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FISSION PRODUCT RELEASE INTO THE PRIMARY COOLANT

by

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ABSTRACT

The analytic evaluation of steady state primary coolant reactor is discussed. The reported calculations account for temperature dependent fuel failure in two particle types and arbitrary radioactive decay chains. A matrix operator technique implemented in the SUVIUS code is used to solve the simultaneous equations. Results are compared with General Atomic Company's published results.

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INTRODUCTION

Fission products are always present in the primary coolant of a High-Temperature Gas-Cooled Reactor (HTGR) after its initial startup. This situation exists due to the physical nature of HTGR fuel that is made up of fissile and fertile fuel particles contained in fuel rods, which are inserted into fuel blocks.[1] Although intact fuel particles are assumed to be impervious to gases, failed fuel particles and small quantities of contamination from manufacturing of fuel particles are sources of fission gas to the primary coolant. Experimentally, this source of fission gases can be defined in terms of the ratio of the release rate of an isotope to its birth rate in a specific fuel volume.[2]

The small fraction of nuclides that escape the fuel enter the primary coolant stream. The helium coolant is assumed to be a well-mixed gas and therefore the fission gases, which are primarily inert gases and halogens, are homogeneously distributed in the gas volume. Once in the primary coolant, the gaseous fission products behave differently depending on their nuclear and chemical properties.

Several processes compete for the fission gases as they are carried by the primary coolant around the coolant loop. A filter system is present that removes all fission gases from the withdrawn fraction before returning the helium coolant to the circuit. As the coolant contacts exposed surfaces inside the primary coolant boundary, some fission gases deposit onto these surfaces at rates which depend on their chemical properties. Radioactive fission gases are also removed from the primary coolant by decay.

Since fission products are present in the coolant of a gas reactor it is necessary to quantify them for both safety and operational considerations. To properly predict the consequences of a hypothetical release accident a reasonable estimate of the steady-state activity and nuclide distribution is essential. For routine maintenance of contaminated equipment a reliable estimate of surface activity is needed before maintenance procedures can be prepared.

Experiments are valuable in establishing this information on a small scale. For extending this experimental knowledge to a level at which it is useful for a power reactor a substantial amount of calculation is required.

To efficiently do this an analytic algorithm has been developed.

The SUVIUS computer program utilizes this algorothm to analytically solve the system that has been briefly discussed.[3] Using experimentally defined fuel data, the SUVIUS code can calculate the inventory of an arbitrary radioactive decay chain in the fuel, coolant, filter system, and on plateout surfaces of an HTGR. These calculations can be time dependent and are performed for multiple fuel regions.

ANALYTIC MODEL

Consider the reactor primary containment system shown in Fig. 1. 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 plateout surface whose inventory is given by $\vec{P}$. There also is some fission product inventory left in the core, $\vec{B}$.

The cleanup and plateout 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.

$$\vec{S} = \vec{S}_0 + t\vec{S}_1 \tag{1}$$

This gives rise to a system of four differential equations. This family of equations can readily be displayed in matrix form as in Eq. (2).

