)=F
      FDOT(I)=RATE/3600.0
      SUM1=SUM1+FDOT(I)*RI
      SUM2=SUM2+FGAS(I)*RI
25  CONTINUE
C
40  IF (TMAT(NSTEP/2,2).LE.680.0) ENHANC=STEAM
    IF (TMAT(NSTEP/2,2).GT.680.0) ENHANC=1.0
    EI(1)=(SUM1/RF)*ENHANC

```



```

      EIO(1)=EI(1)
C
      FRAC(1)=SUM2/RF
C
50 RETURN
      END
C
      SUBROUTINE FVAL(TEMP,BURN,FDOT,F)
      REAL K1,K1K2,TEMP
      K1=EXP(-(6916.67/TEMP)+1.84)
      K1K2=0.25*EXP(-11894.44/TEMP)
      F=1.0-(1.0-K1)*((1.0-EXP(-0.6347*K1K2*BURN))/(0.6347*K1K2*BURN))
      IF(F.LT.0.0)F=0.0
      FDOT=(1.0-K1)*(1.0-(1.0+0.6347*K1K2*BURN)*EXP(-0.6347*K1K2*BURN))
      &/(0.4028*K1K2*BURN**2)
      RETURN
      END
C
C-----
C..... CALCULATES THE TRANSIENT EFFLUX .....
C
      SUBROUTINE EFTRAN
C
      COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
      COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
      COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
      COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
      COMMON/CONTRL/NSTEP,NP
      COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
      COMMON/GAS2/AMAT(50,50),TMAT(50,2),BVEC(50),A,B1,C,B2,TOUT,JN,JO
      COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE
      COMMON/SUBGAS/FVAL
      COMMON/SUBTRN/A1,A2,A3,A4,GRADT
C
      REAL CON1(50)
      INTEGER P
C
      CA=CY(1)*SIGF*FLUXO/(AL(4)+EIO(1))
      CB=CY(2)*SIGF*FLUXO/(AL(6)+EIO(1))
      CC=CY(3)*SIGF*FLUXO/(AL(10)+EIO(1))
      CO=CA+CB+CC
      A1=(7.68E16)*CO**(-0.7654)
      A2=37800.0
      A3=-1833.26+77.8269*ALOG(CO)-0.823859*(ALOG(CO))**2
      A4=0.0266916-(4.89386E-4)*ALOG(CO)
C
      RI=0.0
      SUM2=0.0
      DO 50 I=1,NSTEP
      RI=RI+DELR
      IF(I.GT.1)GRADT=ABS((TMAT(I-1,2)-TMAT(I,2))/DELR)

```

```

      IF(I.EQ.1)GRADT=0.0
      IF(IFLG.EQ.0)THEN
      IF(I.GT.1)THEN
      CON1(I)=FDOT(I)/(A1*GRADT*EXP(-(A2/TMAT(I,2))-(A3+A4*TMAT(I,2))
&*FGAS(I)))
      ELSE
      CON1(I)=0.0
      END IF
      END IF
      FDOT(I)=CON1(I)*A1*GRADT*EXP(-(A2/TMAT(I,2))-(A3+A4*TMAT(I,2))
&*FGAS(I))
      IF(TMAT(I,2).LE.618.0)ENHANC=STEAM
      IF(TMAT(I,2).GT.618.0)ENHANC=1.0
      SUM2=SUM2+FDOT(I)*RI*ENHANC
50 CONTINUE
C
      EI(1)=SUM2/RF
C
      IFLG=1
      RETURN
      END
C
C*****
C..... CALCULATES CONCENTRATIONS IN THE PELLETT AND GAP .....
C
      SUBROUTINE CONC
C
      COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
      COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
      COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
      COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
      COMMON/CONTRL/NSTEP,NP
      COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
      COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE
      COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
      COMMON/SUB1/VFVG,II,SB(3),TEM(3),TE(3),ISB,ITEM,ITE
      COMMON/SUB13/SBG(3),TEMG(3),TEG(3)
      COMMON/SUB12/GM1,GM2,GM3,GM4,GM5
C
      INTEGER P
C
      DO 55 I=1,3
C
      IF(I.EQ.1)THEN
      ISB=1
      ITEM=2
      ITE=3
      II=4
      GM1=0.15
      GM2=0.2
      GM3=0.85

```

```

GM4=1.0
GM5=0.8
END IF
IF(I.EQ.2)THEN
ITE=5
II=6
GM2=0.0
GM3=0.0
GM4=1.0
GM5=0.0
END IF
IF(I.EQ.3)THEN
ISB=7
ITEM=8
ITE=9
II=10
GM1=0.72
GM2=0.13
GM3=0.28
GM4=1.0
GM5=0.87
END IF

```

C

```

IF(P.EQ.1)THEN
VFVG=(RF**2)/(2.0*RF*THG+THG**2)

```

C

C.....STEADY-STATE CONCENTRATIONS IN THE FUEL .....

C

```

SB(I)=DY(ISB)*SIGF*FLUXO/(AL(ISB)+EI(1))
TEM(I)=(DY(ITEM)*SIGF*FLUXO+GM1*AL(ISB)*SB(I))/(AL(ITEM)+EI(1))
TE(I)=(DY(ITE)*SIGF*FLUXO+GM2*AL(ITEM)*TEM(I)+GM3*AL(ISB)*SB(I)
&/ (AL(ITE)+EI(1))
CONCR(I)=(DY(II)*SIGF*FLUXO+GM4*AL(ITE)*TE(I)+GM5*AL(ITEM)*TEM(I)
&)/(AL(II)+EI(1))

```

C

C.....STEADY-STATE CONCENTRATIONS IN THE GAP .....

