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QUANTITIES OF ACTINIDES IN NUCLEAR REACTOR FUEL CYCLES

by

Kiat Poon Ang

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ABSTRACT

The quantities of plutonium and other fuel actinides have been calculated for equilibrium fuel cycles for 1000 Mw water reactors fueled with slightly enriched uranium, water reactors fueled with plutonium and natural uranium, fast-breeder reactors, gas-cooled reactors fueled with thorium, and highly enriched uranium, and gas-cooled reactors fueled with thorium, plutonium, and recycled uranium. The radioactivity quantities of plutonium, americium, and curium processed yearly in these fuel cycles are greatest for the water reactors fueled with natural uranium and recycled plutonium. The total amount of actinides processed is calculated for the predicted future growth of the United States nuclear power industry. For the same total installed nuclear power capacity, the introduction of the plutonium breeder has little effect upon the total amount of plutonium processed in this century. The estimated amount of plutonium in the low-level process wastes in the plutonium fuel cycles is comparable to the amount of plutonium in the high-level fission product wastes. The amount of plutonium processed in the nuclear fuel cycles can be considerably reduced by using gas-cooled reactors to consume plutonium produced in uranium-fueled water reactors. These, and other reactors dedicated for plutonium utilization, could be co-located with facilities for fuel reprocessing and fuel fabrication to eliminate the off-site transport of separated plutonium.

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INTRODUCTION

The isotopic composition of the actinide elements present in spent power reactor fuels is of importance to shipping container design, fuel reprocessing and refabrication techniques, and waste disposal procedures. The alpha activity of plutonium, and the presence of ^{236}Pu and its daughters in spent fuels, greatly increases the difficulty of recovery of plutonium and fabrication of recycle fuels. The isotope ^{241}Am is one of the principal sources of heat in nuclear reactor wastes, which must be stored for thousands of years. The quantities and radiological properties of these actinides produced and processed will depend very much upon the properties of the nuclear reactors and upon the type of fuel charged in these reactors. The plutonium fuel cycles which are likely to emerge in this country during the remainder of this century are the fuel cycles for the light-water reactors and for future fast-breeder reactors. The light-water reactors now in operation and the many similar water reactors under construction are designed to be fueled with uranium slightly enriched in fissile ^{235}U. Within a few years, the plutonium recovered from the discharged uranium fuel will be recycled as water-reactor fuel, and this will establish the plutonium fuel industry in this country. Around the middle 1980's, when the fast-breeder reactor is introduced, the plutonium recovered from these uranium-fueled water reactors will be needed to supply the initial inventory of fissile plutonium to start up the breeders. Most of the plutonium then recovered from breeder discharge fuel will be recycled for fabricating fresh fuel, and a portion of the recovered plutonium will be used, along with plutonium still being produced in water reactors, to start up new breeders.

The high-temperature gas-cooled reactors recently introduced as alternative nuclear power plants produced fissile ^{233}U from the ^{235}U-thorium

fuel. Although no important material quantities of plutonium are produced in this reactor, significant radioactivity quantities of plutonium will appear in the high-level radioactive wastes from reprocessing fuel discharged from the reactors. These gas-cooled reactors are also adaptable to utilizing plutonium recovered from water-reactor fuel.

In each of these fuel cycles, plutonium is an important public health issue because of the large amount of radioactivity associated with the alpha-emitting and beta-emitting plutonium radionuclides, which are recovered in spent fuel reprocessing and which are to be shipped and fabricated into recycle fuel. The actinides in the wastes generated by these fuel-cycle process operations contain sufficient quantities of long-lived radionuclides that they dictate the most significant and ultimate long-term management requirements for the radioactive wastes associated with the nuclear power industry.

The purpose of this thesis is to calculate and compare the actinide and radioactive quantities in typical 1000 Mw light-water reactors, fast breeder reactors, and high-temperature gas cooled reactors fuel cycles at equilibrium. An equilibrium fuel cycle is defined here as a fuel cycle where each succeeding charge of fresh fuel is of the same composition as the previous fuel charge. A total of seven different fuel cycles were studied. The results of the calculations are presented in Chapters III, IV, and V. The light water reactors fueled with enriched uranium, as well as fueled with recycled plutonium and natural uranium are considered in Chapter III. Chapter IV presents the results of the calculations of two fast breeder reactors, the Atomics International and the General Electric Follow-On Liquid Metal Fast Breeder Reactors. Three fuel cycles for the high temperature gas-cooled reactors are considered in Chapter V, they are the uranium-thorium fuel cycle, the uranium-thorium-recycled plutonium fuel cycle, and the uranium-

thorium with makeup plutonium fuel cycle.

In each case, calculations were made of the compositions and activities of the actinides present in the spent fuels of these fuel cycles, as a function of time after reactor discharge and reprocessing using the ORIGEN isotope generation and depletion code.[1] The yearly throughput and inventories of the actinides and radioactive quantities in the external fuel cycle, such as in shipment, reprocessing, conversion, fabrication, isotope separation and in the high-level and low-level wastes, were also calculated based on the results of ORIGEN with losses and holdup times associated with each process taken into account. The results of these calculations are presented in Chapters III through V.

Finally, the total amounts of actinides processed were calculated for the predicted future growth of the U.S. nuclear power industry. For the same total installed nuclear power capacity, six scenarios for the rate of introduction of nuclear reactors were considered and the total amounts of actinides reprocessed were compared. The results and comparisons are presented in Chapter VI.

I. DESCRIPTION OF MATHEMATICAL MODEL AND METHOD

A general expression for the formation and destruction of a nuclide by nuclear transmutation and radioactive decay may be written as follows:

$$\frac{dX_i}{dt} = \sum_{j=1}^{N} \ell_{ij} \lambda_j X_j + \bar{\phi} \sum_{k=1}^{N} f_{ik} \sigma_k X_k - (\lambda_i + \bar{\phi} \sigma_i) X_i \quad (i=1,.....N) \quad (1)$$

where X_i is the atom density of nuclide i, λ_i is the radioactive disintegration constant for nuclide i, σ_i is the spectrum-averaged neutron absorption cross section of nuclide i, and ℓ_{ij} and f_{ik} are the fractions of radioactive disintegration and neutron absorption by other nuclides which lead to the formation of species i. Also in Eq. (1), $\bar{\phi}$ is the volume-energy-averaged neutron flux, which is also assumed to be constant over short intervals of time. The neutron flux will vary with changes in the composition of the fuel for constant power. However, this variation with time is slow and, if the neutron flux is considered to be constant over short intervals, the system of Eq. (1) is a homogeneous set of simultaneous first-order differential equations with constant coefficients, which may be written in matrix notation:

$$\underset{\sim}{\dot{X}} = \underset{\approx}{A}\, \underset{\sim}{X}. \quad (2)$$

Equation (2) has the known solution

$$\underset{\sim}{X} = \exp(\underset{\approx}{A}\, t)\, \underset{\sim}{X}(0) \quad (3)$$

where $\underset{\sim}{X}(0)$ is a vector of initial atom densities and $\underset{\approx}{A}$ is a transition matrix containing the rate coefficients for radioactive decay and neutron capture. The function $\exp(\underset{\approx}{A}\, t)$ in Eq. (3) is a matrix exponential function, a matrix of dimension N^2, which is defined as

$$\exp(\underset{\approx}{A}\, t) = \underset{\approx}{I} + \underset{\approx}{A}\, t + \frac{(\underset{\approx}{A}\, t)^2}{2!} + ... = \sum_{m=0}^{\infty} \frac{(\underset{\approx}{A}\, t)^m}{m!} . \quad (4)$$

This function was generated from the transition matrix by the ORIGEN code[1] and the solution of the nuclide chain equations was obtained.

Computation of Neutron Flux

In order to compute changes in fuel composition during irradiation at constant power, it is necessary to take into account changes in the neutron flux with time as the fuel is depleted. At the start of the computation, the known parameters are the initial fuel composition and the constant specific power that the fuel must produce during a time interval. The instantaneous neutron flux may be related to the fuel composition at a fixed time by the equation

$$P = 3.20 \times 10^{-17} \Sigma_f(t)\ \phi(t) \qquad (5)$$

where P is the volume averaged specific power, in Mw thermal per unit of fuel; Σ_f is the spectrum-averaged macroscopic fission cross section, in cm^2 per unit of fuel; and ϕ is the instantaneous volume-energy-averaged neutron flux, in neutrons per cm^2-sec. The constant in Eq. (5) is derived by assuming a value of 200 MeV per fission or 3.204×10^{-17} Mw-sec per fission. An approximate expression for the value of the neutron flux as a function of time is obtained by expansion in a Taylor series about the start of the interval:

$$\phi(t) = 3.125 \times 10^{16} P[\Sigma(0)^{-1} - \frac{t}{2}\frac{\dot{\Sigma}(0)}{\Sigma(0)^2} + \frac{t^2}{2}\left(\frac{2\,\dot{\Sigma}(0)^2 - \ddot{\Sigma}(0)\,\Sigma(0)}{\Sigma(0)^3}\right) + \ldots]$$

or

$$\phi(t) = \phi(0)\left[1 - t\,\frac{\dot{\Sigma}(0)}{\Sigma(0)} + \frac{t^2}{2}\left(\frac{2\,\dot{\Sigma}(0)^2 - \ddot{\Sigma}(0)\,\Sigma(0)}{\Sigma(0)^2}\right) + \ldots\ldots\right] . \qquad (6)$$

The average neutron flux during the interval is obtained by integrating over the interval and dividing by t:

$$\bar{\phi} = \phi(0)\left[1 - \frac{t}{2}\,\frac{\dot{\Sigma}(0)}{\Sigma(0)} + \frac{t^2}{6}\left(\frac{2\,\dot{\Sigma}(0)^2 - \ddot{\Sigma}(0)\,\Sigma(0)}{\Sigma(0)^2}\right) + \ldots\ldots\right] . \qquad (7)$$

Here, the notation $\Sigma(0)$ is used for the macroscopic fission cross section at the start of the time interval, and $\dot{\Sigma}(0)$ and $\ddot{\Sigma}(0)$ are the first and second time derivatives evaluated at the start of the interval. Eq. (7) is used in the computer program to estimate the average flux during an interval, based on conditions at the start of the interval.

Thermal Reactor Spectra and Actinide Cross Sections

In order to compute the effective thermal neutron absorption cross sections for thermal reactors, the ORIGEN code used a three energy-group model. The volume averaged neutron spectrum in the fuel material was assumed to have the same energy dependence for all thermal reactor fuel types, but was allowed only to vary in magnitude. The differential neutron flux used was broken into three energy groups - a Maxwell-Boltzmann distribution of neutron energies near thermal energy, a 1/E energy distribution in the resonance region, and a group with energy dependence of the fission spectrum for high energy neutrons. For thermal water reactors fueled with enriched uranium, the energy width and weights assigned to these groups were:[2]

$$\phi_1'(E) = \bar{\phi} \frac{E}{(KT)^2} e^{-E/KT} \qquad 0 \le E \le 0.5 \text{ eV}$$

$$\phi_2'(E) = \frac{0.333\ \bar{\phi}}{E} \qquad 0.5 \text{ eV} \le E < 1 \text{ MeV}$$

$$\phi_3'(E) = 2\ \bar{\phi}\ F'(E) \qquad 1 \text{ MeV} \le E$$

where $F'(E)$ is the differential energy spectrum of fission neutrons ($F'(E) = 0.484\ e^{-E} \sinh \sqrt{2E}$)[3], K is Boltzmann's constant and T is the neutron temperature. The quantity $\bar{\phi}$ is defined as the volume-averaged mean thermal neutron flux; it is equal to the 2200 meter per second neutron flux multiplied by the ratio $\sqrt{\frac{4T}{\pi T_0}}$.[4] The resonance region was assumed to be

between 0.5 eV and 1 MeV. The above flux spectrum assumes a ratio of the resonance flux per unit lethargy to the integrated thermal neutron flux of 0.333 and a ratio of the integrated flux above 1 MeV to the integrated thermal neutron flux of 2. This assumed spectrum was then used to compute the effective thermal neutron absorption cross sections for the enriched-uranium water reactor:[2,5]

$$\bar{\sigma} = \sqrt{\frac{\pi T_0}{4T}}\, g\sigma_o + 0.333\, I + 2\, \sigma_{f.s.} \qquad (8)$$

where σ_o is the cross section of the nuclide for neutrons with speed of 2200 meters per second, g is the Wescott's non 1/v correction factor, I is the resonance integral of the nuclide corrected for temperature and resonance self shielding, $\sigma_{f.s.}$ is the fission spectrum averaged cross section, and T_0 is equal to 293.6 ^{o}K. The values for $g\sigma_o$, I, and $\sigma_{f.s.}$ were compiled from available sources by Oak Ridge National Laboratory and were written on magnetic tape available for use with the ORIGEN code. The values of the effective thermal neutron cross sections thus calculated were used in Eq. (7) to compute the mean thermal neutron flux necessary to maintain the required specific power for a given fuel composition, for thermal reactors fueled with enriched uranium.

In general, for all thermal reactors, the effective neutron absorption cross section of Eq. (8) is written as:[1]

$$\bar{\sigma} = \text{THERM}*g\sigma_o + \text{RES}*I + \text{FAST}*\sigma_{f.s.}$$

where

THERM = ratio of the neutron reaction rate for a 1/v absorber with a population of neutrons that has a Maxwell-Boltzmann distribution of energies at absolute temperature, T, to the reaction rate with 2200-m/sec neutrons.

RES = ratio of the resonance flux per unit lethargy to the integrated thermal neutron flux.

FAST = ratio of the integrated flux above 1 MeV to the integrated thermal neutron flux.

The values of these spectral indices for the thermal reactor fuel cycles considered in this study were obtained from Oak Ridge National Laboratory[6] and are listed in Table 1. When fuel cycles are converted from uranium to plutonium fuel, the neutron spectrum is hardened as indicated by the increase in the values of RES and FAST. It is assumed that these spectral indices remain constant during the irradiation of the fuel. That is, the normalized volume-averaged neutron spectrum was assumed to remain constant during irradiation.

Table 1

Values of Spectral Indices for Thermal Reactors

	THERM	RES	FAST
Water reactor fueled with enriched uranium.	0.632	0.333	2.00
Water reactor fueled with recycled plutonium and natural uranium.	0.50	0.55	4.00
High temperature gas cooled reactor fueled with uranium and thorium	0.466	0.12	0.58
High temperature gas cooled reactor fueled with recycled plutonium and thorium.	0.369	0.198	1.160

The values of g_o and 1 for the actinides in the water-reactor data library were updated using Mughabghab et al[7] and Benjamin[8]. The isotopes whose cross section values were found to be different from those in the original data library are shown in Table 2. In addition, for water reactors fueled with recycled plutonium and natural uranium, the cross section values of uranium and plutonium were corrected for self-shielding effects as recommended by Oak Ridge National Laboratory[6] and are listed in Table 3.

Table 2

Corrected Cross Section Values of Actinides for Water Reactors Fueled with Enriched Uranium[a]

Isotope	(Barns)			
	$g\sigma_o(n,\gamma)$	$I(n,\gamma)$	$g\sigma_o(n,f)$	$I(n,f)$
^{236}U	5.3 [8]	358 [8]	0	0
^{237}U	411 [7]	290 [7]	0	0
^{237}Np	170	650 [8]	0.019	0
^{238}Np	0	0	2200 [8]	1500 [8]
^{238}Pu	559 [8]	150	17.5	25
^{242}Pu	190 [8]	1280	0.035	5 [7]
^{241}Am	832 [7]	1540 [8]	3.14 [8]	0
^{242m}Am	1400 [7]	7000 [7]	7600 [8]	1570 [7]
^{242}Am	0	0	2100 [8]	300 [8]
^{243}Am	77 [8]	1810 [8]	0.45	1.50
^{242}Cm	30	0	5	150 [8]
^{244}Cm	14 [8]	606 [8]	1.10 [8]	18 [8]
^{245}Cm	342 [8]	102 [8]	2020 [8]	772 [8]
^{246}Cm	1.3 [8]	121	0.17 [8]	10 [8]
^{249}Cf	475 [8]	765 [8]	1690 [8]	2110 [8]

(a) Unless referenced, the values are those in the water-reactor data tape library.

Table 3

Cross Section Values of Uranium and Plutonium for Water Reactors Fueled with Recycled Plutonium and Natural Uranium

Isotope	(Barns)			
	$g\sigma_0(n,\gamma)$	$I(n,\gamma)$	$g\sigma_0(n,f)$	$I(n,f)$
^{235}U	101	144	577	274
^{238}U	2.73	22.0	0.0	0.0
^{238}Pu	560	150	16.5	25.0
^{239}Pu	662	130	1450	300
^{240}Pu	366	1200	0.0	0.0

For the high temperature gas cooled reactor (HTGR) fueled with uranium and thorium, the ^{233}U cross section values in the HTGR data library were corrected upon recommendation by Oak Ridge.[6] The thermal fission cross section, $g\sigma_0(n,f)$, was decreased to 505 barns from 525 barns, and the resonance fission integral, I(n,f), was decreased to 86.2 barns from 862 barns. Again, for the HTGR fueled with recycled plutonium and thorium, the cross section values of plutonium in the HTGR data tape library were corrected for self-shielding effects using the data of Gulf General Atomic[9] and are listed in Table 4.

Table 4

Cross Section Values of Plutonium for HTGRs Fueled with Recycled Plutonium and Thorium

Isotope	(Barns)			
	$g\sigma_0(n,\gamma)$	$I(n,\gamma)$	$g\sigma_0(n,f)$	$I(n,f)$
^{239}Pu	1118	134	1756	333
^{240}Pu	361	2000	0.0	0.0
^{241}Pu	568	139	1486	537

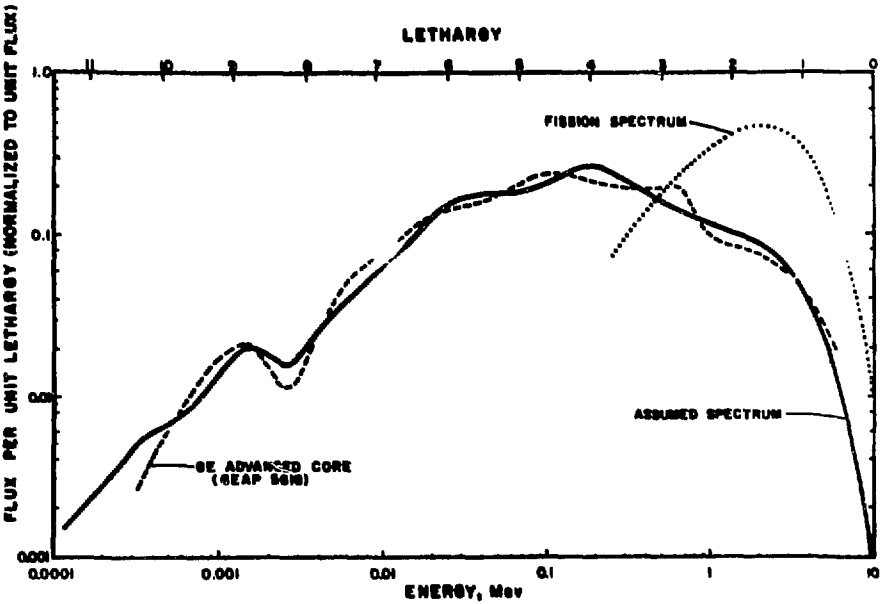
Fast Reactor Spectrum and Actinide Cross Sections

The variables RES, THERM, and FAST were not employed for the fast-reactor library. Reactor-spectrum-averaged capture, fission, (n,2n) and (n,3n) cross sections were generated by averaging the 18-energy-group A1/ENDF cross sections over a fast reactor core spectrum shown in Figure 1.[1,2] The average cross sections for nuclides in the radial and axial blankets were assumed to be the same as in the reactor core. However, the capture and fission cross sections for the uranium and plutonium isotopes were corrected based on data from General Electric.[10] The data from General Electric were 28 region averaged cross sections for a liquid metal fast breeder reactor. These 28 region cross section data were averaged to obtain capture and fission cross sections of the uranium and plutonium isotopes for the core, axial and radial blankets by using the equation:

$$\bar{\sigma}^j = \frac{\sum_{i=1}^{n} V_i N_i \sigma_i^j \phi_i}{\sum_{i=1}^{n} V_i N_i \phi_i}$$

where V_i is the volume of region i, N_i is the atom density of region i, σ_i^j is the spectrum-averaged cross section of nuclei j in region i, and ϕ_i is the spectrum-averaged flux in region i. The averaged cross section thus derived are shown in Table 5.

The power output in the core and blankets were allowed to vary during irradiation[1] such that at the beginning of cycle (BOC) the core is producing 92.8% of the total reactor output, at the middle of cycle (MOC) it is producing 90% and at the end of cycle (EOC) it is producing 87.3% of the total reactor power output. This variation in power output for the core, axial, and radial blankets is shown in Table 6.



Assumed Volume Averaged Neutron Energy Spectrum Used for Fast Reactor Calculations

Table 5

Spectrum Averaged Capture and Fission Cross Sections of Uranium and Plutonium in Fast Reactors

(Barns)

	Core		Axial Blanket		Radial Blanket	
Isotope	$\bar{\sigma}_c$	$\bar{\sigma}_f$	$\bar{\sigma}_c$	$\bar{\sigma}_f$	$\bar{\sigma}_c$	$\bar{\sigma}_f$
^{235}U	0.694	2.05	1.27	2.92	1.26	2.90
^{236}U	0.496	0.117	0.859	0.0713	0.880	0.0631
^{238}U	0.302	0.0432	0.404	0.0230	0.389	0.0209
^{239}Pu	0.496	1.81	0.967	2.26	0.999	2.28
^{240}Pu	0.392	0.355	0.849	0.273	0.985	0.250
^{241}Pu	0.441	2.63	0.772	3.50	0.894	3.74
^{242}Pu	0.595	0.183	0.993	0.183	1.35	0.145

Table 6

Power Variation During Irradiation

	Percent of Total Power		
	Beginning of Cycle	Middle of Cycle	End of Cycle
Core	92.8	90.0	87.3
Axial Blanket	4.2	6.3	8.4
Radial Blanket	3.0	3.7	4.3

Use of the ORIGEN Code

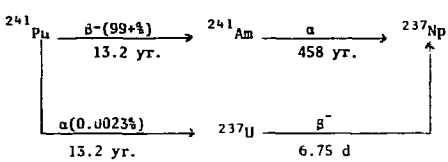
The ORIGEN code, written for the IBM 360 computer, was converted for use on the CDC 7600 computer at the Lawrence Berkeley Laboratory. A listing of ORIGEN and its nuclear data library are shown in the appendix in microfiche form. The computations were then initiated by specifying the initial fresh fuel charge composition, specific power and irradiation time as input data to ORIGEN, and the program was executed. The output of the program was the compositions and activities of the isotopes present in the spent fuel as a function of time after reactor discharge for cooling times up to ten years. After a cooling time of between 30 to 150 days, the spent fuel was reprocessed and recycled along with makeup fuel when necessary, such that the total amount of fissile material in the fresh fuel charge composition remained constant. The fresh fuel charge composition for the second cycle was then used as input data to ORIGEN and the program executed again . This process was repeated several times until an equilibrium cycle was obtained whereby the fresh fuel charge composition remained the same for two consecutive cycles. The output from ORIGEN also includes the compositions and activities of the isotopes present in the wastes after reprocessing as a function of time after

reprocessing.

The results of seven different fuel cycles considered in this study are presented in the following chapters.

II. NUCLEAR REACTIONS IN URANIUM-FUELED NUCLEAR REACTORS

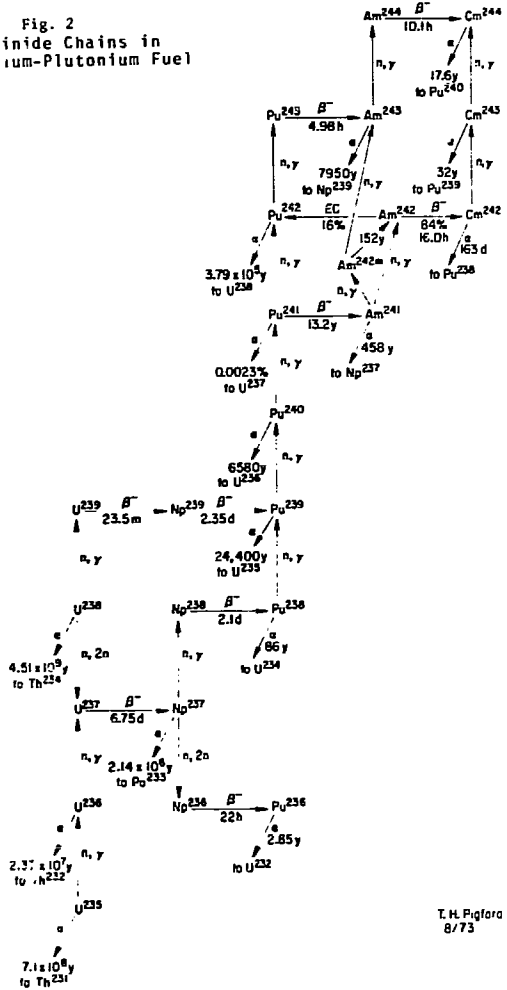
The nuclear reactions which lead to the formation of radionuclides of neptunium, plutonium, americium and curium in nuclear reactor fuel are shown in Figure 2. The principal plutonium isotope formed is ^{239}Pu, with a half-life of 24,400 years, produced by the capture of neutrons in ^{238}U, leading through short-lived ^{239}U and ^{239}Np to fissile ^{239}Pu. Non-fission capture of neutrons in ^{239}Pu results in ^{240}Pu, and its neutron capture results in fissile ^{241}Pu. The isotopes ^{239}Pu and ^{241}Pu are fissionable with thermal and fast neutrons and contribute significantly to the energy sources in thermal and fast reactors. Because of its half-life of 6,580 years, ^{240}Pu is a very strong and persistent alpha source in reactor plutonium, and 13.2 years ^{241}Pu is an extremely intense beta source. The decay of ^{241}Pu is predominantly beta to form alpha emitting ^{241}Am. A small amount (0.0023%) of ^{241}Pu undergoes alpha decay:[11]



The gammas from ^{241}Pu decay are relatively weak (20.8 KeV), but its decay daughters ^{241}Am and ^{237}U emit higher energy gammas and are important sources of external radiation from plutonium fuel material.

Non-fission capture of neutrons in ^{241}Pu results in ^{242}Pu, and because of its long half-life, the radioactivity of ^{242}Pu is not important compared to the other plutonium isotopes. Its neutron-capture daughter ^{243}Pu is short-lived and decays away within a few days after plutonium is removed from the neutron environment of the reactor.

Fig. 2
Actinide Chains in
Uranium-Plutonium Fuel



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The greatest amount of alpha radioactivity in reactor-produced plutonium results from 86-year ^{238}Pu, which is produced by the reaction chain initiated by non-fission neutron capture in ^{235}U and by fast-neutron (n, 2n) reactions with ^{238}U, as shown in Figure 2. Some ^{238}Pu is also produced by fast-neutron (n, 2n) reactions with ^{239}Pu.

Neutron absorption in ^{237}Np also generates the 2.85 year ^{236}Pu. The decay daughters of ^{236}Pu also contribute to the radioactivity in separated plutonium containing ^{236}Pu.

$$^{236}Pu \xrightarrow[2.85\ yr]{\alpha} {}^{232}U \xrightarrow[72\ yr]{\alpha} {}^{228}Th \xrightarrow[1.91\ yr]{\alpha} {}^{224}Ra \xrightarrow[3.64\ d]{\alpha} {}^{220}Rn$$

$$^{220}Rn \xrightarrow[55\ s.]{\alpha} {}^{216}Po \xrightarrow[0.15\ s.]{\alpha} {}^{212}Pb \xrightarrow[10.64\ h]{\beta}$$

$$^{212}Bi \xrightarrow[60.6\ m]{\beta} {}^{212}Po \xrightarrow[3.0 \times 10^{-7}\ s.]{\alpha} {}^{208}Pb$$

$$^{212}Bi \xrightarrow[36\%]{\alpha} {}^{208}Tl \xrightarrow[3.10\ m.]{\beta} {}^{208}Pb$$

The short-lived beta emitters, ^{212}Bi and ^{208}Tl, are accompanied by penetrating high-energy gammas.

Radioactive decay of ^{241}Pu and ^{243}Pu result in the formation of ^{241}Am and ^{243}Am, which are also important and persistent sources of alpha radioactivity. Neutron absorption in these americium isotopes leads to 163-day ^{242}Cm and 17.6-year ^{244}Cm. These, together with the 32-year ^{243}Cm formed by neutron capture in ^{242}Cm, are the most intense sources of alpha radioactivity in discharged uranium fuel. Also, ^{242}Cm, ^{243}Cm, and ^{244}Cm alpha decay to form ^{238}Pu, ^{239}Pu, and ^{240}Pu, respectively. A long-lived decay source of ^{241}Pu is 9300-year ^{245}Cm formed by neutron capture in ^{244}Cm. ^{243}Am alpha decays to ^{239}Np which quickly decays to ^{239}Pu. These decay reactions are the most significant sources of

plutonium in the high-level radioactive wastes resulting from reprocessing uranium fuel. Therefore, americium and curium radioactivities are important considerations in the plutonium fuel cyles.

III. FUEL CYCLES FOR THE 1000 MW WATER REACTORS

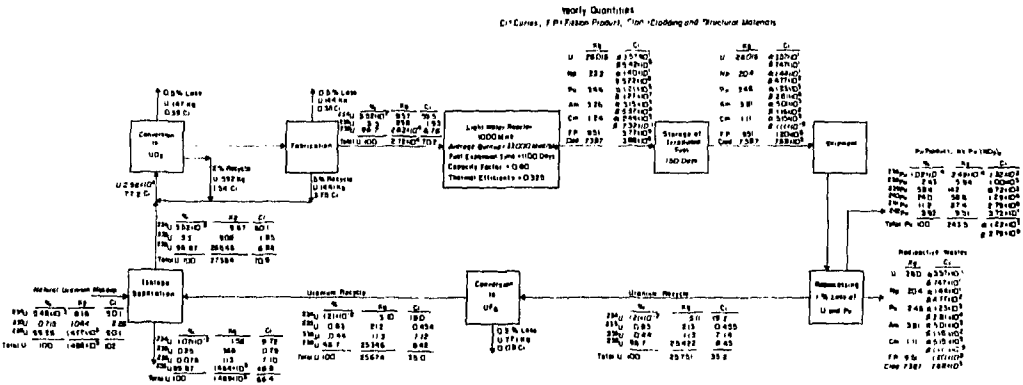
Light Water Reactor Fueled with Enriched Uranium

The material and radioactive quantities of the fuel actinides - uranium, plutonium, americium, curium - involved in the typical fuel cycle for the uranium-fueled water reactor[11] were calculated and are shown in Figure 3. Listed are yearly quantities calculated for a pressurized water reactor operating at an electrical power output of 1000 Mw at 80% load factor. The quantities indicated are characteristic of an equilibrium fuel cycle, whereby each succeeding charge of fresh fuel is of the same composition as the previous fuel charge. Although it neglects the perturbations of the start-up and shut-down cycles, the equilibrium fuel cycle is characteristic of the operation over most of the plant life. In the water reactors, equilibrium fueling occurs by replacing one-third of the reactor fuel every year, so that each fuel element remains within the reactor for three years prior to discharge, corresponding to an average thermal exposure of 33,000 Mw days per Mg of uranium charged and an average thermal specific power of 30 Mw per Mg.

The uranium fuel charged to the reactor is Zircaloy-clad uranium dioxide, enriched to 3.3 isotopic percent ^{235}U in total uranium. During the three-year operating period, about 3.5% of the total uranium will have been fissioned, either directly as in the case of ^{235}U and ^{238}U fast fission, or indirectly through conversion of fissile plutonium. The discharge fuel is stored at the reactor site for 150 days to allow for decay of fission products, especially 8.05-day ^{131}I which must not be allowed to escape from fuel reprocessing in any but minute quantities and ^{237}U. The discharge fuel is then shipped to a reprocessing facility where it is separated into uranium, plutonium, a high-level waste containing the mixed fission products

Fig. 3

Detailed Fuel Cycle Flowsheet for Uranium-Fueled Water Reactor



and remaining actinides, and a high-level waste consisting of activated cladding and fuel-assembly structure. The recovered uranium, containing 0.83% ^{235}U, is then returned as an input to the isotope-separation plant for re-enrichment. The percentage of input material which appears as processing losses and as scrap recycle in each fuel cycle operation is taken from a recent AEC study[12] on reactor fuel cycle costs.

The material and radioactive quantities of actinides (U, Np, Pu, Am, Cm) in the charge and discharge fuel, in shipment, and recovered from fuel reprocessing are indicated on the flow sheet and are tabulated in Table 7. The radioactive quantities of fission products and fuel cladding are also shown in Table 7. The inventories of uranium are average inventories, all other inventory quantities were calculated on the basis of the composition of discharge fuel. A total of 246 Kg/yr of plutonium is contained in the discharge fuel to be reprocessed, and the recovered plutonium contains 170 Kg/yr of fissile plutonium.

For an estimated value of fissile plutonium of $7.50 per gram as water-reactor recycle fuel, the value of the recovered plutonium is about $1.4 million per year. This is over twice the value of the recovered uranium. It is to realize the value of the contained plutonium that is the main justification for processing fuel from this reactor.

The plutonium thus recovered in each year contains 1.22×10^5 curies of alpha emitting radionuclides and 2.79×10^6 curies of beta emitting ^{241}Pu. The isotopic composition of the recovered plutonium is shown in the first column of Table 8, and the radioactivity resulting from each of these plutonium isotopes is shown in the first column of Table 9.

Table 7

Material and Radioactive Quantities in Reactor and Fuel Cycle For a 1000 Mw Uranium-Fueled Water Reactor

	CHARGE		DISCHARGE		150 DAYS		CORE INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
U234	9.47E+00	5.92E+01	3.14E+00	1.96E+01	3.14E+00	1.96E+01	1.91E+01	1.18E+02
U235	8.99E+02	1.93E+00	2.15E+02	4.61E-01	2.15E+02	4.61E-01	1.67E+03	3.58E+00
U236	0.	0.	1.14E+02	7.22E+00	1.14E+02	7.22E+00	3.42E+02	2.17E+01
U237	0.	0.	4.27E-01	3.49E+07	9.15E-07	7.47E+01	1.28E+00	1.05E+08
U238	2.63E+04	8.78E+00	8.96E+00	2.97E+04	2.57E+04	8.54E+00	7.80E+04	2.60E+01
U239	0.	0.	1.51E-02	6.07E+08	0.	0.	4.54E-02	1.52E+09
TOTAL	2.72E+04	6.99E+01	2.60E+04	9.48E+08	2.60E+04	9.40E+04	7.99E+04	8.13E+08
		α6.99E+01		α3.57E+01		α1.57E+01		α1.58E+02
		β0.		β5.42E+08		β7.47E+01		β1.63E+09
NP236	0.	0.	2.04E-07	1.21E+12	0.	0.	6.12E-07	3.69E+02
NP237	0.	0.	1.99E+01	1.41E+01	2.04E+01	1.44E+01	5.98E+01	4.22E+01
NP238	0.	0.	5.00E-02	1.92E+07	0.	0.	1.74E-01	4.59E+07
NP239	0.	0.	2.19E+00	8.06E+00	2.05E-06	4.78E+02	6.57E+00	1.42E+09
TOTAL	0.	0.	2.22E+01	5.22E+09	2.04E+01	4.92E+02	6.65E+01	1.52E+09
				α1.41E+01		α1.44E+01		α4.22E+01
				β5.22E+09		β4.77E+02		β1.58E+09
PU236	0.	0.	2.77E-04	1.47E+02	2.51E-04	1.34E+02	8.30E-14	4.41E+02
PU238	0.	0.	6.03E+00	2.98E+04	5.99E+00	1.01E+05	1.75E+01	2.96E+05
PU239	0.	0.	1.42E+02	8.60E+03	1.44E+02	8.82E+03	4.25E+02	2.61E+04
PU240	0.	0.	9.91E+01	1.30E+04	5.91E+01	1.30E+04	1.77E+02	3.91E+04
PU241	0.	0.	2.82E+01	2.07E+06	2.77E+01	2.01E+06	8.47E+01	6.61E+06
PU242	0.	0.	4.65E+00	3.76E+01	4.65E+00	3.76E+01	2.90E+01	1.13E+02
PU243	0.	0.	3.79E-03	9.89E+06	2.75E-15	7.14E-06	1.14E-02	2.96E+07
TOTAL	0.	0.	2.44E+02	1.20E+07	2.46E+02	2.94E+06	7.13E+02	3.85E+07
				α1.20E+05		α1.23E+05		α3.61E+05
				β1.27E+07		β2.81E+06		β3.81E+07
AM241	0.	0.	7.78E-01	2.47E+03	1.32E+00	4.53E+03	2.33E+00	8.00E+03
AM242M	0.	0.	1.19E-02	1.16E+02	1.19E-02	1.16E+02	3.50E-02	3.40E+02
AM242	0.	0.	2.01E-03	1.63E+06	1.43E-07	1.16E+02	6.04E-03	4.09E+06
AM243	0.	0.	2.44E+00	4.77E+02	2.48E+00	4.77E+02	7.43E+00	1.43E+03
AM244	0.	0.	1.26E-04	3.71E+04	0.	0.	3.78E-04	1.12E+07
TOTAL	0.	0.	3.27E+00	9.12E+06	3.48E+00	5.24E+03	9.81E+00	1.61E+07
				α3.14E+03		α5.01E+03		α9.43E+03
				β5.40E+06		β1.16E+02		β1.61E+07

Table 7 (continued)

	CHARGE		DISCHARGE		100 DAYS		CORP INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM242	0.	0.	2.50E-01	8.20E+05	1.33E-01	4.40E+05	7.50E-01	2.48E+06
CM243	0.	0.	1.70E-03	9.11E+01	1.90E-03	9.03E+01	5.94E-03	2.73E+02
CM244	0.	0.	9.25E-01	7.40E+04	9.11E-01	7.30E+04	2.78E+00	2.25E+05
CM245	0.	0.	6.54E-02	2.79E+00	6.54E-02	2.79E+00	1.96E-01	8.36E+00
CM246	0.	0.	8.23E-03	1.03E+00	8.23E-03	1.02E+00	1.47E-02	5.77E+00
CM247	0.	0.	8.08E-05	7.14E-06	8.08E-05	7.14E-06	2.42E-04	2.14E-05
CM248	0.	0.	9.49E-06	2.25E-05	9.49E-06	2.25E-05	1.68E-05	6.74E-05
TOTAL	0.	0.	1.24E+00	9.01E+05	1.11E+00	8.11E+05	3.72E+00	2.71E+06
				a9.03E+05		a8.13E+05		a2.71E+06
				B7.32E-01		B1.11E-01		B2.20E+00
BK249	0.	0.	6.12E-06	1.02E-01	4.46E-06	7.14E-02	1.83E-07	3.07E-01
BK250	0.	0.	4.71E-11	1.03E-01	0.	0.	1.41E-10	3.50E-01
TOTAL	0.	0.	6.12E-06	2.05E-01	4.46E-06	7.14E-02	1.84E-07	6.56E-01
				a0.		a0.		a0.
				B2.85E-01		B7.34E-02		B2.50E-01
CF249	0.	0.	7.02E-09	7.10E-05	2.51E-08	1.02E-04	2.11E-08	9.57E-05
CF250	0.	0.	1.01E-08	1.10E-03	9.08E-09	1.09E-03	3.02E-08	3.30E-03
CF251	0.	0.	5.07E-09	8.01E-06	5.07E-09	8.01E-06	1.52E-08	2.41E-05
CF252	0.	0.	2.75E-09	1.45E-03	2.48E-09	1.31E-03	8.27E-09	4.45E-03
CF253	0.	0.	4.20E-12	1.21E-04	1.22E-14	3.55E-07	1.26E-11	3.65E-04
TOTAL	0.	0.	2.74E-08	2.74E-03	4.23E-08	2.52E-03	7.72E-08	8.23E-03
				a2.62E-03		a2.52E-03		a7.86E-03
				B1.23E-04		B3.55E-07		B3.65E-04
TOTAL ACT.	2.72E+04	6.99E+01	2.63E+04	1.04E+09	2.63E+04	3.40E+06	8.03E+04	1.62E+09
FISSION PROD.	0.	0.	9.51E+02	1.77E+09	9.51E+02	1.20E+08	2.85E+03	1.13E+10
CLAD	7.19E+01	0.	7.19E+03	5.08E+06	7.39E+01	7.60E+04	2.22E+04	5.63E+06

Table 8

Isotopic Composition of Plutonium in Reprocessed Discharge Fuel, For 1000 Mw Power Plants

	Uranium-Fueled Water Reactor Wt.%	Plutonium-Fueled Water Reactor Wt.%	Fast-Breeder[a] Reactor Wt.%
^{236}Pu	1.0×10^{-4}	3.7×10^{-5}	1.5×10^{-6}
^{238}Pu	2.4	4.3	6.9×10^{-2}
^{239}Pu	58.4	37.2	71.7
^{240}Pu	24.0	27.8	25.1
^{241}Pu	11.3	18.6	2.4
^{242}Pu	3.9	12.1	0.76
	100	100	100

Table 9

Curies of Plutonium Radionuclides Reprocessed Yearly, For 1000 Mw Power Plants

		Uranium-Fueled Water Reactor Curies/Yr	Plutonium-Fueled Water Reactor Curies/Yr	Fast-Breeder[a] Reactor Curies/Yr
^{236}Pu		1.34×10^{2}	1.76×10^{2}	1.59×10^{1}
^{238}Pu		3.01×10^{5}	6.50×10^{5}	2.25×10^{4}
^{239}Pu		8.82×10^{3}	2.03×10^{4}	8.51×10^{4}
^{240}Pu		1.30×10^{4}	5.44×10^{4}	1.07×10^{5}
^{241}Pu		2.81×10^{6}	1.69×10^{7}	4.67×10^{6}
^{242}Pu		3.76×10^{1}	4.20×10^{2}	5.74×10^{1}
Total	α	1.23×10^{5}	7.25×10^{5}	2.18×10^{5}
Total	β	2.81×10^{6}	1.69×10^{7}	4.67×10^{6}

(a) Atomics International Follow-On Liquid Metal Fast Breeder Reactor

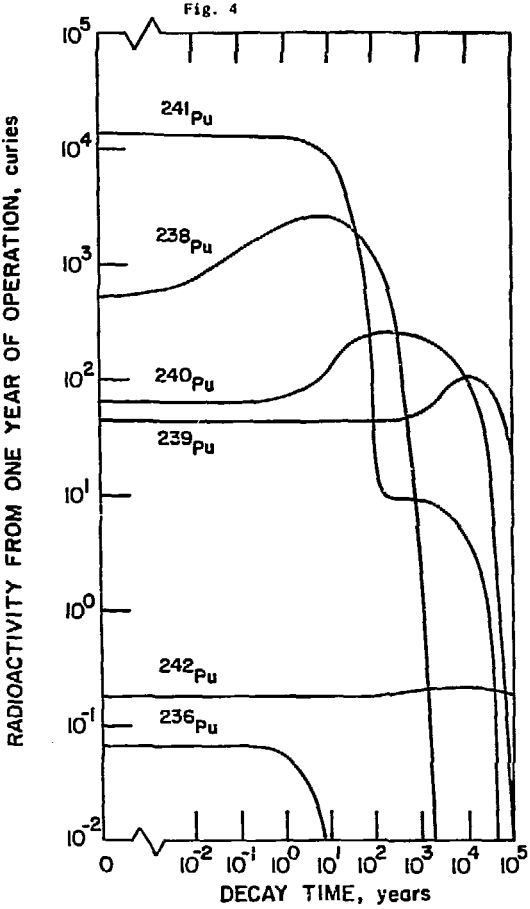
The yearly production of americium and curium appear in Table 7 under the column heading '150 Days'; that is, 150 days after the fuel is discharged from the reactor.