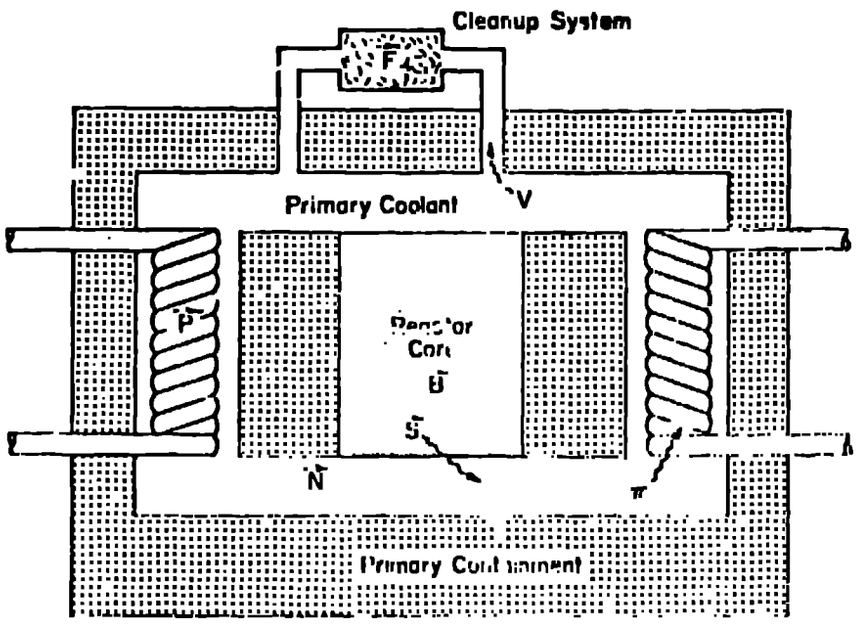

Fig. 1 Schematic SUVIUS model

$$\frac{d\vec{X}}{dt} = A\vec{X} + \vec{S}_o + t\vec{S}_1 \tag{2a}$$

where

$$X = \begin{bmatrix} \vec{B} \\ \vec{N} \\ \vec{F} \\ \vec{P} \end{bmatrix}, \quad \vec{S} = \vec{S}_o + t\vec{S}_1 = \begin{bmatrix} \vec{S}_o^B + t\vec{S}_1^B \\ \vec{S}_o^N + t\,\vec{S}_1^N \\ 0 \\ 0 \end{bmatrix} \tag{2b}$$

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

In the supermatrix, A, the matrix Σ accounts for the decay of material in the fuel, Σ^* is the source of material into the coolant from the fuel, Λ is the removal and decay of materials in the primary coolant, $\bar{\lambda}$ the decay in the cleanup system, λ the removal and decay of material on the plateout surfaces, λ^* is the return of plated out material to the coolant, V is the cleanup removal rate, and π is the plateout removal rate matrix.

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. (2) is given by Eq. (3).

$$\vec{X}(\tau) = e^{A\tau}\vec{X}(0) + (-A)^{-1}\,(1-e^{A\tau})\,\vec{S}_o + \left((-A)^{-1}\tau - (A)^{-2} + A^{-2}e^{A\tau}\right)\vec{S}_1 \tag{3}$$

When Eq. (3) is written in terms of operators the solution is given by Eq. (4).

$$\vec{X}(\tau) = [I + A\tau D(A\tau)]\,\vec{X}(0) + \tau D(A\tau)\vec{S}_o + \tau^2 Z(A\tau)\vec{S}_1 \tag{4}$$

The matrix operators $D(A\tau)$ and $Z(A\tau)$ are defined by

$$D(A\tau) = (A\tau)^{-1}\,(e^{A\tau} - I) = \sum_{n=0}^{\infty} \frac{(A\tau)^n}{(n+1)!} \tag{5}$$

and

$$Z(A\tau) = (A\tau)^{-1}\,(D(A\tau) - I) = \sum_{n=0}^{\infty} \frac{(A\tau)^n}{(n+2)!} \tag{6}$$

These operators exist even if A is singular.[3,4]

ACTIVITY CALCULATIONS

The radioactive decay chain ending with the stable nuclide ^{85}Rb, Fig. 2, has been evaluated using the SUVIUS code for a 3000 MW(t) HTGR with a capacity factor of 0.80 and a 30 day down time for refueling.

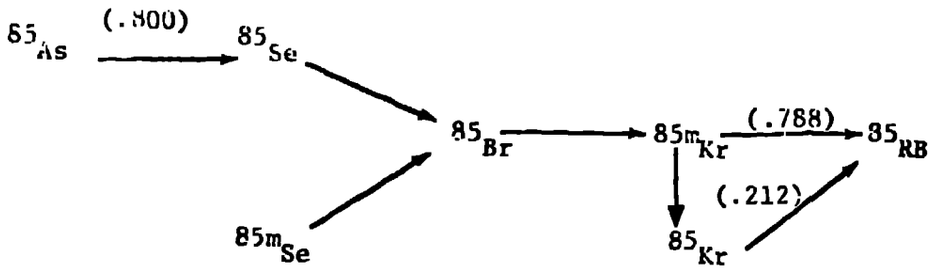

Fig. 2 Mass-85 chain

For this calculation the core average temperature is taken to be 890°C and the purification removal rate for all nuclides is $4.27 \times 10^{-5} s^{-1}$. The ^{85}As and ^{85}Rb diffusion parameters are chosen conservatively and all diffusion parameters have an activation energy of 12.7 kcal/mole. The basic nuclear and chemical data for these calculations is given in Table I.[5,6]

Fuel failure data is taken from work done by Shenoy and McEachern.[7] The reported data has been averaged over four equilibrium years to obtain TRISO and BISO failure curves as a function of time for an average reload segment in a 3000 MW(t) HTGR, (Figs. 3 and 4).