```

SBG(I)=VFVG*EI(1)*SB(I)*ABSSB/(AL(ISB)+R)
TEMG(I)=(VFVG*EI(1)*TEM(I)*ABSTE+GM1*AL(ISB)*SBG(I)
&/ (AL(ITEM)+R)
TEG(I)=(VFVG*EI(1)*TE(I)*ABSTE+GM2*AL(ITEM)*TEMG(I)
&GM3*AL(ISB)*SBG(I))/(AL(ITE)+R)
CONCG(I)=(VFVG*EI(1)*CONCR(I)*ABSFAC+GM4*AL(ITE)*TEG(I)
&GM5*AL(ITEM)*TEMG(I))/(AL(II)+R)

```

C

ELSE

C

C.....CALCULATES ANTIMONY CONCENTRATION IN THE FUEL .....

C

```

CS1=DELT*FSB(SB(I))
CS2=DELT*FSB(SB(I)+0.5*CS1)
CS3=DELT*FSB(SB(I)+0.5*CS2)
CS4=DELT*FSB(SB(I)+CS3)

```

```

      SB(I)=SB(I)+(CS1+2.0*CS2+2.0*CS3+CS4)/6.0
C
C.....CALCULATES TELLURIUM-M CONCENTRATION IN THE FUEL .....
C
      CTM1=DELT*FTEM(TEM(I))
      CTM2=DELT*FTEM(TEM(I)+0.5*CTM1)
      CTM3=DELT*FTEM(TEM(I)+0.5*CTM2)
      CTM4=DELT*FTEM(TEM(I)+CTM3)
      TEM(I)=TEM(I)+(CTM1+2.0*CTM2+2.0*CTM3+CTM4)/6.0
C
C.....CALCULATES TELLURIUM CONCENTRATION IN THE FUEL .....
C
      CT1=DELT*FTE(TE(I))
      CT2=DELT*FTE(TE(I)+0.5*CT1)
      CT3=DELT*FTE(TE(I)+0.5*CT2)
      CT4=DELT*FTE(TE(I)+CT3)
      TE(I)=TE(I)+(CT1+2.0*CT2+2.0*CT3+CT4)/6.0
C
C.....CALCULATES IODINE CONCENTRATION IN THE FUEL .....
C
      CI1=DELT*FIR(CONCR(I))
      CI2=DELT*FIR(CONCR(I)+0.5*CI1)
      CI3=DELT*FIR(CONCR(I)+0.5*CI2)
      CI4=DELT*FIR(CONCR(I)+CI3)
      CONCR(I)=CONCR(I)+(CI1+2.0*CI2+2.0*CI3+CI4)/6.0
C
C.....CALCULATES ANTIMONY CONCENTRATION IN THE GAP .....
C
      CS1=DELT*FSBG(SBG(I))
      CS2=DELT*FSBG(SBG(I)+0.5*CS1)
      CS3=DELT*FSBG(SBG(I)+0.5*CS2)
      CS4=DELT*FSBG(SBG(I)+CS3)
      SBG(I)=SBG(I)+(CS1+2.0*CS2+2.0*CS3+CS4)/6.0
C
C.....CALCULATES TELLURIUM-M CONCENTRATION IN THE GAP .....
C
      CTM1=DELT*FTEMG(TEMG(I))
      CTM2=DELT*FTEMG(TEMG(I)+0.5*CTM1)
      CTM3=DELT*FTEMG(TEMG(I)+0.5*CTM2)
      CTM4=DELT*FTEMG(TEMG(I)+CTM3)
      TEMG(I)=TEMG(I)+(CTM1+2.0*CTM2+2.0*CTM3+CTM4)/6.0
C
C.....CALCULATES TELLURIUM CONCENTRATION IN THE GAP .....
C
      CT1=DELT*FTEG(TEG(I))
      CT2=DELT*FTEG(TEG(I)+0.5*CT1)
      CT3=DELT*FTEG(TEG(I)+0.5*CT2)
      CT4=DELT*FTEG(TEG(I)+CT3)
      TEG(I)=TEG(I)+(CT1+2.0*CT2+2.0*CT3+CT4)/6.0
C

```

C.....CALCULATES IODINE CONCENTRATION IN THE GAP .....

C

```
CG1=DELT*FIG(CONCG(I))
CG2=DELT*FIG(CONCG(I)+0.5*CG1)
CG3=DELT*FIG(CONCG(I)+0.5*CG2)
CG4=DELT*FIG(CONCG(I)+CG3)
CONCG(I)=CONCG(I)+(CG1+2.0*CG2+2.0*CG3+CG4)/6.0
```

C

END IF

C

55 CONTINUE

C

```
RETURN
END
```

C

```
FUNCTION FSB(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
COMMON/SUBI/VFVG,II,SB(3),TEM(3),TE(3),ISB,ITEM,ITE
COMMON/SUBI2/GM1,GM2,GM3,GM4,GM5
FSB=DY(ISB)*SIGF*FLUX-(AL(ISB)+EI(1))*X
RETURN
END
```

C

