

**TITLE:** DOPC FISSION PRODUCT RELEASE AND CIRCULATING ACTIVITY CALCULATIONS FOR GAS-COOLED REACTORS

CONF-770108--10

**AUTHOR(S):** C. E. Apperson, Jr  
L. M. Carruthers,  
C. E. Lee

**SUBMITTED TO:** ANS meeting to be held in Sunvalley, Idaho  
August 1, 1977.

By acceptance of this article for publication, the publisher recognizes the Government's (license) rights in any copyright and the Government and its authorized representatives have unrestricted right to reproduce in whole or in part said article under any copyright secured by the publisher.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the USERDA.

**NOTICE**  
The report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ALAC 108

  
**los alamos**  
**scientific laboratory**  
of the University of California  
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

LOFC FISSION PRODUCT RELEASE AND CIRCULATING  
ACTIVITY CALCULATIONS FOR GAS-COOLED REACTORS

by

Courtney E. Apperson, Jr.  
Lucy M. Carruthers  
Clarence E. Lee

Los Alamos Scientific Laboratory  
Los Alamos, New Mexico

INTRODUCTION

The inventories of fission products in a gas-cooled reactor under accident and normal steady state conditions are time and temperature dependent. To obtain a reasonable estimate of these inventories it is necessary to consider fuel failure, a temperature dependent variable, and radioactive decay, a time dependent variable. Using arbitrary radioactive decay chains and published fuel failure models for the High Temperature Gas-Cooled Reactor (HTGR), methods have been developed to evaluate the release of fission products during the Loss of Forced Circulation (LOFC) accident and the circulating and plate-out fission product inventories during steady state non-accident operation.

The theoretical and numerical data base for the modeling of fission product release from an HTGR during a LOFC has been described previously in the discussion of the LARC-1 code.<sup>1</sup> This release code includes the effects of temperature modeling, fission product release rates, coated fuel particle (BISO and TRISO) fuel failure fraction, and aged coated fuel particle failure fraction using analytic fits. The effects of diffusion, adsorption, and evaporation of metallics and of precursors were neglected. The LARC code theory has now been expanded to include arbitrary radioactive decay chains. Using this theoretical extension of LARC-1, the LARC-2 code has been developed.<sup>2</sup>

The LARC-2 model presented here neglects the time delays in the release from the HTGR due to diffusion of fission products from particles in the fuel rod through the graphite matrix. It also neglects the adsorption and evaporation process of metallics at the fuel rod-graphite and graphite-coolant hole interfaces. Any time delay due to the finite time of transport of fission products by convection through the coolant to the outside of the prestressed concrete reactor vessel (PCR) is also neglected. This model assumes that all fission products released from fuel particles are immediately deposited outside the PCR with no time delay. The real situation, assuming the same data base, will be time delayed from the solutions presented.

The circulating and plate-out fission product inventory inside the primary containment of an HTGR is determined by the partitioning between the primary coolant, the cleanup system, the plate-out surfaces, and the fuel. A theoretical data base has been developed to model this system. This model includes the effects of coated particle fuel failure, aged coated fuel particle failure fraction using analytic fits, removal of fission products by a primary coolant filter, plate-out onto the internal surfaces of components inside the PCRV, fission product release from failed and intact fuel particles as a function of temperature, and arbitrary radioactive decay chains. The SUVIUS code has been developed from this model.<sup>3</sup>

The SUVIUS code assumes that the source of fission products to the primary coolant from the fuel is linear for small time steps and follows an Arrhenius relation for both intact and failed fuel particles. It is further assumed that the primary coolant of an HTGR is well mixed and that the filtration and plate-out removal rates are constant for each nuclide being considered. Fuel failure is determined from the analytic fits developed for the LARC code series and fission product production rates are based on the reactor power.

The required mathematical tools for both of these models were originally developed and applied to the calculation of the release from a reactor containment building.<sup>4,5</sup> The solution methods used there have been extended and refined for solving the more complex problems of LARC-2 and SUVIUS.

#### MULTICOMPONENT DECAY MODEL

##### Release from HTGR During LOFC (LARC-2)

Consider the system shown in Fig. 1 composed of an HTGR core during an LOFC, from which fission products are emitted from failed and intact BISO and TRISO particles in a time dependent temperature field,  $T(t)$ . The fission products act as a source,  $\vec{S}$ , of radioactive materials from the PCRV to the containment building.

Let  $\vec{N}_i^\alpha$  be the amount of an isotope in a chain ( $\vec{N}$ ) resulting from failed ( $i = 1$ ) or intact ( $i = 2$ ) release of fission products from BISO ( $\alpha = B$ ) or TRISO ( $\alpha = T$ ) particles in the fuel. The diagonal release rate matrices are defined by  $r_i^\alpha$ . The source to the containment building is composed of the released fission products as given by

$$\vec{S} = \sum_{\alpha,i} r_i^\alpha \vec{N}_i^\alpha \quad (1)$$

This assumption, of course, ignores any time delays due to diffusion hold-up, plate-out, lift-off, etc., or convection delay in coolant circulation. Thus, this model is "conservative" in not giving any credit to those processes which, in fact, have a non-negative decay associated with them.

The PCRV in Fig. 1 is surrounded by a containment building, which leaks at a rate  $L(\text{sec}^{-1})$ . Inside the containment building there is a cleanup filter having a cleanup rate  $V(\text{sec}^{-1})$ . Noble gases are not removed by the filter. Let  $\vec{N}$  be the amount of the isotope in the chain in the containment building and  $\vec{F}$  be the total amount absorbed on the filter.