The high-level radioactive wastes from fuel reprocessing are to be stored for an interim period of 5 to 10 years at the fuel reprocessing site. They are then to be shipped, in a consolidated form, to a federal repository for perpetual storage.

Detailed plots of the growth and decay of plutonium in the high-level waste are shown in Figure 4. It was assumed, for the purpose of this calculation, that 0.5% of the uranium and plutonium in the reprocessed fuel and all of the remaining actinides follow the high-level wastes. For a period of about 10 years after reprocessing the concentration of ^{238}Pu increases with time in the high-level waste because of the relatively large amounts of its precursors ^{242}Am and ^{242}Cm and it remains in appreciable concentration for over 100 years. For a period of about 10,000 years, the concentration of ^{239}Pu increases in the high-level waste because of the relatively large concentrations of its radioactive-decay precursors ^{243}Am and ^{243}Cm. Similarly, the concentration of ^{240}Pu increases for several hundred years because of the relatively large amount of its precursor ^{244}Cm. The long-lived decay source of ^{241}Pu is 9300-year ^{245}Cm.

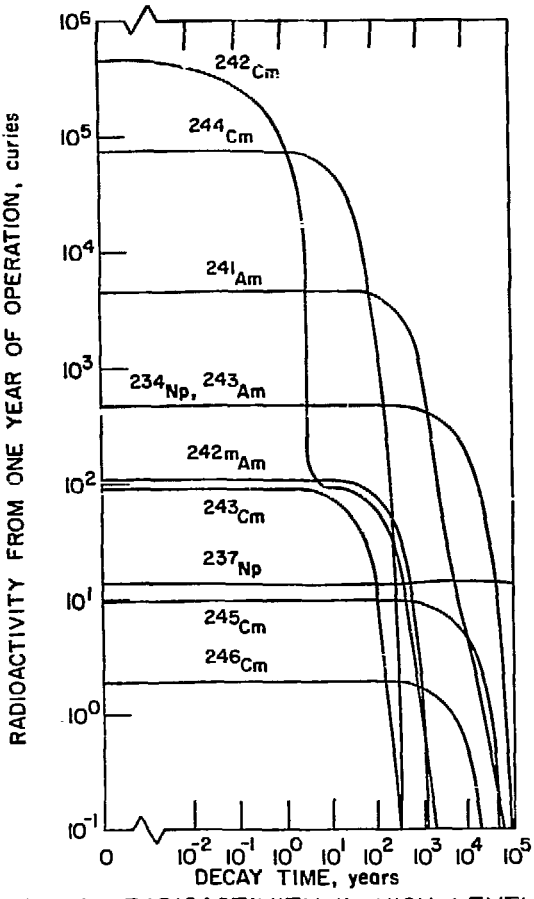
The radioactive inventories of neptunium, americium, and curium radionuclides in high-level wastes, as a function of waste storage time, are shown in Figure 5. In Figure 6 are shown the radioactive inventories in high-level wastes of the elements neptunium, plutonium, americium, and curium, and the total of all the actinides present in the high-level wastes. It is apparent that for storage periods of less than one hundred years the main contribution to total actinide radioactivity is due mainly

Fig. 4



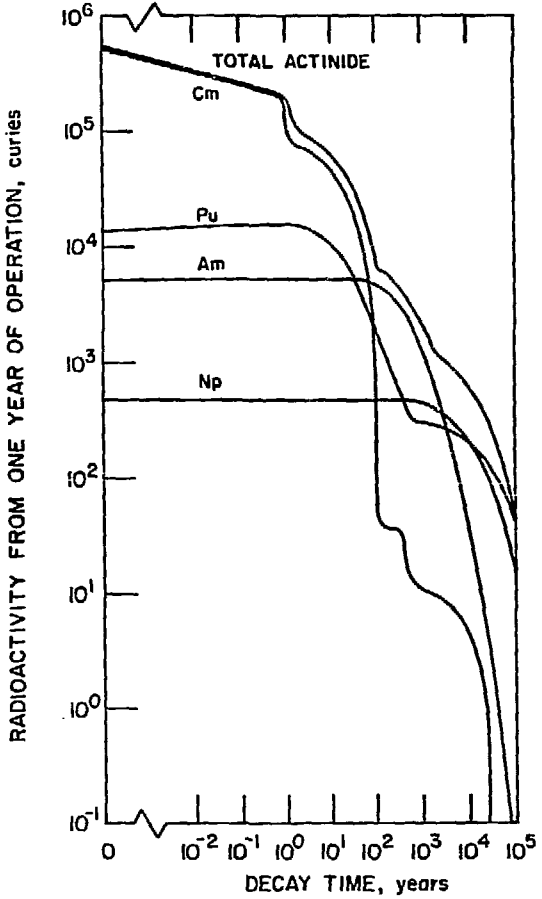
PLUTONIUM RADIOACTIVITY IN HIGH-LEVEL WASTES FROM URANIUM-FUELED WATER REACTOR

Fig. 5



Np, Am, Cm RADIOACTIVITY IN HIGH-LEVEL WASTES FROM URANIUM-FUELED WATER REACTOR

Fig. 6



ACTINIDE RADIOACTIVITY IN HIGH-LEVEL WASTES FROM URANIUM-FUELED WATER REACTORS

to neptunium, plutonium and americium.

The recovered plutonium product builds up additional radioactivity with time due to the radioactive decay of 13.2-year ^{241}Pu to form ^{241}Am and ^{237}U and due to the radioactive decay of 2.85-year ^{236}Pu to form ^{232}U, ^{228}Th and the ^{228}Th decay daughters.

The radioactive inventories of plutonium in the fuel cycle operations were calculated, with process hold-up times obtained from a study by Pigford[11], along with the associated inventories in the fuel cycle operations and are shown in Table 10. The total fuel cycle mass inventory is 879 Kg with alpha and beta activities of 4.33×10^5 and 4.39×10^7 curies respectively.

Light-Water Reactor Fueled with Natural Uranium and Recycled Plutonium

There are several alternate means of utilizing plutonium as recycle fuel in water reactors. As one alternative, the plutonium may be blended with natural or slightly enriched uranium as self-generated recycle fuel in the reactor in which it was originally produced, thereby reducing the required amount of uranium isotope separation for that reactor. Portions of the reactor core may be assigned to mixed PuO_2-UO_2 fuel, with other portions fueled with isotopically enriched UO_2. Because of the high neutron absorption cross section of plutonium some modification in the reactor control absorbers may be necessary. Alternatively, it might be more desirable to design some water reactors to be fueled entirely with a mixture of natural uranium and make-up plutonium recovered from fuel discharged from uranium-fueled water reactors. The plutonium recovered from fuel discharged from such reactors is to be blended with natural uranium and make-up plutonium. This concept has the advantage that all fuel within the reactor consists of the mixture of natural

Table 10

Inventories of Plutonium in Fuel Cycle of 1000 Mw Water Reactor Fueled with Uranium

	Hold-up time	Plutonium Inventory[a] Total Pu Kg	Fissile Pu Kg	Alpha Pu curies	Beta Pu curies
Reactor	3 years	733	510	3.61×10^5	3.81×10^7
Post-irradiation cooling.	150 days	100	70	4.93×10^4	5.22×10^6
Shipment to fuel reprocessing	38.4 days	26	18	1.29×10^4	2.95×10^5
Fuel reprocessing	30 days	20	14	1.01×10^4	2.31×10^5
Total external to reactor		146	102	7.23×10^4	5.75×10^6
Total in reactor and external fuel cycle		879	612	4.33×10^5	4.39×10^7
Recovered plutonium produced in one year of operation		244	169	1.22×10^5	2.79×10^6
Plutonium in radioactive wastes from one year of operation		2.46	1.71	1.23×10^3	2.81×10^4

(a) Fissile plutonium: $^{239}Pu + ^{241}Pu$

Alpha: $^{236}Pu + ^{238}Pu + ^{239}Pu + ^{240}Pu + ^{242}Pu$

Beta: $^{241}Pu + ^{243}Pu$

uranium and plutonium. It is this concept which is the basis for the plutonium recycle in the present analysis. These results can be used as a good approximation to the flowsheet for fuel elements fabricated from natural uranium and recycle plutonium and used in partial core loadings in the first alternative described above, providing the throughputs and inventories are scaled according to the power generated by these recycle fuel elements.

The fuel cycle flowsheet for the plutonium-uranium fueled water reactor[13] is shown in Figure 7. As in the case of the uranium-fueled water reactor, each fuel element is discharged after three years. To maintain sufficient fissile content of the fresh fuel, 505 Kg/yr of makeup plutonium is required from the recovered fuel of the uranium-fueled water reactors. Since each of the 1000 Mw reference uranium-fueled water reactors, as shown in Figure 3, produces 244 Kg/yr of recovered plutonium, a total generating capability of 2070 Mw of uranium-fueled water reactors is required to support 1000 Mw of plutonium recycle. This ratio will vary with specific designs. Table II lists the mass and radioactivity for the charge and discharge and the fuel composition 150 days after discharge, as well as the reactor inventory. The inventories of uranium and plutonium are average inventories, all other inventory quantities were calculated on the basis of the composition of discharge fuel. As shown in Figure 7, a total of 1450 Kg/yr of recycle and makeup plutonium is supplied to the fuel fabrication operation. The uranium-plutonium mixture fabricated into fresh fuel contains 5.0% total plutonium and 3.0% fissile plutonium. The ^{241}Am in the fresh fuel results from the radioactive decay of 13.2 yr ^{241}Pu in the recycled fuel after its separation in fuel reprocessing.

Fig. 7

Fuel Actinide Flowsheet for 1000-Mwe U-Pu Fueled Water Reactor
Yearly Quantities, 80 % Load Factor
Ci = curies

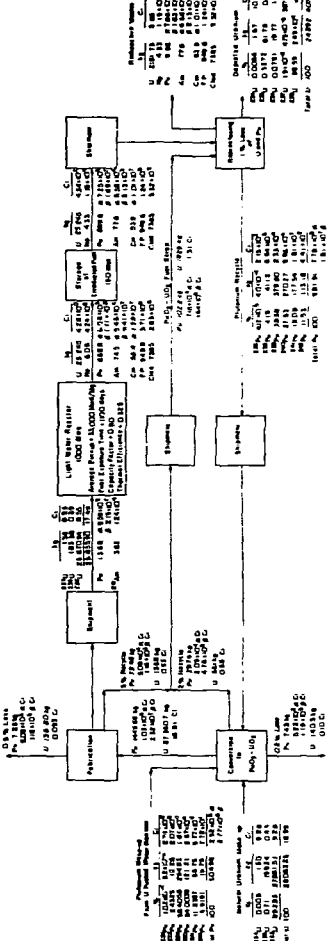


Table 11

Material and Radioactive Quantities in Reactor and Fuel Cycle for a 1000 Mw Plutonium-Fueled Water Reactor

	CHARGE		DISCHARGE		150 DAYS		CORE INVENTORY	
	KG/YR	CURIES/YR	KG/YR	CURIES/YR	KG/YR	CURIES/YR	KGM	CURIES
U235	[illegible]	[illegible]	1.56E+02	[illegible]	[illegible]	1.04E+01	4.41E+03	[illegible]
U236	[illegible]	[illegible]E-01	[illegible]	1.77E-01	[illegible]	1.77E-01	1.27E+03	[illegible]
[illegible]	0.	0.	[illegible]	[illegible]	[illegible]	1.22E+00	5.50E+01	[illegible]
U237	0.	0.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
U238	[illegible]E+04	[illegible]	2.51E+04	[illegible]	[illegible]	[illegible]	7.62E+04	[illegible]
[illegible]	0.	0.	1.20E-02	[illegible]	0.	0.	[illegible]	[illegible]
TOTAL	[illegible]	1.75E+01	2.52E+04	[illegible]	2.52E+04	4.34E+02	7.67E+04	[illegible]
		α1.75E+01		α[illegible]		α[illegible]		α[illegible]
		β0.		β[illegible]		β[illegible]		β[illegible]
NP236	0.	0.	[illegible]E-04	[illegible]E+01	0.	0.	1.77E-07	[illegible]
NP237	0.	0.	[illegible]	[illegible]	4.73E+00	[illegible]	1.27E+01	[illegible]
NP238	0.	0.	[illegible]E-01	[illegible]	0.	[illegible]	[illegible]E-02	[illegible]
NP239	0.	0.	[illegible]	[illegible]	5.71E-05	[illegible]	[illegible]	[illegible]
TOTAL	0.	0.	[illegible]	[illegible]	4.33E+00	[illegible]	1.42E+01	[illegible]
				α2.59E+09		α1.00E+00		α[illegible]
				β[illegible]		β1.17E+04		β1.27E+05
PU236	[illegible]E-04	[illegible]E+02	[illegible]	[illegible]E+02	3.31E-04	1.76E+02	1.42E-03	[illegible]
PU238	[illegible]E+01	[illegible]	[illegible]E+01	[illegible]E+05	3.65E+01	[illegible]E+05	1.29E+02	[illegible]
PU239	[illegible]E+02	[illegible]	[illegible]E+03	[illegible]	3.31E+03	[illegible]E+04	1.42E+03	[illegible]
PU240	[illegible]	[illegible]	2.46E+02	[illegible]	2.47E+02	[illegible]	[illegible]	[illegible]
PU241	[illegible]E+02	[illegible]	[illegible]E+03	1.73E+07	1.66E+02	[illegible]	5.77E+02	[illegible]
PU242	[illegible]E+02	4.72E+02	[illegible]E+02	4.20E+02	[illegible]E+02	[illegible]E+02	3.45E+02	[illegible]
PU243	0.	0.	[illegible]E-12	[illegible]E+07	3.07E-13	[illegible]	1.0[illegible]E-01	[illegible]
TOTAL	1.17E+03	[illegible]	[illegible]E+02	[illegible]E+08	8.40E+02	[illegible]E+07	[illegible]	[illegible]
		α[illegible]E+05		α[illegible]		α7.2[illegible]E+05		α[illegible]
		β[illegible]		β[illegible]		β[illegible]		β[illegible]
AM241	[illegible]	[illegible]E+06	1.25E+01	[illegible]	1.57E+01	[illegible]E+04	2.31E+01	[illegible]
AM242M	0.	0.	2.19E-01	2.13E+03	2.19E-01	2.12E+03	6.57E-01	[illegible]
AM242	0.	0.	2.02E-0[illegible]	[illegible]E+07	[illegible]E-06	2.13E+03	6.05E-02	[illegible]
AM243	0.	0.	6.1[illegible]E+01	[illegible]	6.18E+01	[illegible]E+04	[illegible]E+02	[illegible]
AM244	0.	0.	[illegible]	[illegible]E+07	0.	[illegible]	7.07E-0[illegible]	[illegible]
TOTAL	[illegible]E+00	[illegible]E+06	7.45E+01	[illegible]E+07	7.78E+01	7.01E+04	1.17E+02	[illegible]
		α1.2[illegible]E+06		α[illegible]E+04		α[illegible]E+04		α[illegible]
		β0.		β9.41E+07		β2.13E+03		β[illegible]

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Table 11 (continued)

	CHARGE		DISCHARGE		150 DAYS		CORE INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM242	0.	0.	3.43E+02	1.33E+07	1.92E+00	7.37E+04	1.65E+01	3.71E+07
CM243	0.	0.	2.90E+00	1.54E+05	2.24E-05	1.31E+01	5.77E-03	3.11E+07
CM244	0.	0.	3.73E+01	3.40E+06	4.42E+01	4.34E+06	1.41E+02	1.16E+07
CM245	0.	0.	5.27E+00	9.21E+05	9.23E+00	9.21E+02	1.47E+01	2.76E+03
CM246	0.	0.	5.13E+01	1.58E+03	5.12E+01	1.58E+03	1.54E+00	4.74E+02
CM247	0.	0.	9.01E+03	7.69E+06	9.01E+03	7.69E+06	2.70E+02	2.30E+03
CM248	0.	0.	7.73E+04	9.60E+03	7.73E+04	9.60E+01	2.70E+03	9.31E+02
TOTAL	0.	0.	1.09E+01	1.49E+07	8.79E+01	1.01E+07	1.09E+02	4.74E+07
				Q1.49E+07		Q1.01E+07		Q4.74E+07
				B4.34E+01		B8.45E+00		B5.61E+02
RH242	0.	0.	1.60E-05	1.48E+01	7.21E-06	1.20E+01	7.01E-05	5.23E+01
RH240	0.	0.	4.31E-05	1.49E+01	0.	1.78E-10	9.61E-08	5.61E+01
TOTAL	0.	0.	7.10E-05	1.49E+01	7.21E-06	1.20E+01	1.01E-04	1.12E+02
				Q0.		Q0.		Q0.
				B3.45E+01		B3.22E+01		B1.01E+02
CF252	0.	0.	1.99E-06	7.95E-03	4.76E-06	1.59E-02	5.91E-06	2.37E-02
CF250	0.	0.	1.20E-06	1.41E-01	1.27E-06	1.33E-01	1.07E-06	4.23E-01
CF251	0.	0.	7.49E-07	1.25E-03	7.49E-07	1.25E-03	2.77E-06	3.75E-03
CF249	0.	0.	2.94E-07	1.93E-03	2.64E-07	1.91E-01	8.81E-07	6.23E-01
CF248	0.	0.	3.22E-10	4.73E-03	6.30E-13	2.73E-05	9.66E-10	3.08E-02
TOTAL	0.	0.	4.31E-06	1.17E-01	7.08E-06	1.01E-01	1.20E-05	9.62E-01
				Q1.6E-01		Q3.01E-01		Q9.26E-01
				B9.13E-03		B2.72E-05		B2.50E-02
TOTAL	2.72E+04	2.28E+07	2.63E+04	1.63E+07	2.63E+04	2.78E+07	4.02E+04	1.69E+07
FISSION Prod.	0.	0.	4.69E+02	3.71E+06	9.50E+02	1.24E+08	2.85E+01	1.11E+10
CLAD	7.18E+02	0.	7.18E+03	2.65E+06	7.38E+03	8.32E+05	2.72E+04	3.97E+06

After 150-day storage for radioiodine decay, the fuel is shipped to reprocessing. The recovered plutonium is recycled to fuel conversion and fabrication. The recovered uranium, containing 0.33% ^{235}U, is not worth recycling. The required net input of natural uranium from external sources is 28,060 Kg/yr. The process losses and scrap recycle fractions are those used in a recent AEC[12] study on reactor fuel cycles.

The isotopic composition of the plutonium recovered in fuel reprocessing and the radioactivity quantities of the plutonium reprocessed yearly are shown in the second columns of Tables 8 and 9. The concentration of high-mass plutonium isotopes is relatively high because all of the plutonium is recycled, except for the small amount involved in process losses. As a result, relatively large quantities of americium and curium are produced, as shown in the second columns of Tables 12 and 13, resulting in much greater quantities of alpha activity in the high-level wastes and in much greater amounts of plutonium ultimately present in these wastes from americium and curium decay. The radioactive content of plutonium in discharge fuel is over six times greater than that in the uranium-fueled water reactor, and the content of americium and curium is over ten times greater. The total inventory of plutonium in the reactor and external fuel cycle is calculated and listed in Table 14. The total mass inventory is about five times greater for the uranium-plutonium fueled reactor than for the uranium-fueled reactor, and the total alpha radioactivity is about seven times greater for the uranium-plutonium fueled reactor than for the uranium-fueled reactor.

From Figur it can be seen that each year about 1490 Kg of plutonium, containing 905 Kg of fissile plutonium, 1.05×10^6 curies of plutonium alpha activity and 2.4×10^7 curies of plutonium beta activity.

Table 12

Americium Radionuclides Reprocessed Yearly for 1000 Mw Power Plants

	Uranium-Fueled Water Reactor	Plutonium-Fueled Water Reactor	Fast[a] Breeder Reactor
		Kilograms/Year	
^{241}Am	1.32	15.7	4.05
^{242m}Am	0.011	0.218	0.0712
^{243}Am	2.48	61.8	1.92
Total	3.81	77.7	6.04
		Curies/Year	
^{241}Am	4.53×10^3	5.39×10^4	1.39×10^4
^{242m}Am	1.16×10^2	2.12×10^3	6.92×10^2
^{242}Am	1.16×10^2	2.12×10^3	6.92×10^2
^{243}Am	4.77×10^2	1.19×10^4	3.69×10^2
Total α	5.01×10^3	6.58×10^4	1.43×10^4
Total β	1.16×10^2	2.12×10^3	6.92×10^2

(a) Atomics International Follow-On Liquid Metal Fast Breeder Reactor.

Table 13

Curium Radionuclides Reprocessed Yearly for 1000 Mw Power Plants

	Uranium-Fueled Water Reactor	Plutonium-Fueled Water Reactor	Fast Breeder Reactor [a]
	Kilograms/Year		
^{242}Cm	0.133	1.92	0.113
^{243}Cm	0.002	0.022	0.006
^{244}Cm	0.911	46.2	0.127
^{245}Cm	0.055	5.22	0.004
Total	1.101	53.36	0.250
	Curies/Year		
^{242}Cm	4.40×10^{5}	6.36×10^{6}	3.76×10^{5}
^{243}Cm	9.03×10^{1}	1.03×10^{3}	2.87×10^{2}
^{244}Cm	7.38×10^{4}	3.74×10^{6}	1.03×10^{4}
^{245}Cm	9.79	9.21×10^{2}	6.29×10^{-1}
Total	5.15×10^{5}	1.01×10^{7}	3.87×10^{5}

(a) Atomics International Follow-On Liquid Metal Fast Breeder Reactor.

Table 14

Inventories of Plutonium in Fuel Cycle of 1000 Mw Water Reactor
Fueled with Natural Uranium and Recycle Plutonium

	Hold-up time	Total Pu Kg	Fissile Pu Kg	Alpha Pu curies	Beta Pu curies
Reactor	3 yr.	3380	1997	2.47×10^6	2.00×10^8
Post-irradiation cooling	150 days	356	205	2.87×10^5	4.56×10^7
Shipment to fuel reprocessing	38.4 days	93.6	52.3	7.62×10^4	1.78×10^6
Fuel reprocessing	30 days	73.1	40.8	5.95×10^4	1.39×10^6
Shipment to fuel conversion	8.4 days	22.6	12.8	1.79×10^4	4.16×10^5
Fuel fabrication	30 days	119	72.8	8.38×10^4	1.91×10^6
Shipment to reactor	12 days	44.9	27.4	3.15×10^4	7.20×10^5
Pre-irradiation inventory	36 days	134.7	82.2	9.45×10^4	2.16×10^6
Scrap recycle shipment	12 days	3.4	2.0	2.36×10^3	5.39×10^4
Total external to reactor		954	555	7.20×10^5	5.56×10^7
Total in reactor and external fuel cycle		4334	2552	3.19×10^6	2.56×10^8
Plutonium makeup from one year of operation		505	352	2.52×10^5	5.77×10^6

must be carried through several operations of chemical conversion, fabrication, and shipping for such a 1000 Mw reactor. The process losses to the environment must be controlled to extremely low levels in order to maintain the public risks at low and acceptable levels.

The plutonium activity in the high-level wastes resulting from one year of operation is shown as a function of storage time in Fig. 8. The radioactivity of Am, Cm, and Pu in high-level wastes from uranium-fueled water reactors and uranium-plutonium fueled water reactors are compared in Fig. 9. The plutonium activity is well over ten-fold higher in the wastes from the plutonium-recycle water reactor, and the curium activity is greater by an even larger factor.

The flowsheet of Fig. 7 indicates estimates of the losses of plutonium to other solid wastes in the fuel-cycle operations. These wastes generally contain plutonium and other actinides at very low concentrations, so they are referred to here as low-level wastes. These plutonium losses are not environmental releases, as acceptable environmental releases must be many orders of magnitude less than the losses to these wastes. Therefore, the wastes associated with these process losses must be subject to permanently protected storage or disposal. It is assumed here that these wastes are made up of 0.5% of the plutonium in fuel reprocessing, 0.5% in oxide conversion, and 0.5% in fuel fabrication. Therefore, for such a plutonium-recycle flowsheet, the amount of plutonium appearing in these low-level wastes is greater than that associated with the high-level fission-product wastes at the time these process operations occur, although the high-level wastes ultimately contain more plutonium because of the americium and curium. The amounts of plutonium are significant, and careful attention must be given to a waste management program which assures adequate control of all of these wastes. On the basis of equal

protection to the environment, the management of the low-level plutonium wastes may be a more difficult problem than the management of high-level wastes, because of the comparable quantities of plutonium and because of the much larger volume of material involved in the low-level wastes.

Fig. 8

Plutonium Activity in High-Level Wastes from a Uranium-Plutonium-Fueled Water Reactor

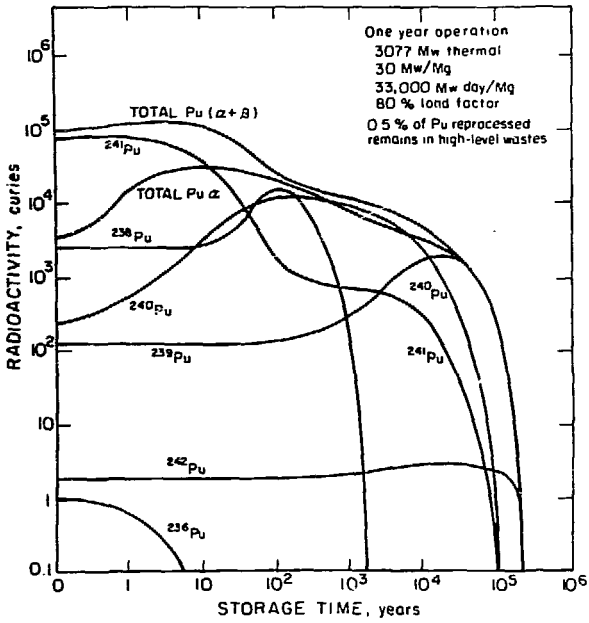
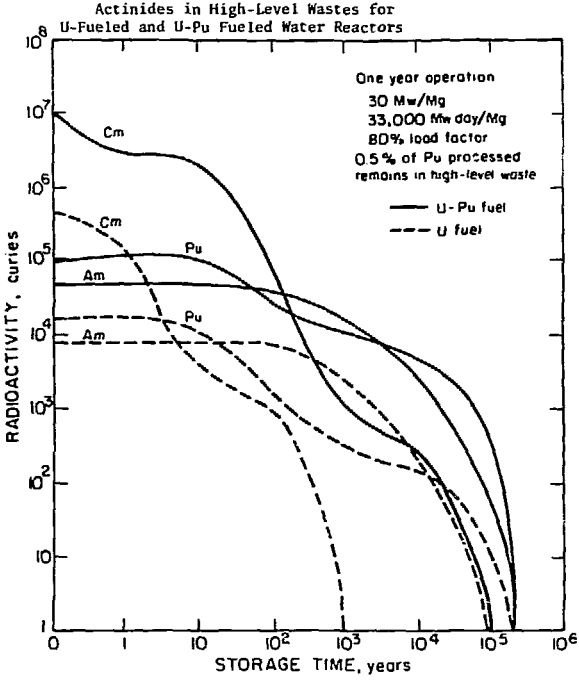


Fig. 9


Actinides in High-Level Wastes for
U-Fueled and U-Pu Fueled Water Reactors
One year operation
30 Mw/Mg
33,000 Mw day/Mg
80% load factor
0.5% of Pu processed
remains in high-level waste
U-Pu fuel
U fuel
Cm
Cm
Pu
Am
Pu
Am
RADIOACTIVITY, curies
STORAGE TIME, years
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
0
1
10
10^2
10^3
10^4
10^5
10^6

IV. FUEL CYCLES FOR THE 1000 Mw LIQUID METAL FAST BREEDER REACTOR

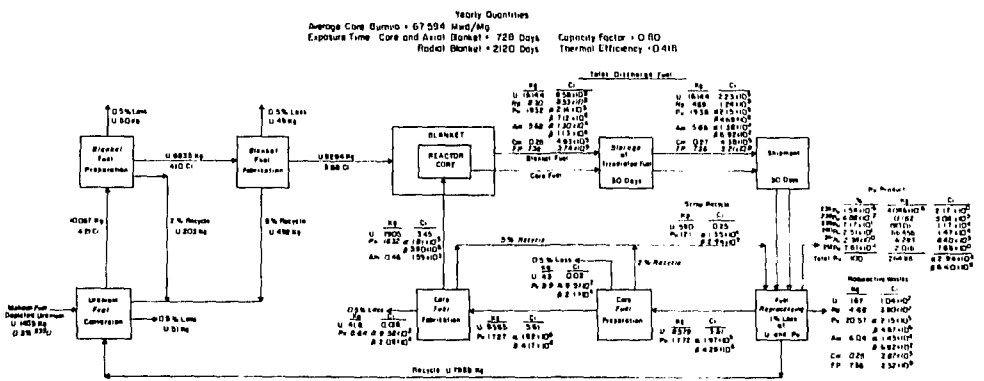
Atomics International Follow-On Liquid Metal Fast Breeder Reactor (AIFO LMFBR)

Two types of reference design fast breeder reactors were considered. The first one described here is the AIFO design[14] which is assumed to be typical of early LMFBRs that may begin commercial operation beginning in 1986. The fuel-cycle flowsheet for this 1000 Mw LMFBR fueled with depleted uranium (0.25% ^{235}U) obtained from the tails from uranium isotope separation operations, is shown in Figure 10. Fuel charged to the reactor core consists of mixed oxides of uranium and recycle plutonium recovered from discharge fuel, with a Pu/U ratio of 0.206. The reactor core contains 19.1 metric tons of uranium and plutonium. The core fuel operates to an average thermal exposure of 67,600 Mw days per Mg prior to discharge, corresponding to an average core fuel lifetime of 1.99 years at 80% capacity factor.

Surrounding the reactor core is a blanket of depleted uranium, which absorbs neutrons leaking from the reactor core to produce additional plutonium. The axial blanket consists of axial extensions of the cylindrical core-fuel rods and is discharged along with the core fuel. The radial blanket consists of full-length rods of depleted uranium which operate for 5.81 years, at 80% capacity factor, prior to discharge. Heat is generated in the axial and radial blankets by fissions in uranium and in generated plutonium. The average thermal powers generated are 2214.6, 106.8, and 73.8, megawatts, for the core, axial, and radial blankets, respectively. The average thermal specific powers, expressed in megawatt per metric ton of U-Pu fuel charged to each region, are 116 for the core, 8.1 for the axial blanket, and 4.7 for the radial blanket, based upon full power.

Fig. 10

Fuel Actinide Flowsheet for the 1000 Mw A. I. Follow-On LMFBR.



The percentage of input material which appears as processing losses and as scrap recycle in each fuel cycle operations is taken from Pigford's report to the Ford Foundation.[11] The flowsheet quantities are based upon an overall thermal efficiency of 41% expected[14] for commercial fast-breeder reactors.

The plutonium in the discharge fuel is the total of that in fuel discharged from the core and from the blanket and are assumed to be shipped and reprocessed together, such that the plutonium product and wastes will be blended. Table 15 lists the amount of fuel charged and discharged from the core, axial blanket, and radial blanket, and the total of the three regions of the reactor. Every year, 1630 Kg of plutonium is charged to core and 1620 Kg is discharged from the core. 201 Kg and 113 Kg are discharged from the axial and radial blanket respectively every year, making a total discharge of 1934 Kg/yr. The plutonium in the blanket is relatively rich in the lower-mass plutonium isotopes, particularly ^{239}Pu, whereas the plutonium in the core discharge contains higher concentrations of the higher-mass plutonium isotopes, as well as americium and curium. This is shown in Table 16. The assumed mixing of plutonium recovered from discharged blanket and core fuel, and the continuous removal of a portion of this recovered plutonium as plutonium product, result in less overall buildup of the higher-mass plutonium isotopes in the equilibrium fuel cycle of the fast breeder, as compared with the equilibrium fuel cycle of the water reactor fueled with recycle plutonium. This is indicated in Table 8.

As shown in Table 9, the lower concentration of ^{238}Pu and ^{241}Pu in breeder plutonium results in less alpha and beta activity in plutonium processed yearly as compared with the uranium-plutonium fueled water reactor.