```
FUNCTION FTEM(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
COMMON/SUBI/VFVG,II,SB(3),TEM(3),TE(3),ISB,ITEM,ITE
COMMON/SUBI2/GM1,GM2,GM3,GM4,GM5
FTEM=DY(ITEM)*SIGF*FLUX+GM1*AL(ISB)*SB(I)-(AL(ITEM)+EI(1))*X
RETURN
END
```

C

```
FUNCTION FTE(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
COMMON/SUBI/VFVG,II,SB(3),TEM(3),TE(3),ISB,ITEM,ITE
COMMON/SUBI2/GM1,GM2,GM3,GM4,GM5
FTE=DY(ITE)*SIGF*FLUX+GM2*AL(ITEM)*TEM(I)+GM3*AL(ISB)*SB(I)-
&(AL(ITE)+EI(1))*X
RETURN
END
```

C

```
FUNCTION FIR(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
```

```

COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
COMMON/GAS4/CONCR(3), CONCG(3), CONCP(3), FRACT
COMMON/SUBI/VFVG, II, SB(3), TEM(3), TE(3), ISB, ITEM, ITE
COMMON/SUBI2/GM1, GM2, GM3, GM4, GM5
FIR=DY(II)*SIGF*FLUX+GM4*AL(ITE)*TE(I)+GM5*AL(ITEM)*TEM(I)-
&(AL(II)+EI(1))*X
RETURN
END

```

C

```

FUNCTION FSBG(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
COMMON/GAS4/CONCR(3), CONCG(3), CONCP(3), FRACT
COMMON/SUBI/VFVG, II, SB(3), TEM(3), TE(3), ISB, ITEM, ITE
COMMON/SUBI2/GM1, GM2, GM3, GM4, GM5
COMMON/SUBI3/SBG(3), TEMG(3), TEG(3)
FSBG=VFVG*EI(1)*SB(I)-(AL(ISB)+R)*X
RETURN
END

```

C

```

FUNCTION FTEMG(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
COMMON/GAS4/CONCR(3), CONCG(3), CONCP(3), FRACT
COMMON/SUBI/VFVG, II, SB(3), TEM(3), TE(3), ISB, ITEM, ITE
COMMON/SUBI2/GM1, GM2, GM3, GM4, GM5
COMMON/SUBI3/SBG(3), TEMG(3), TEG(3)
FTEMG=VFVG*EI(T)*TEM(I)+GM1*AL(ISB)*SBG(I)-(AL(ITEM)+R)*X
RETURN
END

```

C

```

FUNCTION FTEG(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
COMMON/GAS4/CONCR(3), CONCG(3), CONCP(3), FRACT
COMMON/SUBI/VFVG, II, SB(3), TEM(3), TE(3), ISB, ITEM, ITE
COMMON/SUBI2/GM1, GM2, GM3, GM4, GM5
COMMON/SUBI3/SBG(3), TEMG(3), TEG(3)
FTEG=VFVG*EI(1)*TE(I)+GM2*AL(ITEM)*TEMG(I)+GM3*AL(ISB)*SBG(I)-
&(AL(ITE)+R)*X
RETURN
END

```

C

```

FUNCTION FIG(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L

```

```

COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
COMMON/SUBI/VFVG,II,SB(3),TEM(3),TE(3),ISB,ITEM,ITE
COMMON/SUBI3/SBG(3),TEMG(3),TEG(3)
FIG=VFVG*EI(1)*CONCR(I)+GM4*AL(ITE)*TEG(I)+GM5*AL(ITEM)*TEMG(I)
&-(AL(II)+R)*X
RETURN
END

```

C

C-----

C..... CALCULATES THE LEACH RATE .....

C

SUBROUTINE RCAL

C

```

C THE FOLLOWING SECTION UTILIZES A NUMBER OF TESTS TO DIRECT
C THE MAIN CODE TO THE APPROPRIATE TRANSIENT SUBROUTINE LOCATED
C WITHIN THIS SUBROUTINE WHICH RETURNS THE EFFECTIVE IODINE
C LEACHING RATE TO THE MAIN CODE

```

C

```

COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/CONTRL/NSTEP,NP
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS3/BURN,IORF,BULK,IFLG,STEAM,ABSFAC,ABSSB,ABSTE
COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
COMMON/DEFECT/NDEF,FS
INTEGER P

```

C

C

C

```

IF(P.EQ.1) THEN
IFLGC=0
ICLK=0
IFLGR=0
TIR=TI
IF(NP) 10,20,30
10 CALL SPOWER(TIR)
GO TO 40
20 CALL DPOWER(TIR)
GO TO 40
30 CALL UPOWER(TIR,ICLK)
40 CONTINUE
END IF

```

C

C

```

IF(P.GT.1) THEN
IF(TI.LT.90000.0)THEN
IF(FLUX.NE.FLUXO)THEN
IF(IFLGR.EQ.0) TR=TI
IFLGR=1
IF(NP.EQ.1.AND.IFLGU.EQ.0) THEN
TR=TI

```

```

IFLGU=1
END IF
TIR=TI-TR
IF(NP) 50,60,70
50 CALL SPOWER(TIR)
GO TO 80
60 CALL DPOWER(TIR)
GO TO 80
70 CALL UPOWER(TIR,ICLK)
80 CONTINUE
END IF
END IF
END IF
RETURN
END