Denote  $\vec{\lambda}$  the decay chain matrix, and  $\vec{l}$  and  $V$  the diagonal leak and cleanup matrices, respectively. The negative off-diagonal elements of  $\vec{\lambda}$  include the branching ratio factors.

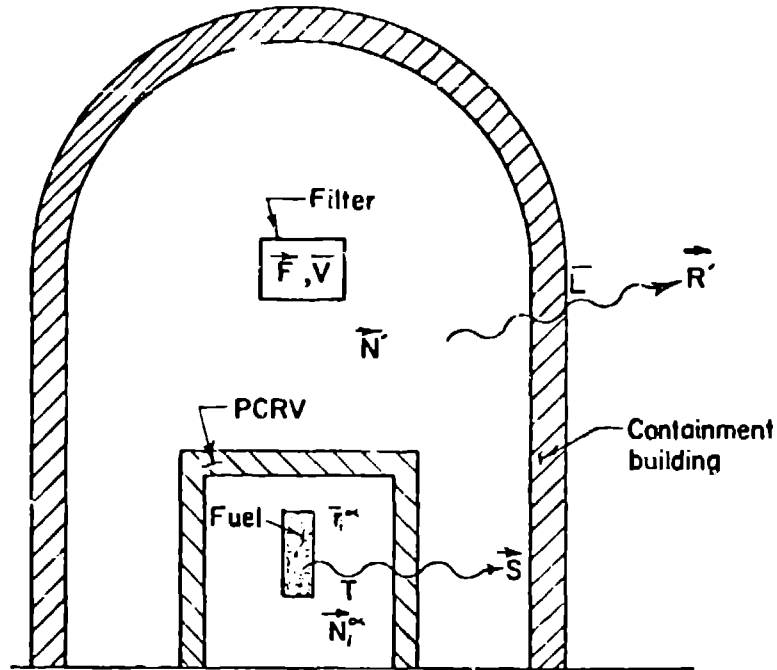


Fig. 1  
SCHEMATIC LARC-2 MODEL

The balance equations describing the release from the particles are given by

$$\frac{d\vec{N}_i^\alpha}{dt} = -\Lambda_i^\alpha \vec{N}_i^\alpha \quad (i = 1, 2; \alpha = B, T), \quad (2)$$

where the matrices  $\Lambda_i^\alpha$  are defined by

$$\Lambda_i^\alpha = \bar{\lambda} + r_i^\alpha, \quad (3)$$

and  $\bar{r}_i^\alpha$  represents the time averaged value of  $r_i^\alpha$  over the time interval  $(0, \tau)$ , as

$$\bar{r}_i^\alpha = \frac{1}{\tau} \left[ r_i^\alpha(0) + r_i^\alpha(\tau) \right]. \quad (4)$$

Similarly, the equations governing the amount of isotope in the containment building,  $\vec{N}$ , and that absorbed in the filter cleanup system,  $\vec{F}$ , are given by

$$\frac{d\vec{N}}{dt} = -\Lambda \vec{N} - \lambda^* \vec{F} + \vec{S}, \quad (5)$$

$$\frac{d\vec{F}}{dt} = \bar{v} \vec{N} - \lambda \vec{F},$$

where the source to the containment building,  $\vec{S}$ , is given by Eq. (1). Symbols used in Eq. (5) are defined as:

$$\begin{aligned}\Lambda &= \bar{\lambda} + \bar{V} + \bar{L}, \\ \lambda &= \bar{\lambda} - \lambda^*, \\ \lambda^* &= \delta \otimes \bar{\lambda},\end{aligned}\tag{6}$$

where  $\bar{V}$  is the time averaged diagonal cleanup matrix, and  $\bar{L}$  is the time averaged diagonal containment building leakage matrix. The matrix  $\delta$ , which is involved in the Cartesian product,  $\otimes$ , in Eq. (6) is defined elementwise by  $\delta_{ij} = \mu_i(1 - \delta_{ij})$ , where  $\mu_i$  is 1 if  $i$  represents a noble gas and 0 otherwise, and  $\delta_{ij}$  is the Kronecker delta.

In the Constant Release-Renormalized model, two assumptions are made:

1. The release rates, cleanup, and leakage rates ( $r_1^{\alpha}$ ,  $V$ , and  $L$ ) are assumed constant over a small time interval  $\tau$ . If  $\bar{y}$  represents a time averaged quantity, then

$$\bar{y} = \frac{1}{2} [y(0) + y(\tau)],\tag{7}$$

where  $y(0)$  and  $y(\tau)$  are the values of the quantity at the beginning and the end of the time interval, respectively.

2. The isotopic densities are renormalized to exactly match the failed fraction versus time relations, as reviewed below.

From a study of the intact-failed transition it became clear that matching the failed fractions for BISO and TRISO particles as a function of time is crucial. The failed fraction is implicitly a function of time since it is a function of the temperature which is a function of time. This analysis leads to the approximation of the Constant Release-Renormalized model in LARC-1. The failed fraction,  $f(t)$ , for a given isotope,  $n_1(t)$ , in a chain is defined by

$$f(t) = \frac{n_1(t)}{n_1(t) + n_2(t)}\tag{8}$$

where  $n_1$  is the amount of the isotope from failed particles and  $n_2$  is the amount from intact particles.