Table 15

Material and Radioactive Quantities in Reactor and Fuel Cycles
for the AIPO LMFBR.
CORE

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
U234	8.57E-02	5.10E-01	8.72E-02	5.19E-01	8.38E-02	5.18E-01	1.07E-01	1.04E+00
U235	3.32E+00	7.11E-03	1.67E+00	3.59E-03	1.68E+00	3.60E-03	4.97E+00	1.07E-02
U236	4.39E+00	2.78E-01	4.24E+00	2.65E-01	4.25E+00	2.49E-01	8.60E+00	5.45E-01
U237	0.	0.	4.48E-02	3.64E+06	5.98E-04	7.82E+03	4.92E-02	7.29E+06
U238	7.90E+03	2.63E+00	7.22E+03	2.40E+00	7.22E+03	2.40E+00	1.51E+04	5.02E+00
U239	0.	0.	1.82E-02	8.09E+08	0.	0.	1.63E-02	1.21E+09
TOTAL	7.91E+03	3.45E+00	7.22E+03	9.12E+00	7.22E+03	7.20E+03	1.51E+04	6.11E+08
		α3.45E+00		α3.18E+00		α1.20E+02		α6.41E+00
		β0.		β6.13E+08		β7.82E+03		β1.22E+09
NP236	0.	0.	1.37E-07	8.27E+01	2.71E-27	1.64E-18	2.73E-07	1.65E+02
NP237	0.	0.	3.01E+00	2.13E+00	3.07E+00	2.17E+00	6.03E+00	4.25E+00
NP238	0.	0.	2.48E-03	6.48E+05	6.22E-15	1.62E-03	4.96E-03	1.29E+06
NP239	0.	0.	2.62E+02	6.68E+08	1.64E-04	1.82E+02	5.21E+00	1.21E+09
TOTAL	0.	0.	5.64E+00	6.10E+08	3.07E+00	3.84E+02	1.12E+01	1.22E+09
				α2.13E+00		α2.17E+00		α4.25E+00
				β6.05E+08		β1.82E+02		β1.21E+09
PU236	2.52E-05	1.34E+01	2.78E-05	1.48E+01	2.66E-05	1.43E+01	5.29E-05	2.81E+01
PU238	1.13E+05	1.90E+04	1.24E+05	2.04E+04	1.27E+05	2.10E+04	2.35E+05	3.67E+04
PU239	1.37E+03	7.11E+03	1.49E+03	8.86E+04	1.09E+03	6.68E+04	2.25E+03	1.30E+05
PU240	4.10E+02	9.03E+04	4.71E+02	1.04E+05	4.71E+02	1.04E+05	8.77E+02	1.93E+05
PU241	3.84E+01	3.90E+05	4.59E+01	4.67E+06	4.56E+01	4.63E+06	8.46E+01	8.54E+06
PU242	1.25E+01	4.49E+01	1.47E+01	5.74E+01	1.47E+01	5.74E+01	2.72E+01	1.06E+02
PU243	0.	0.	9.30E-04	2.41E+06	4.77E-17	1.24E-07	1.85E-03	4.80E+06
TOTAL	1.63E+03	4.08E+06	1.62E+03	7.27E+06	1.62E+03	4.82E+06	3.24E+03	1.13E+07
		α1.41E+05		α1.91E+05		α1.90E+05		α3.71E+05
		β4.90E+06		β7.08E+06		β6.61E+06		β1.09E+07
AM241	4.04E-01	1.54E+03	3.66E+00	1.31E+04	4.02E+00	1.39E+04	4.11E+00	1.46E+04
AM242	0.	0.	7.11E-02	6.52E+03	7.11E-02	6.91E+02	1.42E-01	1.38E+03
AM243	0.	0.	1.04E-03	8.30E+05	8.54E-07	6.81E+02	2.07E-03	1.67E+06
AM244	0.	0.	1.42E+00	2.69E+02	1.42E+00	1.69E+02	1.82E+00	7.35E+02
AM244	0.	0.	9.82E-05	2.61E+08	9.25E-20	2.74E-09	1.96E-05	5.00E+08
TOTAL	4.04E-01	1.54E+03	5.65E+00	1.14E+04	6.01E+00	1.55E+04	6.06E+00	1.14E+04
		α1.54E+03		α1.29E+04		α1.42E+04		α1.45E+04
		β0.		β1.13E+04		β6.91E+02		β2.25E+06

Table 15 (continued)

CORE

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM243	0.	0.	1.46E-01	4.82E+05	1.13E-01	3.76E+05	2.90E-01	9.61E+05
CM244	0.	0.	6.27E-03	2.68E+02	6.25E-03	2.67E+02	1.25E-02	5.35E+02
CM245	0.	0.	1.27E-01	1.03E+04	1.27E-01	1.03E+04	2.54E-01	2.06E+04
CM246	0.	0.	3.56E-03	6.65E-01	3.56E-03	6.29E-01	7.10E-03	1.25E+00
CM247	0.	0.	9.49E-05	2.93E-02	9.49E-05	2.93E-02	1.89E-04	5.83E-02
CM248	0.	0.	1.40E-06	1.24E-07	1.40E-06	1.24E-07	2.79E-06	2.46E-07
TOTAL	0.	0.	2.25E-08	9.24E-08	2.25E-08	9.24E-08	4.49E-08	1.84E-07
			2.83E-01	4.93E+05	2.50E-01	3.86E+05	5.64E-01	9.82E+05
				α4.93E+05		α3.80E+05		α9.82E+05
				β7.67E-09		β7.67E-09		β1.53E-08
PA239	0.	0.	2.17E-10	3.62E-04	1.90E-10	3.17E-04	4.32E-10	7.21E-04
PA250	0.	0.	5.73E-18	2.23E-05	3.84E-23	1.49E-13	1.14E-14	4.44E-05
TOTAL	0.	0.	2.17E-10	3.84E-04	1.90E-10	3.17E-04	4.32E-10	7.66E-04
				α0.		α0.		α0.
				β3.84E-08		β3.17E-04		β7.66E-34
CF248	0.	0.	4.22E-11	1.72E-07	6.90E-11	2.82E-07	8.40E-11	3.43E-07
CF250	0.	0.	3.71E-12	4.06E-07	3.65E-12	4.01E-07	7.40E-12	8.10E-07
CF251	0.	0.	4.10E-14	6.80E-11	4.30E-14	6.90E-11	8.57E-14	1.36E-10
CF252	0.	0.	4.31E-16	2.32E-10	4.15E-16	2.22E-10	8.63E-16	4.63E-10
CF253	0.	0.	1.12E-18	3.24E-11	1.68E-19	5.14E-12	2.23E-18	6.46E-11
TOTAL	0.	0.	4.59E-11	5.79E-07	7.28E-11	6.85E-07	9.15E-11	1.15E-06
				α5.76E-07		α6.82E-07		α1.15E-06
				β3.26E-09		β3.26E-09		β6.49E-09
TOTAL	9.54E+03	0.	8.85E+03	1.23E+05	8.88E+03	5.23E+06	1.83E+04	1.23E+09
FISSION PROD.	0.	0.	6.80E+02	3.48E+09	6.80E+02	2.15E+08	1.35E+03	6.88E+09
CLAD.	3.16E+02	0.	3.36E+03	6.66E+06	3.36E+03	2.58E+06	6.70E+03	6.64E+06

Table 15 (continued)

AXIAL BLANKET

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
U214	6.04E-02	3.74E-01	5.62E-02	3.48E-01	5.63E-02	3.48E-01	1.16E-01	7.19E-01
U215	5.17E+00	1.15E-02	3.78E+00	8.09E-03	3.78E+00	8.04E-03	9.11E+00	1.95E-02
U235	1.09E+00	1.78E-01	3.33E+00	2.11E-01	3.33E+00	2.11E-01	6.45E+00	4.06E-01
U237	0.	0.	1.26E-02	1.03E+06	2.65E-05	2.17E+03	2.51E-02	2.05E+06
U238	6.59E+03	2.19E+00	6.39E+03	2.11E+00	6.34E+03	2.11E+00	1.29E+04	4.29E+00
U233	0.	0.	0.26E-04	2.10E+08	0.	0.	1.29E-02	4.18E+08
TOTAL	6.59E+03	2.77E+00	6.39E+03	2.11E+08	6.38E+03	2.17E+03	1.29E+04	2.10E+08
		α2.77E+00		α2.68E+00		α2.68E+00		α5.44E+00
		β0.		β2.11E+08		β2.17E+03		β4.20E+08
NP236	0.	0.	1.33E-08	8.01E+00	2.63E-28	1.59E-19	2.65E-08	1.60E+01
NP237	0.	0.	1.00E+00	7.05E-01	1.01E+00	7.15C-01	2.00E+00	1.41C+00
NP238	0.	0.	2.41E-04	5.09E+04	6.07E-13	1.99E-04	4.79E-04	1.25E+05
NP239	0.	0.	9.70E-01	2.65E+08	1.47E-08	4.35E+03	1.79E+00	4.17E+08
TOTAL	0.	0.	1.90E+00	2.10E+08	1.01E+00	5.07E+00	3.79E+00	4.18E+08
				α7.06E-01		α7.15E-01		α1.41E+00
				β2.09E+08		β4.36E+00		β4.17E+08
PU236	0.	0.	1.92E-06	1.02E+00	1.86E-06	9.87E-01	3.84E-06	2.04E+00
PU238	0.	0.	3.27E-02	5.62E+02	3.29E-02	5.56E+02	6.52E-02	1.10E+03
PU239	0.	0.	1.92E+02	1.18E+04	1.93E+02	1.19E+04	3.84E+02	2.35E+04
PU240	0.	0.	8.09E+00	1.78E+03	8.09E+00	1.78E+03	1.61E+01	3.56E+03
PU241	0.	0.	1.79E-01	1.03E+04	1.78E-01	1.01E+04	3.58E-01	1.63E+04
PU242	0.	0.	3.62E-03	1.18E-02	3.62E-03	1.18E-02	6.02E-03	2.38E-02
PU243	0.	0.	5.33E-08	2.41E+02	7.67E-25	1.99E-15	1.85E-07	4.80E+02
TOTAL	0.	0.	2.01E+02	3.26E+04	2.02E+02	3.23E+04	4.00E+02	6.50E+04
		α0.		α1.41E+04		α1.42E+04		α2.82E+04
		β0.		β1.85E+04		β1.81E+04		β3.68E+04
AM241	0.	0.	4.58E-03	1.67E+01	5.67E-03	2.09E+01	9.13E-03	3.13E+01
AM242M	0.	0.	1.23E-05	1.19E-01	1.22E-05	1.19E-01	2.44E-05	2.37E-01
AM242	0.	0.	3.79E-07	3.07E+02	1.47E-10	1.19E-01	7.55E-07	6.11E+02
AM243	0.	0.	8.19E-05	9.59E-03	8.20E-05	1.00E-02	1.04E-04	1.99E-02
AM244	3.	0.	7.78E-11	2.31E+00	7.84E-25	2.24E-14	1.55E-10	4.68E+00
TOTAL	0.	0.	4.64E-03	3.25E+02	6.03E-03	2.07E+01	9.29E-03	6.68E+02
		α0.		α1.57E+01		α2.09E+01		α3.13E+01
		β0.		β3.09E+02		β1.19E-01		β4.16E+02

Table 15 (continued)

AXIAL BLANKET

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM242	0.	0.	3.31E-05	1.10E+02	2.59E-05	8.57E+01	6.59E-05	2.19E+02
CM243	0.	0.	1.93E-07	8.89E-01	1.93E-07	8.80E-01	3.85E-07	1.77E-02
CM244	0.	0.	9.10E-27	3.32E-22	4.07E-27	1.30E-02	8.17E-07	6.42E-02
CM245	0.	0.	1.44E-09	1.25E-07	1.44E-09	1.25E-07	3.67E-09	6.49E-07
CM246	0.	0.	7.94E-12	2.45E-09	7.94E-12	2.45E-09	1.58E-11	4.88E-09
CM247	0.	0.	2.25E-14	1.99E-13	2.25E-14	1.99E-13	4.48E-14	3.96E-13
CM248	0.	0.	6.93E-17	2.87E-16	6.49E-17	2.87E-16	1.39E-16	5.71E-16
TOTAL	0.	0.	3.37E-05	1.10E+02	2.65E-05	8.57E+01	6.72E-05	2.19E+02
				α1.10E+02		α8.57E+01		α 2.19E+02
				β2.18E-17		β2.38E-17		β4.74E-17
BK249	0.	0.	1.45E-19	2.42E-13	1.27E-19	2.13E-13	2.89E-19	4.83E-13
UM250	0.	0.	1.12E-24	4.37E-15	4.43E-36	1.76E-26	2.24E-24	8.70E-15
TOTAL	0.	0.	1.45E-19	2.47E-13	1.27E-19	2.13E-13	2.89E-19	4.92E-13
				α0.		α0.		α0.
				β2.47E-13		β2.13E-13		β4.92E-13
CF249	0.	0.	2.13E-20	8.78E-17	3.93E-20	1.60E-16	4.25E-20	1.73E-16
CF250	0.	0.	5.10E-22	5.58E-17	5.06E-22	5.54E-17	1.02E-21	1.11E-16
CF251	0.	0.	9.62E-25	1.52E-21	9.62E-25	1.52E-21	1.92E-24	3.03E-21
CF252	0.	0.	0.	0.	0.	0.	0.	0.
CF253	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	2.18E-20	1.43E-16	3.98E-20	2.16E-16	4.35E-20	2.05E-16
				α1.42E-16		α2.15E-16		α 2.04E-16
				β4.46E-19		β4.43E-19		β8.89E-19
TOTAL	6.59E+01	2.77E+00	6.65E+03	4.20E+08	6.65E+03	3.46E+04	1.31E+04	4.19E+08
FISSION PROD.	0.	0.	3.26E+01	2.34E+08	3.26E+01	1.29E+07	6.49E+01	4.67E+08
CLAD	2.32E+03	0.	2.32E+03	1.40E+06	2.32E+03	5.59E+05	4.62E+03	1.39E+06

Table 15 (continued)

RADIAL BLANKET

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
U234	2.48E-02	1.94E-01	2.28E-02	1.41E-01	2.28E-02	1.41E-01	1.38E-01	8.55E-01
U235	2.21E+00	4.73E-03	1.32E+00	2.82E-03	1.32E+00	2.82E-03	1.02E+01	2.19E-02
U236	1.27E+00	8.06E-02	1.19E+00	8.32E-02	1.19E+00	8.32E-02	7.72E+00	4.92E-01
U237	0.	0.	2.15E-03	1.75E+05	4.83E-06	3.70E+02	1.25E-02	1.02E+06
U238	2.70E+03	9.01E-01	2.47E+03	8.56E-01	2.57E+03	8.90E-01	1.53E+04	5.10E+00
U239	0.	0.	1.01E-03	1.39E+07	0.	0.	5.88E-03	1.97E+06
TOTAL	2.71E+03	1.14E+00	2.57E+03	3.41E+07	2.57E+03	3.71E+02	1.53E+04	9.89E+07
		α 1.14E+00		α 1.09E+00		α 1.09E+00		α 6.47E+00
		β 0.		β 3.41E+07		β 3.70E+02		β 1.99E+08
NP236	0.	0.	3.34E-06	2.02E+00	6.62E-29	1.99E-20	1.94E-08	1.17E+01
NP237	0.	0.	6.07E-01	4.28E-01	5.10E-01	4.30E-01	3.53E+00	2.49E+00
NP238	0.	0.	6.06E-05	1.58E+04	1.52E-13	3.97E-05	3.82E-04	9.19E+04
NP239	0.	0	1.46E-01	3.35E+07	3.24E-09	7.53E-01	8.46E-01	1.97E+08
TOTAL	0.	0.	7.51E-01	3.39E+07	6.10E-01	1.18E+00	4.37E+00	1.97E+08
				α 4.28E-01		α 4.30E-01		α 2.49E+00
				β 3.39E+07		β 7.53E-01		β 1.97E+08
PU238	0.	0.	1.22E-06	6.49E-01	1.17E-06	6.25E-01	7.08E-06	3.77E+00
PU239	0.	0.	2.91E-02	4.92E+02	2.92E-02	4.93E+02	1.65E-01	2.88E+03
PU240	0.	0.	1.06E+02	6.46E+03	1.06E+02	6.49E+03	6.14E+02	3.76E+04
PU241	0.	0.	6.44E+00	1.51E+03	6.49E+00	1.51E+03	3.57E+01	8.76E+03
PU242	0.	0.	2.30E-01	2.43E-04	2.37E-01	2.41E+04	1.39E+00	1.41E+05
PU243	0.	0.	7.11E-03	2.77E-02	7.13E-03	2.77E-02	4.13E-02	1.61E-01
PU244	0.	0.	1.24E-07	3.20E+02	1.85E-23	4.79E-14	7.18E-07	1.88E+03
TOTAL	0.	0.	1.13E+02	3.31E+04	1.13E+02	3.26E+04	6.55E+02	1.92E+05
		β 0.		α 8.49E+03		α 8.50E+03		α 4.93E+04
		β 0.		β 2.46E+04		β 2.41E+04		β 1.43E+05
AM241	0.	0.	2.19E-02	7.52E+01	2.38E-02	8.15E+01	1.27E-01	4.36E+02
AM242M	0.	0.	8.47E-05	8.23E-01	8.46E-05	8.23E-01	4.91E-04	4.78E+00
AM242	0.	0.	7.65E-07	6.11E+02	1.02E-09	8.23E-01	4.38E-06	3.55E+03
AM243	0.	0.	2.53E-04	4.87E-02	2.53E-04	4.88E-02	1.47E-03	2.83E-01
AM244	0.	0.	1.88E-10	4.67E+00	1.54E-24	4.50E-14	9.15E-10	2.71E+01
TOTAL	0.	0.	2.23E-02	6.92E+02	2.41E-02	8.32E+01	1.29E-01	4.02E+03
		α 0.		α 7.53E-01		α 8.10E+01		α 4.37E+02
		β 0.		β 6.16E+02		β 8.23E-01		β 3.57E+03

Table 15 (continued)

RADIAL BLANKET

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM242	0.	0.	1.14E-04	3.76E+02	8.85E-05	2.91E+02	6.99E-04	2.18E+03
CM243	0.	0.	1.03E-06	4.73E-02	1.02E-06	4.71E-02	5.57E-06	2.74E-01
CM244	0.	0.	2.93E-06	2.37E-01	2.91E-06	2.36E-01	1.70E-05	1.38E+00
CM245	0.	0.	1.97E-08	3.47E-06	1.97E-08	3.47E-06	1.16E-07	2.02E-05
CM246	0.	0.	1.30E-10	3.95E-08	1.28E-10	3.85E-08	7.43E-10	2.29E-07
CM247	0.	0.	5.42E-13	4.79E-14	5.42E-13	4.79E-14	4.15E-12	2.70E-13
CM248	0.	0.	2.54E-15	1.04E-14	2.54E-15	1.04E-14	1.47E-14	6.03E-14
TOTAL	0.	0.	1.17E-04	3.76E+02	9.24E-05	2.93E+02	6.82E-04	2.18E+03
				α3.76E+02		α2.93E+02		α2.18E+03
				β8.62E-16		β8.62E-16		β5.01E-15
BK249	0.	0.	5.84E-18	9.76E-12	5.12E-18	8.56E-12	3.39E-17	5.66E-11
BK250	0.	0.	1.08E-21	7.30E-14	1.59E-31	6.21E-22	1.09E-22	4.24E-13
TOTAL	0.	0.	5.84E-18	9.83E-12	5.12E-18	8.55E-12	3.39E-17	5.71E-11
				α0.		α0.		α0.
				β9.83E-12		β8.56E-12		β5.71E-11
CF249	0.	0.	3.16E-18	1.29E-14	3.08E-18	1.25E-14	1.83E-17	7.48E-14
CF250	0.	0.	4.90E-20	5.36E-15	4.86E-20	5.32E-15	2.84E-19	3.11E-14
CF251	0.	0.	1.95E-22	3.08E-19	1.95E-22	3.08E-19	1.13E-21	1.79E-18
CF252	0.	0.	4.76E-25	2.55E-19	4.76E-25	2.55E-19	2.76E-24	1.48E-18
CF254	0.	0.	2.93E-28	5.93E-21	2.09E-28	5.93E-21	1.19E-27	3.44E-20
TOTAL	0.	0.	3.21E-18	1.82E-14	3.93E-18	2.12E-14	1.82E-17	1.06E-13
				α1.82E-14		α2.11E-14		α1.06E-13
				β4.29E-17		β4.26E-17		β2.49E-16
TOTAL	2.71E+03	1.14E+00	2.68E+03	6.81E+07	2.68E+03	3.33E+04	1.57E+04	1.98E+08
FISSION PROD.	0.	0.	2.34E+01	4.98E+07	2.30E+01	3.43E+06	1.38E+02	2.89E+08
CLAD.	9.54E+02	0.	9.54E+02	2.69E+05	9.54E+02	1.22E+05	5.54E+03	7.70E+05

Table 15 (continued)

REACTOR TOTAL

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
U234	1.71E-01	1.06E+00	1.41E-01	9.98E-01	1.63E-01	1.01E+00	4.22E-01	2.61E+00
U235	1.09E+01	2.13E-02	8.77E+00	1.45E-2	8.77E+00	1.45E-02	2.43E+01	5.21E-02
U236	8.79E+00	5.95E-01	8.66E+00	5.68C-01	8.97E+00	5.69E-01	2.27E+01	1.44E+00
U237	0.	0.	5.58E-02	4.86E+06	1.27E-04	1.04E+04	1.27E-01	1.04E+07
U238	1.72E+04	5.72E+00	1.61E+04	5.17E+00	1.61E+04	5.37E+00	4.32E+04	1.44E+01
U239	0	0.	2.55E-02	A.53E+08	0.	0.	5.66E-0.	1.03E+09
TOTAL	1.72E+04	7.16E+00	1.61E+04	8.37E+08	1.61E+04	1.04E+04	4.33E+04	9.20E+08
		α 7.16E+00		α6.98E+00		α 6.97E+00		α 1.85F+01
		β0.		β8.57E+08		β 1.04F+04		β 1.04E+09
NP236	0.	0.	1.54E-07	9.28E+01	3.04E-27	1.81E-18	3.19C-07	1.93E+02
NP237	0.	0.	4.63E+00	3.27E+00	4.69E+00	3.31E+03	1.16C+01	8.14E+00
NP238	0.	0.	2.74C-01	7.27E+05	0.67E-12	1.82E-03	5.77E-03	1.51E+06
NP239	0.	0.	3.66E+00	8.52E+04	1.66E-06	3.47E+02	7.86F+00	1.83E+09
TOTAL	0.	0.	8.30E+00	8.53E+08	4.69E+00	3.50E+02	1.94E+01	1.03E+09
				α 3.27E+00		α 3.31E+00		α 8.14E+00
				β8.52E+08		β3.47E+02		β 1.03E+09
PU236	2.52E-08	1.18E+01	3.10E-08	1.69E+01	2.98E-08	1.59E+01	6.38E-08	3.39E+01
PU238	1.13E+00	1.48E+04	1.30E+00	2.14E+04	1.33E+00	2.29E+04	2.59E+00	4.37E+04
PU239	1.17E+02	7.18E+04	1.38E+03	8.49E+04	1.39E+03	8.51E+04	3.25E+01	4.99E+08*
PU240	4.10E+02	9.03E+04	4.66E+02	1.07E+05	4.68E+02	1.07E+05	9.33E+02	2.06E+05
PU241	3.84E+01	3.90E+06	4.63E+01	4.71E+06	4.60E+01	4.67E+06	8.57E+01	8.72E+06
PU242	1.29E+01	4.89E+01	1.47E+01	8.75E+01	1.47E+01	8.75E+01	2.72E+01	1.06E+02
PU243	0.	0.	9.30E-04	2.91E+06	4.77E-17	1.24E-07	1.86E-03	4.80E+06
TOTAL	1.63E+03	4.08E+06	1.93E+01	7.33E+06	1.94E+03	4.09E+06	4.30E+03	1.16E+07
		α1.41E+05		α 2.14E+05		α 2.15E+05		α 4.49E+05
		β3.94E+06		β 7.12E+06		β 4.87E+06		β 1.11E+07
AM241	4.64C-01	1.59E+03	3.69E+00	1.32E+04	4.09E+00	1.39E+04	4.25E+00	1.51E+04
AM242M	0.	0.	7.12E-02	6.93E+02	7.12E-02	6.92E+02	1.42E-01	1.38E+03
AM242	0.	0.	1.04E-03	8.43E+05	8.68E-07	6.92E+02	2.07E-03	1.68E+06
AM243	0.	0.	1.92E+00	3.69E+02	1.92E+00	3.69E+02	3.82E+00	7.38E+02
AM244	0.	0.	9.82E-06	2.91E+05	9.26E-20	2.74E-09	1.96C-05	5.80E+05
TOTAL	4.64E-01	1.59E+03	5.68E+00	1.18E+06	8.04E+00	1.96E+04	6.23E+00	1.19E+06
		α1.59E+03		α1.30E+04		α1.43E+04		α 1.49E+04
		β0.		β1.13E+06		β6.92E+02		β 2.26E+06

Table 15 (continued)

REACTOR TOTAL

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM242	0.	0.	1.44E-01	4.03E+05	1.14E-01	3.76E+05	2.91E-01	9.63E+05
CM243	0.	0.	6.27E-03	2.08E+02	6.29E-03	2.47E+02	1.25E-02	5.75E+02
CM244	0.	0.	1.27E-01	1.03E+04	1.27E-01	1.03E+04	2.54E-01	2.06E+04
CM245	0.	0.	3.66E-03	6.29E-01	3.66E-03	6.29E-01	7.10E-03	1.25E+00
CM246	0.	0.	9.49E-05	2.53E-02	9.49E-05	2.53E-02	1.89E-04	5.03E-02
CM247	0.	0.	1.40E-06	1.24E-07	1.40E-06	1.24E-07	2.79E-06	2.46E-07
CM248	0.	0.	2.25E-08	9.24E-08	2.25E-08	9.24E-08	4.49E-08	1.84E-07
TOTAL	0.	0.	2.83E-01	4.03E+05	2.50E-01	3.67E+05	5.65E-01	9.85E+05
				α 4.93E+05		α 1.07E+05		α 9.85E+05
				β 7.67E-05		β 7.67E-05		β 1.53E-08
BK249	0.	0.	2.17E-10	3.68E-04	1.90E-10	3.17E-04	4.32E-10	7.21E-04
BK250	0.	0.	5.73E-15	2.23E-05	3.84E-23	1.49E-13	1.14E-14	4.44E-05
TOTAL	0.	0.	2.17E-10	3.84E-04	1.90E-10	3.17E-04	4.32E-10	7.66E-04
				α 0.		α 0.		α 0.
				β 3.84E-04		β 3.17E-04		β 7.66E-04
CF249	0.	0.	4.22E-11	1.72E-07	6.90E-11	2.82E-07	8.40E-11	3.43E-07
CF250	0.	0.	3.71E-12	4.06E-07	3.69E-12	4.03E-07	7.46E-12	8.10E-07
CF251	0.	0.	4.30E-14	8.80E-11	4.30E-14	8.80E-11	8.57E-14	1.76E-10
CF252	0.	0.	4.33E-16	2.32E-10	4.18E-16	2.22E-10	8.63E-16	4.63E-10
CF253	0.	0.	1.12E-18	3.24E-11	1.08E-19	3.14E-12	2.23E-18	6.46E-11
TOTAL	0.	0.	4.59E-11	5.79E-07	7.28E-11	6.85E-07	9.15E-11	1.15E-06
				α 5.76E-07		α 6.82E-07		α 1.15E-06
				β 3.26E-09		β 3.24E-09		β 6.49E-09
TOTAL	1.80E+04	3.91E+00	1.81E+04	1.72E+09	1.61E+04	5.30E+06	4.71E+04	1.84E+09
FISSION PROD.	0.	0.	7.36E+02	3.73E+09	7.36E+02	2.31E+08	1.56E+03	7.63E+09
CLAD	6.63E+03	0.	6.63E+03	8.32E+06	6.63E+03	3.26E+06	1.69E+04	8.80E+06

Also, as shown in Tables 12 and 13, the frequent replacement and the lower concentrations of ^{241}Pu and ^{242}Pu result in less build-up of americium and curium in the fast-breeder fuel, as compared with the uranium-plutonium fueled water reactor. The ^{236}Pu content in breeder produced plutonium is calculated to be considerably less than that in plutonium in light-water reactors because of the lower concentration of ^{235}U in the depleted uranium used in fast breeders.

Table 16

Isotopic Composition of Plutonium in Discharged AIFO LMFBR Fuel

	Core wt. %	Axial Blanket wt. %	Radial Blanket wt. %
^{236}Pu	1.7×10^{-6}	9.6×10^{-7}	1.1×10^{-6}
^{238}Pu	7.6×10^{-2}	1.6×10^{-2}	2.6×10^{-2}
^{239}Pu	67.2	95.9	93.7
^{240}Pu	29.0	4.0	6.0
^{241}Pu	2.8	8.9×10^{-2}	2.1×10^{-1}
^{242}Pu	9.1×10^{-1}	1.5×10^{-3}	6.3×10^{-3}
	100	100	100

It is planned[15] that fast-breeder fuel will be stored for 30 days at the reactor before it is shipped for reprocessing. This is shorter than the 150 day storage period planned for light-water nuclear plants because of the economic incentive to minimize plutonium inventories in the fast-breeder fuel cycle. As shown in Table 17, the yearly amounts of plutonium in the fast-breeder fuel cycle are about eight-fold greater than in uranium-fueled light-water reactors, and the inventory of plutonium in any fuel cycle operation with a given hold-up time is cor-

respondingly greater. Therefore, there is considerable incentive to reduce hold-up time in all the fast-breeder fuel cycle operations, in order to minimize the time the fast-breeder must operate on purchased plutonium makeup fuel before reaching the equilibrium fuel cycle shown in Figure 10. However, the shortened storage period of 30 days introduces new problems in fuel reprocessing because of the large amount, 3.6 million curies per year, of radioactive iodine fission products remaining after 30 days.

Table 17

Material Quantities of Plutonium Handled Yearly in the Fuel Cycles of 1000 Mw Power Plants

	Uranium-Fueled Water Reactor Kg/yr	Plutonium-Fueled Water Reactor Kg/yr	Fast-Breeder[b] Reactor Kg/yr
Plutonium into fuel reprocessing	246	992	2058
Plutonium into fuel fabrication	0	1.450	1727
Net production rate of thermally fissile plutonium	170	-352[a]	196

(a) Required make-up from uranium-fueled water reactor.
(b) Atomics International Follow-On Liquid Metal Fast Breeder Reactor.

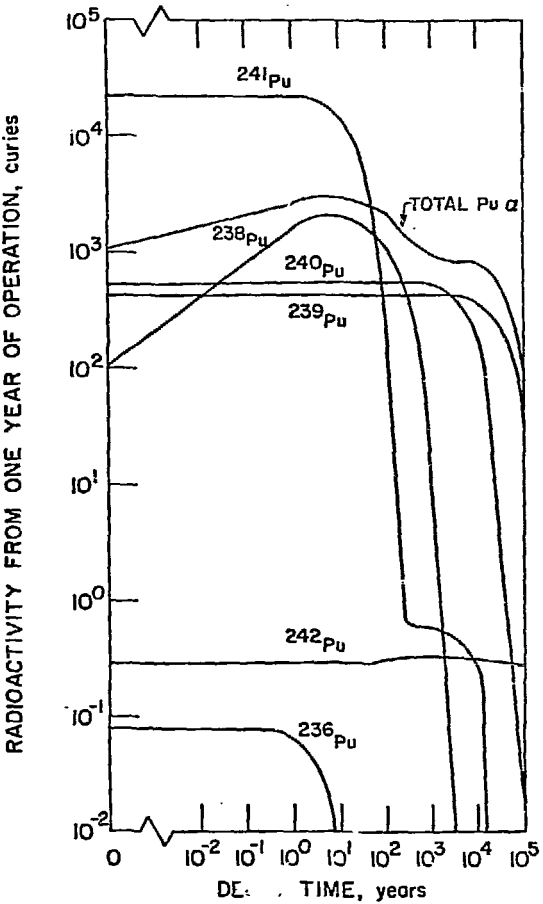
Shorter cooling also results in about a four-fold greater amount of radioactivity in the shipped fast-breeder fuel. This increases the shielding requirement for shipping containers and the rate of heat generation in the fuel due to radioactive decay. Shipping short-cooled breeder core fuel will impose more stringent requirements for shipping-container design than for water-reactor fuel.

Based upon a 0.5% loss of uranium and plutonium from reprocessing to the high-level wastes, Figure 11 shows the plutonium radioactivity in the

high-level wastes from one year of operation of the fast-breeder as a function of storage time. Because there is less buildup of americium and curium in the fast-breeder fuel, as compared with the uranium-plutonium fueled water reactor, there is less increase in plutonium activity with storage time in the high-level wastes of the fast-breeder. The total alpha Pu activity in the high-level wastes of the fast-breeder is approximately 3 times less than that in the uranium-plutonium fueled water reactor. Figures 12 and 13 show the neptunium, americium, curium, and total actinide radioactivity in the high-level wastes from one year of operation of the fast breeder reactor as a function of storage time. Although the percentage of higher-mass plutonium isotopes in the discharge fuel is not as high for the breeder reactor as for the uranium-fueled water reactor, the amount of americium produced is significantly greater for the breeder because the higher-mass plutonium isotopes are present during the entire core-irradiation time. Hence the americium radioactivity in the high-level wastes is greater for the breeder than for the uranium-fueled water reactor.

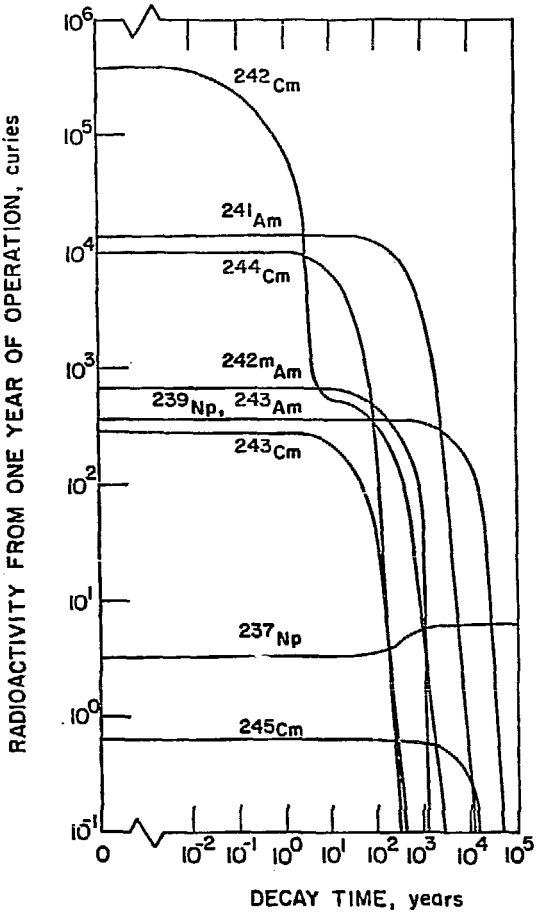
The calculated inventories of plutonium in the fast-breeder fuel cycle are listed in Table 18, based upon the flowsheet quantities shown in Table 15 and Figure 10 and the process hold-up times specified in the 1971 AEC fuel-cycle analysis, escalated by 20% for contingencies.[11,16] The total inventory of plutonium alpha activity in the fast-breeder reactor and fuel cycle is about one-third of the inventory of the uranium-plutonium water reactor and fuel cycle, whereas the total inventory of fissile plutonium is about 36% more for the fast-breeder reactor.

Fig. 11



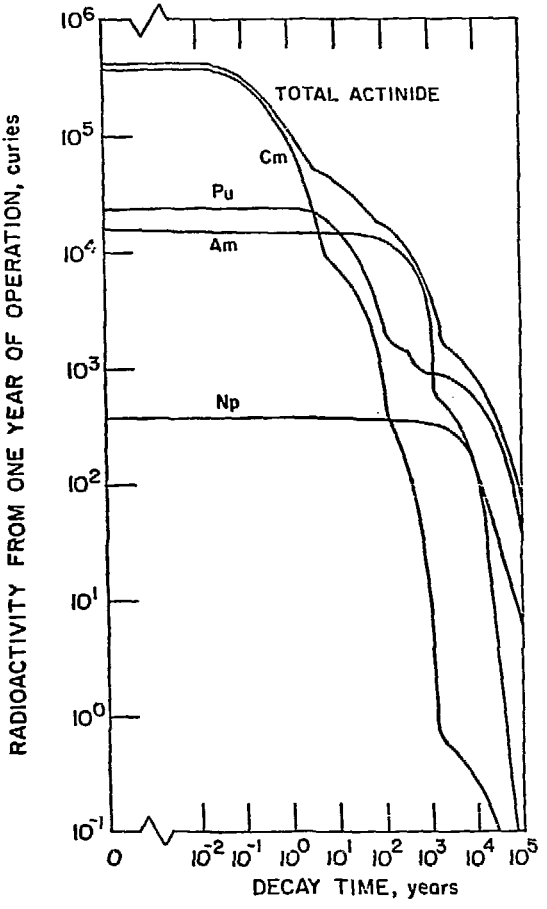
PLUTONIUM RADIOACTIVITY IN HIGH-LEVEL WASTES FROM THE AIFO LMFBR

Fig. 12



Np, Am, Cm RADIOACTIVITY IN HIGH-LEVEL WASTES FROM THE AIFO LMFBR

Fig. 13



ACTINIDE RADIOACTIVITY IN HIGH-LEVEL WASTES FROM THE AIFO LMFBR

Table 18

Inventories of Plutonium in Fuel Cycle of 1000 Mw
AIFO LMFBR

	Hold-up time	Plutonium Inventory			
		Total Pu Kg	Fissile Pu Kg	Alpha Pu curies	Beta Pu curies
Reactor		4300	3336	4.49×10^5	1.11×10^7
Core and axial blanket	1.99 yr.				
Radial blanket	5.81 yr.				
Post-irradiation cooling	30 days	159	117	1.76×10^4	5.85×10^5
Shipment to fuel reprocessing	28.8 days	153	113	1.70×10^4	3.70×10^5
Fuel reprocessing	36 days	191	142	2.12×10^4	4.60×10^5
Shipment to fuel preparation	8.4 days	41	30	4.53×10^3	9.84×10^4
Fuel preparation	12 days	58	43	6.47×10^3	1.41×10^5
Fuel fabrication	12 days	57	42	6.31×10^3	1.37×10^5
Shipment to reactor	14 days	63	47	6.94×10^3	1.49×10^5
Pre-irradiation inventory	36 days	160	119	1.78×10^4	3.84×10^5
Scrap recycle shipment	12 days	4	3	4.44×10^2	9.66×10^3
Total external to reactor		886	656	9.83×10^4	2.33×10^6
Total in reactor and external fuel cycle		5186	3992	5.47×10^5	1.34×10^7
In plutonium product from one year of operation		265	196	2.94×10^4	6.40×10^5

General Electric Follow-On Liquid Metal Fast-Breeder Reactor (GEFO LMFBR)

The second reference design fast-breeder reactor considered is the GEFO design, which is assumed to be typical of the advance LMFBRs.[14] The fuel-cycle flowsheet for this 1000 Mw General Electric breeder reactor is shown in Figure 14. The core fuel of this advance design breeder reactor operates to an average thermal exposure of 104,500 Mw days per Mg prior to discharge, corresponding to an average core fuel lifetime of 2.3 years at 80% capacity factor, compared with an average thermal exposure of 67,600 Mw days per Mg for the core of the Atomics International design. The radial blanket operates for 3.6 years, at 80% capacity factor, prior to discharge. The average thermal specific powers, expressed in megawatt per metric ton of U-Pu fuel charged to each region, are 155.6 for the core, 13.0 for the axial blanket, and 8.5 for the radial blanket, based upon full power of 2058, 193, and 139 megawatts for the core, axial, and radial blankets, respectively.

The material and radioactive quantities in the reactor and fuel cycle for the three regions of the reactor and its total are listed in Table 19. Because of the high core specific power of the GEFO breeder, considerably less fuel is charged annually to the GEFO core than to the AIFO core, 5650 Kg/yr of uranium plus plutonium charged to the GEFO core compared with 9540 Kg/yr for the AIFO core.