C
SUBROUTINE SPOWER(T)
WRITE(6,100)
100 FORMAT(1X,'NO CODE FOR SUDDEN ROD FAILURE YET')
RETURN
END

C
SUBROUTINE UPOWER(TS,ICLK)
REAL*8 KAPA,BETA,QT,GAMMA,H,T,D,D1,D2,TGA1,TGA,TCA,TCA1,DT,X
1,TSAT,PI,EMASS,TC,HGC,CPW,SPV,V,CP
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
COMMON/DEFECT/NDEF,FS
COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT

C
C
C
C THIS PROGRAM USES AN IMPLICIT FINITE DIFFERENCE SCHEME TO SOLVE
C TWO COUPLED LINEAR FIRST-ORDER DIFFERENTIAL EQUATIONS FOR GAP
C AVERAGE TEMPERATURE AND CLAD AVERAGE TEMPERATURE FOR THE SUB-
C COOLED AND SUPERHEATED REGIONS IN THE GAP. THE EFFECTIVE IODINE
C LEACH RATE AS A FUNCTION OF TIME IS THEN CALCULATED BASED ON
C SOLUBILITY AND GAP PHASE DIFFERENCES
C
C
C
C.....INITIALIZE TIME TEMPERATURES AND OTHER QUANTITIES.....
C
C
T=DBLE(TS)
TSAT=3.4476D2
IF(ICLK.EQ.1) GO TO 20
ICLK=1
IF(PCNTDP.LE.0.1.AND.PCNTDP.GE.0.05) GO TO 10
TGA=3.08D2
TCA=3.01D2

```



```

      GO TO 20
10  TGA=3.02D2
    TCA=3.00D2
20  PI=3.141592653538979D0
    H=DBLE(DELT)
C
C.....EVALUATE VARIOUS DIMENSIONAL PARAMETERS.....
C
    GVOL=HT*PI*((RF+THG)**2-(RF**2))
    CVOL=HT*PI*((RF+THG+THC)**2-((RF+THG)**2))
    AIG=HT*PI*RF*2.0D0
    AOG=HT*PI*(RF+THG)*2.0D0
    AOC=HT*PI*(RF+THG+THC)*2.0D0
C
C
C
C
C.....UTILIZE IMPLICIT METHOD AND CRAMERS RULE.....
C
    IF(T.GE.DBLE(RT)) GO TO 50
    T=T+H
    TC=TB(T,DBLE(RT),DBLE(PCNTDP))
    HGC=HG(TC,DBLE(THG))
    CPW=SPECH(TC)
    SPV=SVOL(TC)
    V=VISC(TC)
    BETA=HG(TGA,DBLE(THG))*DBLE(AOG)/DBLE(ROC(SNGL(TCA)))
1/DBLE(CPC(SNGL(TCA)))/DBLE(CVOL)
    KAPA=HFC(TC,CPW,HGC,DBLE(THC),SPV,V,PI,DBLE(THG))*DBLE(AOC)
1/DBLE(ROC(SNGL(TCA)))/DBLE(CPC(SNGL(TCA)))/DBLE(CVOL)
    CP=SPECH(TGA)
    QT=DBLE(AIG)*DBLE(HFLUX(SNGL(T),SNGL(PI),RF))/CP
1/DBLE(GVOL)*SVOL(TGA)
    GAMMA=HG(TGA,DBLE(THG))*DBLE(AOG)/CP
1/DBLE(GVOL)*SVOL(TGA)
    D=(1.0D0+GAMMA*H)*(1.0D0+(BETA+KAPA)*H)-BETA*H**2*GAMMA
    D1=(TGA+H*QT)*(1.0D0+(BETA+KAPA)*H)+GAMMA*H*(TCA+H*KAPA*TC)
    D2=(1.0D0+GAMMA*H)*(TCA+H*KAPA*TC)+BETA*H*(TGA+H*QT)
    TGA1=D1/D
    TCA1=D2/D
    IF(TGA1.GT.TSAT) GO TO 40
C
C.....CALCULATE THE MASS FLOW RATE.....
C
C
    DT=(TGA1-TGA)/H
    EMASS=DABS(DBLE(GVOL)*(-0.8061477D-5*DT+DT*TGA1*2.0D0*0.2074612D-7
1)/SVOL(TGA1)**2)
    TGA=TGA1
    TCA=TCA1
    GO TO 50

```

```

40 DT=(TGA1-TGA)/H
   EMASS=DABS(DBLE(GVOL)*DT*0.1149D-3/SVOL(TGA1)**2)
   TGA=TGA1
   TCA=TCA1
50 CALL LEACH(PI,X,EMASS,TGA,DBLE(GVOL),T,DBLE(FS))
   R=SNGL(X)
   RETURN
   END

C
C.....VARIOUS PROPERTIES,FILM COEFFICIENTS,AND OTHER FUNCTIONS....
C
   FUNCTION HFLUX(T,PI,RF)
C
C.....THIS FUNCTION CALCULATES THE RADIAL HEAT FLUX AS A .....
C   FUNCTION OF POWER RISE TIME AND INITIAL POWER DURING
C   AN UP-POWER TRANSIENT
C
   COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
   H100=1.78D4/2.0D0/PI/RF
   IF(T.LT.RT) GO TO 10
   HFLUX=H100
   GO TO 20
10 HFLUX=H100*PCNTDP+T/RT*(H100-H100*PCNTDP)
20 RETURN
   END