Assuming that we know  $f(t)$  for each isotope, which we do, then we adjust the ratio  $n_1/n_2$  while maintaining the constancy of the sum,  $n_1 + n_2$ . This renormalization of  $n_1(\tau)$ , an element of  $\vec{N}_1^{\alpha}$ , at the end of each time step  $\tau$  to  $n_1(0)$  at the beginning of the next time step is accomplished by the transformation

$$\begin{aligned}f(\tau) [n_1(\tau) + n_2(\tau)] &\rightarrow n_1(0) \\ 1 - f(\tau) [n_1(\tau) + n_2(\tau)] &\rightarrow n_2(0)\end{aligned}\tag{9}$$

for each  $n_1$  in  $\vec{N}_1^{\alpha}$ , for both BISO and TRISO, using the  $f(\tau)$  specific to each type. The failed fraction is a function of the temperature, which is a function of the time and core volume fraction. Thus,  $f(t)$  is implicitly a function of time.

Equations (2), (4), and (5) can be written in a more compact form by defining a supermatrix A and a super vector  $\vec{X}$  by

$$A = \begin{bmatrix} -\Lambda_1^B & 0 & 0 & 0 & 0 & 0 \\ 0 & -\Lambda_2^B & 0 & 0 & 0 & 0 \\ 0 & 0 & -\Lambda_1^T & 0 & J & 0 \\ 0 & 0 & 0 & -\Lambda_2^T & 0 & 0 \\ \bar{r}_1^B & \bar{r}_2^B & \bar{r}_1^T & \bar{r}_2^T & -\Lambda & -\lambda^* \\ 0 & 0 & 0 & 0 & \bar{V} & -\lambda \end{bmatrix}, \quad \vec{X} = \begin{bmatrix} \vec{N}_1^B \\ \vec{N}_2^B \\ \vec{N}_1^T \\ \vec{N}_2^T \\ \vec{N} \\ \vec{F} \end{bmatrix} \quad (10)$$

If m is the number of elements in an arbitrary radioactive chain, the dimension of  $\vec{X}$  is 6m, and A is a 6m by 6m square matrix.

Using the definitions of Eq. (10), the equations for  $\vec{N}_i^\alpha$ ,  $\vec{N}$ , and  $\vec{F}$  take the simple form

$$\frac{d\vec{X}}{dt} = A \vec{X} \quad (11)$$

Assuming that A is constant over the time interval (0,  $\tau$ ), the solution to Eq. (11) is

$$\vec{X}(\tau) = e^{A\tau} \vec{X}(0) \quad (12)$$

where the  $\vec{X}(0)$  represent the initial conditions at the beginning of the interval. The details of the evaluation of  $e^{A\tau}$  are discussed below.

The release from the PCRV and the containment building are quantities of significant interest. Defining the vectors  $\vec{R}(t)$  and  $\vec{R}^*(t)$  as the release from the PCRV and containment building, respectively, the governing equations are given by

$$\frac{d\vec{R}}{dt} = \vec{S} = \sum_{\alpha, i} \bar{r}_i^\alpha \vec{N}_i^\alpha, \quad (13)$$

$$\frac{d\vec{R}^*}{dt} = \bar{L} \vec{N}^*. \quad (14)$$

Defining the supermatrices  $\bar{r}$  and  $\hat{L}$  by

$$\bar{r} = \begin{bmatrix} \bar{r}_1^B & \bar{r}_2^B & \bar{r}_1^T & \bar{r}_2^T & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \hat{L} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & 0 & & \\ & & & & \bar{L} & \\ & & & & & 0 \end{bmatrix} \quad (15)$$

then Eqs. (13) and (14) take the form

$$\frac{d\vec{R}}{dt} = \bar{r}\vec{X}, \quad (16)$$

$$\frac{d\vec{R}'}{dt} = \hat{L}\vec{X}, \quad (17)$$

which have the solution over the interval  $\tau$  given by

$$\vec{R}(\tau) = \bar{r} \int_0^\tau ds \vec{X}(s) = \bar{r} D(A\tau) \vec{X}(0) \quad (18)$$

$$\vec{R}'(\tau) = \hat{L} \int_0^\tau ds \vec{X}(s) = \hat{L} D(A\tau) \vec{X}(0) \quad (19)$$

The evaluation of the  $D(A\tau)$  operator is discussed in the next section.

We are also interested in the amount of the isotope in the coolant so that we may calculate the fraction of the initial atomic inventory released to the containment building, which is given by

$$\vec{U}(t) = e^{-\lambda t} \vec{U}(t-\tau) + \vec{R}(\tau) \quad (20)$$

#### Circulating and Plate-Out Activity at Steady State (SUVIUS)

Consider the reactor primary containment system shown in Fig. 2. The reactor core is a source,  $\vec{S}$ , of fission products to the primary coolant,  $\vec{N}$ . The primary coolant is a source of material to the cleanup system,  $\vec{F}$ , at a removal rate of  $V(s^{-1})$ . Material plates out at a rate of  $\pi(s^{-1})$  onto the plate-out surface whose inventory is given by  $\vec{P}$ . There also is some fission product inventory left in the core,  $\vec{B}$ .

The cleanup and plate-out removal rates can be different for each nuclide in a chain and are most conveniently defined as diagonal matrices. Within this framework an individual nuclide does not have to be plated-out or filtered.

The source,  $\vec{S}$ , is a linear function of time and is the sum of two vectors.

$$\vec{S} = \vec{S}_0 + t\vec{S}_1 \quad (21)$$

This gives rise to four differential equations. This family of equations can readily be displayed in matrix form as in Eqs. (22).