The isotopic composition of the discharge fuel of the LMFBRs is shown in Table 20. The discharge fuel of the GEFO reactor contain a higher concentration of the fissile isotope ^{239}Pu, than the AIFO discharge fuel. This is because less amount of the GEFO core containing higher-mass plutonium isotopes is discharged annually to be blended with the blanket containing lower-mass plutonium isotopes. The total amount

Fig. 14

Actinide Flowsheet for the 1000 Mw G. E. Follow-On LMFBR

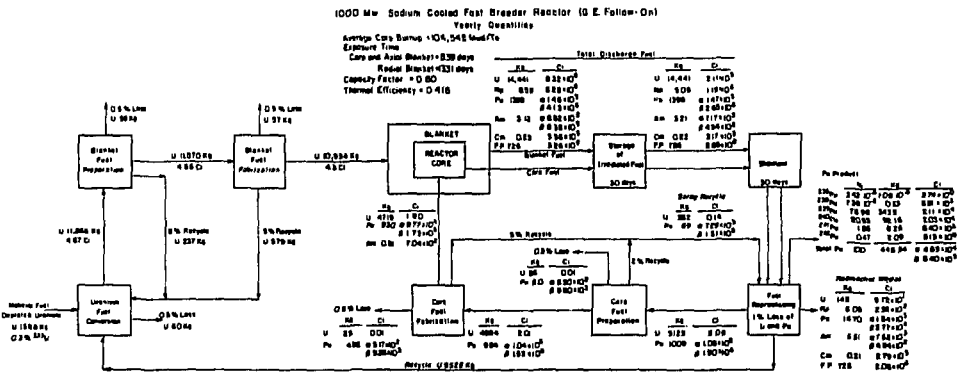


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Table 19

MATERIAL AND RADIOACTIVE QUANTITIES IN REACTOR AND FUEL CYCLES

for the GEFO LMFBR

CORE

	CHARGE		DISCHARGE		EQ DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
U235	2.70E+01	1.61E+01	2.81E-02	1.74E-01	2.52E+02	1.81E+01	6.22E-02	3.85E-01
U236	1.74E+00	3.72E-03	5.94E-01	1.27E-03	5.97E-01	1.28E-03	2.68E+00	5.74E-03
U238	2.84E+00	1.61E-01	2.31E+00	1.46E-01	2.31E+00	1.47E-01	5.57E+00	3.53E-01
U237	0.	0.	1.40E-02	2.44E+06	7.41E-05	6.65E+03	7.59E-02	6.52E+06
U239	4.22E+03	1.52E+05	4.09E+03	1.36E+05	4.09E+03	1.36E+05	1.01E+04	3.42E+05
U240	0.	0.	1.41E-02	4.77E+08	0.	0.	3.27E-02	1.10E+09
TOTAL	4.72E+03		4.09E+03	4.80E+08	4.09E+03	6.05E+03	1.01E+04	5.11E+09
		α1.90E+00		α1.69E+00		α1.69E+00		α1.11E+00
		β0.		β4.09E+08		β6.05E+03		β1.10E+09
NP236	0.	0.	1.98E-07	9.96E+01	3.13E-27	1.89E-18	3.64E-07	2.19E+02
NP237	0.	0.	2.53E+00	1.79E+00	2.57E+00	1.81E+00	5.81E+00	4.10E+00
NP238	0.	0.	2.80E-01	7.98E+05	7.17E-12	1.98E-03	6.58E-03	1.72E+06
NP239	0.	0.	2.93E+00	4.76E+08	9.82E-07	2.20E+02	4.72E+00	1.05E+09
TOTAL	0.	0.	4.58E+00	4.78E+08	2.57E+00	2.30E+02	1.05E+01	1.10E+09
				α1.79E+00		α1.81E+00		α1.10E+09
				β4.78E+08		β2.30E+02		β1.10E+09
PU236	2.20E-05	1.20E+01	2.88E-05	1.51E+01	2.74E-05	1.46E+01	6.25E-05	3.31E+01
PU238	6.80E-01	1.15E+04	1.79E-01	1.47E+04	8.49E-01	1.52E+04	1.72E+00	3.01E+04
PU239	7.15E+02	4.30E+05	6.29E+02	3.89E+05	6.26E+02	3.85E+05	1.54E+03	9.49E+05
PU240	1.42E+02	4.29E+05	2.55E+02	7.72E+05	2.59E+02	7.72E+05	5.19E+02	1.54E+06
PU241	1.70E+01	1.73E+05	2.91E+01	2.96E+05	2.91E+01	2.95E+05	6.03E+01	6.01E+05
PU242	4.30E+00	1.70E+01	8.43E+00	3.50E+01	6.43E+00	2.65E+01	1.25E+01	4.98E+01
PU243	0.	0.	5.63E-06	1.47E+06	1.38E-16	3.59E-07	1.31E-05	3.19E+06
TOTAL	9.29E+02	1.43E+06	9.17E+02	4.16E+06	9.14E+02	2.74E+06	2.12E+03	6.85E+06
		α1.84E+00		1.10E+06		1.11E+06		1.71E+06
		β1.73E+06		4.02E+06		2.63E+06		6.41E+06
AM241	2.65E-01	7.66E+02	1.08E+00	3.44E+03	2.07E+00	7.11E+03	2.39E+00	8.20E+03
AM242M	0.	0.	5.06E-02	4.52E+02	5.65E-02	4.91E+02	1.16E-01	1.13E+03
AM242	0.	0.	7.33E-04	5.45E+05	6.67E-07	4.91E+02	1.69E-03	1.17E+06
AM243	0.	0.	1.13E+00	2.18E+02	1.14E+00	2.18E+02	2.61E+00	5.01E+02
AM244	0.	0.	8.03E-06	2.34E+05	7.63E-20	2.23E-09	1.84E-05	5.47E+05
TOTAL	2.65E-01	7.68E+02	3.07E+00	6.40E+05	3.26E+00	4.91E+03	3.70E+00	9.66E+05
		α7.68E+02		α6.68E+02		α7.32E+03		α4.46E+03
		β0.		β8.33E+05		β9.91E+02		β1.91E+06

Table 19 (continued)

CORE

	CHANGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM242	0.	0.	1.04E-01	3.45E+05	8.13E-02	2.69E+05	2.39E-01	7.93E+05
CM243	0.	0.	6.78E-03	3.12E+02	6.76E-03	3.11E+02	1.56E-02	7.16E+02
CM244	0.	0.	1.11E-01	8.98E+03	1.10E-01	8.92E+03	2.55E-01	2.06E+04
CM245	0.	0.	4.41E-03	7.79E-01	4.41E-03	7.78E-01	1.01E-02	1.79E+00
CM246	0.	0.	1.43E-04	5.69E-02	1.43E-04	5.69E-02	4.22E-04	1.68E-01
CM247	0.	0.	4.06E-06	3.80E-07	4.06E-06	3.80E-07	9.32E-06	8.71E-07
CM248	0.	0.	1.03E-07	4.22E-07	1.03E-07	4.22E-07	2.37E-07	9.70E-07
TOTAL	0.	0.	2.26E-01	3.66E+05	2.03E-01	2.78E+05	5.20E-01	8.14E+05
				aa.55E+05		a2.78E+05		aa.14E+05
				a3.51E-08		a3.51E-08		a8.01E-08
BK249	0.	0.	1.83E-09	2.55E-03	1.34E-09	2.23E-03	3.60E-09	5.69E-03
BK250	0.	0.	5.97E-14	2.17E-04	3.06E-22	1.50E-12	1.20E-13	4.49E-04
TOTAL	0.	0.	1.83E-09	2.77E-03	1.34E-09	2.23E-03	3.60E-09	6.35E-03
				aa.		aa.		aa.
				a2.77E-03		a2.23E-03		a6.35E-03
CF249	0.	0.	3.28E-10	1.32E-06	5.14E-10	2.10E-06	7.46E-10	3.04E-06
CF250	0.	0.	4.16E-11	4.55E-06	4.13E-11	4.52E-06	9.56E-11	1.05E-05
CF251	0.	0.	7.91E-13	1.17E-09	7.91E-13	1.17E-09	1.78E-12	2.64E-09
CF252	0.	0.	1.16E-14	6.20E-09	1.11E-14	5.94E-09	2.66E-14	1.42E-08
CF253	0.	0.	4.25E-17	1.23E-09	4.11E-16	1.19E-10	9.75E-17	2.83E-09
TOTAL	0.	0.	3.67E-10	5.80E-06	5.56E-10	2.62E-06	8.43E-10	1.35E-05
				a5.85E-06		a4.59E-06		a1.13E-05
				a3.70E-08		a3.05E-08		a8.70E-08
TOTAL	5.05E+03	1.83E+06	5.02E+03	9.63E+08	5.02E+03	2.93E+06	1.23E+04	1.11E+09
FISSION PROD.	0.	0.	6.22E+02	2.74E+09	6.22E+02	1.76E+08	1.49E+03	6.30E+09
CLAD	1.99E+03	0.	1.99E+04	5.61E+06	1.99E+03	2.17E+06	4.57E+03	6.33E+06

Table 19 (continued)

AXIAL BLANKET

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
U234	3.04E-02	1.85E-01	2.40E-02	1.73E-01	2.81E-02	1.74E-01	6.73E-02	4.18E-01
U235	4.74E+00	1.02E-02	2.84E+00	6.07E-03	2.80E+00	6.09E-03	8.76E+00	1.87E-02
U236	2.50E+00	1.89E-01	3.22E+00	2.04E-01	3.22E+00	2.06E-01	7.11E+00	4.51E-01
U237	0.	0.	1.59E-02	1.25E+06	3.24E-05	2.64E+03	3.52E-02	2.17E+06
U238	8.63E+03	2.16E+00	9.10E+03	2.28E+00	8.10E+03	2.03E+00	1.44E+04	4.79E+00
U239	0.	0.	7.61E-03	2.58E+08	0.	0.	1.75E-01	9.84E+08
TOTAL	8.69E+03	2.53E+00	6.10E+03	2.56E+08	6.10E+03	2.64E+03	1.44E+04	2.94E+08
		Q2.53E+00		Q2.41E+00		Q2.41E+00		Q5.60E+00
		B0.		B2.56E+08		B2.64E+03		B5.09E+08
NP237	0.	0.	2.37E-08	1.43E+01	4.69E-28	2.83E-19	5.45E-08	3.29E+01
NP237	0.	0.	1.41E+00	9.96E-01	1.43E+00	1.01E+00	3.24E+00	2.29E+00
NP238	0.	0.	9.29E-04	1.12E+05	1.08E-12	2.81E-04	5.67E-04	2.58E+05
NP239	0.	0.	1.10E+00	2.58E+08	2.30E-08	5.36E+00	2.52E+00	5.95E+08
TOTAL	0.	0.	2.51E+00	2.59E+08	1.43E+00	6.36E+00	5.76E+00	5.98E+08
				Q9.90E-01		Q1.01E+00		Q2.29E+00
				B2.58E+08		B5.36E+00		B5.80E+08
PU236	0.	0.	3.44E-06	2.27E+00	3.79E-06	1.99E+00	8.43E-06	4.75E+00
PU238	0.	0.	6.79E-02	1.15E+03	6.83E-02	1.15E+03	1.56E-01	2.63E+03
PU239	0.	0.	2.60E+02	1.60E+04	2.62E+02	1.46E+04	5.98E+02	3.67E+04
PU240	0.	0.	1.64E+01	3.62E+03	1.64E+01	3.62E+03	3.77E+01	8.31E+03
PU241	0.	0.	5.26E-01	5.34E+04	5.20E-01	5.29E+04	1.22E+00	1.22E+05
PU242	0.	0.	1.42E-02	9.17E-02	1.38E-02	5.17E-02	3.04E-02	1.19E-01
PU243	0.	0.	5.17E-07	1.34E+03	2.47E-23	6.40E-14	1.19E-06	3.08E+03
TOTAL	0.	0.	2.77E+02	7.54E+04	2.76E+02	7.37E+04	6.37E+02	1.73E+05
		Q0.		Q2.07E+04		Q2.08E+04		Q4.76E+04
		B0.		B5.46E+04		B5.29E+04		B1.25E+05
AM241	0.	0.	1.60E-03	9.49E+01	2.01E-02	6.49E+01	3.60E-02	1.26E+02
AM242M	0.	0.	6.16E-05	6.18E-01	6.35E-05	6.18E-01	1.46E-04	1.40E+00
AM243	0.	0.	1.40E-04	1.30E+01	7.63E-10	6.18E-01	3.88E-04	3.12E+02
AM244	0.	0.	3.42E-04	6.50E-02	3.03E-04	6.59E-02	7.68E-04	1.51E-01
AM244	0.	0.	6.49E-10	1.93E+01	6.21E-24	1.84E-13	1.49E-09	4.42E+01
TOTAL	0.	0.	1.64E-02	1.44E+03	2.05E-02	7.02E+01	3.78E-02	3.30E+03
		Q0.		Q5.56E+01		Q6.40E+01		Q1.20E+02
		B0.		B1.39E+03		B6.18E-01		B1.17E+03

Table 19 (continued)

AXIAL BLANKET

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM242	0.	0.	1.01E-04	5.34E+02	1.22E-04	4.17E+02	3.76E-04	1.21E+03
CM243	0.	0.	1.42E-06	6.51E-02	1.41E-06	5.49E-02	3.95E-06	1.60E-01
CM244	0.	0.	4.03E-06	3.26E-01	4.01E-06	3.24E-01	5.26E-06	7.50E-01
CM245	0.	0.	2.40E-08	4.73E-06	2.68E-08	4.73E-06	6.15E-08	1.09E-05
CM246	0.	0.	1.72E-10	5.32E-08	1.72E-10	5.32E-08	3.66E-10	1.23E-07
CM247	0.	0.	7.25E-13	6.40E-14	7.25E-13	6.40E-14	1.67E-12	1.47E-13
CM248	0.	0.	3.37E-15	1.38E-14	3.37E-15	1.38E-14	7.73E-15	3.17E-14
TOTAL	0.	0.	1.07E-04	5.34E+02	1.31E-04	4.17E+02	3.83E-04	1.23E+03
				α5.34E+02		α4.17E+02		α1.23E+03
				β1.15E-15		β1.15E-15		β2.63E-15
BK249	0.	0.	1.02E-17	1.70E-11	8.92E-18	1.48E-11	2.34E-17	3.90E-11
BK250	0.	0.	9.06E-23	3.88E-13	6.46E-31	2.51E-21	2.29E-22	8.49E-13
TOTAL	0.	0.	1.02E-17	1.74E-11	8.92E-18	1.49E-11	2.34E-17	3.99E-11
				α0.		α0.		α0.
				β1.74E-11		β1.49E-11		β3.99E-11
CF249	0.	0.	1.77E-18	7.22E-15	3.03E-18	1.24E-14	4.06E-18	1.66E-14
CF250	0.	0.	5.55E-20	6.07E-18	5.51E-20	6.02E-18	1.27E-19	1.39E-14
CF251	0.	0.	2.20E-22	3.49E-19	2.20E-22	3.49E-19	5.06E-22	8.01E-19
CF252	0.	0.	8.75E-25	2.55E-19	8.75E-25	2.55E-19	1.95E-24	5.86E-19
CF253	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	1.82E-18	1.33E-14	3.05E-18	1.84E-14	4.19E-18	3.05E-14
				α1.32E-14		α1.84E-14		α3.04E-14
				β4.25E-15		β4.82E-15		β1.11E-14
TOTAL	6.44E+03	2.53E+00	6.38E+03	5.11E+04	6.30E+03	7.60E+04	1.47E+04	5.87E+05
FISSION PROD.	0.	0.	5.87E+01	3.63E+08	5.87E+01	2.00E+07	1.35E+02	8.46E+08
CLAD	2.27E+03	0.	2.27E+03	1.75E+06	2.27E+03	7.14E+05	5.21E+03	2.01E+06

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Table 19 (continued)

RADIAL BLANKET

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
U239	2.12E-02	1.32E-01	1.97E-02	1.22E-01	1.90E-02	1.23E-01	7.48E-02	4.63E-01
U235	3.13E+00	7.15E-03	1.89E+00	4.05E-03	1.85E+00	4.06E-03	5.52E+00	2.06E-02
U238	2.68E+00	1.32E-01	2.25E+00	1.92E-01	2.25E+00	1.42E-01	1.87E+00	4.59E-01
U237	0.	0.	5.96E-03	4.87E+06	1.26E-05	1.03E+03	2.17E-02	1.78E+06
U236	4.49E+03	1.50E+00	4.24E+03	1.41E+00	4.24E+03	1.41E+00	1.56E+04	5.30E+00
U234	0.	0.	2.03E-03	4.48E+07	0.	0.	1.03E-02	3.98E+08
TOTAL	4.49E+03	1.77E+00	4.24E+03	9.83E+07	4.24E+03	1.43E+03	1.56E+04	1.74E+08
		α1.77E+00		α1.60E+00		α1.68E+00		α6.28E+00
		β0.		β9.83E+07		β1.03E+03		β3.47E+08
NP236	0.	0.	1.01E-08	6.12E+00	2.01E-28	1.21E-19	3.70E-00	2.23E+01
NP237	0.	0.	1.09E+00	7.67E-01	1.09E+00	7.72E-01	3.97E+00	2.80E+00
NP238	0.	0.	1.94E-04	4.90E+04	4.61E-13	1.20E-04	6.70E-04	1.75E+05
NP239	0.	0.	4.04E-01	9.48E+07	9.01E-09	2.10E+00	1.49E+00	3.45E+08
TOTAL	0.	0.	1.50E+00	9.49E+07	1.09E+00	2.82E+00	5.45E+00	3.46E+08
				α7.67E-01		α7.72E-01		α2.80E+00
				β9.49E+07		β2.10E+00		β3.46E+08
PU210	0.	0.	1.50E+00	2.72E-06	1.44E+00	1.03E-05	5.47E+00	3.92E-05
PU238	0.	0.	5.72E-02	9.68E+02	5.73E-02	9.68E+02	2.09E-01	3.52E+03
PU239	0.	0.	1.15E+04	1.89E+02	1.16E+04	1.90E+02	6.86E+02	4.21E+04
PU240	0.	0.	1.34E+01	2.90E+03	1.34E+01	2.50E+03	4.50E+01	1.08E+04
PU241	0.	0.	5.25E-01	5.36E+04	5.21E-01	5.29E+04	1.91E+00	1.95E+05
PU242	0.	0.	1.76E-02	6.99E-02	1.76E-02	6.66E-02	6.21E-02	2.42E-01
PU243	0.	0.	5.03E-07	1.30E+03	7.14E-23	1.84E-13	1.03E-06	4.74E+03
TOTAL	0.	0.	2.02E+02	7.52E+04	2.03E+02	6.84E+04	7.37E+02	2.56E+05
		α0.		α1.56E+04		α1.56E+04		α5.64E+04
		β0.		β5.47E+04		β5.29E+04		β1.99E+05
AM241	0.	0.	3.10E-02	1.20E+02	3.50E-02	1.20E+02	1.13E-01	3.87E+02
AM242M	0.	0.	1.31E-04	1.27E+00	1.31E-04	1.27E+00	4.77E-04	4.68E+00
AM242	0.	0.	1.48E-01	1.48E+03	1.37E-05	1.27E+00	6.67E-06	5.42E+03
AM243	0.	0.	6.60E-04	1.29E+01	6.66E-04	1.20E+01	2.43E-03	4.67E+01
AM244	0.	0.	7.03E-10	2.08E+01	6.95E-24	2.08E-11	2.56E-09	7.58E+01
TOTAL	0.	0.	3.14E-02	1.59E+03	3.58E-02	1.23E+02	1.16E-01	5.76E+03
		α0.		α1.04E+02		α1.20E+02		α4.37E+02
		β0.		β1.48E+03		β1.27E+00		β5.40E+03

Table 19 (continued)

RADIAL BLANKET

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM242	0.	0.	2.30E-04	7.98E+02	1.05E-04	6.14E+02	8.67E-04	2.87E+03
CM243	0.	0.	2.31E-06	1.06E-01	2.30E-06	1.06E-01	8.40E-06	3.86E-01
CM244	0.	0.	8.59E-06	6.99E-01	8.54E-06	6.92E-01	3.13E-05	2.54E+00
CM245	0.	0.	6.31E-08	1.11E-05	6.31E-08	1.11E-05	2.30E-07	4.06E-05
CM246	0.	0.	4.51E-10	1.30E-07	4.51E-10	1.30E-07	1.64E-09	5.07E-07
CM247	0.	0.	2.10E-12	1.85E-13	2.10E-12	1.85E-13	7.64E-12	6.73E-13
CM248	0.	0.	1.08E-14	4.42E-14	1.08E-14	4.42E-14	3.93E-14	1.61E-13
TOTAL	0.	0.	2.49E-04	7.98E+02	1.96E-04	6.15E+02	9.07E-04	2.87E+03
				α7.98E+02		α6.15E+02		α2.87E+03
				β3.66E-15		β3.66E-15		β1.34E-14
PK240	0.	0.	3.14E-17	5.24E-11	2.76E-17	4.59E-11	1.14E-16	1.91E-10
PA240	0.	0.	1.70E-22	6.64E-13	1.31E-30	5.09E-21	6.21E-22	2.42E-12
TOTAL	0.	0.	3.14E-17	5.31E-11	2.76E-17	4.59E-11	1.14E-16	1.93E-10
				α0.		α0.		α0.
				β5.31E-11		β4.59E-11		β1.93E-10
CF249	0.	0.	1.07E-17	4.40E-14	1.47E-17	5.99E-14	3.93E-17	1.60E-13
CF250	0.	0.	2.36E-19	2.89E-14	2.34E-19	2.56E-14	8.58E-19	9.39E-14
CF251	0.	0.	1.03E-21	1.63E-18	1.03E-21	1.63E-18	3.76E-21	5.95E-18
CF252	0.	0.	1.51E-24	1.88E-18	1.51E-24	1.88E-18	1.28E-23	6.07E-18
CF253	0.	0.	5.88E-28	1.70E-20	5.88E-28	1.70E-20	2.14E-27	6.21E-20
TOTAL	0.	0.	1.10E-17	6.97E-14	1.49E-17	8.54E-14	4.01E-17	2.54E-13
				α6.98E-14		α8.52E-14		α2.53E-13
				β2.01E-16		β2.05E-16		β7.51E-16
TOTAL	4.49E+03	1.77E+00	4.48E+03	1.90E+08	4.48E+03	7.02E+04	1.63E+04	3.47E+08
FISSION PROD.	0.	0.	4.50E+01	1.47E+08	4.48E+01	9.61E+06	1.76E+02	5.37E+08
CLAD	1.50E+03	0.	1.58E+03	7.32E+06	1.58E+03	1.28E+05	5.77E+03	1.33E+06

Table 19 (continued)

REACTOR TOTAL

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
U234	2.75E-02	4.82E-01	7.59E-02	4.70E-01	7.72E-02	4.78E-01	2.64E-01	1.26E+00
U235	9.95E+00	2.11E-02	5.32E+00	1.14E-02	5.32E+00	1.14E-02	2.09E+01	4.49E-02
U236	7.00E+00	4.82E-01	7.77E+00	4.93E-01	7.77E+00	4.93E-01	2.06E+01	1.30E+00
U237	0.	0.	5.61E-02	4.58E+06	1.19E-04	9.72E+03	1.37E-01	1.12E+07
U238	1.56E+04	9.21E+00	1.56E+04	9.21E+00	1.56E+04	9.21E+00	4.04E+04	2.39E+01
U239	0.	0.	2.47E-02	8.27E+08	0.	0.	2.65E-02	2.53E+09
U240	1.45E+04	6.19E+00	1.44E+04	8.32E+08	1.44E+04	9.73E+03	4.04E+04	1.02E+09
TOTAL		α6.19E+00		α5.73E+00		α5.79E+00		α2.61E+01
		β0.		β8.32E+08		β9.72E+03		β2.54E+09
NP236	0.	0.	1.42E-07	1.10E+02	3.00E-27	2.30E-18	4.55E-07	2.75E+02
NP237	0.	0.	5.03E+00	3.55E+00	5.04E+00	3.59E+00	1.30E+01	9.19E+00
NP238	0.	0.	3.44E-03	9.94E+05	8.71E-12	2.28E-03	6.23E-03	2.15E+06
NP239	0.	0.	3.55E+00	8.20E+08	1.01E-06	2.33E+02	8.71E+00	2.02E+09
TOTAL	0.	0.	8.59E+00	8.24E+08	5.04E+00	2.36E+02	2.17E+01	2.03E+09
				α3.56E+00		α3.56E+00		α9.19E+00
				β8.24E+08		β2.34E+02		β2.03E+09
PU238	2.26E-05	1.20E+01	3.51E-05	1.87E+01	3.36E-05	1.80E+01	7.77E-05	4.13E+01
PU239	6.80E-01	1.15E+04	6.49E-01	1.09E+04	1.02E+00	1.73E+04	2.19E+00	3.69E+04
PU240	2.43E+00	4.29E+04	2.48E+00	4.38E+04	2.49E+02	4.39E+04	4.68E+02	8.27E+04
PU240	1.40E+00	4.29E+04	2.48E+00	6.33E+04	2.49E+02	6.36E+04	4.68E+02	1.19E+05
PU241	1.70E+01	1.73E+06	2.61E+01	2.64E+06	2.59E+01	2.64E+06	5.14E+01	5.23E+06
PU242	4.36E+00	1.70E+01	4.56E+00	2.50E+01	6.56E+00	2.50E+01	1.20E+01	4.41E+01
PU243	0.	0.	5.71E-06	1.48E+06	1.36E-16	1.58E-07	1.07E-05	3.49E+06
TOTAL	9.24E+02	1.43E+06	1.40E+03	9.24E+06	1.40E+03	2.78E+06	2.63E+03	7.27E+06
		α3.84E+04		β1.47E+05		β1.47E+05		β2.75E+05
		β1.73E+06		β4.11E+06		β2.64E+06		β6.93E+06
AM241	2.26E-01	7.84E+02	1.13E+00	3.90E+03	2.13E+00	7.29E+03	2.56E+00	8.72E+03
AM242M	0.	0.	5.04E-02	4.94E+02	5.07E-02	4.93E+02	1.17E-01	1.14E+03
AM242	0.	0.	7.30E-04	5.58E+05	6.09E-07	4.93E+02	1.70E-03	1.37E+06
AM243	0.	0.	1.14E+00	2.19E+02	1.14E+00	2.19E+02	2.61E+00	5.02E+02
AM244	0.	0.	8.03E-06	2.38E+05	7.53E-20	2.23E-09	1.85E-05	5.47E+05
TOTAL	2.26E-01	7.84E+02	2.31E+00	8.40E+05	3.32E+00	8.50E+03	5.91E+00	9.75E+05
		α7.84E+02		α2.82E+03		α7.51E+03		α9.97E+03
		β0.		β8.36E+05		β4.53E+02		β1.92E+06

Table 19 (continued)

REACTOR TOTAL

	CHARGE		DISCHARGE		60 DAYS		INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
CM242	0.	0.	1.05E-01	3.47E+05	8.16E-02	2.70E+05	2.41E-01	7.97E+05
CM243	0.	0.	6.78E-03	3.12E+02	6.76E-03	3.11E+02	1.56E-02	7.17E+02
CM244	0.	0.	1.11E-01	8.56E+03	1.10E-01	8.49E+03	2.55E-01	2.06E+04
CM245	0.	0.	4.41E-03	7.7HE-01	4.41E-03	7.7HE-01	1.01E-02	1.79E+00
CM246	0.	0.	1.83E-04	5.66E-02	1.83E-04	5.66E-02	4.21E-04	1.30E-01
CM247	0.	0.	4.01E-06	3.5HE-07	4.00E-06	3.5HE-07	9.32E-06	8.23E-07
CM248	0.	0.	1.03E-07	4.22E-07	1.03E-07	4.22E-07	2.37E-07	9.70E-07
TOTAL	0.	0.	2.27E-01	3.56E+05	2.03E-01	3.79E+05	5.22E-01	8.18E+05
				B3.86E+05		B2.79E+05		B8.19E+05
				B3.61E-08		B3.61E-08		B8.05E-08
BK249	0.	0.	1.93E-09	2.65E-03	1.34E-09	2.23E-03	3.50E-09	5.05E-03
BK250	0.	0.	5.57E-14	2.17E-04	3.06E-12	1.60E-12	1.26E-11	4.90E-04
TOTAL	0.	0.	1.93E-09	2.77E-03	1.34E-09	2.23E-03	3.50E-09	6.45E-03
				B0.		B0.		B0.
				B2.77E-03		B2.23E-03		B6.35E-03
CF249	0.	0.	3.25E-10	1.22E-06	5.14E-10	2.10E-06	7.46E-10	3.04E-06
CF250	0.	0.	4.10E-11	4.56E-06	4.13E-11	4.52E-06	9.56E-11	1.05E-05
CF251	0.	0.	7.41E-13	1.17E-09	7.41E-13	1.17E-09	1.70E-12	2.69E-09
CF252	0.	0.	1.16E-14	6.20C-09	1.11E-14	5.94E-09	2.66E-14	1.42E-08
CF253	0.	0.	4.25E-17	1.23E-09	4.11E-18	1.19E-10	9.75E-17	2.83E-09
TOTAL	0.	0.	3.67E-10	5.49E-06	5.56E-10	6.62E-06	8.43E-10	1.35E-05
				B5.49E-06		B6.59E-06		B1.34E-05
				B3.79E-08		B3.65E-08		B8.70E-08
TOTAL	1.66E+04	1.83E+06	1.69E+04	1.66F+09	1.89E+04	2.08E+06	4.33E+04	2.04E+09
FISSION PROD.	0.	0.	7.26E+02	3.26E+09	7.26E+02	2.07E+08	1.73E+03	7.66E+09
CLAD	5.64E+03	0.	5.49E+03	7.99E+06	5.64E+03	1.21E+06	1.25E+04	9.67E+06

of plutonium to be reprocessed annually is 1400 Kg for the GEFO reactor compared with 1940 Kg for the AIFO reactor. Thus, the amount of alpha plutonium radioactivity reprocessed annualy for the GEFO reactor is about two-thirds of that reprocessed annually in the AIFO reactor fuel cycle.

Table 20

Isotopic Composition of Plutonium in Reprocessed Discharge Fuel of LMFBRs

	AIFO wt. %	GEFO wt. %
^{236}Pu	1.54×10^{-6}	2.42×10^{-6}
^{238}Pu	6.88×10^{-2}	7.27×10^{-2}
^{239}Pu	71.7	77.0
^{240}Pu	25.1	20.6
^{241}Pu	2.38	1.85
^{242}Pu	0.76	0.47
	100	100

The calculated inventories of plutonium in the GEFO reactor fuel cycle are listed in Table 21, based upon the same process hold-up times as the AIFO reactor. The amount of plutonium inventory in the reactor and external fuel cycle for the GEFO reactor is more than 1000 Kg less than the inventory in the AIFO reactor. However, the plutonium product from one year of operation is almost 200 Kg more for the GEFO reactor.

The estimated neutron source strength of spent LMFBR core fuels are compared with those from water reactors in Table 22. Most of the neutrons originate from spontaneous fission in the isotopes ^{242}Cm and ^{244}Cm and are of considerable interest in the design of shipping casks for irradiated fuels. The ^{244}Cm isotope, which has a half-life of 17.6 years, is also expected to present a shielding problem in transporting and disposal

of the wastes. Greater than 90% of the neutron source strength is due to ^{242}Cm and ^{244}Cm; in water reactors 70 to 90% of it results from ^{244}Cm, whereas in LMFBR's, approximately 60% is generated by ^{242}Cm. The total neutron spectrum is slightly harder for fast reactor due to a higher (α,n) fraction. The LMFBR source spectra are about 25% (α,n), while the water reactor source spectra are 88 to 95% spontaneous fission. The results of Table 22 indicate that the neutron source in spent LMFBR cores will be greater than from enriched-uranium water-reactor fuel but less than from plutonium-recycle water-reactor fuel. If spent LMFBR fuel elements from both core and blankets are shipped and processed together, the neutron source from the mixed fuel is no more of a hazard than that from water reactor fueled with enriched uranium. This is indicated in Table 23, which shows the neutron source strength of the mixed core-blanket fuel.

Table 21

Inventories of Plutonium in Fuel Cycle of 1000 Mw GEFO LMFBR

	Hold-Up Time	Plutonium Inventory Total Pu Kg	Fissile Pu Kg	Alpha Pu curies	Beta Pu curies
Reactor		3500	2871	2.75×10^5	6.93×10^6
Core and axial blanket	3.0 yr.				
Radial blanket	3.6 yr.				
Post-Irradiation cooling	30 days	115	90	1.21×10^4	3.39×10^5
Shipment to fuel reprocessing	28.8 days	110	86	1.16×10^4	2.09×10^5
Fuel reprocessing	36 days	138	109	1.45×10^4	2.60×10^5
Shipment to fuel preparation	8.4 days	23	18	2.44×10^3	4.37×10^4
Fuel preparation	12 days	33	26	3.48×10^3	6.24×10^4
Fuel fabrication	12 days	32	25	3.42×10^3	6.08×10^4
Shipment to reactor	14 days	36	28	3.74×10^3	6.63×10^4
Pre-irradiation inventory	36 days	92	72	9.63×10^3	1.71×10^5
Scrap recycle shipment	12 days	2.27	1.79	2.40×10^2	4.30×10^2
Total external to reactor		581	456	6.12×10^4	1.21×10^6
Total in shipment		169	132	1.78×10^4	3.19×10^5
Total in reactor and external fuel cycle		4081	3327	3.36×10^5	8.14×10^6
In plutonium product from one year of operation		446	352	4.69×10^4	8.40×10^5

Table 22

Estimated Neutron Source Strength of Spent Power Reactor Fuels

Isotope	Water Reactor Fueled with Enriched Uranium			Water Reactor Fueled with Recycle Plutonium and Natural Uranium		
	Isotope Content (g/ton)[c]	Neutron Source[a][b] α-n (sec^{-1} ton^{-1} x 10^{-6})	S.F. (sec^{-1} ton^{-1} x 10^{-6})	Isotope Content (g/ton)[c]	Neutron Source[a][b] α-n (sec^{-1} ton^{-1} x 10^{-6})	S.F. (sec^{-1} ton^{-1} x 10^{-6})
^{238}Pu	219.9	7.3	0.5	1	47.1	3.3
^{239}Pu	5280	0.5	0	12150	1.2	0
^{240}Pu	2170	0.8	2.0	9058	3.2	8.5
^{242}Pu	354.3	0	0.7	3954	0.02	7.9
^{241}Am	48.55	0.3	0	577.8	4.0	0
^{242}Cm	4.848	47.1	96	70.6	681.6	1387
^{244}Cm	33.44	6.5	381	1698	331.6	19360
^{246}Cm	0.2286	0	2.1	18.81	0.01	173.6
Total		61.8	482		1069	20940
Overall Total		544			22009	

(a) Neutron source strength is at 150 days after fuel is discharged from reactor.

(b) S.F. = spontaneous fission.

(c) "Ton" in this table refers to metric ton of fuel as charged to the reactor.

Table 22 (continued)

Estimated Neutron Source Strength of Spent Power Reactor Fuels

Isotope	AIFO LMFBR Core			GEFO LMFBR Core		
	Isotope Content (g/ton)[c]	Neutron Source[a][b] α-n (sec^{-1} ton^{-1} x 10^{-6})	S.F.	Isotope Content (g/ton)[c]	Neutron Source[a][b] α-n (sec^{-1} ton^{-1} x 10^{-6})	S.F.
^{238}Pu	131.16	4.4	0.3	157.3	5.2	0.4
^{239}Pu	114200	11.0	0	111200	10.7	0
^{240}Pu	48350	17.2	46.4	45960	16.0	43.3
^{242}Pu	1544	0.008	3.1	1157	0.006	2.3
^{241}Am	402.9	2.8	0	350.3	2.4	0
^{242}Cm	13.52	130.5	265.6	16.35	157.9	321.3
^{244}Cm	13.33	2.6	152.0	19.59	3.8	223.3
^{246}Cm	0.01	0	0.09	0.03	0	0.3
Total		168.5	467.5		196	590.9
Overall Total		636			787	

(a) Neutron source strength is at 30 days after fuel is discharged from core.

(b) S.F. = spontaneous fission.

(c) "Ton" in this table refers to metric ton of fuel as charged to the core.

Table 23

Estimated Neutron Source Strength of Spent Power Reactor Fuels

Isotope	AIFO LMFBR Isotope Content (g/ton)[c]	AIFO LMFBR Neutron Source[a] α-n (sec^{-1} ton^{-1} x 10^{-6})	AIFO LMFBR Neutron Source[a] S.F.[b] (sec^{-1} ton^{-1} x 10^{-6})	GEFO LMFBR Isotope Content (g/ton)[c]	GEFO LMFBR Neutron Source[a] α-n (sec^{-1} ton^{-1} x 10^{-6})	GEFO LMFBR Neutron Source[a] S.F.[b] (sec^{-1} ton^{-1} x 10^{-6})
^{238}Pu	69.97	2.3	0.16	61.12	2.04	0.14
^{239}Pu	73750	7.1	0	65008	6.42	0
^{240}Pu	25800	9.0	24.27	17444	6.16	16.4
^{242}Pu	782.8	0.004	1.565	395.6	0.002	0.79
^{241}Am	214.7	1.43	0	122.3	0.85	0
^{242}Cm	6.856	66.18	134.7	5.586	53.9	109.7
^{244}Cm	6.753	1.319	77.01	6.668	1.30	76.0
^{246}Cm	0.005	0	0.05	0.01	0	0.1
Total		87.3	237.7		70.7	203
Overall Total		325			274	

(a) Neutron source strength is at 30 days after fuel is discharged from reactor.

(b) S.F. = spontaneous fission.

(c) "Ton" in this table refers to metric ton of fuel as charged to the reactor.

V. FUEL CYCLES FOR THE 1000 MW HIGH TEMPERATURE GAS-COOLED REACTOR (HTGR)

HTGR Fueled with Thorium and Enriched Uranium

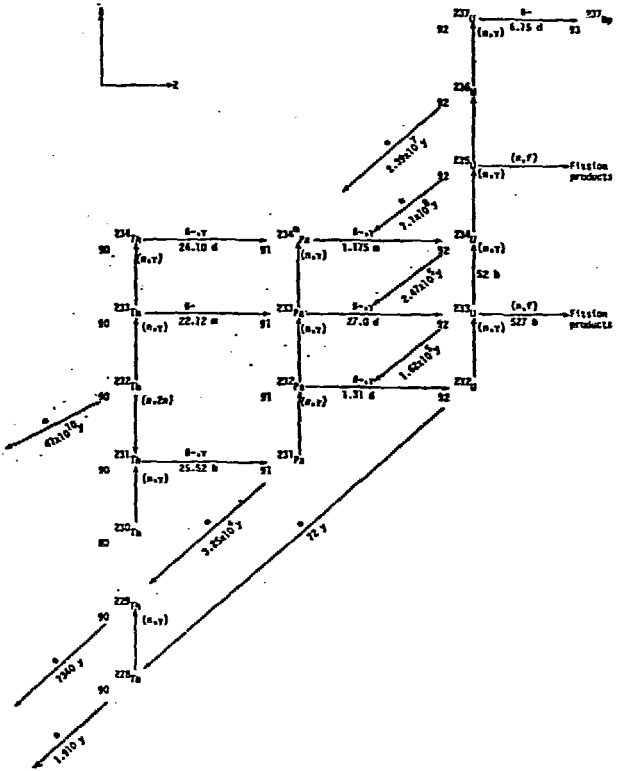
The gas-cooled reactor[17] recently introduced as an alternative nuclear power plant, is a helium-cooled graphite structure fueled with a mixture of natural thorium (^{232}Th) and uranium of high fissile content. Part of the uranium in the reactor fuel consists of make-up highly enriched uranium (93.5% ^{235}U), obtained by enriching natural uranium in an isotope separation plant. The discharged fuel is processed to recover the uranium remaining from the makeup ^{235}U, which is then recycled for only one more pass through the reactor to avoid the penalty from high ^{236}U content.[18] The cost advantage of not recycling the exposed ^{235}U material over a fuel cycle which recycles the exposed ^{235}U material has been estimated to be about 0.06 mills/kwhr averaged over the 30 years of reactor operation.[19] Also recovered for recycling is the largely fissile ^{233}U, formed by neutron-capture reactions in thorium. The thorium is too radioactive to be recycled and is stored for 10 to 15 years to permit the decay of the ^{238}Th and its gamma active daughters before recycling.[20,21] Since the fuel cycle conversion ratio of the reference type HTGR under consideration is about 0.4 with a fuel exposure time of four years, makeup ^{235}U will have to be used throughout the life of the reactor. The fuel cycle considered here is the equilibrium fuel cycle, reached after several years of operation.

The principal actinides involved in using thorium-uranium fuel are shown in Figure 15. The primary chain leading to the formation of uranium in the irradiated HTGR fuel is:

$$^{232}Th \xrightarrow{n,\gamma} {}^{233}Th \xrightarrow[22.2m]{\beta^-} {}^{233}Pa \xrightarrow[27d]{\beta^-} {}^{233}U \qquad (1)$$

Fig. 15

Nuclide Chains from Thorium Irradiation



Neutron capture reactions in ^{233}U generate ^{234}U, ^{235}U, and ^{236}U. In addition, ^{232}U is formed by the initiation of (n, 2n) reactions in ^{232}Th. The primary chain leading to the formation of ^{232}U is:

$$^{232}Th \xrightarrow{n,2n} {}^{231}Th \xrightarrow[25.5h]{\beta^-} {}^{231}Pa \xrightarrow{n,\gamma} {}^{232}Pa \xrightarrow[1.32d]{\beta^-} {}^{232}U \quad (2)$$

The main source of high energy gamma radioactivity in ^{233}U after reprocessing of fuel from HTGRs will be from the decay products of ^{232}U. The decay chain of ^{232}U will contribute both very high energy gamma rays and neutrons from (α, n) reactions with light elements associated with the uranium. The decay chain can be written as

$$^{232}U \xrightarrow[72y]{\alpha} {}^{228}Th \xrightarrow[1.91y]{\alpha} {}^{224}Ra \xrightarrow[3.64d]{\alpha} {}^{220}Rn \xrightarrow[55.3s]{\alpha} {}^{216}Po \longrightarrow$$

$$^{216}Po \xrightarrow[0.15s]{\alpha} {}^{212}Pb \xrightarrow[10.6h]{\beta^-} {}^{212}Bi \xrightarrow[60.6m]{\alpha(36\%)} {}^{208}Tl \xrightarrow[3.1m]{\beta^-} {}^{208}Pb \quad (3)$$

$$^{212}Bi \xrightarrow[60.6m]{\beta^-(64\%)} {}^{212}Po \xrightarrow[0.3\ \mu s]{\alpha} {}^{208}Pb$$

The decay daughters ^{208}Tl and ^{212}Bi produce high energy gammas and are *major sources of* radiation from recycle uranium fuel.

In addition to reaction (1), ^{233}U is also form from neutron capture of ^{232}U:

$$^{233}U \xrightarrow{(n,2n)} {}^{232}U.$$

The principal plutonium isotope formed is ^{238}Pu, formed by the chain initiated with neutron capture in ^{235}U. Higher-mass plutonium isotopes result from neutron absorption in the small amount of ^{238}U (6.5%) present in the highly enriched make-up uranium, as shown in Figure 2.

The fuel elements of the HTGR consist of a hexagonal block of graphite approximately 31.2 inches high and 14.2 inches across the flat with approximately 72 holes for the helium coolant flow and 132 fuel holes.

The fuel is in the form of ceramic kernels coated with pyrolytic carbon and silicon carbide and bonded into sticks of approximately 0.63 inches in diameter that fit into the fuel holes in the graphite blocks.[18]

Each fuel block contains only one of the three types of uranium-thorium fuel so that the spatial arrangement of blocks throughout the reactor containing different types of fissile uranium provides a means of controlling the spatial distributions of neutron flux and power density.

The material properties of each of the three fuel types are given in Table 24. The BISO particles are coated with an inner layer of low density pyrolytic carbon and an outer layer of high density pyrolytic carbon. The TRISO particles are coated with an inner layer of low density pyrolytic carbon and the outer layers being a layer of silicon carbide sandwiched between two layers of high-density pyrolytic carbon. The pyrolytic carbon coatings are to prevent the rapid spread of fission products in the reactor system while the principal function of the silicon carbide coating is to keep the fissile ^{235}U particle intact during the crushing and burning prior to reprocessing so that it can be physically separated from the other particles by size classification. By maintaining separation of the spent ^{235}U from the ^{233}U, the fabrication cost is reduced. This is possible because particles containing only thorium or ^{235}U can be fabricated at considerably lower cost in a separate facility from the ^{233}U particles since shielding is not necessary. The recycled ^{233}U particles must be handled in heavily shielded facilities[22,23] because of high concentration of ^{232}U (0.03%), which has daughter products ^{208}Tl and ^{212}Bi that emit high-energy gamma radiation.

The steam generated by the hot helium coolant from the reactor is at higher temperature and pressure than the steam generated in water reactors, resulting in an overall thermal efficiency of 38.7%. The average thermal

Table 24

HTGR Fuel Particle Descriptions [24]

Property	Initial and Makeup Elements		^{233}U Recycle Elements		^{235}U Recycle Elements	
	Fissile Particle	Fertile Particle	Fissile Particle	Fertile Particle	Fissile Particle	Fertile Particle
Isotope	^{235}U	Th	^{233}U-Th	Th	^{235}U	Th
Kernel Composition	UC_2	ThO_2	$(Th,U)O_2$	ThO_2	UC_2	ThO_2
Kernel Diameter(μm)	200	500	400	500	200	500
Type Coating	TRISO	BISO	BISO	BISO	TRISO	BISO
Coating Thickness (μm)						
Buffer Carbon	85	85	90	85	85	85
Inner Dense Carbon	25				25	
Silicon Carbide	25				25	
Outer Dense Carbon	35	75	80	75	35	75
Total Particle Diameter (μm)	540	820	740	820	540	820

specific power in the reactor core is 64.57 Mw per Mg of uranium and thorium in the fresh fuel. Each year one-fourth of the reactor fuel, contained within 900 graphite fuel blocks, is discharged and replaced with fresh fuel, so that each fuel element remains within the reactor for four years. At an average load factor of 80%, the resulting average thermal exposure is 94,270 Mw days per Mg of uranium and thorium charged. Calculated isotopic compositions of the charge and discharge fuel for each of the three fuel types are listed in Table 25. The compositions of the annual charge and discharge fuel for the reactor are listed in Table 26. Also listed in Table 26 are the compositions of the discharge fuel 150 days and 365 days after the fuel is discharged from the reactor.