C
   FUNCTION TB(T,RT,PCNTDP)
C
C.....THIS FUNCTION CALCULATES THE AVERAGE BULK COOLANT.....
C   TEMPERATURE IN THE CORE AS A FUNCTION OF REACTOR
C   POWER LEVEL, AND THE TIME INTO THE UP-POWER TRANSIENT.
C   IT ASSUMES A 16 DEGREE TEMPERATURE RISE ACROSS THE
C   CORE AT FULL POWER.
C
C
C
C
   IMPLICIT REAL*8(A-H,O-Z)
   IF(T.LT.RT) GO TO 10
   TB=3.16D2
   GO TO 20
10 TB=3.0D2+PCNTDP*1.6D1+T/RT*(1.6D1-PCNTDP*1.6D1)
20 RETURN
   END

C
   FUNCTION HG(TT,THG)
C
C.....THIS FUNCTION CALCULATES THE THERMAL CONDUCTIVITY.....
C   BY A PARAMETRIC EQUATION BASED ON STEAM TABLE DATA FOR
C   WATER AT 15.5 MPA IN THE TEMPERATURE RANGE FROM
C   150 TO 344 DEGREES C., AND AT 15.5 MPA,
C   345 TO 800 DEGREES C. FOR STEAM. THE FUNCTION
C   THEN DIVIDES THE CONDUCTIVITY BY THE GAP WIDTH

```

C TO OBTAIN AN EFFECTIVE FILM COEFFICIENT FOR THE GAP.  
 C  
 C  
 C

```

    IMPLICIT REAL*8(A-H,O-Z)
    SQ=1.0D0
    TSAT=3.4476D2
    IF(TT-TSAT) 10,10,20
10  A=0.5738939D0
    B=0.1856064D-2
    C=-0.7251704D-5
    D=0.3312791D-8
    HG=A+B*TT+C*TT**2+D*TT**3
    IF(TT.NE.TSAT) GO TO 40
20  E=0.1908595192377D5
    F=-0.199843929753D3
    G=0.8656800759426D0
    H=-0.197858979033D-2
    O=0.25171077343609D-5
    P=-0.1689687887258D-8
    Q=0.46760429802869D-12
    HT=(E+F*TT+G*TT**2+H*TT**3+O*TT**4+P*TT**5+Q*TT**6)/1.0D3
    IF(TT.EQ.TSAT) GO TO 30
    HG=HT
    GO TO 40
30  HG=SQ*HT+(1.0D0-SQ)*HG
40  HG=HG/THG
    RETURN
    END
  
```

C

FUNCTION SVOL(TT)

C

C.....THIS FUNCTION UTILIZES A PARAMETRIC EQUATION BASED.....  
 C ON STEAM TABLE DATA TO CALCULATE THE SPECIFIC VOLUME  
 C OF BOTH WATER AND STEAM AT 15.5 MPA. THE RANGE FOR LIQUID  
 C WATER IS FROM 290 TO 344 DEGREES C. AND 345 TO 800  
 C DEGREES FOR STEAM.  
 C  
 C

C

```

    IMPLICIT REAL*8(A-H,O-Z)
    TSAT=3.4476D2
    IF(TT.GT.TSAT) GO TO 10
    A=0.193991D-2
    B=-0.8061477D-5
    C=0.2074612D-7
    SVOL=A+B*TT+C*TT**2
    GO TO 20
10  D=-0.2968472D-1
    E=0.1149D-3
    SVOL=D+E*TT
20  IF(TT.LT.TSAT) GO TO 50
  
```

```

50 RETURN
END
C
FUNCTION SPECH(TT)
C
C.....THIS FUNCTION UTILIZES A PARAMETRIC EQUATION BASED.....
C      ON STEAM TABLE DATA TO CALCULATE THE SPECIFIC HEAT
C      OF BOTH WATER AND STEAM AT 15.5 MPA. THE RANGE FOR LIQUID
C      WATER IS FROM 290 TO 344 DEGREES C. AND 345 TO 800
C      DEGREES FOR STEAM.
C
C
C      IMPLICIT REAL*8(A-H,O-Z)
C      TSAT=3.4476D2
C      IF(TT.GT.TSAT) GO TO 10
C      A=4.5423671D0
C      B=-0.1129279D-1
C      C=0.5288968D-4
C      SPECH=(A+B*TT+C*TT**2)*1.0D3
C      GO TO 20
10  A=0.21845843D4
C      B=-0.210549297D2
C      C=0.80866262448D-1
C      D=-0.1543756023D-3
C      E=0.1464029544D-6
C      F=-0.5516463108D-10
C      SPECH=(A+B*TT+C*TT**2+D*TT**3+E*TT**4+F*TT**5)*1.0D3
20  IF(TT.LE.TSAT) GO TO 50
50  RETURN
END
C
FUNCTION ROC(TT)
C
C.....THIS FUNCTION ASSIGNS A SINGLE VALUE FOR THE DENSITY.....
C      OF THE FUEL CLAD. IT DID NOT VARY SIGNIFICANTLY OVER
C      THE TEMPERATURE RANGE OF THE CLAD OF 300 TO 700 C.
C
C
C      ROC=6.487D3
C      RETURN
C      END
C
FUNCTION CPC(TT)
C
C.....THIS FUNCTION UTILIZES A PARAMETRIC EQUATION TO .....
C      CALCULATE THE SPECIFIC HEAT OF THE CLAD OVER A
C      TEMPERATURE RANGE OF 300 TO 700 DEGREES C.
C
C
C
C
C      TSAT=3.4476D2
C      A=6.72D-2

```