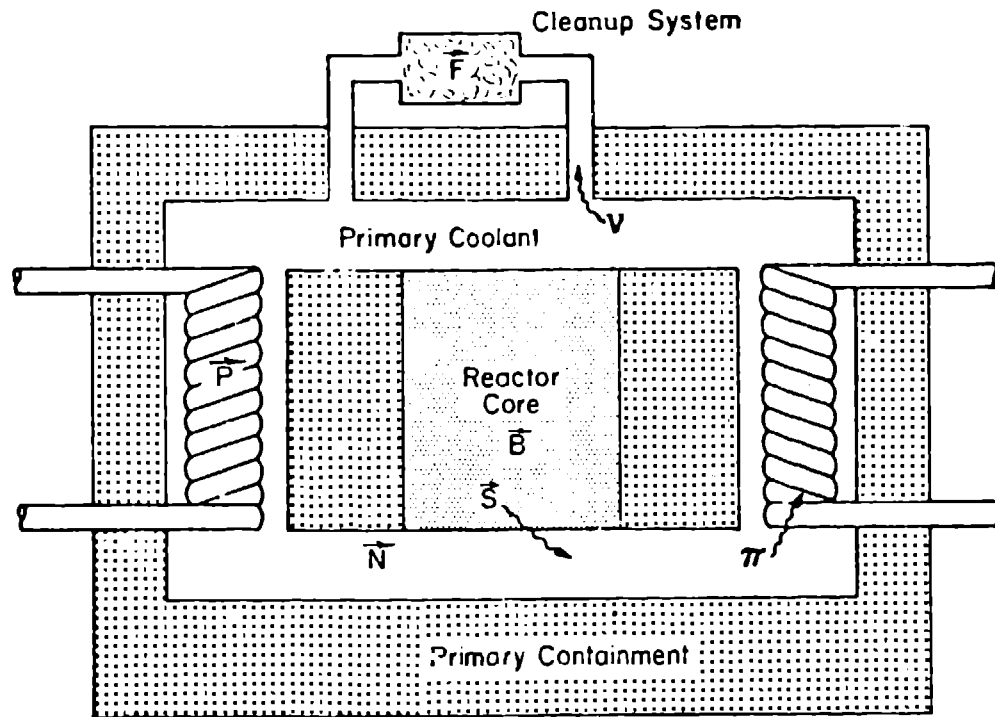


Fig. 2 SCHEMATIC SUIVUS MODEL

$$\frac{d\vec{X}}{dt} = A\vec{X} + \vec{S}_0 + t\vec{S}_1 \quad (22a)$$

where

$$X = \begin{pmatrix} \vec{B} \\ \vec{N} \\ \vec{F} \\ \vec{P} \end{pmatrix} \quad \vec{S} = \vec{S}_0 + t\vec{S}_1 = \begin{pmatrix} \vec{S}_0 + t\vec{S}_1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (22b)$$

$$A = \begin{pmatrix} -\Sigma & 0 & 0 & 0 \\ \Sigma^* & -\Lambda & 0 & \lambda^* \\ 0 & V & -\bar{\lambda} & 0 \\ 0 & \pi & 0 & -\lambda \end{pmatrix}$$

The matrix A is a composite of matrices since all of its elements are matrices. In like manner, the vectors  $\vec{S}_0$  and  $\vec{S}_1$  are made up of four individual vectors. Each vector in X has as many elements as there are nuclides in a given chain, n. This implies the vector X has 4n elements and A is a matrix of dimension 4n x 4n.



In the composite matrix,  $A$ , the matrix  $\Sigma$  accounts for the decay of material in the fuel,  $\Sigma^*$  is the source of material into the coolant,  $\Lambda$  is the removal and decay of materials in the primary coolant,  $\bar{\lambda}$  the decay in the clean-up system,  $\lambda$  the removal and decay of material on the plate-out surfaces,  $\lambda^*$  is the return of plated-out material to the coolant,  $V$  is the cleanup removal rate, and  $\pi$  is the plate-out removal rate matrix.

The  $\Lambda$ ,  $\lambda$ , and  $\lambda^*$  matrices have been defined in Eq. (6). The  $\Sigma$  and  $\Sigma^*$  matrices are defined in Eq. (23).

$$\begin{aligned}
 \Sigma_{ii} &= \bar{\lambda}_{i,i} \\
 \Sigma_{i,j} &= \bar{\lambda}_{i,i}(1-G_i(T))b_{i,j} \\
 &\quad j < i \\
 \Sigma_{i,j} &= 0 \\
 &\quad j > i \\
 \Sigma^*_{i,j} &= 0 \\
 &\quad j > i \\
 \Sigma^*_{i,j} &= \bar{\lambda}_{i,i}G_i(T)b_{i,j} \\
 &\quad j < i
 \end{aligned} \tag{23}$$

where  $b_{i,j}$  is the branching ratio from  $i$  to  $j$  and  $G(T)$  is the temperature dependent release fraction.

If we assume that the elements of the matrix  $A$  and the vector  $\vec{S}$  are constant over a time interval  $(0, \tau)$ , the solution to Eq. (22) is given by Eq. (24).

$$\vec{X}(\tau) = e^{A\tau}\vec{X}(0) + \frac{1}{-A} (I - e^{A\tau})\vec{S}_0 + \left( \frac{\tau}{-A} - \frac{1}{A^2} + \frac{e^{A\tau}}{A^2} \right) \vec{S}_1 \tag{24}$$

When Eq. (24) is written in terms of operators which will be defined in the next section the solution is given by Eq. (25).

$$\vec{X}(\tau) = \left[ I + A\tau D(A\tau) \right] \vec{X}(0) + \tau D(A\tau)\vec{S}_0 + \tau^2 Z(A\tau)\vec{S}_1 \tag{25}$$

These solutions exist even if  $A$  is singular.