The discharge fuel is stored at the reactor site for 150 days[11] to allow time for decay of fission-product radioiodine and ^{237}U. The fuel is then shipped to a reprocessing facility where it is separated into thorium, uranium, and high-level waste containing the mixed fission products and remaining actinides, and a high-level waste consisting of activated cladding and fuel-assembly structure. The shipment to reprocessing facilities is calculated to require 215 days for each annual discharge.[18] All the plutonium present in the fuel and 0.25% of the uranium and thorium are assumed to follow the high-level waste stream. The recovered uranium, except for the once recycled makeup ^{235}U, is returned as input for conversion and refabrication. The percentage of input material which appears as losses and as scrap recycle in each fuel cycle operation is taken from a recent study[17] on the HTGR fuel cycle. A flowsheet of the fuel actinides is shown in Figure 16. It is apparent that the reactor fuel cycle consumes almost ten times as much natural uranium as thorium.

Since it is not planned to recover the plutonium for recycling, so

Table 25

Calculated Uranium Compositions of HTGR Fuel Particles
(Annual Quantities)

Isotope	TH-^{233}U		^{235}U Fresh Makup		^{235}U Recycled Makeup	
	Curies	Kg	Curies	Kg	Curies	Kg
Steady State Charge						
Th	0.7975	7271				
^{232}U	2271	0.106				
^{233}U	1749	184.6				
^{234}U	479.1	77.42	18.18	2.937	0.334	0.054
^{235}U	0.068	31.75	0.701	326.9	0.037	17.11
^{236}U	2.436	38.42			2.780	43.85
^{238}U	3.41×10^{-4}	1.022	6.59×10^{-3}	19.79	6.75×10^{-3}	20.26
Steady State Discharge						
Th	0.737	6740				
^{232}U	2312	0.108	0.057	2.66×10^{-6}	0.070	3.26×10^{-6}
^{233}U	1601	168.9	7.01×10^{-5}	7.40×10^{-6}	3.03×10^{-5}	3.20×10^{-6}
^{234}U	484.9	78.36	0.173	0.028	0.191	0.031
^{235}U	0.069	32.16	0.037	17.32	1.96×10^{-3}	0.914
^{236}U	2.467	38.91	2.815	44.39	1.884	29.71
^{237}U	1.30×10^{7}	0.160	1.49×10^{7}	0.182	9.95×10^{6}	0.122
^{238}U	3.47×10^{-4}	1.043	5.92×10^{-3}	17.76	5.28×10^{-3}	15.84

Table 26

Material and Radioactive Quantities in Reactor and Fuel Cycle for a 1000 Mw Uranium-Fueled HTGR

REACTOR TOTAL

	CHARGE		DISCHARGE		150 DAYS		365 DAYS		CORE INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
TH227	0.	0.	1.36E-09	4.29E-01	1.61E-08	5.06E-01	1.56E-08	6.20E-01	5.43E-08	1.72E+00
TH228	0.	0.	1.46E-03	1.20E+03	1.64E-03	1.35E+01	1.57E-03	1.53E+03	5.82E-03	4.78E+03
TH229	0.	0.	3.29E-03	6.99E-01	3.56E-03	7.62E-01	4.02E-03	8.61E-01	1.10E-02	2.78E+00
TH230	0.	0.	5.17E-03	1.04E-01	8.46E-03	1.00E-01	5.59E-03	1.09E-01	2.15E-02	4.17E-01
TH231	0.	0.	3.76E-04	1.99E+05	8.04E-10	1.04E-01	2.04E-10	1.08E-01	1.50E-03	7.97E+05
TH232	7.27E+03	7.95E-01	6.74E+03	7.17E-01	6.74E+03	7.37E-01	6.74E+03	7.37E-01	2.90E+04	3.08E+00
TH233	0.	0.	1.04E-02	3.81E+08	0.	0.	0.	0.	4.18E-02	1.53E+09
TH234	0.	0.	2.59E-03	5.92E+04	3.42E-05	7.92E+02	7.10E-08	1.64E+00	1.02E-02	2.37E+05
TOTAL	7.27E+03	7.95E-01	6.74E+03	3.82E+08	6.74E+03	8.14E+01	6.74E+03	1.54E+03	2.90E+04	1.53E+09
		α7.95E-01		α1.20E+03		α1.35E+03		α1.53E+03		α4.79E+03
				β3.81E+08		β7.92E+02		β1.75E+00		β1.54E+09
PA231	0.	0.	1.37E-03	6.50E+00	1.38E-01	6.50E+00	1.38E-01	6.56E+00	5.50E-01	2.60E+01
PA232	0.	0.	3.77E-04	1.61E+05	2.33E-38	9.96E-30	0.	0.	1.51E-03	6.43E+05
PA233	0.	0.	1.40E+01	3.28E+08	4.04E-01	8.24E+06	1.76E-03	3.60E+04	5.19E+01	1.07E+09
PA234M	0.	0.	1.09E-05	7.41E+06	1.15E-09	7.92E+02	2.39E-12	1.64E+00	4.33E-05	2.97E+07
PA234	0.	0.	3.54E-03	7.03E+06	3.99E-10	7.93E-01	8.28E-13	1.64E-03	1.42E-02	2.81E+07
TOTAL	0.	0.	1.41E+01	3.82E+08	5.42E-01	8.25E+06	1.39E-01	3.60E+04	5.24E+01	1.53E+09
				α6.55E+00		α6.56E+00		α6.56E+00		α2.62E+01
				β3.82E+08		β8.28E+06		β3.60E+04		β1.53E+09
U232	1.06E-01	2.27E+03	1.08E-01	2.31E+03	1.08E-01	2.31E+03	1.07E-01	2.30E+03	4.28E-01	9.17E+03
U233	1.65E+02	1.71E+03	1.69E+02	1.60E+03	1.68E+02	1.77E+03	1.67E+02	1.77E+03	7.07E+02	6.70E+03
U234	7.78E+01	4.70E+02	7.86E+01	4.88E+02	7.85E+01	4.86E+02	7.85E+01	4.86E+02	3.18E+02	1.93E+03
U235	3.76E+02	8.07E-01	5.04E+01	1.08E-01	5.04E+01	1.08E-01	5.04E+01	1.04E-01	6.52E+02	1.83E+00
U236	8.23E+01	5.22E+00	1.13E+02	7.17E+00	1.13E+02	7.17E+00	1.13E+02	7.17E+00	3.90E+02	2.48E+01
U237	0.	0.	4.64E-01	3.75E+07	1.25E-07	1.02E+01	2.92E-08	2.39E+00	1.85E+00	1.51E+08
U238	4.30E+01	1.47E-02	3.46E+01	1.15E-02	3.46E+01	1.15E-02	3.46E+01	1.15E-02	1.57E+02	5.24E-02
U239	0.	0.	1.97E-04	6.61E+06	0.	0.	0.	0.	7.89E-04	2.64E+07
TOTAL	7.44E+02	4.50E+03	4.45E+02	4.41E+07	4.63E+02	4.59E+03	4.63E+02	4.07E+03	2.42E+03	1.78E+08
		α4.50E+03		α4.40E+03		α4.57E+03		α4.56E+03		α1.70E+04
				β4.45E+07		β1.02E+01		β2.38E+00		β1.77E+08
NP236	0.	0.	2.40E-07	1.40E+02	3.22E-56	7.97E-48	0.	0.	9.59E-07	5.79E+02
NP237	0.	0.	2.57E+01	1.81E+01	2.62E+01	1.84E+01	2.62E+01	1.84E+01	1.03E+02	7.25E+01
NP238	0.	0.	1.11E-01	2.94E+07	3.64E-23	9.76E-15	5.36E-54	1.40E-45	4.50E-01	1.18E+08
NP239	0.	0.	2.03E-02	4.79E+06	2.84E-07	6.61E+01	2.84E-07	6.61E+01	1.13E-01	2.63E+07
TOTAL	0.	0.	2.58E+01	3.42E+07	2.62E+01	8.45E+01	2.62E+01	8.45E+01	1.03E+02	1.44E+08
				α1.81E+01		α1.84E+01		α1.84E+01		α7.25E+01
				β3.60E+07		β6.61E+01		β6.61E+01		β1.44E+08
PU236	0.	0.	4.17E-05	2.22E+01	3.79E-05	2.01E+01	3.28E-05	1.78E+01	1.67E-04	8.87E+01
PU238	0.	0.	1.05E+01	1.77E+05	1.06E+01	1.78E+05	1.05E+01	1.77E+05	4.19E+01	7.07E+05
PU239	0.	0.	2.30E+00	1.41E+02	2.23E+00	1.41E+02	2.33E+00	1.43E+02	9.21E+00	5.65E+02
PU240	0.	0.	1.37E+00	3.02E+02	1.37E+00	3.03E+02	1.38E+00	3.04E+02	5.48E+00	1.21E+03
PU241	0.	0.	1.02E+00	1.04E+05	1.00E+00	1.03E+05	9.76E-01	9.91E+04	4.09E+00	4.16E+05
PU242	0.	0.	1.01E+00	3.93E+00	1.01E+00	3.91E+00	1.01E+00	3.91E+00	4.04E+00	1.57E+01
PU243	0.	0.	4.62E-04	1.20E+06	2.32E-15	6.01E-06	2.32E-15	6.01E-06	1.85E-03	4.79E+06
TOTAL	0.	0.	1.62E+01	1.48E+06	1.63E+01	2.81E+05	1.62E+01	2.77E+05	6.47E+01	5.91E+06
				α1.77E+05		α1.78E+05		α1.77E+05		α7.09E+05
				β1.30E+06		β1.02E+05		β9.91E+04		β5.21E+06

Table 26 (continued)

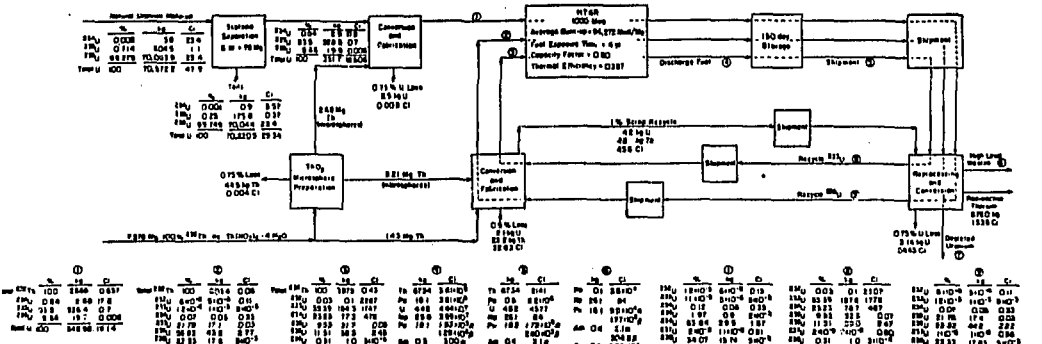
REACTOR TOTAL

	CHARGE		DISCHARGE		150 DAYS		365 DAYS		CORE INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
AM241	0.	0.	7.67E-01	7.67E+01	6.63E-02	1.38E+02	6.80E-02	2.13E+02	8.27E-02	2.86E+02
AM242M	0.	0.	3.20E-04	3.19E-04	3.19E-04	3.19E+00	3.19E-04	3.10E+00	1.28E-03	1.24E+01
AM243	0.	0.	9.23E-05	7.43E+00	8.86E-05	3.11E+01	9.03E-05	3.10E+01	3.59E-04	2.49E+02
AM242	0.	0.	3.43E-01	6.70E+01	3.44E-01	3.44E+01	3.44E-01	6.41E+01	1.37E+00	2.56E+02
AM244	0.	0.	2.13E-05	6.53E+05	9.28E-07	2.75E-16	1.63E-26	4.82E-16	8.53E-26	2.53E-05
TOTAL	0.	0.	7.07E+01	3.64E-01	3.64E-01	2.11E+02	4.12E-01	3.05E+02	1.46E+00	8.63E+06
			a1.37E+02		a2.04E+02			a2.99E+02		a5.48E+02
			B7.07E+05		B3.11E+00			B3.10E+00		B2.83E+06
CM248	0.	0.	1.34E-03	4.44E+04	7.11E-03	2.35E+04	2.85E-03	9.47E+03	5.36E-02	1.78E+05
CM243	0.	0.	2.27E-04	1.04E+01	7.25E-04	1.03E+01	2.92E-04	1.02E+01	1.07E-03	4.17E+01
CM244	0.	0.	2.09E-01	8.06E+01	1.66E+00	8.01E+01	8.01E-01	1.63E+02	8.35E-01	6.77E+02
CM245	0.	0.	1.04E-02	1.49E+02	1.65E-02	1.48E+02	1.66E-02	1.48E+02	6.20E-02	5.92E+02
CM246	0.	0.	1.04E-02	1.49E+02	1.65E-02	1.48E+02	1.66E-02	1.48E+02	6.20E-02	5.92E+02
CM247	0.	0.	7.73E-01	1.15E+00	3.73E-03	1.15E+00	3.73E-03	1.15E+00	1.49E-02	4.61E+00
CM242	0.	0.	8.81E-05	6.01E-04	6.81E-05	6.01E-04	6.81E-05	6.01E-04	2.73E-04	2.41E-03
CM248M	0.	0.	3.51E-04	8.60E-06	1.42E-05	8.60E-06	4.60E-06	3.52E-05	3.48E-05	1.41E-04
TOTAL	0.	0.	2.17E-01	2.27E-01	4.03E+04	2.27E-01	2.18E-01	2.58E+04	8.68E-01	2.48E+05
			a6.13E+04		a4.03E+04			a2.58E+04		a2.48E+05
			B8.10E-07		B8.10E-07			B8.10E-07		B3.24E-06
PA239	0.	0.	1.02E-07	1.79E-01	7.68E-08	1.54E-01	4.70E-08	7.95E-02	4.26E-07	7.11E-01
PA250	0.	0.	1.63E-10	6.27E-01	3.93E-21	1.51E-11	3.93E-21	1.51E-11	6.39E-10	2.46E+00
TOTAL	0.	0.	1.67E-07	8.06E-01	7.68E-08	1.69E-01	4.70E-08	7.96E-02	4.26E-07	3.20E+00
			a2.68E-06		a1.92E-06			a1.19E-06		a1.07E-05
			B8.00E-01		B1.28E-01			B7.96E-02		B3.20E+00
CF251	0.	0.	1.18E-08	4.80E-04	1.18E-08	1.70E-04	7.67E-09	2.88E-04	4.71E-08	1.92E-04
CF249	0.	0.	2.49E-08	3.77E-03	2.49E-08	3.82E-03	2.85E-08	3.12E-03	1.25E-07	1.33E-02
CF252	0.	0.	1.48E-08	9.33E-05	1.48E-08	2.30E-05	1.46E-08	2.30E-05	5.92E-08	9.22E-05
CF250	0.	0.	2.10E-08	1.17E-02	1.06E-08	1.05E-02	1.68E-08	9.92E-03	8.74E-08	4.69E-02
CF248	0.	0.	5.60E-11	1.69E-03	1.63E-13	4.76E-05	3.79E-17	1.10E-09	8.24E-10	6.50E-03
TOTAL	0.	0.	7.81E-08	1.69E-02	1.69E-07	1.24E-02	1.31E-07	1.42E-02	3.13E-07	7.07E-02
			a1.47E-02		a1.36E-02			a1.21E-02		a5.87E-02
			B2.00E-03		B3.38E-04			B2.54E-04		B7.96E-03
TOTAL	8.03E+03	4.91E+01	7.25E+03	8.47E+06	7.25E+03	8.61E+06	7.25E+03	3.54E+05	3.06E+06	1.65E+09
FISSION PRODUCT	0.	0.	7.03E+02	2.37E+09	7.03E+02	7.35E+09	7.03E+02	3.65E+09	3.17E+03	9.47E+09
CLAD	8.46E+04	0.	8.46E+04	8.32E+04	8.46E+04	2.70E+06	8.46E+04	8.02E+06	3.58E+05	1.05E+08

Fig. 16

Actinide Flowsheet for the 1000 Mw Uranium-Fueled HTGR

Yearly Quantities
80% Load Factor



the plutonium, americium, and curium follow the high-level reprocessing wastes with relatively small quantities appearing in the low-level reprocessing wastes. The calculated material and radioactivity quantities of plutonium, americium, and curium in these wastes are listed in Table 26, under the column labeled 365 days since reprocessing occurs 365 days after the fuel is discharged from the reactor. The mass of plutonium contained in these wastes at the time of reprocessing is over 12 times greater than in the uranium-fueled water reactor and about five times greater than in the uranium-plutonium-fueled water reactor. However, the long-term storage problem is no greater for the wastes from the uranium-thorium fuel cycle because far less americium and curium are formed in this cycle since there is relatively small quantity of ^{238}U present in this HTGR fuel. The calculated radioactivity of plutonium in these high-level wastes as a function of storage time is shown in Figure 17. Figure 18 shows the total actinide activity in the high-level wastes as a function of waste storage time.

The material and radioactivity quantities of uranium in the charge and discharge fuel and in fuel reprocessing (356 days after discharge) is shown in Table 26. The principal alpha source in the recycled uranium is the 72-year ^{232}U. After the separation of uranium in chemical processing 1.91-year ^{228}Th, the decay daughter of ^{232}U, builds up and the hard gammas associated with its short-lived daughters will require shielding when fabricating recycle fuel. Based on 100% ^{232}Th in natural thorium, the ^{232}U content in the recycle ^{233}U is calculated to be 338 ppm, resulting in a ^{232}U alpha activity of 2266 Ci in the yearly amount of recycle uranium to be processed. Some natural thorium contains trace quantities of ^{230}Th, a decay product of ^{238}U and evidently occurring because

Fig. 17

Plutonium Radioactivity in High-Level Wastes
Produced in One Year by 1000 Mw HTGR

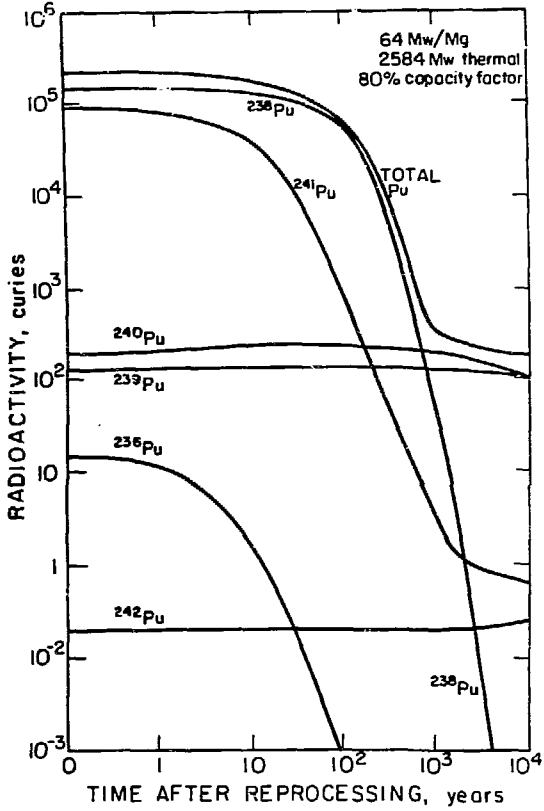
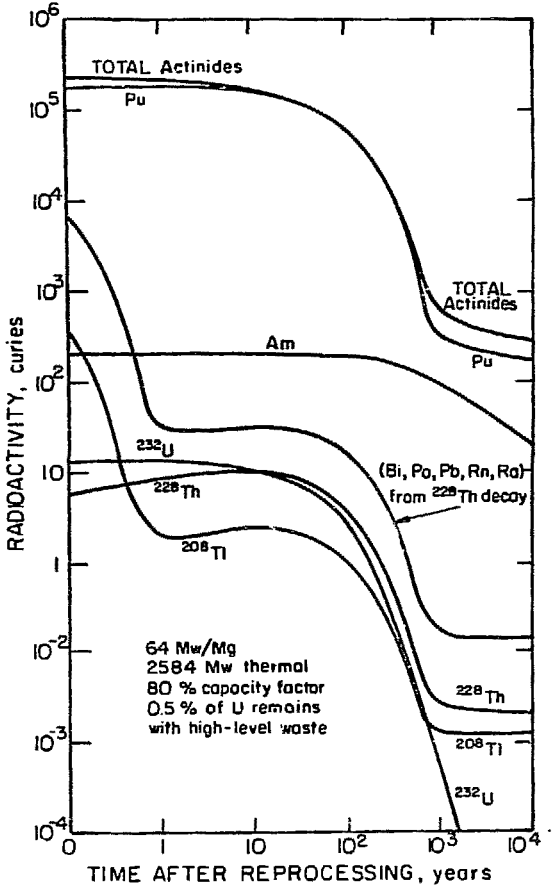


Figure 18

Actinide Radioactivity in High-level Wastes Produced in One Year by 1000 Mw HTGR



of co-existing uranium deposits. Neutron capture in ^{230}Th leads eventually to ^{232}U, as illustrated in Figure 15. Table 27 shows the effects of ^{230}Th in the charge fuel on the concentration of ^{232}U in the discharge fuel. For a concentration of 4 ppm of ^{230}Th in the thorium makeup, the ^{232}U concentration in the recycled uranium is increased by 6.4%. For a concentration of 100 ppm of ^{230}Th in the makeup thorium, the ^{232}U concentration in the recycled uranium is increased by 160% to 879 ppm and a ^{232}U alpha activity of 5892 Ci/yr.

Considerable alpha activity is also associated with ^{233}U, and because of its long half-life of 1.62×10^5 years, ^{233}U in the low-level wastes from recycle process operations will dictate the requirements of long-term waste management. The total alpha activity in the recycled uranium in this fuel cycle is over 150 times smaller than the alpha activity in the fuel recycled in the uranium-plutonium fueled water reactor, and is 50 times smaller than the alpha activity in the fuel recycled in a water reactor operating on slightly enriched uranium fuel with self-generated plutonium recycle.

Plutonium in Fuel Cycles for the HTGR

An alternative means of realizing the fuel value of plutonium recovered from discharge fuel from uranium-fueled water reactors would be to recycle this plutonium in the HTGR. This plutonium could replace the highly enriched ^{235}U makeup fissile material in the uranium-thorium fuel cycle. The plutonium remaining in the discharge fuel will be recovered and recycled along with the fissile uranium formed by neutron absorption in the thorium. It is assumed that the uranium bred from thorium is recycled thrice, after which it is retired.[25] Table 28 and 29 show the steady state annual charge and discharge of the thorium,

Table 27

Thorium and Uranium in the Charge and Discharge Fuel of the 1000 Mw HTGR
Fueled with Thorium and Recycled Uranium

Isotope	0 ppm of ^{230}Th in Charge		4 ppm of ^{230}Th in Charge		100 ppm of ^{230}Th in Charge	
	Charge	Discharge	Charge	Discharge	Charge	Discharge
	[kg/yr]	[kg/yr]	[kg/yr]	[kg/yr]	[kg/yr]	[kg/yr]
^{230}Th		5.37E-03	2.84E-02	1.29E-02	7.27E-01	1.97E-01
^{232}Th	7.27E+03	6.74E+03	7.27E+03	6.74E+03	7.27E+03	6.74E+03
^{232}U	1.06E-01	1.08E-01	1.06E-01	1.15E-01	1.06E-01	2.80E-01
^{233}U	1.85E+02	1.69E+02	1.85E+02	1.69E+02	1.85E+02	1.69E+02
^{234}U	7.74E+01	7.84E+01	7.74E+01	7.84E+01	7.74E+01	7.84E+01
^{235}U	3.76E+02	5.04E+01	3.76E+02	5.04E+01	3.76E+02	5.04E+01
^{236}U	8.23E+01	1.13E+02	8.23E+01	1.14E+02	8.23E+01	1.14E+02
^{237}U		4.64E-01		4.64E-01		4.64E-01
^{238}U	4.40E+01	1.97E-04	4.40E+01	1.97E-04	4.40E+01	1.97E-04

Table 28

1000 Mw HTGR with PU Recycle

Steady State Charge

Radionuclides	Th Particle [Kg/yr]	U-233 1st Recycle [Kg/yr]	U-233 2nd Recycle [Kg/yr]	U-233 3rd Recycle [Kg/yr]	Pu Recycle [Kg/yr]	Pu Makeup [Kg/yr]	Total [Kg/yr]
Th-232	7.07E+03						7.07E+03
U-232		9.80E-02	2.96E-02	8.74E-03			1.36E-01
U-233		2.04E+02	3.51E+01	6.05E+00			2.45E+02
U-234		3.94E+01	3.17E+01	1.38E+01			8.50E+01
U-235		1.17E+01	2.13E+01	1.36E+01			4.67E+01
U-236		1.31E+00	6.72E+00	9.42E+00			1.74E+01
U-238		2.02E-03	2.27E-02	5.78E-02			8.24E-02
Pu-236					1.30E-04	4.87E-04	6.17E-04
Pu-238					9.40E+00	1.16E+01	2.10E+01
Pu-239					2.03E+00	2.78E+02	2.80E+02
Pu-240					1.30E+01	1.15E+02	1.28E+02
Pu-241					1.17E+01	5.35E+01	6.53E+01
Pu-242					3.65E+01	1.86E+01	5.51E+01
Total U		2.57E+02	9.49E+01	4.29E+01			3.94E+02
Total Pu					7.26E+01	4.77E+02	5.50E+02

Table 29

1000 Mw HTGR with Pu Recycle

Steady State Discharge

Radionuclides	Particle [kg/yr]	1st Recycle [kg/yr]	2nd Recycle [kg/yr]	3rd Recycle [kg/yr]	Particle [kg/yr]	Total [kg/yr]
Th-232	6.63E+03	3.71E-07	8.96E-07	1.02E-06	2.62E-09	6.63E+03
U-232	9.96E-02	3.02E-02	8.95E-03	2.62E-03	1.47E-04	1.41E-01
U-233	1.90E+02	3.55E+01	6.13E+00	1.06E+00	4.84E-05	2.33E+02
U-234	4.00E+01	3.21E+0.	1.40E+01	5.25E+00	1.97E-01	9.14E+01
U-235	1.18E+01	2.16E+01	1.38E+01	6.38E+00	1.05E-01	5.38E+01
U-236	1.33E+00	6.79E-00	9.53E+00	8.60E+00	4.31E-02	2.63E+01
U-238	2.04E-03	2.29E-02	5.85E-02	8.67E-02	4.80E-04	1.71E-01
Pu-236	1.20E-07	2.28E-06	5.51E-06	6.20E-06	1.54E-04	1.68E-04
Pu-238	2.40E-02	4.30E-01	1.02E+00	1.14E+00	6.27E+00	8.88E+00
Pu-239	3.00E-03	6.96E-02	1.76E-01	2.03E-01	1.61E+00	2.06E+00
Pu-240	9.30E-04	3.26E-02	9.20E-02	1.09E-01	1.14E+01	1.16E+01
Pu-241	2.59E-04	1.25E-02	3.77E-02	4.58E-02	1.23E+01	1.24E+01
Pu-242	4.41E-05	3.41E-03	1.13E-02	1.43E-02	3.69E+01	3.69E+01
Total U	2.43E+02	9.60E+01	4.35E+01	2.14E+01	3.46E-01	4.05E+02
Total Pu	2.82E-02	5.48E-01	1.34E+00	1.51E+00	6.85E+01	7.18E+01

uranium, and plutonium isotopes. 478 Kg/yr. of makeup plutonium is required from the recovered fuel of the uranium-fueled water reactors. Thus, a total generating capability of 1965 Mw of uranium-fueled water reactors is required to support this 1000 Mw plutonium fueled HTGR for one year. The results from Table 29 show that only negligible ^{233}U is retired, thus recycling thrice is equivalent to full utilization of the bred uranium. More detailed yearly quantities of the charge and discharge fuel are listed in Table 30. The reactor inventories are also listed. The inventories of the thorium, uranium, and plutonium are average inventories, all other inventory quantities were calculated on the basis of the composition of the discharge fuel. A fuel cycle flowsheet illustrating the adaptation of the gas-cooled reactor to plutonium-uranium-thorium fueling is shown in Figure 19. Since the plutonium is recycled, only a relatively small amount of plutonium is lost to the high-level wastes at reprocessing. However, essentially all the americium and curium in the discharge fuel appears in the high-level reprocessing wastes. The calculated radioactivity of plutonium in the high-level wastes is shown in Figure 20. The plutonium radioactivity in these wastes is smaller at the time of reprocessing than for the uranium-fueled HTGR, but for storage time greater than a few hundred years, the plutonium radioactivity is greater than for the uranium-fueled HTGR due to the large amount (42.4 Kg/yr) of ^{244}Cm present in the high-level wastes. The calculated radioactivities of neptunium, americium, and curium in the high-level wastes as a function of storage time is shown in Figures 21 and 22. The curium radioactivity in these wastes is comparable to that produced in the plutonium-fueled water reactor. For the first hundred years of storage, curium is the main contributor to the total actinide radioactivity in the high-level wastes, beyond that, neptunium,

Table 30

Material and Radioactive Quantities in Reactor and Fuel Cycle for a 1000 Mw HTGR Fueled with Thorium, Recycled Plutonium, and Recycled Uranium

U-233 PARTICLE FIRST RECYCLE

	CHARGE		DISCHARGE		100 DAYS		365 DAYS		CORE INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
TH227	0.	0.	1.03E-11	3.24E-04	1.32E-11	4.15E-04	1.73E-11	5.46E-04	6.10E-11	1.70E-03
TH228	0.	0.	9.75E-06	7.84E+02	9.32E-06	7.65E+02	9.03E-06	7.41E+02	3.92E-03	3.14E+03
TH229	0.	0.	2.11E-03	4.51E-01	2.17E-03	4.64E-01	2.26E-03	4.83E-01	8.43E-03	1.80E+00
TH230	0.	0.	2.33E-04	3.94E-03	2.33E-04	4.44E-03	2.91E-04	5.46E-03	8.10E-04	1.57E-02
TH231	0.	0.	4.73E-07	2.51E+02	8.73E-11	4.64E-02	8.70E-11	4.64E-02	1.89E-06	1.00E+03
TH232	0.	0.	3.71E-07	4.05E-11	4.51E-07	4.91E-11	5.65E-07	6.19E-11	1.49E-06	1.62E-10
TH233	0.	0.	6.60E-13	2.55E-02	0.	0.	0.	0.	2.14E-12	8.18E-02
TH234	0.	0.	3.95E-13	9.14E-06	3.31E-13	7.66E-06	1.30E-13	7.64E-06	1.58E-12	3.66E-05
PA231	0.	0.	1.59E-04	7.44E-03	1.57E-04	7.45E-03	1.57E-04	7.46E-03	6.25E-04	2.95E-02
PA232	0.	0.	3.80E-07	1.57E+02	2.29E-41	9.79E-33	0.	0.	1.40E-06	6.10E+02
PA233	0.	0.	2.94E-09	6.06E-01	4.34E-09	8.99E-01	4.35E-08	8.91E-01	1.57E-07	3.28E+00
PA234M	0.	0.	2.72E-14	1.87E-02	6.18E-17	7.06E-06	1.11E-17	7.04E-06	1.29E-13	7.49E-02
PA234	0.	0.	8.40E-12	1.79E-02	3.60E-15	7.55E-09	1.45E-18	7.54E-09	3.53E-11	7.17E-02
U232	2.80E-02	7.19E+02	1.82E-02	6.46E+02	3.01E-02	6.48E+02	2.95E-02	6.40E+02	2.55E-01	5.49E+03
U233	2.04E+02	1.97E+03	3.55E+01	3.37E+02	3.55E+01	3.37E+02	3.55E+01	3.37E+02	4.79E+02	4.53E+03
U234	3.94E+01	2.44E+02	3.21E+01	1.99E+02	3.21E+01	1.99E+02	3.21E+01	1.99E+02	1.43E+02	8.89E+02
U235	1.17E+01	2.50E-02	2.16E+01	4.64E-02	2.16E+01	4.64E-02	2.16E+01	4.64E-02	6.56E+01	1.41E-01
U236	1.31E+00	8.31E-02	6.80E+00	4.31E-01	6.77E+00	4.31E-01	6.80E+00	4.31E-01	1.92E+01	1.23E+00
U237	0.	0.	3.50E-01	2.86E+06	7.52E-09	6.14E-01	3.55E-10	2.99E-02	1.40E-01	1.14E+07
U238	2.02E-03	6.74E-07	2.29E-02	7.64E-06	2.29E-02	7.64E-06	2.29E-02	7.64E-06	4.99E-02	1.66E-05
U239	0.	0.	1.63E-07	5.47E+03	0.	0.	0.	0.	6.53E-07	2.19E+04
NP236	0.	0.	1.84E-09	1.08E+01	9.82E-55	5.91E-49	0.	0.	7.13E-09	4.31E+01
NP237	0.	0.	1.21E+00	8.56E-01	1.26E+00	8.91E-01	1.26E+00	8.91E-01	4.91E+00	3.46E+00
NP238	0.	0.	5.13E-03	1.38E+06	1.11E-28	4.22E-18	2.54E-55	6.39E-47	2.05E-02	5.37E+06
NP239	0.	0.	2.35E-05	5.46E+03	6.60E-10	1.54E-01	6.60E-10	1.53E-01	9.34E-05	2.18E+04
PU236	0.	0.	2.34E-06	1.21E+03	2.57E-06	1.10E+00	1.40E-06	9.55E-01	9.13E-06	4.88E+00
PU238	0.	0.	4.13E-01	7.20E+03	4.21E-01	7.32E+03	4.32E-01	7.21E+03	1.72E+00	2.30E+04
PU239	0.	0.	6.56E-02	4.37E+00	6.95E-02	4.27E+00	6.90E-02	4.27E+00	2.74E-01	1.77E+01
PU240	0.	0.	3.26E-02	7.19E+00	3.29E-02	7.13E+00	3.21E-02	7.19E+00	1.10E-01	2.48E+01
PU241	0.	0.	1.29E-02	1.27E+03	1.22E-02	1.26E+03	1.19E-02	1.21E+03	4.54E-02	4.71E+03
PU242	0.	0.	3.41E-03	1.33E-02	3.41E-03	1.33E-02	3.41E-03	1.33E-02	1.36E-02	5.32E-02
PU243	0.	0.	1.95E-06	5.06E+03	1.15E-19	2.57E-09	1.15E-19	2.97E-09	7.90E-06	2.02E+04
AM241	0.	0.	1.89E-04	6.49E-01	4.90E-04	1.67E+00	7.66E-04	2.62E+00	7.57E-04	2.68E+00
AM242M	0.	0.	2.78E-05	2.72E-02	2.73E-06	2.71E-02	2.78E-06	2.78E-02	1.12E-05	1.09E-01
AM242	0.	0.	7.35E-12	5.71E+02	3.35E-11	2.71E-02	3.14E-11	2.70E-02	2.82E-08	2.38E+03
AM243	0.	0.	7.36E-04	1.53E-01	7.54E-04	1.54E-01	7.90E-04	1.51E-01	3.19E-03	6.12E-01
AM244	0.	0.	5.88E-09	1.78E+01	2.41E-30	7.23E-20	4.86E-30	1.38E-19	2.35E-07	6.48E+01
CM242	0.	0.	6.52E-05	2.16E+02	5.47E-05	1.19E+02	1.39E-05	4.61E+01	2.61E-04	9.63E+02
CM243	0.	0.	4.88E-07	2.22E-02	4.72E-07	2.21E-02	4.73E-07	2.10E-02	1.37E-06	4.40E-02
CM244	0.	0.	2.99E-04	2.41E+01	2.43E-04	2.17E+01	2.67E-04	2.32E+01	1.19E-03	9.65E+01
CM245	0.	0.	1.84E-05	3.26E-03	1.83E-05	3.29E-03	1.94E-05	3.29E-03	7.38E-05	1.30E-02
CM246	0.	0.	2.29E-06	7.07E-04	2.23E-06	7.07E-04	2.29E-06	7.07E-04	9.18E-06	2.83E-03
CM247	0.	0.	3.37E-09	2.97E-09	3.37E-09	2.97E-09	3.37E-09	2.97E-09	1.35E-08	1.19E-08
CM248	0.	0.	2.74E-09	1.12E-08	2.74E-09	1.12E-08	2.74E-09	1.12E-08	1.10E-08	4.49E-08
BK249	0.	0.	3.64E-11	6.09E-05	2.62E-11	4.37E-05	1.63E-11	2.72E-05	1.40E-10	2.43E-04
BK250	0.	0.	4.03E-14	1.57E-08	6.07E-25	2.36E-15	6.07E-25	2.36E-15	1.61E-13	6.28E-08
CF249	0.	0.	3.94E-12	1.44E-08	1.39E-11	5.69E-08	2.38E-11	9.71E-08	1.40E-11	5.95E-08
CF250	0.	0.	6.39E-12	6.98E-07	6.29E-12	6.48E-07	6.04E-12	6.60E-07	2.55E-11	2.79E-06
CF251	0.	0.	3.49E-12	5.53E-09	3.49E-12	5.53E-09	3.49E-12	5.5?E-09	1.40E-11	2.21E-08
CF252	0.	0.	2.41E-12	1.29E-06	2.17E-12	1.16E-06	1.88E-12	9.96E-07	9.65E-12	5.18E-06
CF253	0.	0.	9.04E-15	1.46E-07	1.47E-17	4.26E-10	3.41E-21	9.89E-14	2.08E-14	5.05E-07

Table 30 (continued)