```

B=2.6D-4
CPC=(A+B*TT)*4.18331D3
RETURN
END

```

C

```
FUNCTION VISC(TT)
```

C

```

C.....THIS FUNCTION UTILIZES A PARAMETRIC EQUATION BASED.....
C      ON STEAM TABLE DATA TO CALCULATE THE VISCOSITY
C      FOR WATER AT 15.5 MPA. THE RANGE FOR LIQUID
C      WATER IS FROM 290 TO 344 DEGREES C.
C
C
C

```

```

IMPLICIT REAL*8(A-H,O-Z)
A=0.710752D3
B=-0.6198629D1
C=0.2236857D-1
D=-0.2872D-4
VISC=(A+B*TT+C*TT**2+D*TT**3)*1.0D-6
RETURN
END

```

C

C

```
FUNCTION HFC(TC,CPW,HGC,THC,SPV,V,PI,THG)
```

```

C.....THIS FUNCTION CALCULATES THE HEAT TRANSFER FILM.....
C      COEFFICIENT FROM CLAD TO COOLANT BY USE OF THE
C      DITTUS-BOELTER CORRELATION. IT USES SUCH PLANT PARAMETERS
C      AS CORE MASS FLOW RATE,EFFECTIVE DIAMETER,FLOW AREA,
C      AND VARIOUS PROPERTIES OF WATER DEFINED IN OTHER
C      FUNCTIONS
C
C
C
C
C

```

```

IMPLICIT REAL*8(A-H,O-Z)
D=9.4D-3
P=1.32D0
RN=5.5777D4
FM=1.7222D4
DE=D*(4.0D0/PI*(P**2)-1.0D0)
FA=RN*((P*D)**2-D**2*PI/4.0D0)
UM=SPV/FA*FM
PR=CPW*V/HGC/THG
RE=DE*UM/SPV/V
HFC=HGC*THG*2.3D-2/DE*RE**0.8*PR**0.4
RETURN
END

```

C

C

```
SUBROUTINE LEACH(PI,X,E,TX,G,T,FS)
```

C

```

C.....THIS SUBROUTINE CALCULATES THE LEACH RATE AS .....

```

C DESCRIBED IN THE UP-POWER SECTION OF THE ANALYSIS  
 C IT ASSUMES AN W OF  $1 \times 10^5$  FOR THE TURBULENT  
 C FLOW OSCILLATIONS.  
 C  
 C  
 C

```

IMPLICIT REAL*8(A-H,O-Z)
REAL*8 N
TC=3.08D2
TS=8.00D2
W=2.0D5*PI
AREA=PI*FS**2
UIO=E*2.0D0**0.5/AREA*SVOL(TC)
UOO=E*2.0D0**0.5/AREA*SVOL(TX)
CF=AREA*UIO/SVOL(TC)
CG=AREA*UOO/G
SF=5.0D2/6.774D5
N=W*T/PI
GMASS=G/SVOL(TX)
X=CG*DABS(1.0D0/PI)*(1.0D0+(SF-1.0D0)*(G/GMASS-SVOL(TC)
1)/(SVOL(TS)-SVOL(TC)))
IF(X.GE.5.0D-3) X=5.0D-3
RETURN
END

```

C

SUBROUTINE DPOWER(TS)

C

C THIS ROUTINE CALCULATES THE MASS FLUX INTO AND OUT OF THE FUEL  
 C ROD GAP BASED ON THE TURBULENT OSCILLATIONS OCCURRING IN THE  
 C MAIN STREAM COOLANT CHANNEL, AND THEN CALCULATES THE IODINE LEACH  
 C RATE SIMILAR TO THE UP-POWER CASE  
 C  
 C  
 C

C

```

REAL*8 N,X,GMASS0,ERUF,PI,SVS,SV,DE,FA,CFLOW,V,UM,SK,CP,T,TBK
REAL*8 U,PR,RE,FF,QND,EMASS,GVOL,W,AREA,UIO,UOO,CF,CG,SF,GMT
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
COMMON/DEFECT/NDEF,FS
COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
ERUF=1.5D-6
T=DBLE(TS)
PI=3.1415926535D0
GMASS0=3.05D-4
SVS=2.5575D-2
SV=9.8135D-3

```

C

C.....EVALUATE VARIOUS PLANT FLOW PARAMETERS.....

C

C  
C

```

DE=DBLE(DROD)*(4.0D0/PI*(DBLE(POND)**2)-1.0D0)
FA=DBLE(FLOAT(NRODS))*(DBLE(PITCH)**2-DBLE(DROD)**2*PI/4.0D0)
CFLOW=1.7222D4
TBK=3.0D2+DBLE(PCNTDP)*1.6D1
V=SVOL(TBK)
UM=V/FA*CFLOW
SK=HG(TBK,DBLE(THG))*DBLE(THG)
CP=SPECH(TBK)
U=VISC(TBK)
PR=CP*U/SK
RE=DE*UM/V/U

```

C  
C  
C  
C  
C  
C  
C  
C

.....CALCULATE THE FRICTION FACTOR AND THEN.....  
THE MASS FLOW INTO THE GAP.