#### SOLUTION METHODS

The equations to be solved are of the form

$$\frac{d\vec{X}}{dt} = A\vec{X} + \vec{S} \tag{26}$$

$$\vec{Y}(\tau) = F \int_0^\tau ds \vec{X}(s) \tag{27}$$

where the matrices A and F are constant over the time interval (0, τ). The SUVIUS solution (Eq. 22) comes directly from the solution of Eq. (26). The LARC-2 solutions (Eq. 17, 18, and 19) come from Eq. (26) with  $\vec{S} = 0$  and Eq. (27).

Since the matrix A is constant, the matricant of Eq. (28) can be constructed using the Volterra method of the multiplicative integral.<sup>6,7</sup>

$$\Omega_0^T(A) = \exp \left[ \int_0^T A(s) ds \right] = \exp(AT). \quad (28)$$

The solution to Eq. (26) is given by

$$\vec{X}(\tau) = \Omega_0^T(A) \vec{X}(0) + \int_0^T dt' K(\tau, t') \vec{S}(t'), \quad (29)$$

where

$$K(\tau, t') = \Omega_0^T(A) \left[ \Omega_0^{t'}(A) \right]^{-1} \quad (30)$$

As is readily proved, both the matrix A and  $e^{AT}$  are non-negative.<sup>8</sup>

Substitution of Eq. (28) into Eqs. (29) and (30) gives

$$\vec{X}(\tau) = e^{AT} \vec{X}(0) + e^{AT} \int_0^T dt' e^{-At'} \vec{S}(t'). \quad (31)$$

If  $\vec{S}(t') = 0$  in Eq. (31) the solution to Eq. (11), is obtained (Eq. 12). If  $\vec{S}(t') = \vec{S}_0 + t' \vec{S}_1$  over the interval (0, τ), Eq. (32) is the solution to Eq. (22).

$$\vec{X}(\tau) = e^{AT} \vec{X}(0) + A^{-1} \left( e^{AT} - I \right) \vec{S}_0 + \left( \frac{-I}{A} - \frac{1}{A^2} + \frac{e^{AT}}{A^2} \right) \vec{S}_1 \quad (32)$$

By defining the operators D(AT) and Z(AT) by

$$D(AT) = (AT)^{-1} \left( e^{AT} - I \right) \quad (33)$$

$$Z(AT) = (AT)^{-1} \left( D(AT) - I \right) \quad (34)$$

Equation (32) can be simplified to Eq. (25).

By integrating Eq. (27) with  $S(t') = 0$ , the solution form of Eqs. (18) and (19) is obtained.

$$\vec{Y}(\tau) = FA^{-1} \left( e^{AT} - I \right) \vec{X}(0) \quad (35)$$

Substituting the operator D(AT) into Eq. (35) gives Eq. (36), which is in the same form as Eqs. (18) and (19).

$$\vec{Y}(\tau) = F \left[ \tau D(AT) \right] \vec{X}(0) \quad (36)$$

Note that the matrix operators D(C) and Z(C) defined by

$$D(C) = C^{-1}(e^C - I) = \sum_{n=0}^{\infty} \frac{C^n}{(n+1)!} \quad (37)$$

and

$$Z(C) = C^{-1}(D(C) - I) = \sum_{n=0}^{\infty} \frac{C^n}{(n+2)!} \quad (38)$$

exist even if  $C = AT$  is singular.\* Although the eigenvalues of  $e^C$  are bounded by unity, and the eigenvalues of  $C$  are bounded, but not necessarily by unity, the direct evaluation of  $D(C)$  and  $Z(C)$  would prove difficult computationally if Eqs. (37) and (38) are used. We can scale the matrix  $C$  so that the eigenvalues are bounded by unity. Define

$$H = 2^{-p}C, \quad (39)$$

where  $p$  is determined by

$$\|H\| < \frac{1}{2} \quad (40)$$

or

$$p > \ln \left( \sum_{ij} |C_{ij}|^2 \right) / (2 \ln 2).^{7,8} \quad (41)$$

We approximate the  $D(H)$  and  $Z(H)$  matrix operators by a finite number of terms  $M$  using Eqs. (37) and (38).

$$D^M(H) \approx \sum_{n=0}^M \frac{H^n}{(n+1)!} \quad (42)$$

$$Z^M(H) \approx \sum_{n=0}^M \frac{H^n}{(n+2)!} \quad (43)$$

$M$  is determined such that the excluded terms have an error less than some  $\epsilon$ , or

$$\frac{(\|H\|)^{M+1}}{(M+2)!} < \frac{1}{2^{M+1}(M+2)!} < \epsilon. \quad (44)$$

Knowing  $D(H)$  and  $Z(H)$ , we may recur upwards by powers of 2 in  $H$  to find  $D(C)$  and  $Z(C)$  where  $C = 2^p H$ , using the recursion relations

$$D(2^{p+1}H) = D(2^p H) \left[ I + \frac{1}{2}(2^p H)D(2^p H) \right] \quad (45)$$

and

$$Z(2^{p+1}H) = \frac{1}{2} Z(2^p H) + \frac{1}{4} \left[ D(2^p H)^2 \right].^5 \quad (46)$$

\*For example, a chain involving a stable isotope will lead to a matrix that is singular.