TABLE I

NUCLEAR AND CHEMICAL DATA[5,6]

NUCLIDE	DECAY CONSTANT (s^{-1})	FISSION YIELD U-233	FISSION YIELD U-235	PLATE-OUT RATE (s^{-1})	DIFFUSION PARAMETER IN FUEL AT 1100°C (s^{-1}) FAILED	DIFFUSION PARAMETER IN FUEL AT 1100°C (s^{-1}) INTACT
^{85}As	0.3415	1.417×10^{-3}	2.044×10^{-3}	0.535	1.50×10^{-5}	1.5×10^{-11}
^{85}Se	0.01777	7.154×10^{-3}	4.598×10^{-3}	0.535	1.94×10^{-9}	4.38×10^{-15}
^{85m}Se	0.03648	7.154×10^{-3}	4.598×10^{-3}	0.535	1.94×10^{-9}	4.38×10^{-15}
^{85}Br	4.025×10^{-3}	5.820×10^{-3}	1.718×10^{-3}	0.100	1.94×10^{-9}	4.38×10^{-15}
^{85m}Kr	4.298×10^{-5}	1.860×10^{-4}	1.542×10^{-4}	0.0	1.94×10^{-9}	4.38×10^{-15}
^{85}Kr	2.047×10^{-9}	2.150×10^{-4}	2.333×10^{-5}	0.0	1.94×10^{-9}	4.38×10^{-15}
^{85}Rb	0.0	6.530×10^{-7}	8.234×10^{-7}	0.535	1.00×10^{-18}	1.00×10^{-18}

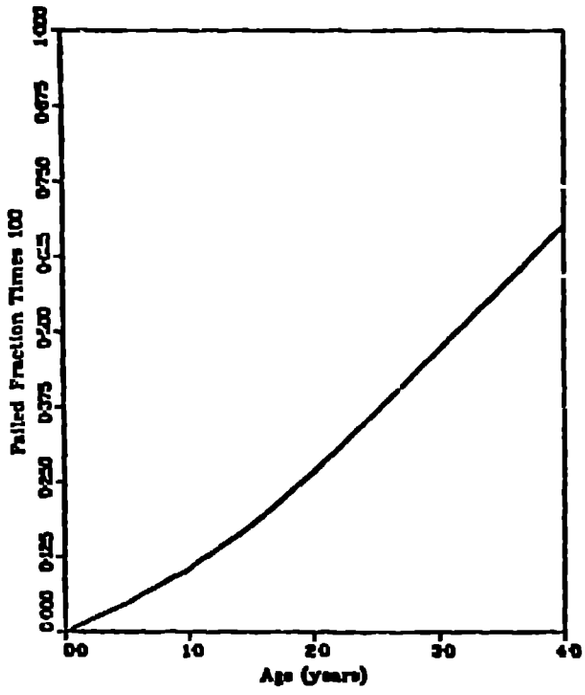

Fig. 3 TRISO Failed Fraction

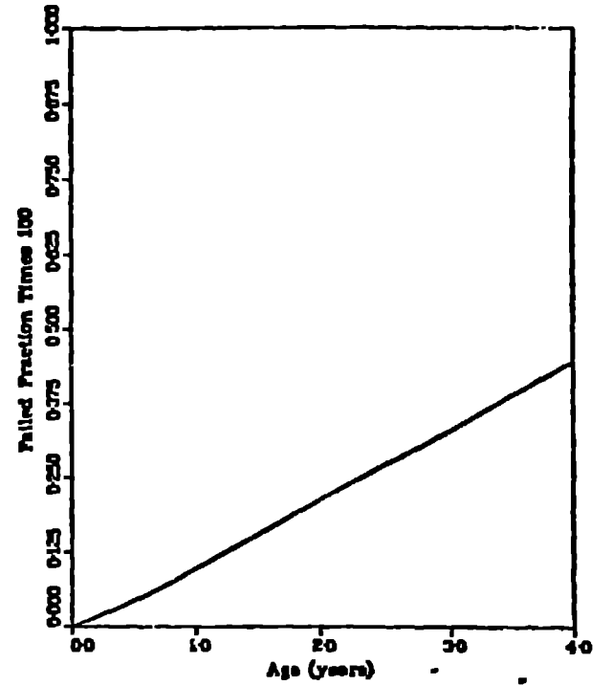

Fig. 4 BISO Failed Fraction

The division of fissions between TRISO and BISO fuel in a reload segment is based on a curve reported by Haire and McEachern, Fig. 5.[8]