```

FF=2.5D-1/(DABS(DLOG10(ERUF/3.7D0/DE)+(5.74D0/RE**0.9)))**2
QND=4.108D-1*FF**5.0D-1*(1.0D0-1.181D1*DE/DBLE(FS)/RE/FF**5.0D-1)
EMASS=QND*UM*DBLE(FS)**2*PI/4.0D0/V
GVOL=PI*DBLE(HT*((RF+THG)**2-(RF**2)))
W=PI*2.0D5
AREA=PI*DBLE(FS)**2
UI0=EMASS*2**0.5/AREA*SVOL(TBK)
U00=EMASS*2**0.5/AREA*SV
CF=AREA*UI0/SVOL(TBK)
CG=AREA*U00/GVOL
SF=5.00D2/6.774D5
N=W*T/PI
GMT=GMASS0*DEXP(-N*CG/W)+2.0D0*CF/W*((1.0D0-DEXP(-CG*(N+2.0D0)/W
1))/ (1.0D0-DEXP(-2.0D0*CG/W))-CF/W
X=CG*DABS(1.0D0/PI)*(1.0D0+(SF-1.0D0)*(GVOL/GMT-V)/
1(SVS-V))
R=SNGL(X)
RETURN
END

```

C  
C  
C  
C  
C  
C

..... CALCULATES THE CONCENTRATIONS IN THE PRIMARY COOLANT .....

SUBROUTINE PRIM

```

COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/GEOM/RF,THG,THC,POND,PITCH,DROD,DCORE,NRODS,HT
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT

```

```

COMMON/VOLS/VOLF,VOLG,VOLC
COMMON/DEFECT/NDEF,FS
COMMON/GAS1/RI, TI, RHO, SPH, KF1, KF2, I, P, DELR, ICF, BCF, NSUB, TSTEP, L
COMMON/GAS3/BURN, IORF, BULK, IFLG, STEAM, ABSFAC, ABSSB, ABSTE
COMMON/GAS4/CONCR(3), CONCG(3), CONCP(3), FRACT
COMMON/SUBI3/SBG(3), TEMG(3), TEG(3)
COMMON/SUBP2/GM1, GM2, GM3, GM4, GM5, ISB, ITEM, ITE, II, VGVP
COMMON/SUBP3/SBC(3), TEMC(3), TEC(3)
COMMON/SUBP4/REMSB(3), REMTE(3), REMTEM(3), REMI(3)

C
  INTEGER P
C
  DO 25 I=1,3
C
    IF(I.EQ.1)THEN
      ISB=1
      ITEM=2
      ITE=3
      II=4
      GM1=0.15
      GM2=0.2
      GM3=0.85
      GM4=1.0
      GM5=0.8
      END IF
    IF(I.EQ.2)THEN
      ITE=5
      II=6
      GM2=0.0
      GM3=0.0
      GM4=1.0
      GM5=0.0
      END IF
    IF(I.EQ.3)THEN
      ISB=7
      ITEM=8
      ITE=9
      II=10
      GM1=0.72
      GM2=0.13
      GM3=0.28
      GM4=1.0
      GM5=0.87
      END IF
C
    IF(P.EQ.1)THEN
      VGVP=(8.0*RF*THG+4.0*THG**2)/(DCORE**2-NRODS*DROD**2)
C
C.....STEADY-STATE CONCENTRATIONS IN THE COOLANT .....
C
      REMSB(I)=FRACT*EXP(-AL(ISB)*TIML)/TIMC-(1.0/TIMC)-AL(ISB)

```



```

REME(I)=FRACT*EXP(-AL(ITE)*TIML)/TIMC-(1.0/TIMC)-AL(ITE)
REMEM(I)=FRACT*EXP(-AL(ITEM)*TIML)/TIMC-(1.0/TIMC)-AL(ITEM)
REMI(I)=FRACT*EXP(-AL(II)*TIML)/TIMC-(1.0/TIMC)-AL(II)
C
SBC(I)=-NDEF*VGVP*R*SBG(I)/REMSB(I)
TEMC(I)=- (NDEF*VGVP*R*TEMG(I)+GM1*AL(ISB)*SBC(I))/REMEM(I)
TEC(I)=- (NDEF*VGVP*R*TEG(I)+GM2*AL(ITEM)*TEMC(I)+GM3*AL(ISB)*
&SBC(I))/REME(I)
CONCP(I)=- (NDEF*VGVP*R*CONCG(I)+GM4*AL(ITE)*TEC(I)+GM5*AL(ITEM)*
&TEMC(I))/REMI(I)
C
ELSE
C
C.....CALCULATES ANTIMONY CONCENTRATION IN THE COOLANT .....
C
CS1=DELT*FSBC(SBC(I))
CS2=DELT*FSBC(SBC(I)+0.5*CS1)
CS3=DELT*FSBC(SBC(I)+0.5*CS2)
CS4=DELT*FSBC(SBC(I)+CS3)
SBC(I)=SBC(I)+(CS1+2.0*CS2+2.0*CS3+CS4)/6.0
C
C.....CALCULATES TELLURIUM-M CONCENTRATION IN THE COOLANT .....
C
CTM1=DELT*FTEMC(TEMC(I))
CTM2=DELT*FTEMC(TEMC(I)+0.5*CTM1)
CTM3=DELT*FTEMC(TEMC(I)+0.5*CTM2)
CTM4=DELT*FTEMC(TEMC(I)+CTM3)
TEMC(I)=TEMC(I)+(CTM1+2.0*CTM2+2.0*CTM3+CTM4)/6.0
C
C.....CALCULATES TELLURIUM CONCENTRATION IN THE COOLANT .....
C
CT1=DELT*FTEC(TEC(I))
CT2=DELT*FTEC(TEC(I)+0.5*CT1)
CT3=DELT*FTEC(TEC(I)+0.5*CT2)
CT4=DELT*FTEC(TEC(I)+CT3)
TEC(I)=TEC(I)+(CT1+2.0*CT2+2.0*CT3+CT4)/6.0
C
C.....CALCULATES IODINE CONCENTRATION IN THE COOLANT .....
C
CP1=FP(CONCP(I))
CP2=FP(CONCP(I)+CP1/2.0)
CP3=FP(CONCP(I)+CP2/2.0)
CP4=FP(CONCP(I)+CP3)
CONCP(I)=CONCP(I)+DELT*(CP1+2.0*CP2+2.0*CP3+CP4)/6.0
C
END IF
C
25 CONTINUE
C
RETURN

```

END

C