### FISSION PRODUCT RELEASE CALCULATION

The LARC-2 code requires input of nuclide data including branching ratios, decay constants, atomic masses, initial concentrations, and isotope group for release constants. Initial concentrations may be in atoms or curies - output will be in the same units. Also, input of time steps, cleanup rate data and leakage rate data is needed.

As a sample calculation, the 131 chain shown in Fig. 3

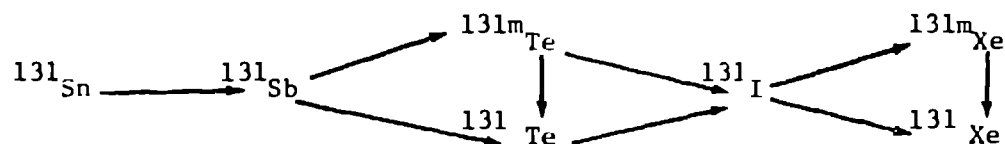


Fig. 3 MASS-131 Chain

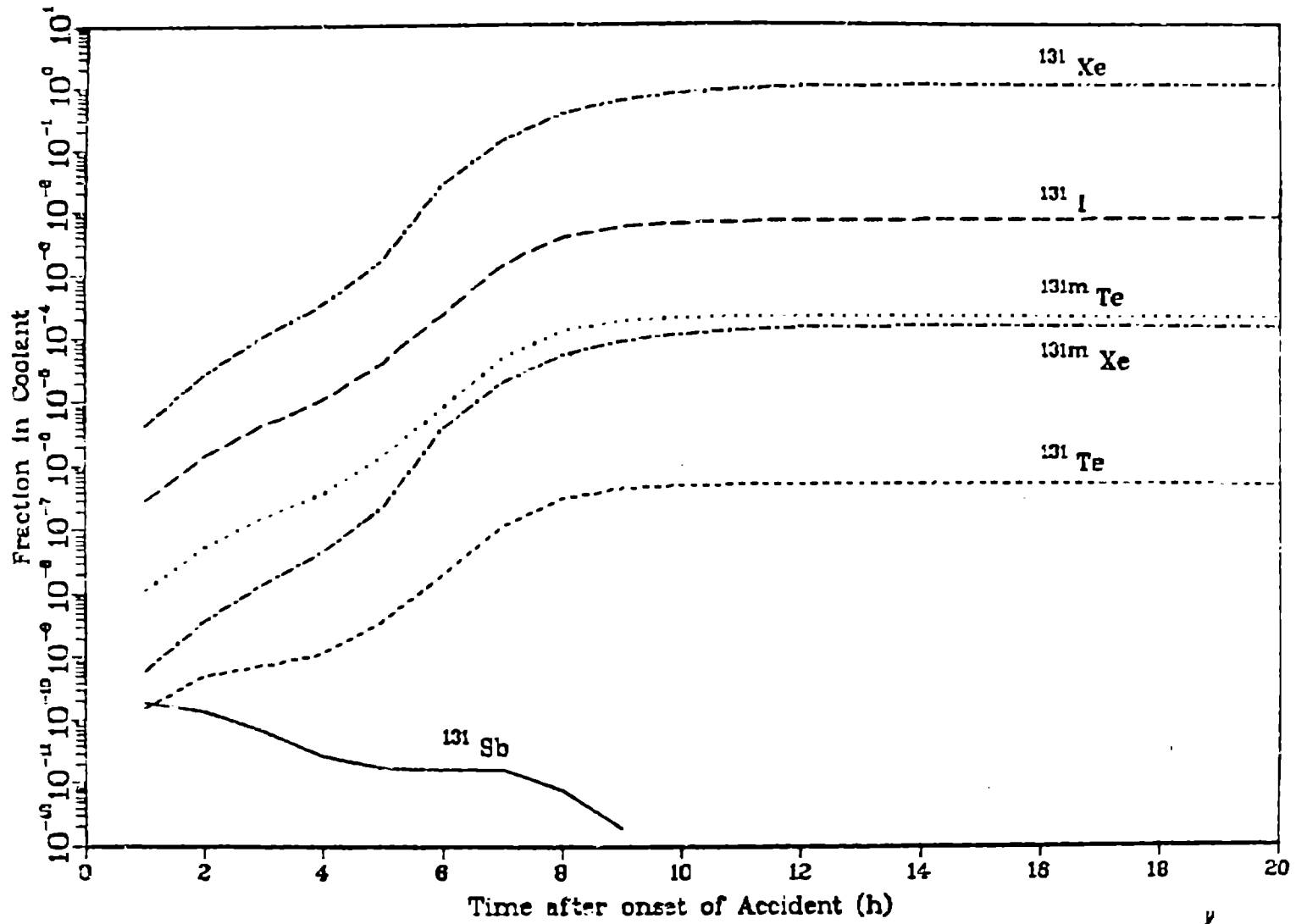
using data shown in Table I

TABLE I  
MASS-131 CHAIN DATA

NUCLIDE	DECAY CONSTANT (s <sup>-1</sup> )	ISOTOPE GROUP FOR RELEASE RATES (See Table VI Ref. 1)	INITIAL CONCENTRATION (Curies)
131 <sub>Sn</sub>	1.10023 x 10 <sup>-2</sup>	8	6.67 x 10 <sup>2</sup>
131 <sub>Sb</sub>	5.02281 x 10 <sup>-4</sup>	10	1.55 x 10 <sup>4</sup>
131 <sub>m</sub> Te	6.41803 x 10 <sup>-6</sup>	10	5.96 x 10 <sup>3</sup>
131 <sub>Te</sub>	4.62098 x 10 <sup>-4</sup>	10	1.79 x 10 <sup>3</sup>
131 <sub>I</sub>	9.97707 x 10 <sup>-7</sup>	10	2.29 x 10 <sup>4</sup>
131 <sub>m</sub> Xe	4.23695 x 10 <sup>-7</sup>	5	1.37 x 10 <sup>2</sup>
131 <sub>Xe</sub>	0.	5	1.83 x 10 <sup>1</sup>

produces results shown in Fig. 4 for the fraction in the coolant over a 20 hour period of the LOFC accident situation.