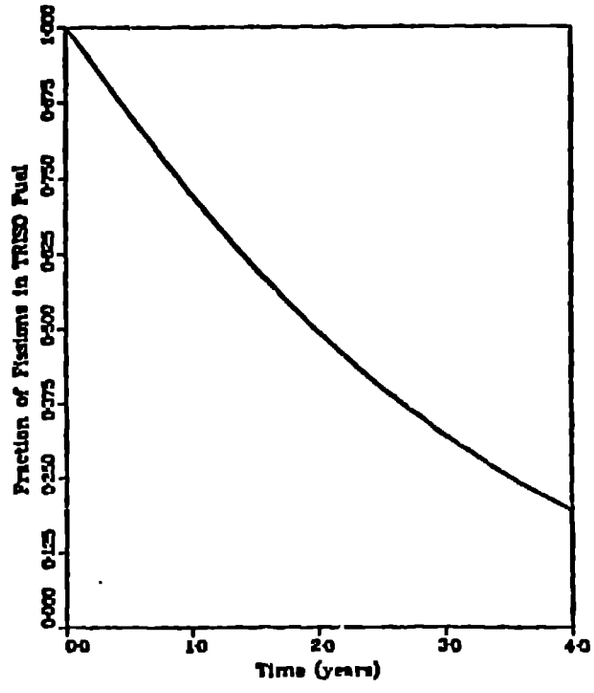

Fig. 5 TRISO BISO Fission Split

The problem was run for seven years assuming, as General Atomic Company, that the seventh year approximates an equilibrium core. The SUVIUS estimates of the activity in the system due to the decay chain ending with ^{85}Rb during an equilibrium year are given in Figs. 6-10. The ^{85}Rb inventory is given in grams. All other inventories are stated in curies.

The total system inventory, Fig. 6, shows a monotonic change with time. As more fissions occur in the BISO fertile fuel particles the ^{233}U yield has a stronger influence. The result of this is that the ^{85}As inventory decreases and the remaining members of the chain increase.

The inventory in the fuel body, Fig. 7, follows the system inventory very closely since only a small fraction of the fission products escape the fuel. The same reasoning applies here as was used for the total system inventory.

In the coolant, Fig. 8, all the inventories are increasing. Even though the previously discussed effects of fission yields is present, the major factor in this estimate is fuel failure. The average fuel failure, Figs. 3 and 4, is monotonically increasing. Since the release rate from failed fuel greatly exceeds that from manufacturing contamination, the influence of fuel failure is to increase the coolant inventory with time independent of its fuel type origin.

The only source of activity to the filter system is the coolant. The filter inventory, Fig. 9, is therefore also monotonically increasing. The magnitude and the ordering of the nuclides vary since the filter is a dead end.

The inventory on the plateout surfaces, Fig. 9, is monotonically increasing. As for the filter inventory, the plateout inventory follows the primary coolant inventory. It should be noted that the inert gases, ^{85m}Kr and ^{85}Kr, are not present in Fig. 10 since gases do not plateout.

COMPARISONS

The SUVIUS results can be compared directly with the accident initiation and progression analysis estimates generated by General Atomic Company (GAC).[6] The GAC reported results are not as detailed as those reported here since they only report selected nuclide activities at the middle of an equilibrium cycle.

Comparing the two sets of results, Table II, reveals some interesting differences. If we assume that the fuel body inventory approximates the total system inventory, the SUVIUS results estimate that there is 10% less ^{85}Kr in the system than the GAC AIPA results predict. The difference is independent of everything except the basic nuclear data and the calculational technique. The calculational methods differ in that SUVIUS treats the arbitrary radioactive decay chains analytically as a system while the KAD code used in the AIPA analysis considers only one nuclide at a time.[9] Slight differences in decay constants and fission yields should not cause the magnitude of difference apparent in Table II. The difference can therefore be accounted for by the more rigorous treatment of radioactive decay in SUVIUS.