U-233 PARTICLE SECOND RECYCLE

	CHARGE		DISCHARGE		150 DAYS		365 DAYS		CORE INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
TH227	0.	0.	6.91E-13	2.13E-05	8.59E-12	2.71E-04	1.11E-11	3.51E-04	2.72E-11	9.61E-04
TH228	0.	0.	7.83E-04	6.14E+02	7.74E-04	6.29E+02	6.69E-04	5.71E+02	1.14E-03	9.30E+02
TH229	0.	0.	3.69E-04	9.53E-02	4.09E-04	8.75E-02	4.74E-04	9.07E-02	1.54E-03	3.91E-01
TH230	0.	0.	1.12E-04	2.19E-03	1.24E-04	2.49E-03	1.31E-04	2.91E-03	4.49E-04	9.72E-03
TH231	0.	0.	2.62E-07	1.39E+02	5.58E-11	2.98E-02	5.52E-11	2.95E-02	1.75E-06	5.36E+02
TH232	0.	0.	8.96E-07	9.90E-11	1.01E-05	1.10E-10	1.17E-05	1.29E-10	3.59E-06	1.17E-10
TH233	0.	0.	1.31E-12	4.94E-02	0.	0.	0.	0.	9.41E-12	1.49E-01
TH234	0.	0.	1.03E-12	2.39E-05	8.45E-13	1.96E-05	9.49E-13	1.95E-05	4.11E-12	9.51E-05
PA231	0.	0.	9.94E-05	4.57E-03	9.77E-05	4.59E-03	9.62E-05	4.58E-03	3.46E-06	1.51E-02
PA232	0.	0.	2.27E-07	9.67E+01	1.67E-41	8.99E-35	0.	0.	9.77E-07	3.97E+02
PA233	0.	0.	7.99E-08	1.61E+03	8.32E-08	1.70E+00	5.33E-08	1.71E+00	3.10E-07	6.43E+00
PA234M	0.	0.	5.93E-14	3.73E-02	2.89E-17	1.96E-05	2.89E-17	1.95E-05	2.17E-13	1.49E-01
PA234	0.	0.	1.71E-11	3.50E-02	9.86E-18	1.50E-09	9.93E-18	1.99E-09	7.17E-11	1.48E-01
U232	2.96E-02	6.33E+02	8.94E-03	1.92E+02	8.91E-03	1.91E+02	8.86E-03	1.90E+02	2.70E-02	1.65E+03
U233	3.51E+01	3.37E+02	6.11E+00	5.91E+01	6.13E+00	5.81E+01	6.13E+00	5.91E+01	8.75E+01	7.03E+02
U234	7.17E+01	1.49E+02	1.40E+01	8.68E+01	1.40E+01	8.68E+01	1.40E+01	8.69E+01	9.14E+01	5.69E+02
U235	7.13E+01	4.93E-02	1.34E+01	2.56E-02	1.38E+01	2.95E-02	1.38E+01	2.98E-02	7.02E+01	1.50E-01
U236	6.72E+00	4.28E-01	9.53E+00	6.04E-01	9.53E+00	6.04E-01	9.53E+00	6.04E-01	3.29E+01	2.09E+00
U237	0.	0.	4.91E-02	4.01E+06	1.11E-08	9.10E-01	1.17E-09	8.77E-02	1.30E-01	1.06E+07
U238	2.37E-02	7.97E-06	2.45E-02	1.95E-05	2.45E-02	1.09E-05	8.95E-02	1.95E-05	1.02E-01	5.41E-05
U239	0.	0.	4.17E-07	1.40E+04	0.	0.	0.	0.	1.57E-06	5.59E+04
NP235	0.	0.	3.44E-04	2.08E+01	1.90E-07	1.14E-09	0.	0.	1.19E-02	4.31E+01
NP237	0.	0.	2.37E+00	1.67E+00	2.42E+00	1.71E+00	2.42E+00	1.71E+00	9.67E+00	6.66E+00
NP238	0.	0.	9.91E-03	2.59E+06	3.17E-24	8.14E-16	4.72E-39	1.27E-46	3.98E-02	1.74E+07
NP239	0.	0.	5.93E-05	1.39E+04	2.34E-09	5.45E-01	2.34E-09	5.45E-01	2.19E-04	5.57E+04
PU236	0.	0.	5.51E-06	2.93E+00	5.00E-06	2.68E+00	4.39E-06	2.39E+00	2.20E-05	1.17E+01
PU238	0.	0.	1.32E+00	1.71E+04	1.42E+00	1.83E+04	1.52E+00	1.72E+04	4.00E+00	6.96E+04
PU239	0.	0.	1.70E-01	1.08E+01	1.77E-01	1.09E+01	1.77E-01	1.09E+01	2.39E-01	4.33E+01
PU240	0.	0.	9.20E-02	2.03E+01	9.21E-02	2.03E+01	9.21E-02	2.03E+01	3.69E-01	8.12E+01
PU241	0.	0.	3.77E-03	3.83E+03	3.69E-03	3.75E+03	3.59E-03	3.65E+03	1.51E-02	1.53E+04
PU242	0.	0.	1.13E-02	4.42E-02	1.13E-02	4.42E-02	1.13E-02	4.42E-02	4.54E-02	1.77E-01
PU243	0.	0.	6.47E-30	1.68E+04	4.05E-19	1.08E-08	4.99E-19	1.20E-08	2.79E-09	6.72E+04
AM241	0.	0.	6.18E-04	2.12E+00	1.38E-03	4.61E+00	2.16E-03	8.07E+00	2.47E-03	8.47E+00
AM242M	0.	0.	9.23E-06	9.00E-02	9.22E-06	8.99E-02	9.22E-06	8.99E-02	3.70E-05	3.60E-01
AM242	0.	0.	7.33E-08	1.40E+03	1.11E-10	8.99E-02	1.11E-10	8.96E-02	9.70E-08	7.85E+03
AM243	0.	0.	2.83E-03	5.44E-01	2.83E-03	5.45E-01	2.83E-03	5.45E-01	1.13E-02	2.19E+00
AM244	0.	0.	2.09E-27	6.26E+03	1.78E-29	3.80E-19	2.05E-29	6.09E-19	8.36E-07	2.48E+04
CM242	0.	0.	2.27E-04	7.51E+02	1.21E-04	4.07E+02	4.84E-05	1.60E+02	9.07E-04	3.00E+03
CM243	0.	0.	1.77E-06	8.13E-02	1.78E-06	8.05E-02	1.73E-06	7.96E-02	7.07E-06	3.25E-01
CM244	0.	0.	1.11E-03	9.17E+01	1.11E-03	8.99E+01	1.06E-03	8.78E+01	4.51E-03	3.65E+02
CM245	0.	0.	7.17E-05	1.23E-02	7.13E-05	1.27E-02	7.19E-05	1.27E-02	2.88E-04	4.94E-02
CM246	0.	0.	4.17E-06	2.84E-03	9.17E-06	2.93E-03	9.17E-06	2.83E-03	3.75E-05	1.15E-02
CM247	0.	0.	1.47E-07	1.26E-08	1.47E-07	1.26E-08	1.47E-07	1.26E-08	5.70E-07	5.01E-08
CM248	0.	0.	1.22E-08	4.92E-08	1.20E-08	4.92E-08	1.20E-08	4.92E-08	4.90E-08	1.97E-07
BK249	0.	0.	1.41E-10	2.72E-04	1.17E-10	1.95E-04	7.20E-11	1.28E-04	6.51E-10	1.09E-03
BK250	0.	0.	1.80E-13	7.01E-04	2.72E-24	1.06E-14	2.72E-24	1.06E-14	7.21E-13	2.80E-03
CF249	0.	0.	1.07E-11	6.78E-09	6.23E-11	2.55E-07	1.07E-10	4.35E-07	6.63E-11	2.70E-07
CF250	0.	0.	2.09E-11	3.16E-08	2.94E-11	3.11E-06	2.76E-11	3.02E-06	1.10E-10	1.20E-05
CF251	0.	0.	1.61E-11	2.53E-08	1.60E-11	2.53E-08	1.59E-11	2.53E-08	6.38E-11	1.01E-07
CF252	0.	0.	1.11E-11	6.08E-06	1.02E-11	5.46E-06	8.72E-12	4.68E-06	4.53E-11	2.43E-05
CF253	0.	0.	2.34E-14	6.91E-07	6.95E-17	2.01E-09	1.61E-20	4.64E-13	9.84E-14	2.70E-06

Table 30 (continued)

U-233 PARTICLE THIRD RECYCLE

	CHARGE		DISCHARGE		180 DAYS		365 DAYS		CORE INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
TH227	0.	0.	2.07E-12	9.07E-05	3.60E-12	1.14E-04	4.66E-12	1.47E-04	1.15E-11	3.63E-04
TH228	0.	0.	8.19E-05	6.69E+01	8.19E-05	6.71E+01	7.91E-05	6.50E+01	1.36E-04	2.26E+02
TH229	0.	0.	7.07E-05	1.08E-02	8.05E-05	1.72E-02	8.11E-05	1.73E-02	3.19E-04	6.77E-02
TH230	0.	0.	4.92E-05	8.79E-04	5.17E-05	9.95E-04	5.97E-05	1.18E-03	1.81E-04	3.57E-03
TH231	0.	0.	1.08E-07	5.61E+01	2.59E-11	1.37E-02	2.58E-11	1.37E-02	4.73E-07	2.24E+02
TH232	0.	0.	1.02E-06	1.11E-10	1.17E-06	1.27E-10	1.20E-06	1.30E-10	4.07E-06	4.45E-10
TH233	0.	0.	1.54E-12	5.61E-02	0.	0.	0.	0.	6.14E-12	2.25E-01
TH234	0.	0.	1.07E-12	3.46E-05	1.29E-12	2.84E-05	1.25E-12	2.89E-05	5.87E-12	1.18E-04
PA231	0.	0.	3.97E-05	1.80E-01	3.95E-05	1.90E-01	3.40E-05	1.90E-01	1.59E-04	7.56E-03
PA232	0.	0.	4.19E-33	4.00E+01	8.81E-42	2.48E-31	0.	0.	3.75E-07	1.60E+02
PA233	0.	0.	8.20E-08	1.69E+03	8.82E-08	1.78E+00	8.63E-08	1.77E+00	3.10E-07	6.74E+00
PA234M	0.	0.	5.21E-19	3.92E-02	4.21E-17	2.03E-04	4.20E-17	2.04E-05	2.29E-11	1.97E-01
PA234	0.	0.	1.88E-11	3.16E-02	1.50E-17	2.83E-07	1.45E-17	2.89E-08	7.94E-11	1.57E-01
U232	5.74E-03	1.17E+02	2.22E-03	4.61E+01	2.21E-03	5.99E+01	2.60E-03	5.56E+01	2.22E-02	4.77E+02
U233	6.05E+00	5.73E+01	1.06E+00	1.00E+01	1.06E+00	1.00E+01	1.06E+00	1.00E+01	1.42E+01	1.35E+02
U234	1.30E+01	8.59E+01	9.75E+00	3.29E+01	9.29E+00	3.25E+01	9.26E+00	3.29E+01	1.52E+01	2.36E+02
U235	1.36E+01	2.92E-02	6.38E+00	1.37E-02	6.38E+00	1.37E-02	6.38E+00	1.37E-02	4.00E+01	8.59E-02
U236	9.42E+00	5.97E-01	8.60E+00	5.49E-01	8.60E+00	5.45E-01	8.60E+00	5.49E-01	7.07E+01	2.20E+00
U237	0.	0.	4.43E-02	3.62E+06	1.09E-08	8.90E-01	1.31E-09	1.08E-01	1.77E-01	1.45E+07
U238	5.78E-07	1.93E-09	8.67E-07	2.89E-09	8.67E-07	2.89E-09	8.67E-07	2.89E-09	2.59E-06	9.67E-09
U239	0.	0.	6.17E-07	2.07E+04	0.	0.	0.	0.	2.42E-06	8.26E+04
NP236	0.	0.	3.18E-09	3.14E+01	1.97E-57	1.14E-45	0.	0.	1.43E-07	5.44E+01
NP237	0.	0.	2.40E+00	1.73E+00	2.50E+00	1.77E+00	2.50E+00	1.77E+00	9.56E+00	6.74E+00
NP238	0.	0.	1.03E-02	2.69E+06	3.24E-24	8.40E-16	4.90E-35	1.29E-40	4.12E-02	1.08E+07
NP239	0.	0.	8.99E-05	2.08E+04	3.03E-09	7.03E-01	3.02E-09	7.03E-01	1.34E-04	8.28E+04
PU236	0.	0.	4.29E-06	3.30E+03	5.61E-06	3.07E+03	6.40E-06	3.50E+00	2.84E-05	1.12E+01
PU238	0.	0.	1.14E+00	1.97E+04	1.14E+00	1.93E+04	1.14E+00	1.92E+04	4.54E+00	7.67E+04
PU239	0.	0.	2.03E-01	1.24E+01	2.03E-01	1.24E+01	2.03E-01	1.24E+01	8.11E-01	4.97E+01
PU240	0.	0.	1.10E-01	2.42E+01	1.10E-01	2.42E+01	1.10E-01	2.42E+01	4.19E-01	9.66E+01
PU241	0.	0.	4.57E-02	4.66E+03	4.49E-02	4.57E+03	4.37E-02	4.46E+03	1.75E-01	1.88E+04
PU242	0.	0.	1.43E-02	5.57E-02	1.43E-02	5.57E-02	1.43E-02	5.57E-02	5.71E-02	2.23E-01
PU243	0.	0.	8.16E-08	2.11E+04	6.71E-18	1.76E-08	6.70E-18	1.76E-09	7.26E-08	1.88E+04
AM241	0.	0.	7.72E-04	2.65E+00	1.64E-03	5.85E+00	2.69E-03	9.27E+00	3.09E-03	1.06E+01
AM242M	0.	0.	1.16E-05	1.13E-01	1.16E-05	1.13E-01	1.16E-05	1.13E-01	4.65E-05	4.53E-01
AM242	0.	0.	2.60E-09	2.11E+03	1.39E-10	1.13E-01	1.39E-10	1.13E-01	1.15E-08	9.11E+03
AM243	0.	0.	3.64E-03	7.01E-01	3.65E-03	7.03E-01	3.65E-03	7.03E-01	1.46E-02	2.80E+00
AM244	0.	0.	2.69E-27	7.49E+03	1.54E-29	4.61E-14	2.95E-29	8.71E-19	1.09E-06	3.70E+04
CM242	0.	0.	2.40E-03	9.60E+03	1.19E-03	5.17E+03	5.10E-04	2.19E+03	1.16E-02	1.88E+04
CM243	0.	0.	2.10E-05	1.08E-01	2.24E-05	1.09E-01	2.25E-05	1.06E-01	9.22E-05	4.24E-01
CM244	0.	0.	1.49E-03	1.21E+02	1.47E-03	1.14E+02	1.43E-03	1.16E+02	5.95E-03	4.81E+02
CM245	0.	0.	9.64E-05	1.72E-02	9.64E-05	1.70E-02	9.64E-05	1.72E-02	3.94E-04	6.91E-02
CM246	0.	0.	1.24E-05	3.57E-03	1.24E-05	3.57E-03	1.24E-05	3.57E-03	5.15E-05	1.50E-02
CM247	0.	0.	1.44E-07	1.26E-08	1.44E-07	1.26E-08	1.44E-07	1.26E-08	7.96E-07	7.37E-08
CM248	0.	0.	1.72E-08	7.03E-09	1.72E-08	7.03E-09	1.72E-08	7.03E-09	6.80E-08	2.81E-08
BK249	0.	0.	2.15E-10	3.93E-04	1.69E-10	2.89E-04	1.09E-10	1.76E-04	9.41E-10	1.97E-03
BK250	0.	0.	2.01E-13	1.01E-03	3.94E-24	1.94E-14	3.94E-24	1.94E-14	1.04E-17	4.06E-03
CF249	0.	0.	2.42E-11	9.05E-08	9.09E-11	3.70E-07	1.24E-10	6.30E-07	9.70E-11	3.96E-07
CF250	0.	0.	4.21E-11	4.61E-08	4.19E-11	4.53E-08	4.07E-11	4.40E-08	1.68E-10	1.84E-07
CF251	0.	0.	2.34E-11	3.71E-08	2.34E-11	3.71E-08	2.34E-11	3.70E-08	9.37E-11	1.48E-07
CF252	0.	0.	1.09E-11	9.09E-06	1.52E-11	8.16E-06	1.30E-11	7.00E-06	6.70E-11	3.64E-05
CF253	0.	0.	3.69E-14	1.04E-08	1.04E-16	3.01E-09	2.43E-20	7.04E-13	1.43E-13	4.16E-08

Table 30 (continued)

PU PARTICLE

	CHARGE		DISCHARGE		180 DAYS		365 DAYS		CORE INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
TH227	0.	0.	3.20E-14	1.04E-06	4.44E-14	1.41E-06	6.09E-14	1.93E-06	1.31E-13	4.19E-06
TH228	0.	0.	2.25E-06	2.17E+00	2.24E-06	2.13E+00	3.14E-06	2.59E+00	1.06E-05	8.70E+00
TH229	0.	0.	5.14E-07	1.10E-04	5.14E-07	1.10E-04	5.14E-07	1.10E-04	2.39E-06	4.40E-04
TH230	0.	0.	9.40E-07	1.88E-05	1.29E-06	2.31E-05	1.58E-06	3.07E-05	3.80E-06	7.51E-05
TH231	0.	0.	2.28E-09	1.20E+00	4.29E-13	2.28E-08	4.26E-13	2.28E-04	9.01E-09	4.79E+00
TH232	0.	0.	2.42E-07	2.27E-13	3.11E-07	3.42E-14	3.87E-09	4.23E-13	1.09E-06	1.19E-12
TH233	0.	0.	3.99E-15	1.44E-04	0.	0.	0.	0.	1.59E-14	5.70E-04
TH234	0.	0.	7.34E-15	1.70E-07	7.58E-15	1.47E-07	7.72E-15	1.80E-07	2.73E-14	6.90E-07
PA231	0.	0.	6.20E-07	2.95E-05	6.22E-07	2.95E-05	6.22E-07	2.90E-05	2.49E-06	1.14E-04
PA232	0.	0.	1.47E-09	6.22E-01	9.07E-44	3.87E-39	0.	0.	5.96E-09	2.50E+00
PA233	0.	0.	4.35E-10	1.03E-02	8.35E-10	1.10E-02	5.90E-10	1.19E-02	1.98E-09	4.25E-02
PA234M	0.	0.	3.42E-16	2.35E-04	2.43E-19	1.47E-07	2.42E-19	1.80E-07	1.37E-15	9.40E-04
PA234	0.	0.	1.13E-13	2.24E-04	8.43E-20	1.67E-10	4.27E-20	1.80E-10	4.52E-13	8.36E-04
U232	0.	0.	1.47E-04	3.15E+00	1.61E-04	3.44E+00	1.70E-04	3.91E+00	9.09E-04	1.26E+01
U233	0.	0.	4.84E-05	4.59E-04	4.84E-05	4.59E-04	4.85E-05	4.59E-04	1.96E-04	1.84E-03
U234	0.	0.	1.92E-01	1.22E+00	2.17E-01	1.35E+00	2.40E-01	1.54E+00	7.99E-01	4.88E+00
U235	0.	0.	1.09E-01	2.36E-04	1.06E-01	2.28E-04	1.06E-01	2.25E-04	4.22E-01	9.04E-04
U236	0.	0.	4.31E-03	2.73E-03	4.36E-02	2.78E-03	4.43E-02	2.81E-03	1.72E-01	1.09E-02
U237	0.	0.	2.22E-04	1.82E+04	3.66E-07	2.98E+01	1.52E-07	2.87E+01	4.50E-04	7.27E+04
U238	0.	0.	4.40E-04	1.60E-07	5.60E-04	1.49E-07	5.47E-04	1.42E-07	1.92E-03	5.40E-07
U239	0.	0.	3.42E-07	1.14E+02	0.	0.	0.	0.	1.37E-06	4.56E+02
NP236	0.	0.	2.10E-10	1.71E-01	1.20E-59	7.23E-51	0.	0.	8.70E-10	5.24E-01
NP237	0.	0.	1.53E-02	1.06E-02	1.59E-02	1.12E-02	1.71E-02	1.20E-02	5.94E-02	4.22E-02
NP238	0.	0.	6.20E-05	1.64E+04	1.97E-26	5.15E-18	2.40E-57	7.79E-49	2.51E-04	6.59E+04
NP239	0.	0.	2.57E-05	5.97E+03	2.51E-05	5.83E+03	2.51E-05	5.83E+03	1.03E-04	2.34E+04
PU236	4.17E-04	1.20E+02	1.94E-04	8.19E+01	1.99E-04	7.41E+01	1.21E-04	6.43E+01	1.94E-03	8.20E+02
PU238	2.10E+01	1.54E+05	6.22E+03	1.06E+05	6.70E+00	1.13E+05	6.96E+00	1.19E+05	5.45E+01	9.20E+05
PU239	7.00E+02	1.72E+04	1.61E+03	9.85E+01	1.61E+00	9.85E+01	1.61E+00	9.87E+01	5.61E+02	3.45E+04
PU240	1.20E+02	2.91E+04	1.14E+01	2.50E+03	1.23E+01	2.40E+03	1.30E+01	2.96E+03	2.71E+02	6.17E+04
PU241	4.33E+01	6.44E+06	1.21E+01	1.20E+06	1.21E+01	1.23E+06	1.10E+01	1.20E+06	1.49E+02	1.54E+07
PU242	5.51E+01	2.19E+02	3.63E+01	1.44E+02	3.69E+01	1.44E+02	3.69E+01	1.44E+02	1.86E+02	7.17E+02
PU243	0.	0.	2.11E-08	5.47E+02	1.58E-12	4.09E-03	1.59E-12	4.09E-03	2.44E-02	2.19E+08
AM241	0.	0.	6.95E-01	3.06E+03	1.13E+00	3.88E+03	1.46E+00	5.02E+03	1.58E+00	1.25E+04
AM242M	0.	0.	1.50E-02	1.54E+02	1.59E-02	1.54E+02	1.58E-02	1.53E+02	6.14E-02	6.17E+02
AM242	0.	0.	3.34E-01	2.70E+05	1.92E-07	1.54E+02	1.90E-07	1.53E+02	1.33E-03	1.08E+07
AM243	0.	0.	3.03E+01	5.83E+03	3.03E+01	5.83E+03	3.03E+01	5.81E+03	1.21E+02	2.34E+04
AM244	0.	0.	2.24E-01	6.94E+07	9.92E-24	2.02E-14	1.40E-23	4.73E-13	8.96E-03	2.60E+08
CM242	0.	0.	9.61E-01	3.18E+06	8.77E-01	1.67E+00	2.04E-01	6.70E+05	3.44E+03	1.27E+07
CM243	0.	0.	1.63E-02	2.49E+02	1.61E-02	7.41E+02	1.59E-02	7.32E+02	6.50E-02	2.94E+03
CM244	0.	0.	4.41E+01	3.57E+06	4.34E+01	3.51E+06	4.24E+01	3.44E+06	1.76E+02	1.43E+07
CM245	0.	0.	4.54E+00	8.01E+02	4.54E+00	8.02E+02	4.54E+00	8.02E+02	1.82E+01	3.21E+03
CM246	0.	0.	1.65E+00	5.09E+02	1.65E+00	5.08E+02	1.65E+00	5.08E+02	6.55E+00	2.07E+03
CM247	0.	0.	4.61E-02	4.09E-03	4.63E-02	4.09E-03	4.63E-02	4.09E-03	1.85E-01	1.64E-02
CM248	0.	0.	7.94E-03	3.25E-02	7.94E-03	3.25E-02	7.94E-03	3.25E-02	3.17E-02	1.30E-01
BK249	0.	0.	1.82E-04	2.83E+02	1.09E-04	1.82E+02	6.70E-05	1.13E+02	6.37E-04	1.01E+03
BK250	0.	0.	1.69E-07	6.54E+02	3.26E-18	1.27E-08	3.26E-18	1.27E-08	6.72E-07	2.62E+03
CF249	0.	0.	2.10E-05	8.55E-02	6.37E-05	2.60E-01	1.08E-04	4.29E-01	8.14E-05	3.42E-01
CF250	0.	0.	3.29E-05	3.59E+00	3.23E-05	3.53E+00	3.17E-05	3.43E+00	1.31E-04	1.44E+01
CF251	0.	0.	2.12E-05	3.36E-02	2.12E-05	3.36E-02	2.12E-05	3.36E-02	8.49E-05	1.34E-01
CF252	0.	0.	2.53E-05	1.36E+01	2.27E-05	1.22E+01	1.98E-05	1.04E+01	1.01E-04	5.43E+01
CF253	0.	0.	6.94E-08	1.72E+00	1.73E-10	8.02E-03	4.02E-14	1.17E-06	2.38E-07	6.69E+00

Table 30 (continued)

TH PARTICLE

	CHARGE		DISCHARGE		150 DAYS		365 DAYS		CORE INVENTORY	
	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM/YR	CURIES/YR	KGM	CURIES
TH227	0.	0.	[illegible]	5.63E-01	2.16E-05	6.64E-01	2.20E-08	8.55E-01	7.12E-08	2.29E+00
TH228	0.	0.	7.74E-04	6.37E+02	1.03E-03	8.49E+02	1.33E-03	1.09E+03	3.10E-03	2.55E+03
TH229	0.	0.	1.69E-03	3.59E-01	2.03E-03	4.34E-01	2.54E-03	5.43E-01	6.71E-03	1.44E+00
TH230	0.	0.	6.36E-03	1.24E-01	6.41E-03	1.24E-01	6.47E-03	1.26E-01	2.54E-02	4.94E-01
TH231	0.	0.	5.75E-04	3.05E+05	4.77E-11	2.53E-02	4.77E-11	2.53E-02	2.30E-03	1.22E+06
TH232	7.07E+03	7.73E-01	6.67E+03	7.29E-01	6.67E+03	7.29E-01	6.63E+03	7.29E-01	2.70E+04	3.30E+00
TH233	0.	0.	1.00E-04	3.66E+06	0.	0.	0.	0.	4.06E-02	1.46E+09
TH234	0.	0.	1.61E-03	3.73E+04	2.15E-05	4.99E+02	4.44E-08	1.03E+00	6.44E-03	1.49E+05
PA231	0.	0.	2.09E-01	9.93E+00	2.09E-01	9.96E+00	2.09E-01	9.96E+00	8.34E-01	3.97E+01
PA232	0.	0.	4.99E-04	2.11E+05	1.69E-38	1.32E-29	0.	0.	2.00E-03	4.31E+05
PA233	0.	0.	1.71E+01	3.50E+08	3.85E-01	7.99E+06	1.67E-03	3.42E+04	6.68E+01	1.40E+09
PA234M	0.	0.	1.19E-05	8.10E+06	7.26E-10	4.94E+02	1.5[illegible]E-12	1.03E+00	4.75E-05	3.26E+07
PA234	0.	0.	3.90E-03	7.75E+06	2.51E-10	4.99E-01	5.16E-13	1.03E-03	1.58E-02	3.10E+07
U232	0.	0.	9.00E-02	2.12E+03	9.51E-02	2.18E+03	9.42E-02	2.12E+03	3.99E-01	8.54E+03
U233	0.	0.	1.90E+02	1.80E+03	2.07E+02	1.98E+03	2.07E+02	1.99E+03	7.59E+02	7.29E+03
U234	0.	0.	4.00E+01	2.47E+02	4.00E+01	2.47E+02	4.00E+01	2.47E+02	1.60E+02	9.89E+02
U235	0.	0.	1.18E+01	2.53E-02	1.18E+01	2.53E-02	1.18E+01	2.53E-02	4.72E+01	1.01E-01
U236	0.	0.	1.33E+00	8.61E-02	1.33E+00	8.61E-02	1.33E+00	8.61E-02	5.31E+00	3.45E-01
U237	0.	0.	6.92E-03	5.67E+05	1.40E-09	1.14E-01	7.40E-17	6.04E-09	2.73E-02	2.23E+06
U238	0.	0.	2.06E-03	6.92E-07	2.04E-03	6.86E-07	2.04E-03	6.80E-07	8.16E-03	2.72E-06
U239	0.	0.	1.45E-05	4.87E+05	0.	0.	0.	0.	5.91E-05	1.98E+06
NP235	0.	0.	1.75E-37	1.06E+03	9.65E-59	9.83E-59	0.	0.	7.31E-09	4.74E+00
NP237	0.	0.	1.21E-01	8.51E-02	1.29E-01	8.99E-02	1.28E-01	8.99E-02	4.91E-01	3.45E-01
NP238	0.	0.	5.04E-04	1.32E+05	1.59E-25	4.15E-17	2.40E-57	6.29E-49	2.02E-03	5.29E+05
NP239	0.	0.	2.02E-06	4.65E+02	5.70E-12	1.34E-03	5.76E-12	1.34E-03	8.15E-06	1.94E+03
PU236	0.	0.	1.20E-07	6.39E-02	1.10E-07	5.83E-02	9.50E-08	5.05E-02	4.40E-07	2.35E-01
PU238	0.	0.	2.19E-02	4.04E+02	2.44E-02	4.11E+02	2.39E-02	4.09E+02	9.57E-02	1.62E+03
PU239	0.	0.	3.13E-04	1.94E-02	3.13E-04	1.94E-02	3.10E-04	1.94E-02	1.20E-03	7.16E-02
PU240	0.	0.	9.30E-04	2.05E-01	9.30E-04	2.05E-01	9.30E-04	2.05E-01	3.72E-03	8.20E-01
PU241	0.	0.	2.53E-04	2.59E+01	2.51E-04	2.59E+01	2.47E-04	2.51E+01	1.04E-03	1.05E+02
PU242	0.	0.	4.41E-05	1.72E-04	4.41E-05	1.72E-04	4.41E-05	1.72E-04	1.76E-04	6.86E-04
PU243	0.	0.	2.52E-08	6.53E+01	2.61E-21	6.76E-12	2.61E-21	6.79E-12	1.01E-07	2.61E+02
AM241	0.	0.	2.69E-06	9.12E-03	7.69E-06	2.63E-02	1.47E-05	5.03E-02	1.07E-05	3.67E-02
AM242M	0.	0.	3.53E-09	3.40E-05	3.59E-08	3.49E-04	3.57E-08	3.47E-04	1.44E-07	1.40E-03
AM242	0.	0.	9.54E-10	7.72E-01	4.30E-13	3.49E-04	4.29E-13	3.47E-04	3.99E-08	3.23E+01
AM243	0.	0.	6.94E-06	1.33E-03	6.60E-06	1.34E-03	6.60E-06	1.34E-03	2.79E-05	5.56E-03
AM244	0.	0.	8.13E-09	1.59E+01	1.64E-31	1.09E-22	7.31E-31	2.17E-22	2.05E-09	6.39E+01
CM242	0.	0.	6.36E-07	2.11E+00	3.40E-07	1.13E+00	1.34E-07	4.42E-01	2.54E-06	8.42E+00
CM243	0.	0.	3.41E-09	1.57E-04	3.38E-09	1.56E-04	3.34E-09	1.54E-04	1.36E-08	6.27E-04
CM244	0.	0.	1.70E-06	1.38E-01	1.65E-06	1.34E-01	1.64E-06	1.33E-01	6.91E-06	5.51E-01
CM245	0.	0.	8.26E-08	1.46E-05	8.26E-08	1.46E-05	8.26E-08	1.46E-05	3.30E-07	5.83E-05
CM246	0.	0.	6.97E-09	2.15E-06	6.97E-09	2.15E-06	6.97E-09	2.15E-06	2.79E-08	8.60E-06
CM247	0.	0.	7.26E-11	6.76E-12	7.42E-11	6.76E-12	7.42E-11	6.74E-12	3.00E-10	2.70E-11
CM248	0.	0.	4.53E-12	1.86E-11	4.53E-12	1.86E-11	4.53E-12	1.86E-11	1.81E-11	7.42E-11
BK249	0.	0.	4.94E-14	8.25E-08	3.45E-14	5.94E-08	2.21E-14	3.64E-08	1.98E-13	3.10E-07
BK250	0.	0.	5.47E-17	2.13E-08	7.47E-28	2.89E-19	7.42E-28	2.89E-19	2.10E-16	8.52E-08
CF249	0.	0.	4.14E-15	1.69E-11	1.81E-14	7.39E-11	3.15E-14	1.28E-10	1.66E-14	6.79E-11
CF250	0.	0.	7.69E-15	8.38E-10	7.53E-15	8.24E-10	7.30E-15	7.98E-10	3.08E-14	3.36E-09
CF251	0.	0.	3.70E-15	5.98E-12	3.77E-15	5.97E-12	3.77E-15	5.97E-12	1.51E-14	2.39E-11
CF252	0.	0.	2.01E-15	1.08E-09	1.80E-15	9.67E-10	1.59E-15	8.55E-10	8.03E-15	4.31E-09
CF253	0.	0.	3.89E-18	1.13E-10	1.13E-20	3.29E-13	2.65E-24	7.38E-17	1.56E-17	4.51E-10

Table 30 (continued)

REACTOR TOTAL

	CHARGE KGM/YR	CHARGE CURIES/YR	DISCHARGE KGM/YR	DISCHARGE CURIES/YR	150 DAYS KGM/YR	150 DAYS CURIES/YR	365 DAYS KGM/YR	365 DAYS CURIES/YR	CORE INVENTORY KGM	CORE INVENTORY CURIES
TH227	0.	0.	1.79E-08	5.64E-01	2.17E-08	6.85E-01	2.71E-08	8.55E-01	7.13E-08	2.25E+00
TH228	0.	0.	2.10E-03	1.73E+03	2.31E-03	1.91E+03	2.58E-03	2.12E+03	8.40E-03	6.90E+03
TH229	0.	0.	4.26E-03	9.12E-01	4.61E-03	1.00E+00	5.30E-03	1.14E+00	1.71E-02	3.65E+00
TH230	0.	0.	6.72E-03	1.31E-01	8.21E-03	1.17E-01	8.98E-03	1.36E-01	2.49E-02	5.83E-01
TH231	0.	0.	5.74E-08	3.08E+05	2.17E-10	1.15E-01	2.17E-10	1.15E-01	3.30E-03	1.77E+06
TH232	7.07E+03	7.71E-01	6.63E+03	7.29E-01	6.61E+03	7.25E-01	6.63E+03	7.29E-01	2.14E+04	2.36E+00
TH233	0.	0.	1.00E-32	3.60E+09	0.	0.	0.	0.	4.30E-02	1.46E+09
TH234	0.	0.	1.61E-21	3.73E+04	2.14E-09	4.99E+02	4.44E-08	1.03E+00	6.44E-03	1.49E+05
TOTAL	7.07E+03	7.71E-01	6.63E+03	3.66E+06	6.61E+03	2.41E+03	6.63E+03	2.13E+03	2.14E+04	1.47E+09
		α7.73E-01		α1.73E+03		α1.91E+03		α2.12E+03		α6.91E+03
				β3.66E+06		β4.99E+02		β1.14E+00		β1.46E+09
PA231	0.	0.	2.03E-01	9.95E+00	2.02E-01	9.97E+00	2.09E-01	9.47E+00	8.33E-01	4.08E+01
PA232	0.	0.	9.60E-24	2.13E+05	3.60E-30	1.12E-22	0.	0.	2.00E-02	8.53E+05
PA233	0.	0.	1.71E+01	3.50E+09	3.95E-01	7.88E+06	1.57E-03	3.42E+04	6.94E+01	1.40E+09
PA234M	0.	0.	1.19E-05	8.10E+06	7.20E-10	4.93E+02	1.50E-12	1.03E+00	4.75E-05	3.22E+07
PA234	0.	0.	3.90E-03	7.75E+06	2.51E-10	4.99E-01	5.19E-13	1.03E-03	1.58E-02	3.10E+07
TOTAL	0.	0.	1.73E+01	3.52E+09	5.97E-01	7.88E+06	2.11E-01	3.42E+04	6.93E+01	1.46E+09
				α9.95E+00		α9.97E+00		α9.97E+00		α3.98E+01
				β3.66E+08		β7.88E+06		β3.42E+04		β1.46E+09
U232	1.36E-01	2.91E+03	1.41E-01	3.03E+03	1.41E-01	3.03E+03	1.41E-01	3.01E+03	5.50E-01	1.19E+04
U233	2.45E+02	2.32E+03	2.31E+02	2.20E+03	2.49E+02	2.36E+03	2.50E+02	2.37E+03	9.56E+02	9.09E+03
U234	8.50E+01	5.29E+02	9.15E+01	5.66E+02	9.16E+01	5.66E+02	9.16E+01	5.67E+02	3.53E+02	2.18E+03
U235	4.67E+01	1.09E-01	5.39E+01	1.15E-01	5.30E+01	1.13E-01	5.30E+01	1.15E-01	2.01E+02	4.31E-01
U236	1.74E+01	1.10E+00	2.61E+01	1.67E+00	2.63E+01	1.67E+00	2.63E+01	1.67E+00	8.75E+01	5.58E+00
U237	0.	0.	1.39E-01	1.11E+07	3.90E-07	3.20E+01	3.50E-07	2.73E+01	5.42E-01	4.43E+07
U238	8.24E-02	2.75E-05	1.71E-01	5.68E-05	1.71E-01	5.68E-05	1.71E-01	5.68E-05	5.06E-01	1.69E-04
U239	0.	0.	1.21E-06	4.07E+04	0.	0.	0.	0.	4.98E-06	1.63E+05
TOTAL	3.94E+02	5.76E+03	4.03E+02	1.11E+07	4.21E+02	5.99E+03	4.22E+02	5.99E+03	1.60E+03	4.44E+07
		α5.76E+03		α5.80E+03		α5.96E+03		α5.95E+03		α2.31E+04
				β1.11E+07		β3.20E+01		β7.90E+01		β4.44E+07
NP236	0.	0.	8.09E-08	5.43E+01	4.09E-57	2.99E-49	0	0.	3.60E-07	2.17E+02
NP237	0.	0.	6.17E+00	4.37E+00	6.33E+00	4.46E+00	6.33E+00	4.46E+00	2.44E+01	1.75E+01
NP238	0.	0.	2.59E-02	6.77E+06	8.14E-24	2.13E-15	1.73E-54	3.22E-46	1.04E-01	2.71E+07
NP239	0.	0.	2.86E-04	6.64E+06	2.31E-09	5.84E+03	2.31E-09	5.84E+03	1.09E-03	1.66E+05
TOTAL	0.	0.	6.22E+00	6.82E+06	6.33E+00	5.84E+03	6.33E+00	5.84E+03	2.49E+01	2.73E+07
				α4.37E+00		α4.46E+00		α4.46E+00		α1.75E+01
				β6.82E+06		β5.84E+03		β5.84E+03		β2.73E+07
PU236	8.17E-04	3.28E+02	1.66E-04	8.95E+01	1.59E-04	8.10E+01	1.37E-04	7.02E+01	1.97E-03	8.35E+02
PU238	2.10E+01	3.54E+05	8.87E+00	1.50E+05	9.32E+00	1.58E+05	9.37E+00	1.62E+05	8.77E+01	1.01E+06
PU239	2.90E+02	1.77E+04	2.06E+00	1.22E+02	2.06E+00	1.24E+02	2.06E+00	1.25E+02	5.64E+02	3.47E+04
PU240	1.28E+02	2.11E+04	1.10E+01	2.50E+03	1.31E+01	2.70E+03	1.32E+01	2.91E+03	2.78E+02	6.14E+04
PU241	8.53E+01	6.94E+06	1.24E+01	1.28E+06	1.22E+01	1.24E+06	1.19E+01	1.20E+06	1.55E+02	1.58E+07
PU242	5.51E+01	2.15E+02	3.69E+01	1.44E+02	3.69E+01	1.44E+02	3.69E+01	1.44E+02	1.84E+02	7.18E+02
PU243	0.	0.	2.11E-02	5.47E+07	1.58E-12	4.09E-03	1.58E-12	4.09E-03	8.45E-02	2.19E+08
TOTAL	5.49E+02	7.30E+06	7.19E+01	5.61E+07	7.28E+01	1.40E+06	7.36E+01	1.37E+06	1.24E+03	2.38E+08
		α4.00E+05		α1.63E+06		α1.60E+05		α1.65E+05		α7.11E+06
		β6.64E+06		β5.60E+07		β1.24E+06		β1.20E+06		β2.35E+08

phase shifts as obtained in fits to the two body scattering data by MacGregor, Arndt and Wright [20], and obtain f(0) by summing the s, p and d partial waves. Then, since we desire an average interaction corrected for many-body effects we perform two averages and two corrections sequentially in a Fermi gas approach as follows:

i) Average over spin and isospin statistics. We define the fraction of non-identical particle collisions

$$\zeta = \frac{N_1 Z_2 + Z_1 N_2}{A_1 A_2} \tag{17}$$

where N and Z represent neutron number and proton number, respectively of the interacting ions 1 and 2. Then we evaluate the average amplitude

$$f(0) = \zeta f_{np}(0) + (1-\zeta) f_{pp}(0) \tag{18}$$

For an N=Z projectile on an arbitrary target $\zeta = 1/2$ and the results of this procedure are demonstrated at the top of Figs. 5a and 5b for the real and imaginary components respectively of f(0). All quantities are plotted on a scale of incident lab kinetic energy from 0 to 70 MeV. At the highest energy depicted we expect about a 2-3% error in f_{np} and f_{pp} due to neglect of the higher partial waves.

ii) Average over the Fermi motion. This we do because we want to eliminate the complexity of the full momentum dependence of the nucleon-nucleon interaction. The nucleons colliding in the two-ion medium sample a wide range of momentum components of the interaction due to their Fermi motion. If both nuclei are represented by Fermi gases, the average amplitude is

Fig. 19
Actinide Flowsheet for 1000 Mw U-Pu-Fueled HTGR

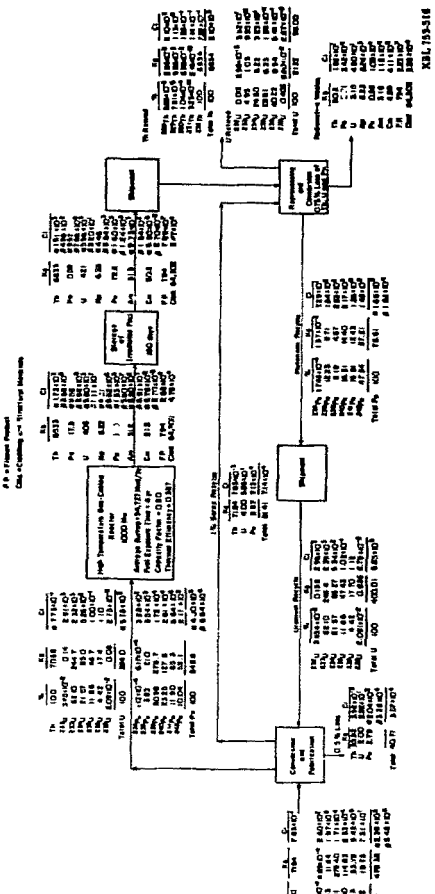
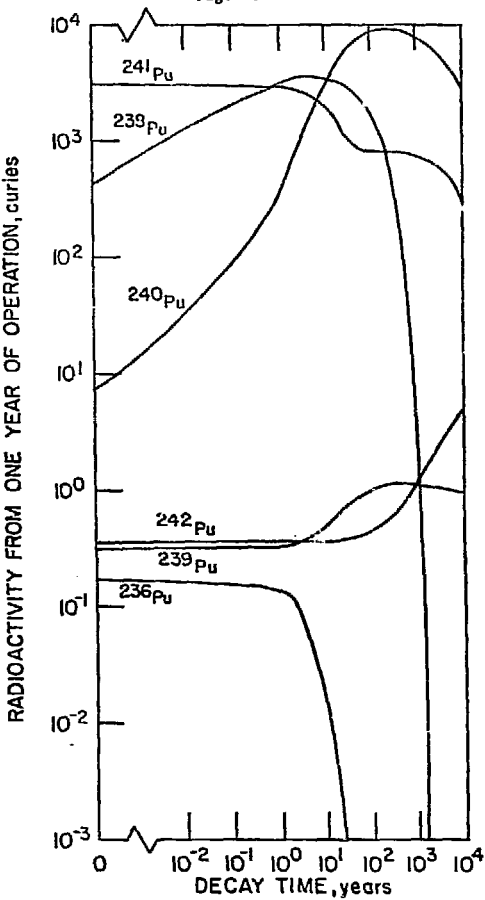
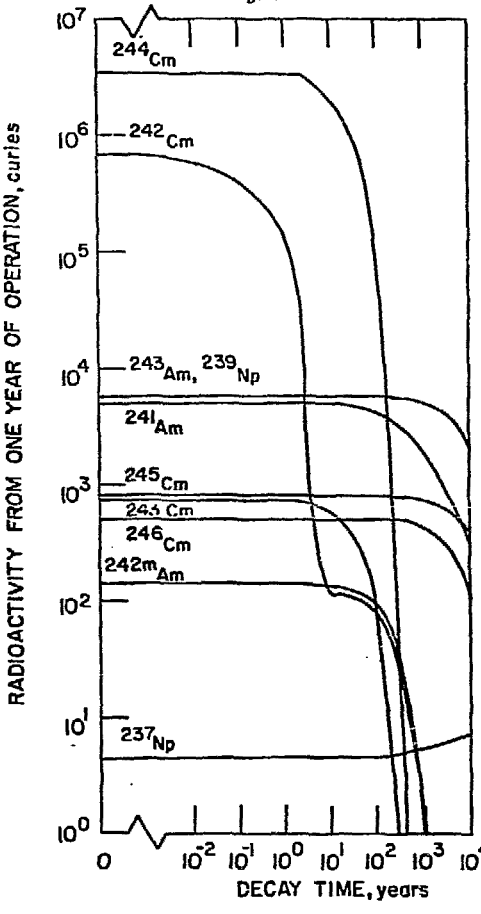


Fig. 20



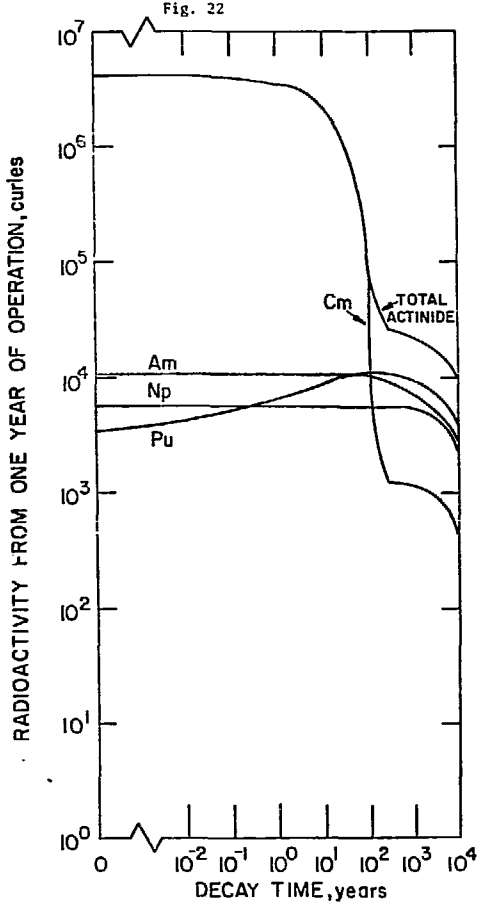
PLUTONIUM RADIOACTIVITY IN HIGH-LEVEL WASTES PRODUCED IN ONE BY 1000 Mw PLUTONIUM-FUELED HTGR

Fig. 21



Np, Am AND Cm RADIOACTIVITY IN HIGH-LEVEL WASTES PRODUCED IN ONE YEAR BY 1000 Mw PLUTONIUM-FUELED HTGR

Fig. 22



ACTINIDE RADIOACTIVITY IN HIGH-LEVEL WASTES PRODUCED IN ONE YEAR BY 1000 Mw PLUTONIUM -FUELED HTGR

plutonium, and americium all contribute to the total actinide radioactivity. The contribution of uranium to the high-level wastes radioactivity is small. It was calculated that the radioactivity of uranium in these wastes at the time of reprocessing was 14.9 curies and after one thousand years, it was 9.47 curies.