Fig 4



BETTER QUALITY AND REDUCED FIG. TO BE INSERTED BEFORE SUBMITTAL.

LARC-2 Results



The fraction in the coolant is defined as the number of atoms in the coolant for the individual isotope divided by the total number of atoms belonging to that chain initially present in the system. Time = 0. is taken as the time of the loss of forced circulation. The reactor is assumed to be shut down at this time so that fissions stop and the total number of atoms for a given chain is constant throughout the problem.

Data for initial concentrations is taken from Table 11.1-5 of Gassar-6.<sup>9</sup> The table gives the equilibrium concentration of fission products per fuel element - these are multiplied by 3944, the number of fuel elements in a 3000 MW reactor. Fuel types of Ft. St. Vrain or Gassar-6 may be selected - this affects fuel failure rates and release constants for the individual isotopes. The number of fuel types available will be extended to include another GA-estimate<sup>10</sup> and an NRC-Tokar model.<sup>11</sup>

The sample calculation is done with the Gassar-6 fuel model, SORS temperature model, 60% BISO loading, reactor age 4 years, aged fuel (1/4 of the fuel replaced every year).

## CIRCULATING AND PLATE OUT ACTIVITY RESULTS

A calculation of the mass-85 chain as defined in Fig. 5 has been performed to demonstrate the SUVIUS code and to provide comparison with published results.

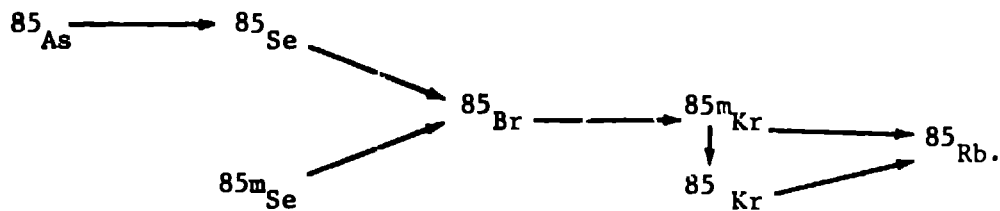


Fig. 5 Mass-85 Chain

The basic data used by the code to solve this problem is displayed in Table II.<sup>12,13</sup>

TABLE II  
MASS-85 CHAIN DATA\*

NUCLIDE	DECAY CONSTANT ( $\text{s}^{-1}$ )	PLATE OUT RATE ( $\text{s}^{-1}$ )	DIFFUSION PARAMETER AT 110 C IN FUEL	
			FAILED	INTACT
$^{85}\text{As}$	.3415	.535	$1.5 \times 10^{-9}$	$1.5 \times 10^{-11}$
$^{85}\text{Se}$	.01777	.535	$1.94 \times 10^{-9}$	$4.38 \times 10^{-15}$
$^{85\text{m}}\text{Se}$	.03648	.535	$1.94 \times 10^{-9}$	$4.38 \times 10^{-15}$
$^{85}\text{Br}$	.004025	.0	$1.94 \times 10^{-9}$	$4.38 \times 10^{-15}$
$^{85\text{m}}\text{Kr}$	$4.298 \times 10^{-5}$	.0	$1.94 \times 10^{-9}$	$4.38 \times 10^{-15}$
$^{85}\text{Kr}$	$2.047 \times 10^{-9}$	.535	$1.94 \times 10^{-9}$	$4.38 \times 10^{-15}$
$^{85}\text{Rb}$	.0	.0	$1.0 \times 10^{-18}$	$1.0 \times 10^{-18}$

\*The purification removal rate for all nuclides is  $4.27 \times 10^{-5} \text{ s}^{-1}$ . The  $^{85}\text{As}$  and  $^{85}\text{Rb}$  diffusion parameters are chosen conservatively and all diffusion parameters have an activation energy of 12.7 kcal/mole.

The reference problem was run assuming an HTGR operating at 3,000 MW(th) with fuel failure occurring as defined by Shenoy and McEachern.<sup>10</sup> The results are displayed graphically in Fig. 6 for the primary coolant and in Fig. 7 for the total plate out inventory for the sixth year of operation. The shorter lived isotopes,  $^{65}\text{As}$ ,  $^{85}\text{Se}$ , and  $^{85\text{m}}\text{Se}$ , are not shown since their activity is significantly lower than the other isotopes being considered. Inert gases don't plate out; they therefore are only present in the coolant.