```

FUNCTION FSBC(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/DEFECT/NDEF,FS
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
COMMON/SUBI3/SBG(3),TEMG(3),TEG(3)
COMMON/SUBP2/GM1,GM2,GM3,GM4,GM5,ISB,ITEM,ITE,II,VGVP
COMMON/SUBP3/SBC(3),TEMC(3),TEC(3)
COMMON/SUBP4/REMSB(3),REMTE(3),REMTEM(3),REMI(3)
FSBC=NDEF*VGVP*R*SBG(I)+REMSB(I)*X
RETURN
END

```

C

```

FUNCTION FTEMC(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/DEFECT/NDEF,FS
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
COMMON/SUBI3/SBG(3),TEMG(3),TEG(3)
COMMON/SUBP2/GM1,GM2,GM3,GM4,GM5,ISB,ITEM,ITE,II,VGVP
COMMON/SUBP3/SBC(3),TEMC(3),TEC(3)
COMMON/SUBP4/REMSB(3),REMTE(3),REMTEM(3),REMI(3)
FTEMC=NDEF*VGVP*R*TEMG(I)+GM1*AL(ISB)*SBC(I)+REMTEM(I)*X
RETURN
END

```

C

```

FUNCTION FTEC(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/DEFECT/NDEF,FS
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT
COMMON/SUBI3/SBG(3),TEMG(3),TEG(3)
COMMON/SUBP2/GM1,GM2,GM3,GM4,GM5,ISB,ITEM,ITE,II,VGVP
COMMON/SUBP3/SBC(3),TEMC(3),TEC(3)
COMMON/SUBP4/REMSB(3),REMTE(3),REMTEM(3),REMI(3)
FTEC=NDEF*VGVP*R*TEG(I)+GM2*AL(ITEM)*TEMC(I)+GM3*AL(ISB)*SBC(I)
&+REMTE(I)*X
RETURN
END

```

C

```

FUNCTION FP(X)
COMMON/NUCDA/AL(10),CY(10),DY(10),FLUXO,POWO,SIGF,FLUX,POW,WF
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/DEFECT/NDEF,FS
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
COMMON/GAS4/CONCR(3),CONCG(3),CONCP(3),FRACT

```

```
COMMON/SUBP2/GM1,GM2,GM3,GM4,GM5,ISB,ITEM,ITE,II,VGVP
COMMON/SUBP3/SBC(3),TEMC(3),TEC(3)
COMMON/SUBP4/REMSB(3),REMTE(3),RENTM(3),REMI(3)
FP=NDEF*VGVP*R*CONCG(I)+GM4*AL(ITE)*TEC(I)+GM5*AL(ITEM)*TEMC(I)
```

```
&REMI(I)*X
```

```
RETURN
END
```

```
C
```

```
C-----
```

```
C..... DEFINE AND INITIALIZE TIME STEP VARIABLES .....
```

```
C
```

```
SUBROUTINE TIMVAL
COMMON/EFFLUX/EI(3),EIO(3),FRAC(3),FGAS(50),FDOT(50),FI(3),R
COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
COMMON/VOLS/VOLF,VOLG,VOLC
COMMON/CONTRL/NSTEP,NP
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
```

```
C
```

```
INTEGER NSTEP,TSTEP
```

```
C
```

```
DELT=0.1
DELTT=10.0
NSTEP=30
TSTEP=120000
NP=0
```

```
C
```

```
RETURN
END
```

```
C
```

```
C-----
```

```
C..... DETERMINES WHEN TO STOP EXECUTION .....
```

```
C
```

```
SUBROUTINE QUIT(IQUIT)
```

```
C
```

```
COMMON/TIMES/TIMC,TIML,DELT,DELTT,TOFDP,PCNTDP,TOTDP,RT
COMMON/TIMES1/TOTUP,ICASE
COMMON/CONTRL/NSTEP,NP
COMMON/GAS1/RI,TI,RHO,SPH,KF1,KF2,I,P,DELR,ICF,BCF,NSUB,TSTEP,L
```

```
C
```

```
INTEGER P
IF(P.EQ.1)IQUIT=0
IF(ICASE.EQ.1.AND.TI.GT.TOTDP)IQUIT=1
IF(ICASE.EQ.2)THEN
  IF(TI.GE.TOTDP)NP=1
  IF(TI.GT.TOTDP+TOTUP)IQUIT=1
END IF
```

```
C
```

```
RETURN
END
```

```
C
```

```
C$ENTRY
```

```
4.095E-3 8.2E-5 5.72E-4 1.32 1.25E-2 0.94E-2 3.37 55777 3.66
```

21.3 0.71 11.0  
0.99965 33 0.73E-4 16.0 0.20 0.80 0.4  
30000.0 589.0  
5.090E17  
1.0 0.01 36000.0  
015.0 00150.0  
1

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