Table 31 shows the inventories of plutonium in this 1000 Mw plutonium-fueled HTGR fuel cycle. The holdup times for the various processes were assumed to be the same as those in the uranium-fueled HTGR fuel cycle and were obtained from the recent study on the HTGR fuel cycles.[17]

The neutron source strength of the spent HTGR fuels is listed in Table 32. Because of the very high concentration of ^{244}Cm, the HTGR fueled with recycled plutonium and thorium has the highest total neutron source strength of all the fuel cycles considered in this study, 66,569 x 10^6 neutrons/sec/metric ton of fuel charge compared with 22,009 x 10^6 neutrons/sec/metric ton of fuel charge for the water reactor fueled with recycled plutonium and natural uranium. Over 92% of the total neutron source strength is contributed by the spontaneous fission of ^{244}Cm. The total neutron source strength of the spent fuel of the HTGR fueled with recycled plutonium and thorium is less than that in the enriched uranium water reactor's spent fuel but more than that in the core-blanket mixture of the LMFBR's spent fuel.

Because of its relatively high thermal-absorption cross-section, most of the makeup plutonium will be consumed during the first cycle of irradiation, and recovery and recycle of the plutonium remaining in the discharge fuel may not be economically necessary. Thus, an alternative fuel cycle would be to recycle the fissile uranium formed by neutron absorption in thorium, but not to recycle the irradiated makeup plutonium. The alpha activity associated with this recycle uranium would be only a

Table 31

Inventories of Plutonium in Fuel Cycle of 1000 Mw HTGR Fueled with Plutonium

	Hold-up time	Total Pu Kg	Fissile Pu Kg	Alpha Pu curies	Beta Pu curies
Reactor	4 yrs.	1240	719	1.11×10^{6}	2.35×10^{8}
Post-irradiation cooling	*150 days*	*29.5*	*5.94*	6.28×10^{4}	2.30×10^{7}
Shipment to fuel reprocessing	215 days	42.9	8.39	9.42×10^{4}	7.30×10^{5}
Fuel reprocessing and conversion	56 days	11.3	2.14	2.53×10^{4}	1.84×10^{5}
Shipment to fuel fabrication	3.5 days	0.75	0.17	1.61×10^{3}	1.21×10^{4}
Fuel fabrication	30 days	45.7	28.8	3.34×10^{4}	5.52×10^{5}
Shipment to reactor	215 days	322.9	203.1	2.35×10^{5}	3.91×10^{6}
Pre-irradiation inventory	36 days	54.1	34.0	3.94×10^{4}	6.54×10^{5}
Scrap recycle shipment	10 days	0.15	0.10	2.23×10^{1}	3.68×10^{2}
Total external to reactor		*507.3*	*282.6*	4.92×10^{5}	2.90×10^{7}
Total in reactor and external fuel cycle		1747	1002	1.60×10^{6}	2.64×10^{8}
Plutonium makeup from one year of operation		478.4	333.2	2.39×10^{5}	5.46×10^{6}

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Table 32

Estimated Neutron Source Strength of Spent HTGR Fuels

Isotope	HTGR Fueled with Recycled Uranium and Thorium			HTGR Fueled with Recycled Plutonium and Thorium		
	Isotope Content (g/ton)[c]	Neutron Source[a] α-n (sec^{-1} ton^{-1} x 10^{-6})	S.F.[b]	Isotope Content (g/ton)[c]	Neutron Source[a] α-n (sec^{-1} ton^{-1} x 10^{-6})	S.F.[b]
^{238}Pu	1314	43.8	3.0	1162	38.73	2.7
^{239}Pu	290	0.03	0	256.8	0.02	0
^{240}Pu	170.9	0.06	0.16	1529	0.53	1.4
^{242}Pu	135.6	0	0.25	4607	0.02	9.2
^{241}Am	5.027	0.03	0	141.6	0.99	0
^{242}Cm	0.8871	8.6	17.4	63.59	613.8	1249
^{244}Cm	25.58	5.0	291.7	5412	1057	61700
^{246}Cm	0.4642	0	4.3	205.4	0.12	1896
Total		57.5	316.8		1711	64858
Overall Total		374			66569	

(a) Neutron source strength is at 365 days after fuel is discharged from reactor.

(b) S. F. = spontaneous fission.

(c) "Ton" in this table refers to metric ton of fuel as charged to the reactor.

few thousand curies per year. Such a fuel cycle would avoid the continued build-upof plutonium to the high concentrations, the large inventories, and the large amounts of alpha activity processed and refabricated when plutonium is multiply recycled.

A fuel cycle flowsheet illustrating the adaptation of the gas-cooled reactor to this plutonium-uranium-thorium fueling is shown in Fig. 23. The calculated yearly quantities of fuel actinides are listed in Table 33. Except for the relatively small process losses to low-level wastes, essentially all the plutonium, americium, and curium in the discharge fuel appears in the high-level reprocessing wastes. The amount of plutonium in these wastes is greater at the time of reprocessing than for any of the other plutonium fuel cycles described herein, but the amounts of americium and curium are still lower than for the fuel cycles involving multiple recycle of plutonium. The amount of alpha radioactivity in the chargedplutonium is almost half of that in HTGR with multiple recycle of plutonium. The makeup plutonium required is 495 Kg/yr, thus a generating capability of 2033 Mw of uranium-fueled water reactors is required, compared with 1965 Mw for the multiple plutonium recycle HTGR. The plutonium inventories in the fuel cycle of this HTGR fueled with thorium, plutonium, and recycled uranium are shown in Table 34. The total mass inventory is 1556 Kg and the total alpha inventory is 1.04×10^6 curies, compared with 1747 Kg and 1.60×10^6 curies respectively for the HTGR with multiple recycle of plutonium. Thus, the amount of plutonium and its associated alpha activity processed can be reduced by not recycling the plutonium in the HTGR, and the increase in the amount of makeup plutonium required from not recycling the plutonium is small, about 17 kg/yr.

An alternative concept of fueling a gas-cooled reactor entirely with

water-reactor plutonium with no thorium in the fuel and no recycle of plutonium, has been described by Brogli, et al.[26]

Fig. 23

Fuel Cycle for Gas-Cooled Reactor Fueled with Thorium, Plutonium, and Recycle Uranium (yearly quantities)

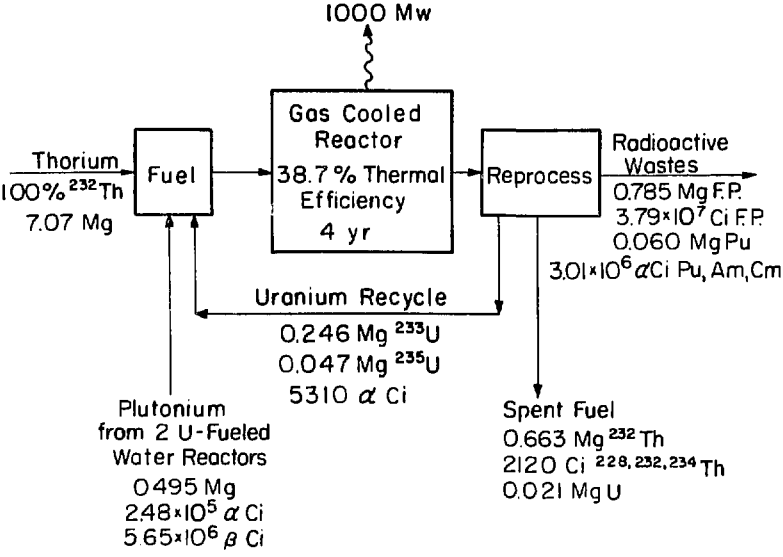


Table 33

Fuel Actinides in 1000-Mw HTGR Fueled with Thorium, Plutonium, and Recycled Uranium [a]

	Fuel Charged to Reactor		Reprocessed Fuel	
	kg/yr	Ci/yr	kg/yr	Ci/yr
^{228}Th	0	0	2.58×10^{-3}	2.12×10^{3}
^{232}Th	7.07×10^{3}	7.73×10^{-1}	6.63×10^{3}	7.25×10^{-1}
^{234}Th	0	0	4.72×10^{-8}	1.09
Total Th	7.07×10^{3}	7.73×10^{-1}	6.63×10^{3}	2.12×10^{3}
^{232}U	1.36×10^{-1}	2.91×10^{3}	1.42×10^{-1}	3.04×10^{3}
^{233}U	2.44×10^{2}	2.32×10^{3}	2.50×10^{2}	2.36×10^{3}
^{234}U	8.49×10^{1}	5.25×10^{2}	9.17×10^{1}	5.68×10^{2}
^{235}U	4.67×10^{1}	1.00×10^{-1}	5.38×10^{1}	1.15×10^{-1}
^{236}U	1.74×10^{1}	1.10	2.65×10^{1}	1.68
^{237}U	0	0	3.18×10^{-7}	2.60×10^{1}
^{238}U	8.24×10^{-2}	2.74×10^{-5}	1.75×10^{-1}	5.84×10^{-5}
Total U	3.94×10^{2}	5.76×10^{3}	4.22×10^{2}	6.00×10^{3}
^{236}Pu	5.06×10^{-4}	2.70×10^{2}	1.10×10^{-4}	5.84×10^{1}
^{238}Pu	1.20×10^{1}	2.03×10^{5}	7.70	1.30×10^{5}
^{239}Pu	2.89×10^{2}	1.77×10^{4}	1.58	9.67×10^{1}
^{240}Pu	1.19×10^{2}	2.62×10^{4}	1.11×10^{1}	2.44×10^{3}
^{241}Pu	5.57×10^{1}	5.65×10^{6}	1.06×10^{1}	1.08×10^{6}
^{242}Pu	1.94×10^{1}	7.58×10^{1}	2.88×10^{1}	1.12×10^{2}
Total Pu	4.95×10^{2}	α 2.45×10^{5}	5.98×10^{1}	α 1.33×10^{5}
		β 5.65×10^{6}		β 1.08×10^{6}

Table 33 (continued)
Fuel Actinides in 1000-MW HTGR Fueled with Thorium, Plutonium, and Recycled Uranium [a]
(Continued)

	Fuel Charged to Reactor		Reprocessed Fuel	
	kg/yr	Ci/yr	kg/yr	Ci/yr
^{241}Am	0	0	1.31	4.50×10^{3}
^{242m}Am	0	0	1.41×10^{-2}	1.37×10^{2}
^{243}Am	0	0	2.12×10^{1}	4.21×10^{3}
Total Am	0	0	2.24×10^{1}	8.85×10^{3}
^{242}Cm	0	0	1.91×10^{-1}	6.32×10^{5}
^{243}Cm	0	0	1.45×10^{-2}	6.86×10^{2}
^{244}Cm	0	0	2.76×10^{1}	2.23×10^{6}
^{245}Cm	0	0	2.87	5.07×10^{2}
^{246}Cm	0	0	9.70×10^{-1}	2.99×10^{2}
Total Cm	0	0	3.16×10^{1}	2.86×10^{6}

[a] Calculated from an equilibrium fuel cycle, 4-yr fuel life, 38.7% thermal efficiency, no recycle of thorium and plutonium, uranium retired after third recycle, fuel reprocessed one year after discharge.

Table 34

Inventories of Plutonium in Fuel Cycle of 1000 Mw HTGR Fueled with Thorium, Plutonium, and Recycled Uranium

	Hold-up time		Total Pu Kg	Fissile Pu Kg	Alpha Pu curies	Beta Pu curies
Reactor	4	yrs.	1108	715	7.20×10^5	1.02×10^8
Post-irradiation cooling	150	days	24.1	5.2	4.61×10^4	1.86×10^7
Shipment to fuel reprocessing	215	days	34.5	7.5	6.61×10^4	6.36×10^5
Fuel reprocessing	52.5	days	8.6	1.8	1.91×10^4	1.55×10^5
Fuel fabrication	30	days	40.7	28.3	2.03×10^4	4.64×10^5
Shipment to reactor	215	days	291	203	1.46×10^5	3.33×10^6
Pre-irradiation inventory	36	days	48.8	34.0	2.44×10^4	5.57×10^5
Total external to reactor			478	280	3.22×10^5	2.37×10^7
Total in reactor and external fuel cycle			1556	995	1.04×10^6	1.26×10^8
Plutonium makeup from one year of operation			495	345	2.48×10^5	5.65×10^6

VI. GROWTH OF NUCLEAR POWER IN THE UNITED STATES

The calculated throughputs and inventories of actinides in the nuclear fuel cycles presented in Chapters III through V can be used to estimate the amounts of plutonium, americium and curium to be handled in the total United States nuclear power industry involving specified amounts of power from each of the seven fuel cycles considered. For the expected growth of nuclear power in the United States, we rely here on data in the forecast by the Atomic Energy Commission,[27] wherein the "most likely" yearly additions of total nuclear power capacity are specified for the period from 1973 through the year 2000. The AEC assumptions used here to determine the quantities of water reactors, both uranium-fueled and uranium-plutonium fueled, of fast-breeder reactors and of gas-cooled reactors as a function of time are as follows:

1. The fast breeders are assumed to penetrate the nuclear power market beginning in 1986, with the installation in that year of 1.5 Gw.[a] An additional 22 Gw of fast breeder plants is expected to be installed by 1990, and the total fast breeder capacity by the year 2000 is expected to be 400 Gw.

2. Gas-cooled reactors are assumed to penetrate the non-breeder portion of the nuclear power market to the extent of 10% of the non-breeder additions in 1980 and to increase to 15% by 1985 and remain at that level for the remainder of the century.

3. The remaining additions are water reactors. Initially these are uranium-fueled water reactors. The plutonium recovered from these reactors

---

(a) 1 Gw (gigawatt) = 10^9 watts = 10^3 Mw.

Capacities quoted are electrical generating capacities, operating at an assumed load factor of 80%.

is stockpiled until 1977, at which time one-fourth of the recovered plutonium is recycled as make-up fuel for water reactors. This fraction increases to one-half in 1978, to three-fourths in 1979, and to unity in 1980. When the breeders are introduced, they will have first priority for the available plutonium for start-up inventory. Plutonium recycle in water reactors will be discontinued to the extent necessary to make plutonium available for breeder start-up.

It is assumed in this analysis that the plutonium production-consumption and inventory properties of the water reactors, fast breeder reactors, and gas-cooled reactors are those described in Chapters III through V. A new uranium-plutonium fueled reactor can be started up when the available plutonium equals the reactor inventory for the equilibrium fuel cycle. It is assumed that plutonium is recovered from discharge fuel on the average of two years after the generation of a given amount of energy. Additional make-up plutonium for reactor inventory is necessary until this recovered plutonium is available. Thereafter, each reactor is assumed to operate in its equilibrium fuel cycle, the plutonium-recycle water reactors requiring net make-up plutonium from the uranium-fueled water reactors and the fast-breeder reactors producing a net plutonium product. Process losses are indicated on the flowsheets. These assumptions provide sufficient constraints for the calculation of a reactor growth pattern that satisfies a material balance of plutonium production and consumption. The initial conditions on plutonium inventory are as follows:[11]

2000 Kg. of water-reactor plutonium was available for reprocessing at the end of 1972,

520 Kg. of water-reactor plutonium was expected to be available from fuel reprocessing at the end of 1973,

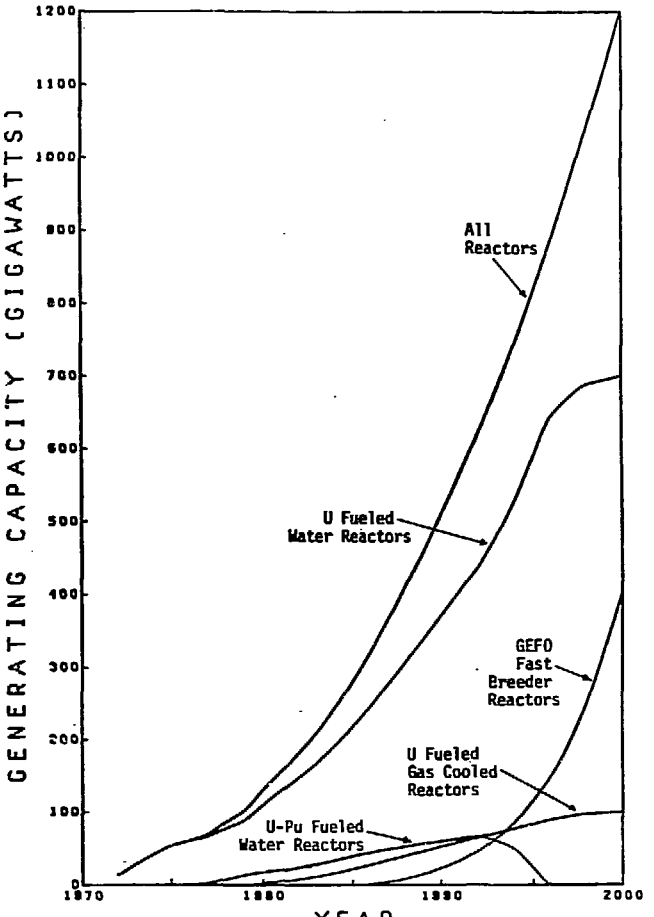
and additional 1400 Kg. of water-reactor plutonium was expected

to be available at the end of 1974.

The results of the power-growth calculation are shown in Fig. 24 and are summarized in Table 35. The data for total installed power and installed power for fast breeders, gas-cooled reactors, and water reactors result from the AEC projections. The allocation of water reactors to uranium fueling and uranium-plutonium fueling result from the plutonium material balance calculations described above. According to these calculations, the uranium-plutonium fueled water reactors reached a peak capacity of about 67 Gw. in 1992, which is about 13% of the total water-reactor capacity at that time. Thereafter, these reactors must be converted to enriched-uranium fuel so that their plutonium make-up requirement and their plutonium inventory in reactors and fuel cycle can be diverted to start up fast breeders.

In this first case studied, the GEFO fast breeder reactors were assumed to be the fast breeder reactors that will be operating in the United States. When this assumption was changed to the AIFO fast breeder reactors being the fast breeder reactors that will be operating in this country, it was found that even without the recycling of plutonium in water reactors, there will not be enough plutonium to satisfy the AEC assumption of 400 Gw. of total fast breeder capacity by the year 2000. The results of the projected growth of nuclear generating capacity for this case are shown in Figure 25. Without the recycling of plutonium in water reactors, the total installed capacity of the AIFO fast breeder reactors is 392.5 gigawatts by the year 2000. It is not possible to install 400 Gw of total AIFO fast breeder capacity by the year 2000 because of the large amount of plutonium inventory required by the AIFO fast breeder reactors, a reactor inventory of 4300 Kg compared with 3500 Kg for the GEFO fast breeder reactor.

Fig. 24



Projected Growth of Nuclear Generating Capacity in the United States (Case 1)

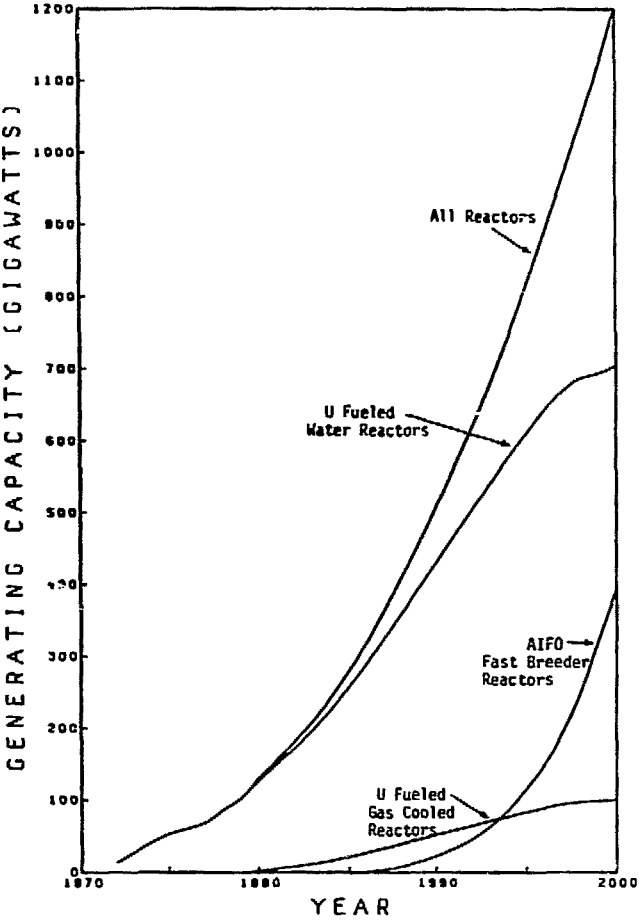
Table 35

GROWTH OF NUCLEAR POWER REACTORS IN THE UNITED STATES
(Case 1)

INSTALLED ELECTRICAL CAPACITY, GW

YEAR	URANIUM FUELED WATER REACTORS	PLUTONIUM FUELED WATER REACTORS	GEFO FAST BREEDER REACTORS	URANIUM GAS COOLED REACTORS	ALL REACTORS
1972	13.7	0.0	0.0	0.0	13.7
1973	28.9	0.0	0.0	0.0	28.9
1974	42.3	0.0	0.0	0.0	42.3
1975	54.2	0.0	0.0	0.0	54.2
1976	61.2	0.0	0.0	0.0	61.2
1977	66.7	2.6	0.0	0.0	69.3
1978	78.5	8.2	0.0	0.0	86.7
1979	89.3	14.0	0.0	0.0	103.3
1980	110.8	18.0	0.0	2.8	131.6
1981	130.7	20.7	0.0	5.6	157.0
1982	149.4	24.8	0.0	8.7	183.0
1983	169.2	29.4	0.0	12.4	211.0
1984	192.4	34.6	0.0	17.0	244.0
1985	217.4	40.2	0.0	22.4	280.0
1986	245.3	45.0	1.5	28.2	320.0
1987	276.0	49.2	4.5	34.3	364.0
1988	307.3	53.2	8.9	40.6	410.0
1989	338.2	56.9	15.2	46.7	457.0
1990	371.0	60.4	23.5	53.1	508.0
1991	403.9	63.7	33.9	59.5	561.0
1992	436.5	66.9	46.8	65.8	616.0
1993	478.7	60.6	64.6	72.1	676.0
1994	526.4	49.0	87.1	78.5	741.0
1995	585.9	23.4	117.2	84.5	811.0
1996	642.6	0.0	151.0	90.4	884.0
1997	669.0	0.0	195.0	95.0	959.0
1998	687.7	0.0	251.0	98.3	1037.0
1999	693.6	0.0	324.0	99.4	1117.0
2000	699.6	0.0	400.0	100.4	1200.0

Fig. 25



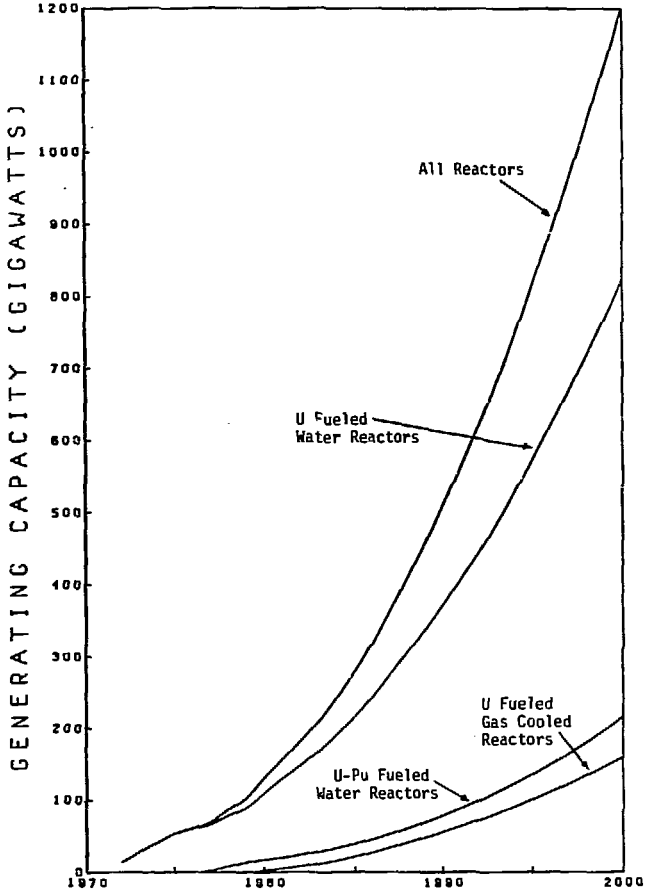
Projected Growth of Nuclear Generating Capacity in the United States (Case 2)

In addition, the plutonium product from one year of operation per gigawatt of the AIFO fast breeder reactor is less than the plutonium product of the GEFO fast breeder reactor, 265 kg per year per gigawatt for the AIFO reactor compared with 446 kg per year per gigawatt for the GEFO reactor.

A third case considered is a nuclear power industry without fast breeder reactors. Plutonium is recycled into the water reactors at the rate described above, that is that there is no plutonium recycling until 1977 at which time one-fourth of the recovered plutonium is recycled into water reactors, and this fraction increases to one-half in 1978, to three-fourths in 1979 and to unity in 1980 and beyond. The results of the projected growth of nuclear generating capacity for this third case are shown in Fig. 26. The total generating capacity of the uranium-plutonium-fueled water reactors increased continuously to the year 2000, giving a total capacity of 217 gagawatts. The total generating capacity of the uranium-thorium-fueled gas-cooled reactors is also increased to 160 gigawattts in the year 2000, compared with 100 gigawatts in Case 1, as all capacity additions are non-breeder additions. The remaining nuclear generating capacity is made up of uranium-fueld water reactor, totaling 823 gagawatts by the year 2000.

In the absence of fast breeder reactors in the nuclear power industry, it is possible that the plutonium recovered from uranium-fueled water reactors will be recycled in the gas-cooled reactors as well as in water reactors. Thus, in the fourth case considered in this study, we assumed that all gas-cooled reactors in Case 3 are fueled with uranium, thorium, and recycled plutonium. The plutonium discharged from these gas-cooled reactors are recycled back into the reactors after reprocessing and refabrication. This is not to be confused with the fuel cycle for the

Fig. 26



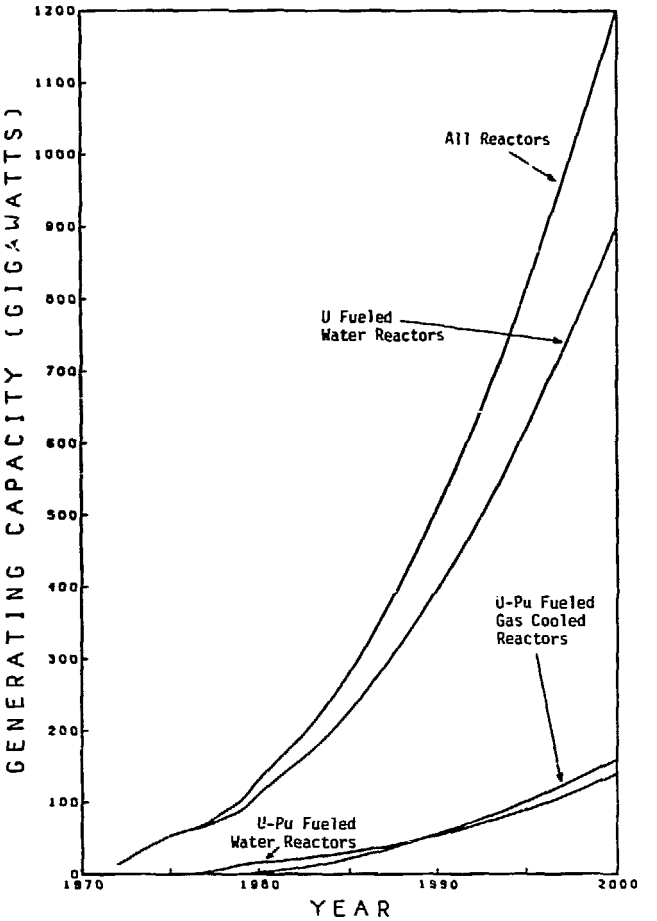
Projected Growth of Nuclear Generating Capacity in the United States (Case 3)

plutonium-fueled gas-cooled reactors in which the discharge plutonium is not recycled, but follows the high-level wastes stream, such a fuel cycle will be considered later. The results of the project growth of nuclear generating capacity, using these assumptions are shown in Fig. 27. Since plutonium is being consumed in the gas-cooled reactors, the generating capacity of the uranium-plutonium-fueled water reactors in the year 2000 is decreased to 141 gagawatts in this fourth case from 217 gagawatts in the third case. The generating capacity of the uranium-fueled water reactors is increased to 899 giagawatts in the year 2000 to make up for the decrease of the generating capacity of the uranium-plutonium water reactors.

In the fifth case studied, it was assumed that the recovered plutonium will not be recycled in water reactors, but that it will be stockpiled until the year 1980, at which time one fourth of the recovered plutonium is recycled into gas-cooled reactors and this fraction increases to unity in 1990. The uranium-thorium gas-cooled reactors are again assumed to be 10% of the non-breeder additions in 1980 and to increase to 15% by 1985 and to remain at that level for the remainder of the century. The results of the projected growth of nuclear generating capacity in this fifth case are shown in Figure 28. The generating capacity of the thorium-uranium-plutonium gas-cooled reactors is 320 gigawatts in the year 2000 while the thorium-uranium gas-cooled reactors' generating capacity is 160 gagawatts and the uranium-fueled water reactors' generating capacity is 720 gigawatts in the year 2000.

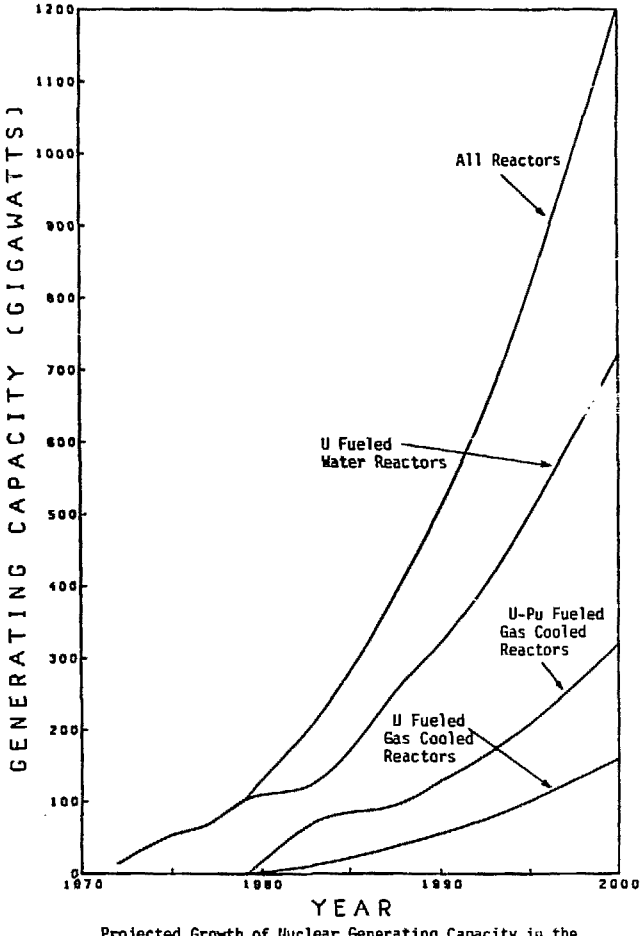
As was mentioned in the last chapter, an alternative fuel cycle for utilizing plutonium in gas-cooled reactors would be to use plutonium recovered from water reactors as make-up fuel for the gas-cooled reactors and to retire the plutonium remaining in the spent fuel of these gas-cooled

Fig. 27



Projected Growth of Nuclear Generating Capacity in the United States (Case 4)

Fig. 28



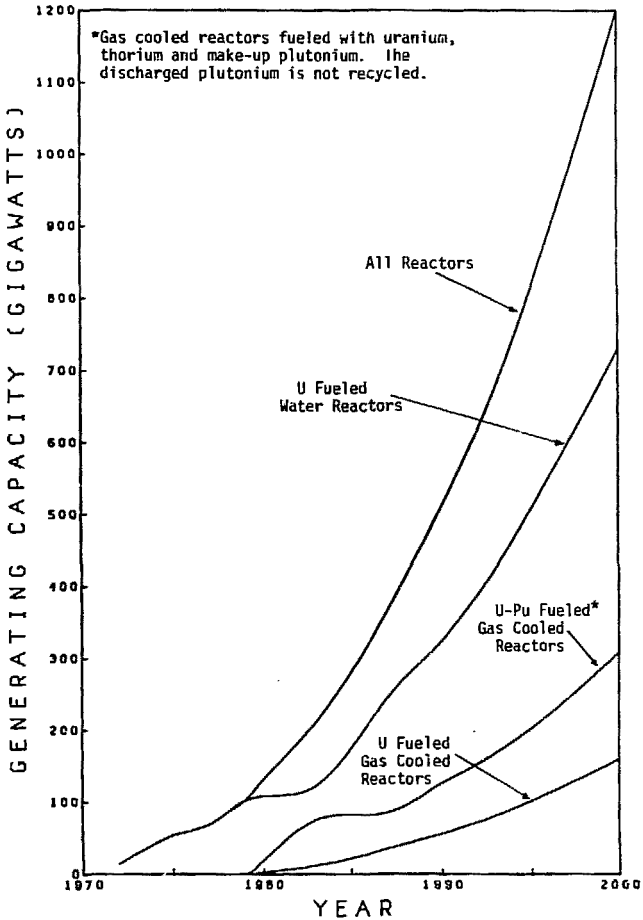
Projected Growth of Nuclear Generating Capacity in the United States (Case 5)

reactors into the high-level wastes. This is the fuel cycle for the final case studied. The assumptions in the final case is the same as those made for the fifth case except the plutonium discharged from the gas-cooled reactors are not recycled, but are discharged as part of the high-level wastes. Since the plutonium from gas-cooled reactors are not recycled, less plutonium is available for recycling in this final case than in the fifth case, thus the generating capacity of the thorium-uranium-plutonium-fueled gas-cooled reactors is less for the final case than in the fifth case, and the uranium-fueled water reactors' generating capacity is more in the final case than in the fifth case. The project growth of nuclear capacity for the final case is shown in Fig. 29. The generating capacity of the thorium-uranium-plutonium-fueled gas-cooled reactors is 309 gagawatts in the year 2000, for the thorium-uranium-fueled gas-cooled reactors, it is 160 gigawatts and for the uranium-fueled water reactors, it is 730 gigawatts.