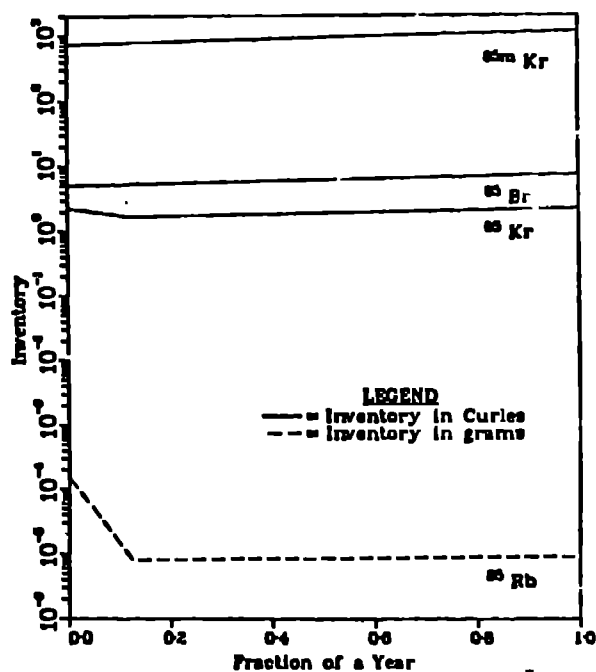


Fig. 6 Coolant Inventory

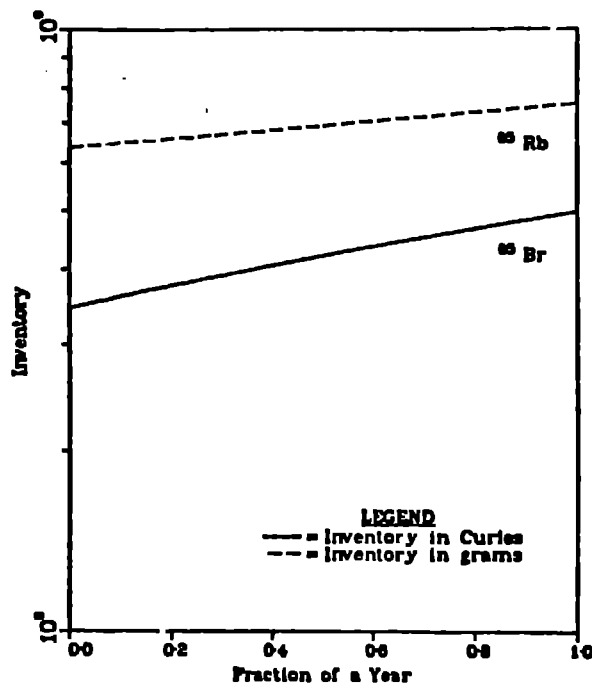


Fig. 7 Plate Out Inventory

General Atomic Company has published results for the same mass chain<sup>13</sup> for the middle of an equilibrium cycle. These results are compared in Table III with the SUVIUS middle of cycle results for circulating activity (Fig. 6).

TABLE III  
COMPARISON OF CIRCULATING ACTIVITIES  
AT  
MIDDLE OF CYCLE

NUCLIDE	ACTIVITY (Ci)	
	GA-AIPA	SUVIUS
$^{85\text{m}}\text{Kr}$	776.00	937.2
$^{85}\text{Kr}$	1.10	1.91



The contrast in the results can be accounted for by the detailed burnup calculation in the SUVIUS code which is not present in the General Atomic code used in their study and the use of different "best" fission yields.

#### REFERENCES

1. L. M. CARRUTHERS and C. E. LEE, LARC-1: A Los Alamos Release Calculation Program for Fission Product Transport in HTGR's During the LOFC Accident, Los Alamos Scientific Laboratory Report, LA-NUREG-6567-MS, November 1976.
2. L. M. CARRUTHERS and C. E. LEE, LARC-2: A Multicomponent Decay Model for Fission Product Transport in HTGR's During the LOFC Accident, Los Alamos Scientific Laboratory Report, to be published.
3. C. E. APPERSON, SUVIUS: A Circulating and Plate Out Activity Program for Gas Cooled Reactors with Arbitrary Radioactive Decay Chains, Los Alamos Scientific Laboratory Report, to be published.
4. C. E. LEE, The Calculation of Isotopic Mass and Energy Production by a Matrix Operator Method, Los Alamos Scientific Laboratory Report, LA-6483-MS, September 1976.
5. C. E. LEE, C. E. APPERSON, JR., and J. E. FOLEY, LEAF: A Computer Program to Calculate Fission Product Release from a Reactor Containment Building for Arbitrary Decay Chains, Los Alamos Scientific Laboratory Report, LA-NUREG-6570-MS, November 1976.
6. F. R. GANTMACHER, The Theory of Matrices, (Chelsea Publishing Company, New York, 1960), pp. 125ff, 185ff.
7. E. BODEWIG, Matrix Calculus, (Interscience Publishers, New York, 1963), p. 67ff.
8. C. E. LEE, The Calculation of Isotopic Mass and Energy Production by a Matrix Operator Method, Los Alamos Scientific Laboratory Report, LA-6483-MS, September 1976.
9. GASSAR, General Atomic Company Report, GA-A13200, Table 11.1-5.
10. A. S. SHENOY and D. W. MCEACHERN, HTGR Core Thermal Design Methods and Analysis, General Atomic Company Report, GA-A12985, December 1974.
11. Fuel Particle Coating Failure Model and Data, NUREG-0111, November, 1976.
12. T. T. ENGLAND and R. E. SCHENTER, ENDF/B-IV Fission Product Files Summary of Major Nuclide Data, Los Alamos Scientific Laboratory Report, LA-6116-MS, October 1975.
13. D. ALBERSTEIN, C. E. APPERSON, JR., D. L. HANSON, B. F. MYERS and W. W. PFEIFFER, HTGR Accident Initiation and Progression Analysis Status Report, Vol. 5, General Atomic Company Report, GA-A13617, February 1976.