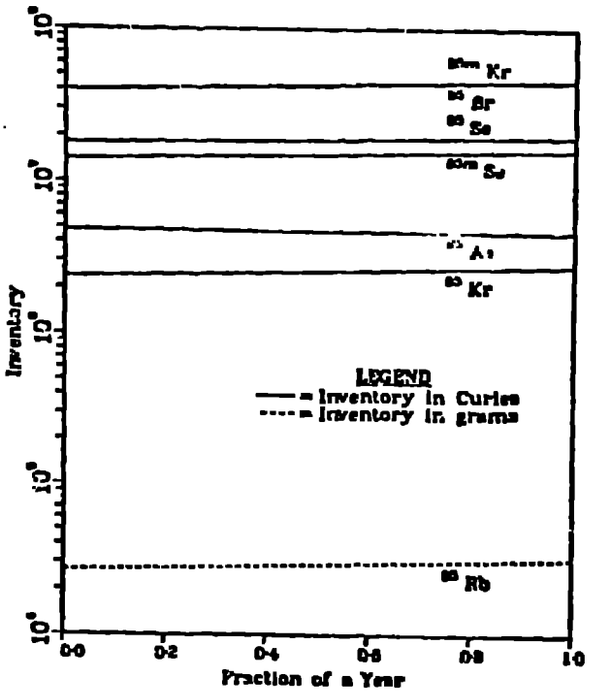

Fig. 6 Total System Inventory

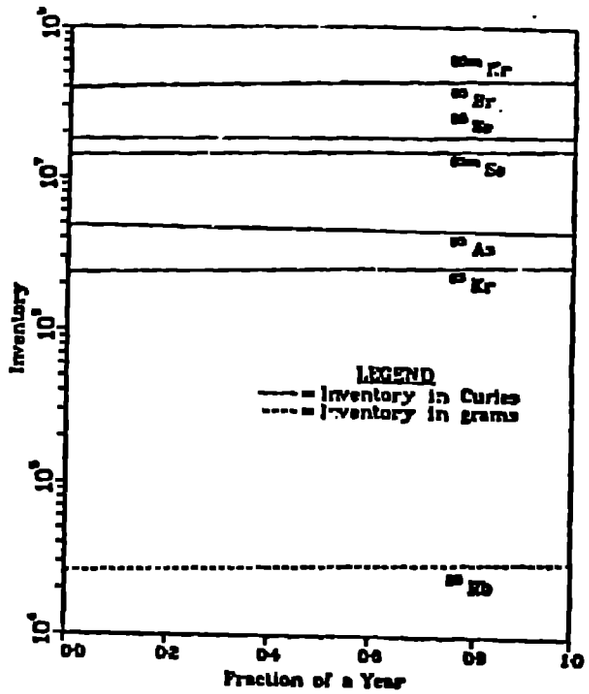

Fig. 7 Fuel Inventory

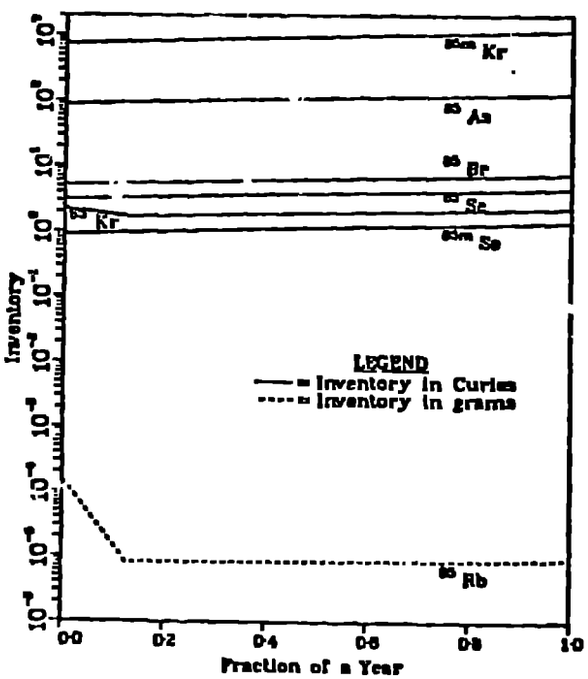

Fig. 8 Coolant Inventory

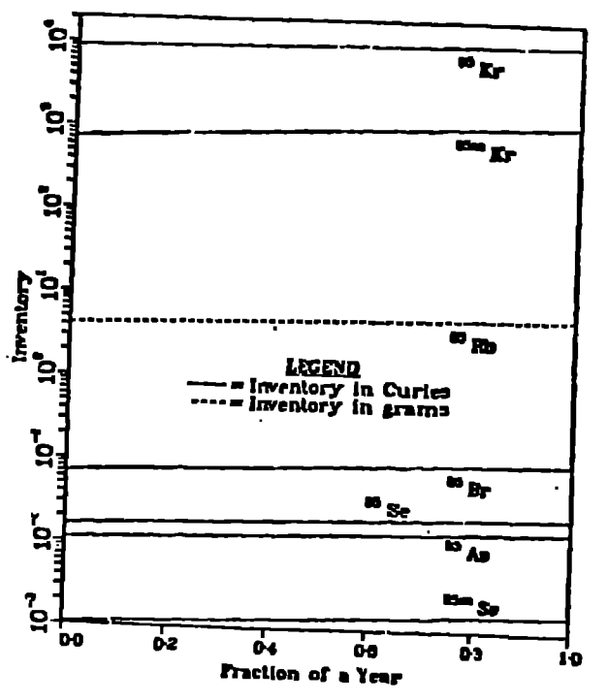

Fig. 9 Filter Inventory

TABLE II

COMPARISON OF ACTIVITIES

AT MIDDLE OF EQUILIBRIUM CYCLE

NUCLIDE	ACTIVITY (Ci) FUEL BODY SUVIUS	FUEL BODY GA-AT	PRIMARY COOLANT SUVIUS	PRIMARY COOLANT GA-AIPA	PRIMARY COOLANT GA-AIPA LESS 15%
^{85m}Kr	4.285×10^7	4.733×10^7	937.2	776	660
^{85}Kr	2.524×10^6	1.921×10^6	1.908	1.10	.94

In the primary coolant SUVIUS predicts activities that are from 19% to 50% higher than GAC has reported. As before, the most probable factor in causing this difference is the SUVIUS computational method. Subsequent to the AIPA results, GAC has reported that their previous conservative treatment of the core buffer blocks increased the coolant activity estimates for the Fort Saint Vrain reactor by 15%.[10] Assuming this same degree of conservation to be present in the AIPA activity estimates, the SUVIUS results are further separated from the GAC estimates than originally indicated.

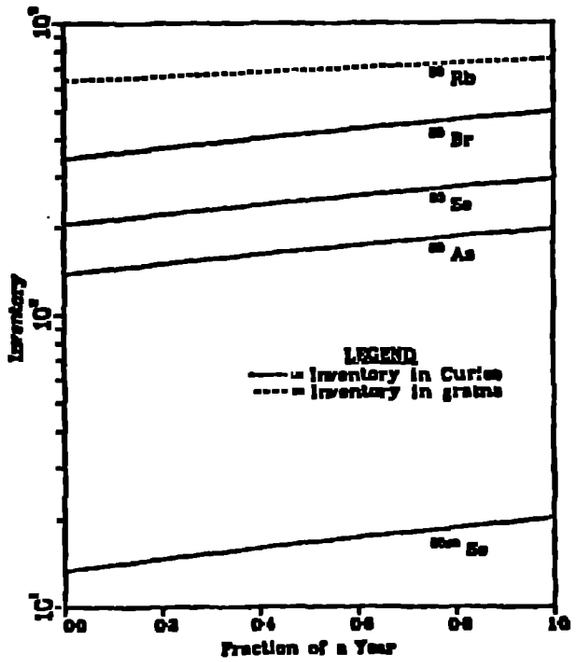

Fig. 10 Plateout Inventory

CONCLUSION

The difference in the SUVIUS and GA-AIPA results are significant enough for the nuclide chain evaluated to warrent further study and a more detailed comparison of the methods utilized in evaluating median activities. It should be noted however, that the SUVIUS estimates do not exceeed the activities reported by GAC for the 3000 MW(t) reactor in GASSAR.[1]

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