Projected Quantities of Plutonium, Americium, and Curium in Fuel Reprocessing

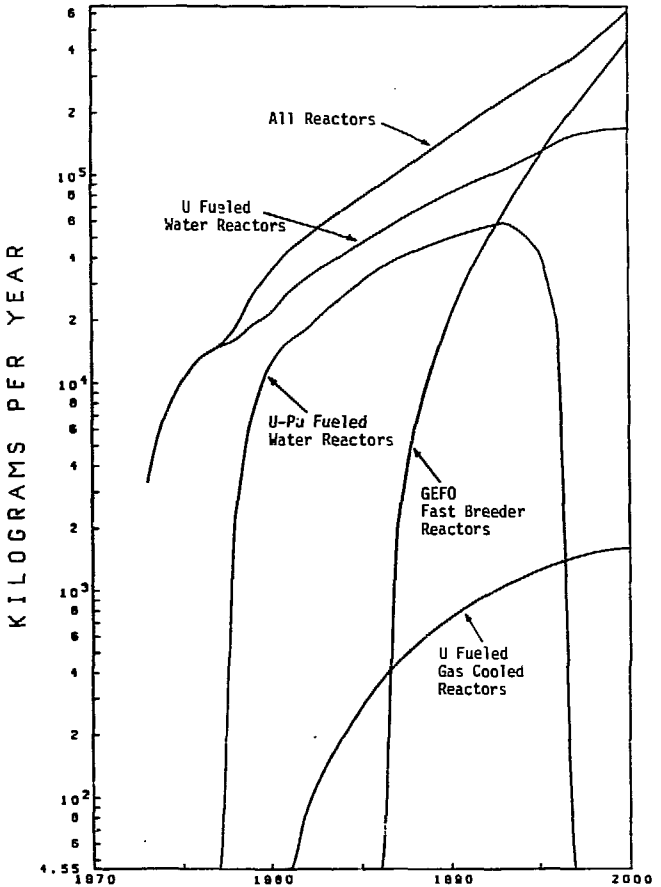
The power growth calculations were used to estimate the total amount of plutonium reprocessed yearly from each of the four reactor types in Case 1, and is shown in Fig. 30. Even with plutonium recycle in water reactors, most of the annual plutonium reprocessed is from uranium-fueled water reactors until towards the end of the century when most of the plutonium to be reprocessed will come from the fast breeder reactors. The integrated amount of plutonium reprocessed is shown in Fig. 31. According to these estimates, a total 620 metric tons of plutonium will be reprocessed yearly in the year 2000, and a total of 4,450 metric tons will have been reprocessed by the end of this century. The integrated amount of plutonium reprocessed is greatest for the uranium-fueled water reactors, because

Fig. 29



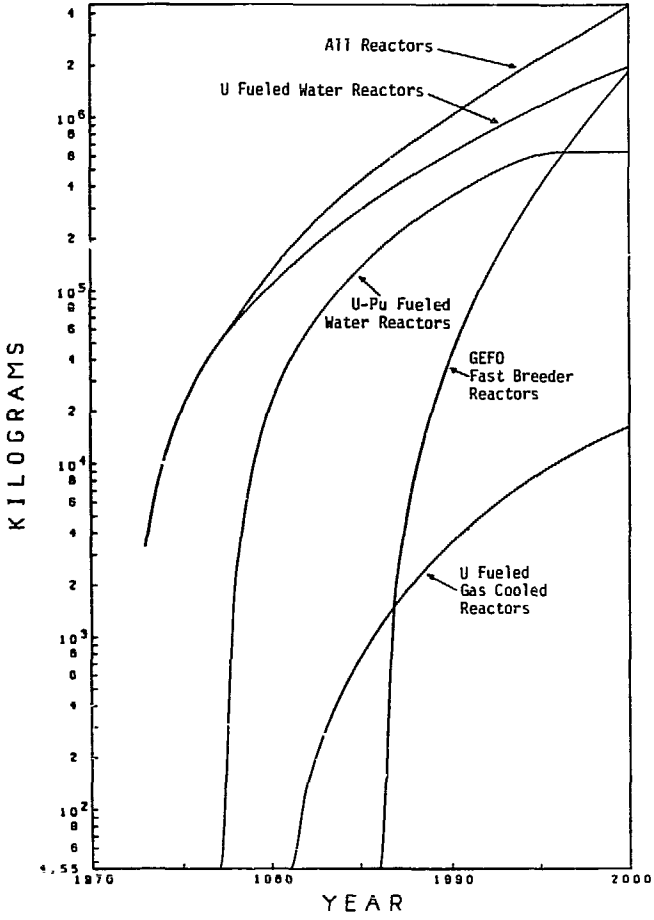
Projected Growth of Nuclear Capacity in the United States (Case 6)

Fig. 30



Plutonium Reprocessed Yearly
(Case 1)

Fig. 31

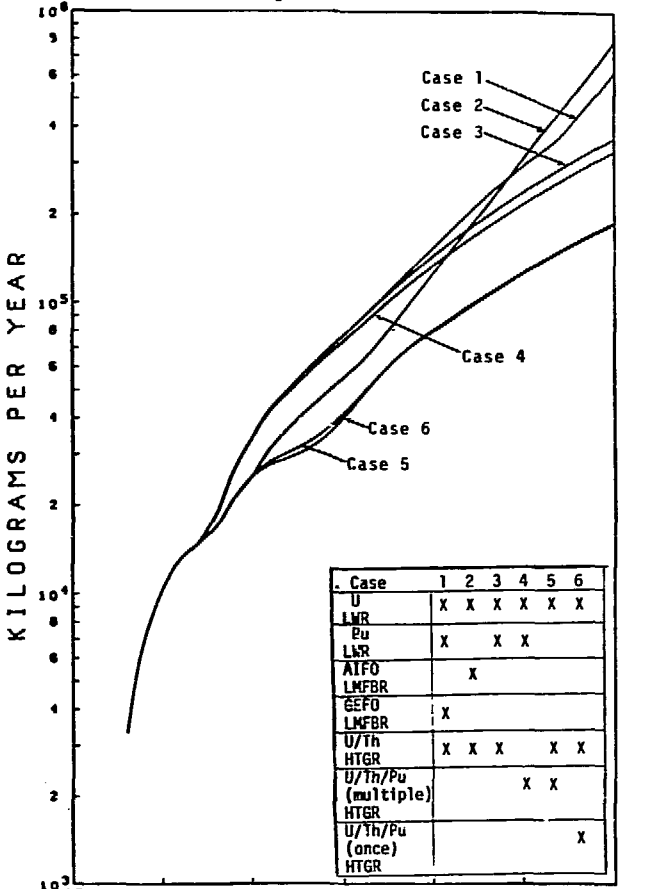


Total Plutonium Reprocessed
(Case 1)

considerably more energy will have been generated from these reactors in this century than from any others.

The yearly rate of plutonium reprocessing for the six cases described in the last section are compared in Fig. 32. The annual rate of plutonium reprocessing is smallest for Cases 5 and 6 where there are no fast breeder reactors or uranium-plutonium-fueled water reactors, and all plutonium is recycled in the gas-cooled reactors. One reason for this is because the plutonium inventories in the fuel cycles for the plutonium-fueled gas-cooled reactors are less than the plutonium inventories in the fuel cycles of the plutonium-fueled water reactors, since the plutonium gas-cooled reactors are partly fueled with fissile ^{233}U and partly with fissile plutonium in the plutonium makeup fuel, while the plutonium-fueled water reactors considered in this study are fueled almost entirely with fissile plutonium from the plutonium makeup fuel with little fissile ^{235}U from the natural uranium makeup fuel. Thus, less amount of plutonium is charged as well as discharged from the plutonium-fueled gas-cooled reactors than from the plutonium-fueled water reactors. The annual rate of plutonium reprocessing is largest for Case 1 and eventually Case 2, both cases involved the introduction of fast breeder reactors into the nuclear industry. The GEFO fast breeder reactors discharge about 1400 Kg of plutonium per gigawatt per year and the AIFO fast breeder reactors discharge about 1940 Kg of plutonium per gigawatt per year. In addition, fast breeder reactors produce more plutonium than they consume, thus more generating capacity is fueled with plutonium in Cases 1 and 2 than in the other four cases. The annual rate of plutonium reprocessing is smaller for Case 2 than Cases 1, 3, and 4 until 1990 because no plutonium fueled reactors are introduced until 1986 when the AIFO fast breeder reactor

Fig. 32



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

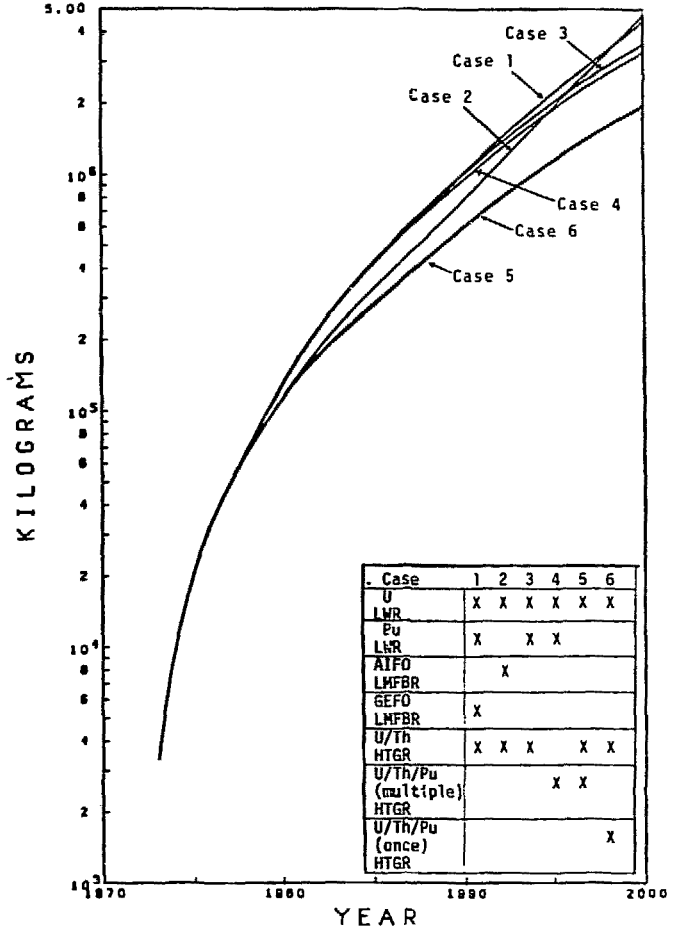
Plutonium Reprocessed Yearly

penetrates the nuclear generating industry. The integrated amount of plutonium reprocessed is compared in Fig. 33. The integrated amount of plutonium reprocessed is greatest for Case 2, totaling 4690 Kg of plutonium reprocessed, and is smallest for Case 6, totaling 1930 Kg of plutonium reprocessed.

Thus the effect of the introduction of fast breeders is to increase the amount of plutonium reprocessed and the effect of the introduction of plutonium-fueled gas-cooled reactors is to lower the amount of plutonium reprocessed, assuming that the plutonium produced in the water reactors will be recycled in either of the three reactor types.

Similar trends are noted in the calculations of the plutonium alpha activity reprocessed yearly and in the integrated amounts of plutonium alpha activity reprocessed, as shown in Fig. 34 and Fig. 35 for each of the fuel cycles considered in Case 1. Because of the high concentrations of ^{238}Pu and ^{240}Pu in the plutonium-fueled water reactors, the amounts of alpha-active plutonium reprocessed yearly from these reactors exceed the yearly reprocessing rate of alpha-active plutonium from all the uranium-fueled water reactors in the period 1984 to 1989, even though the Kilograms of plutonium reprocessed yearly during that period is less for the plutonium-fueled water reactors than for the uranium-fueled water reactors. Conversely, because of the relatively low concentrations of ^{238}Pu and ^{240}Pu in the fast-breeder plutonium the amounts of alpha-active plutonium reprocessed are less for the power-growth plan including breeders, as shown in Fig. 36 and Fig. 37. Because of the high concentration of ^{238}Pu in the plutonium discharged from the plutonium-fueled gas-cooled reactors, the amounts of alpha-active plutonium reprocessed are comparable for the power growth plan including breeders (Cases 1 and 2), and for the power growth plan including plutonium-fueled gas-cooled reactors (Cases 5

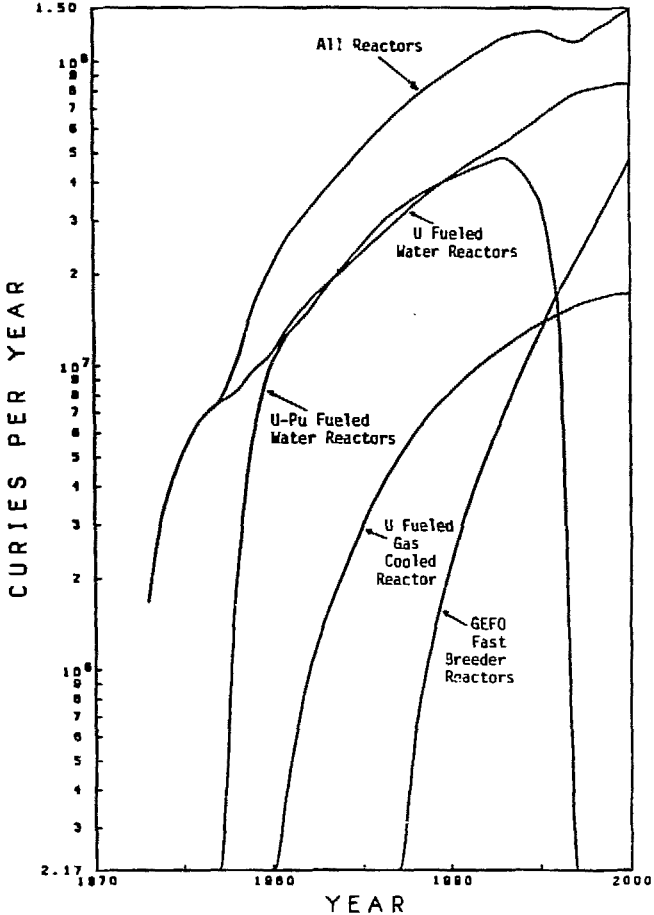
Fig. 33



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

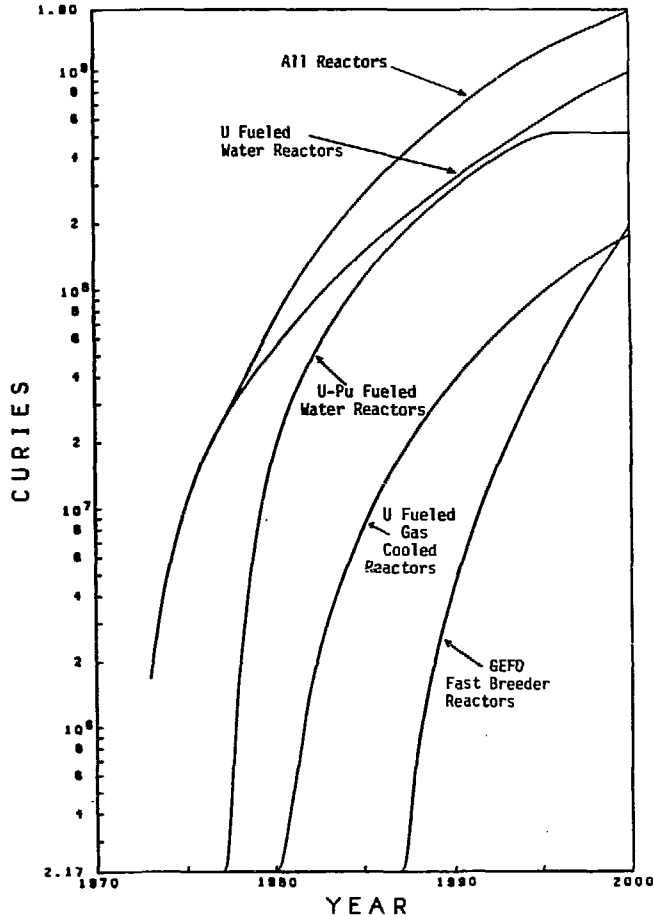
Total Plutonium Reprocessed

Fig. 34



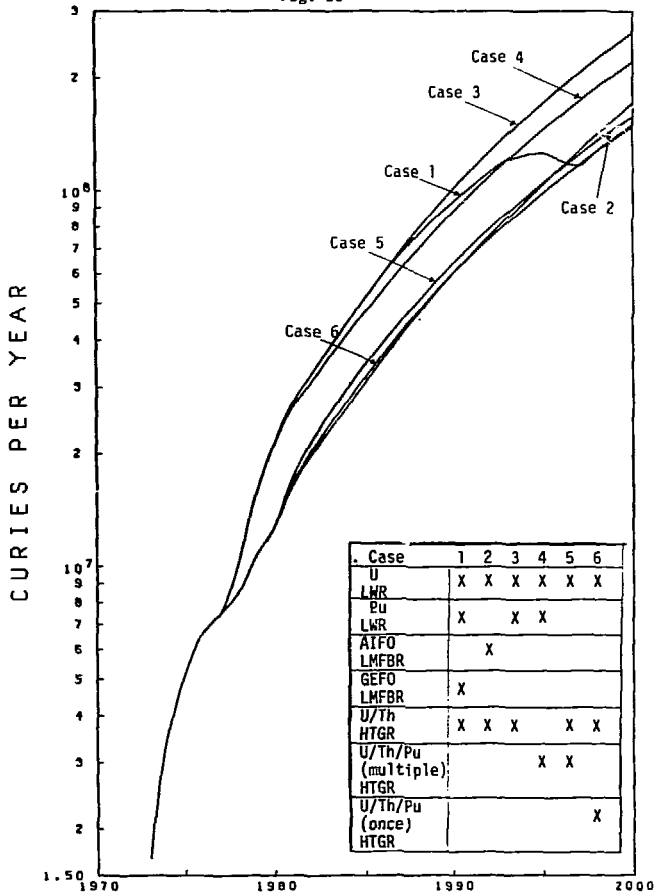
Plutonium Alpha Activity Reprocessed Yearly
(Case 1)

Fig. 35



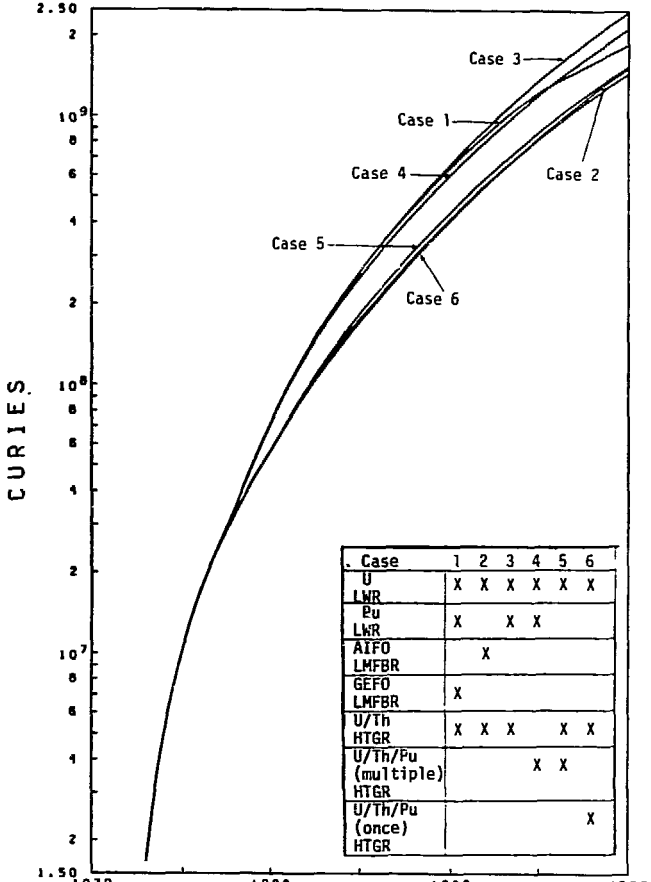
Total Plutonium Alpha Activity Reprocessed
(Case 1)

Fig. 36



Plutonium Alpha Activity Reprocessed Yearly

Fig. 37



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Total Plutonium Alpha Activity Reprocessed

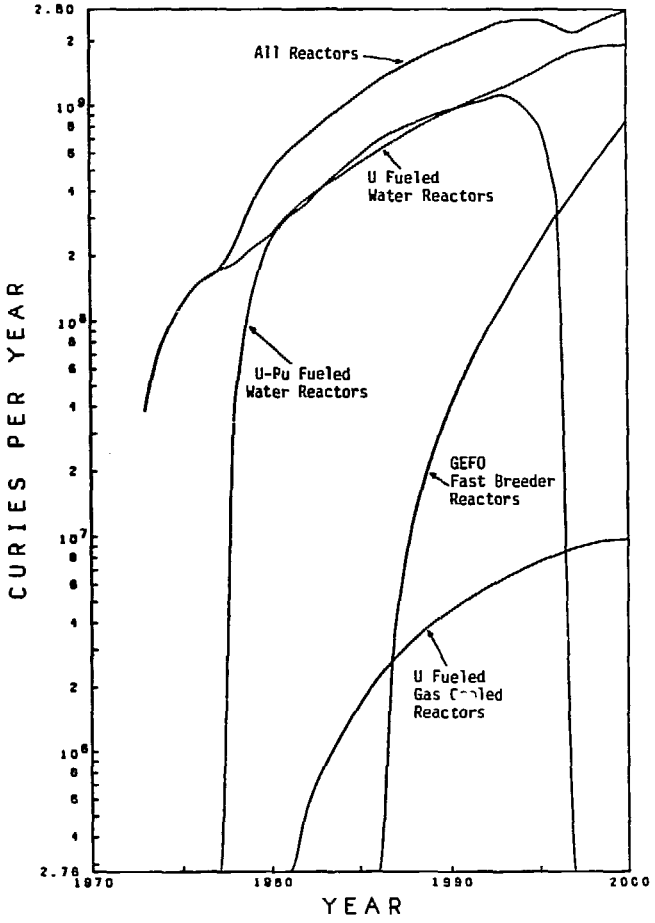
and 6), as shown in Figs. 36 and 37, even though more plutonium is reprocessed in Cases 1 and 2. The cumulative amounts of alpha-active plutonium reprocessed in Case 5 actually exceeds the cumulative amounts of alpha-active plutonium reprocessed in Case 2, up to the year 2000. The cumulative amounts of alpha-active plutonium reprocessed up to the year 2000 are 1540 million curies for Case 5 and 1530 million curies for Case 2.

Thus, one effect of the introduction of breeders into the nuclear power industry is to lower the amounts of alpha-active plutonium reprocessed compared with a power-growth plan where all plutonium is recycled in water reactors. The amounts of alpha-active plutonium reprocessed are least for the power-growth plan where all plutonium from water reactors is used as make-up fuel in gas-cooled reactors; that is, Case 6.

Figures 38 and 39 show the annual and cumulative curie amounts of beta-active ^{241}Pu reprocessed for each fuel cycle in Case 1. The trends are similar as for those found for the alpha-active plutonium reprocessed. This is a result of the low concentrations of ^{241}Pu in the fast breeder reactors compared with the concentrations of ^{241}Pu in the plutonium-fueled water reactors. Figures 40 and 41 indicate that the greatest amounts of ^{241}Pu reprocessed are in the case where all plutonium is recycled into water reactors; that is, Case 3. The smallest amounts of ^{241}Pu reprocessed occur in Case 6 where all plutonium is used as makeup fuel for the gas-cooled reactors. This is because the amounts of plutonium reprocessed are smallest for Case 6.

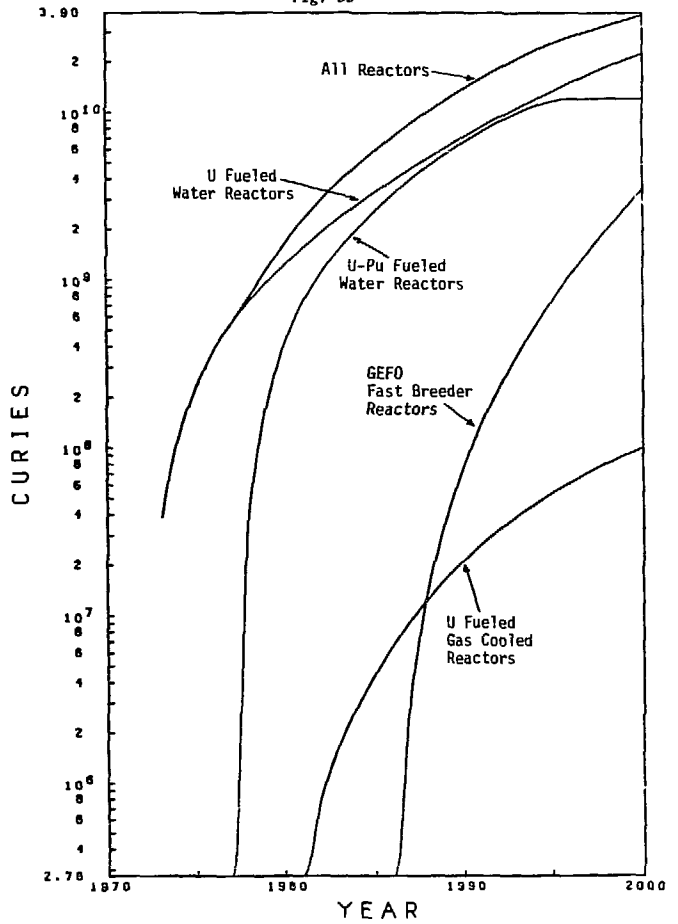
In considerations of radiological safety and public health, attention is usually focused on alpha-active plutonium because of the short range of alpha particles and their large energy deposition per unit mass of tissue. However, the relatively large radioactive quantities of ^{241}Pu

Fig. 38



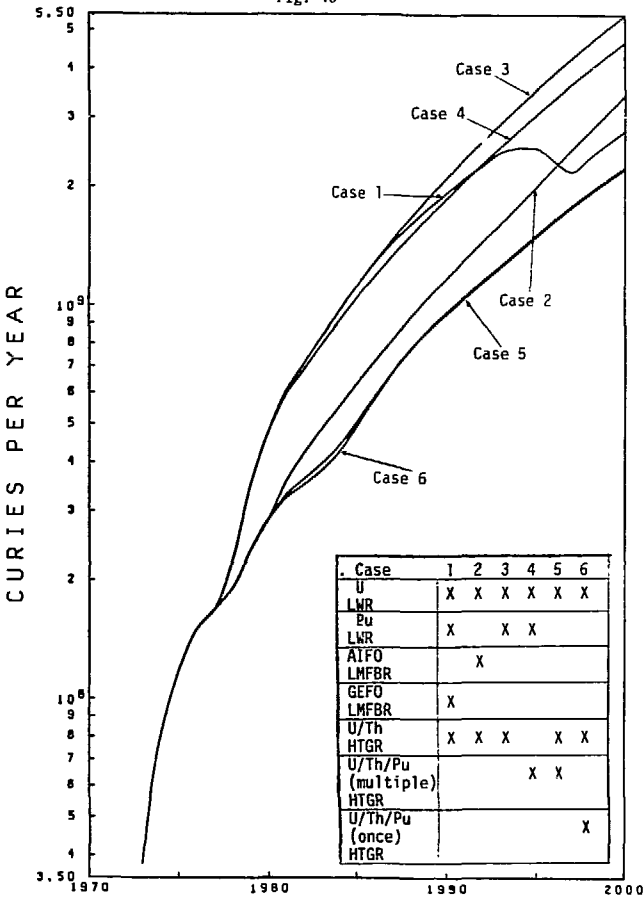
Plutonium Beta Activity Reprocessed Yearly
(Case 1)

Fig. 39



Total Plutonium Beta Activity Reprocessed
(Case 1)

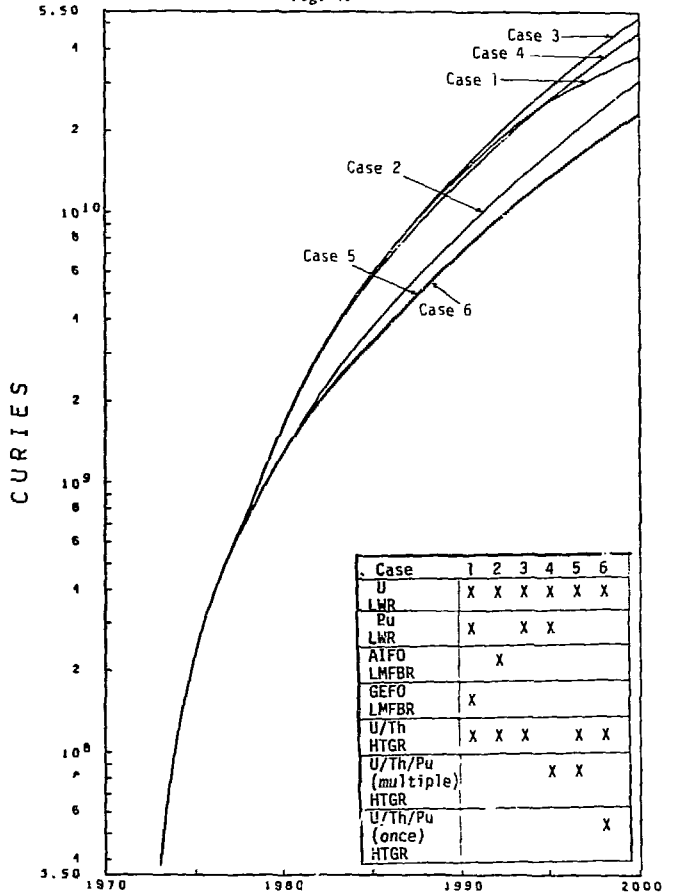
Fig. 40



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Plutonium Beta Activity Reprocessed Yearly

Fig. 41



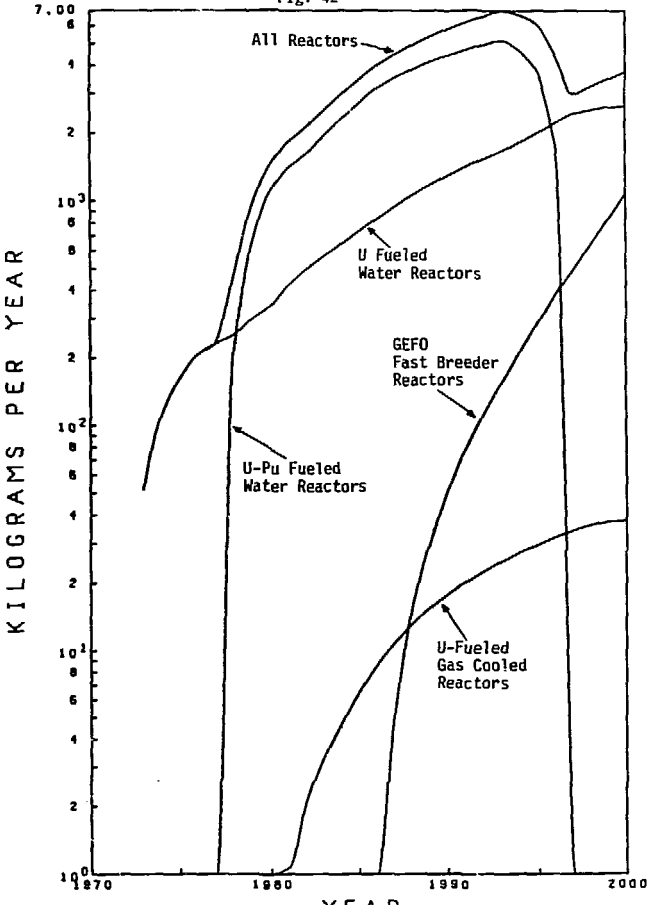
Total Plutonium Beta Activity Reprocessed

activity being reprocessed, especially during the era of plutonium recycle in water reactors, indicates that special attention be given to the radiological effects of this radionuclide and its daughters. For example, during the year 1990 about 1.9 billion curies of ^{241}Pu are expected to be reprocessed in Case 1, some 20 times greater than the 92 million curies of alpha-active plutonium reprocessed.

The yearly amounts of americium reprocessed in discharged reactor fuel in Case 1 are shown in Fig. 42, and their cumulative amounts are shown in Fig. 43. The americium production in this case is dominated by the relatively few uranium-plutonium-fueled water reactors, because of the relatively high ^{242}Pu concentrations in these reactors and the relatively large production of ^{243}Am, approximately 78 Kilograms per year per gigawatt compared with 1.9 Kilograms per year per gigawatt for the AIFO fast breeders and 2.5 Kilograms per year per gigawatt for the uranium-fueled water reactors. About 30.3 Kilograms per year per gigawatt of ^{243}Am are produced in the multiple-plutonium-recycle gas-cooled reactors and 21.2 Kilograms per year per gigawatt for the once-through-plutonium-recycle gas-cooled reactors.[a] Thus, the amounts of americium reprocessed yearly are least for Case 2 where all plutonium is recycled in the AIFO fast reactors, as shown in Fig. 44. When all plutonium-fueled water reactors are retired in Case 1, the amounts of americium reprocessed per year are even smaller than for Case 2. In the event of no breeder introduction, americium production is least when the plutonium is recycled only once in the gas-cooled reactors, that is Case 6, as shown in Figs. 44 and 45. By the year 2000, the cumulative amounts of

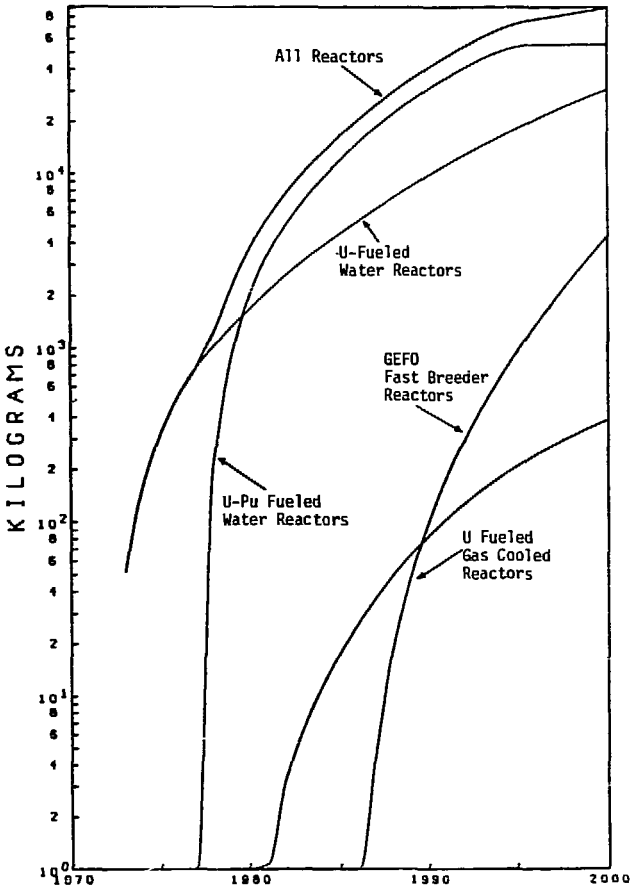
(a) Plutonium is not multiply recycled in these gas-cooled reactors.

Fig. 42



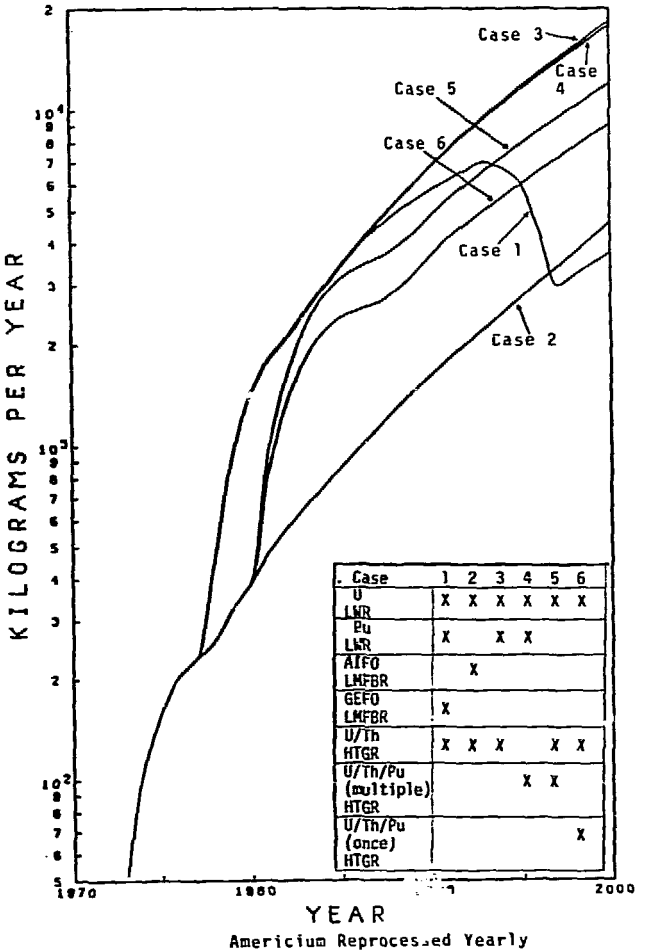
Americium Reprocessed Yearly
(Case 1)

Fig. 43



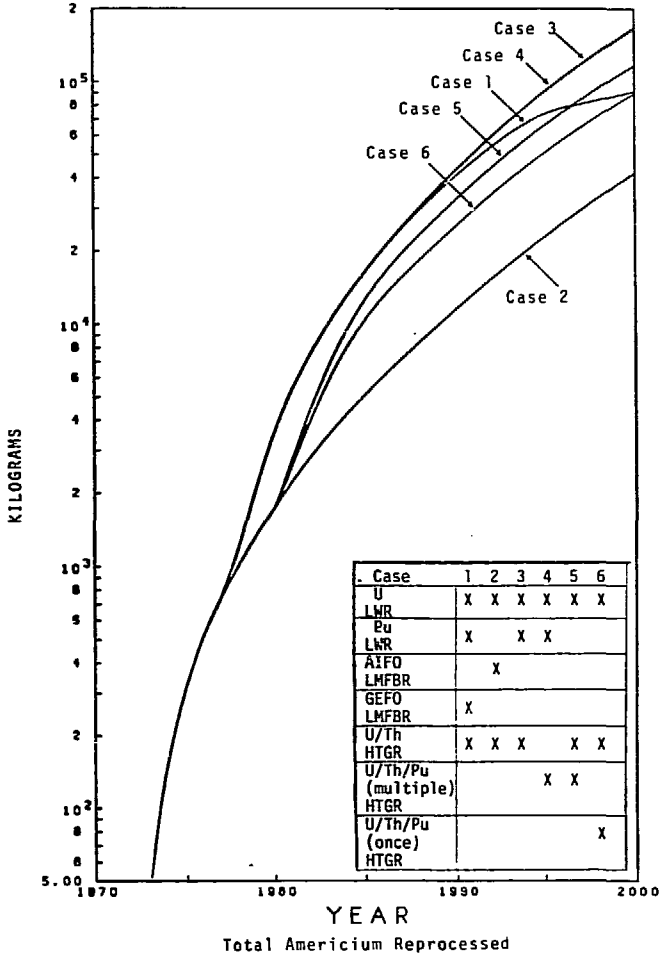
Total Americium Reprocessed
(Case 1)

Fig. 44



Americium Reprocessed Yearly

Fig. 45

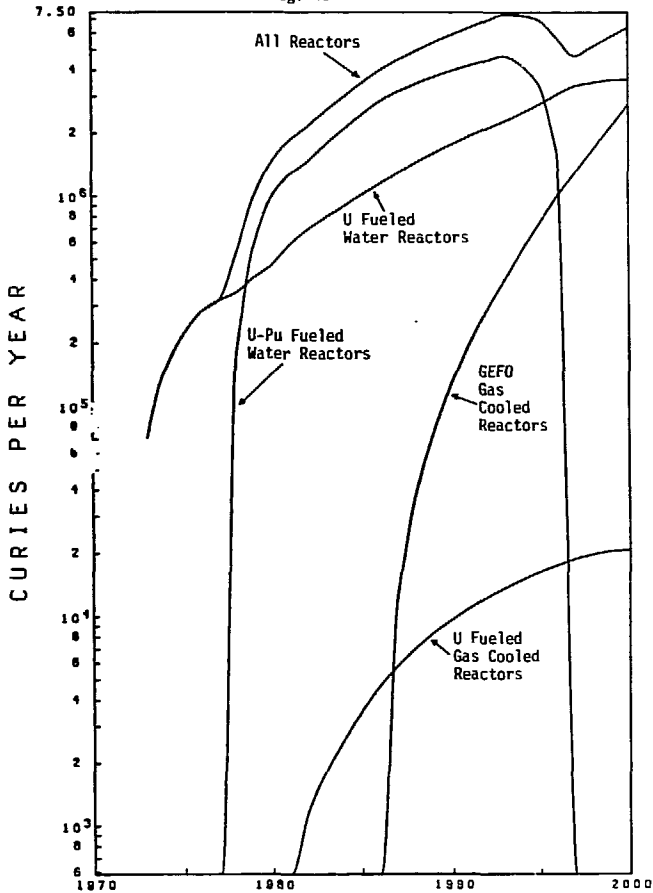


Total Americium Reprocessed

americium reprocessed are 41.5 thousand Kilograms for Case 2, 89 thousand Kilograms for Case 6, and 167 thousand Kilograms for Case 3. As has been illustrated, the americium radioactivity is the major contributor to radioactivity in high-level wastes from fuel reprocessing after storage periods of several hundred years. The annual and cumulative amounts of americium activity reprocessed are shown in Figs. 46 and 47 for Case 1. The trends are similar to those for americium production in Figs. 42 and 43. The amounts of americium activity reprocessed are 15,000 curies per gigawatt per year for the AIFO fast reactors, 8,500 curies per gigawatt per year for the GEFO fast reactors, 11,200 curies per gigawatt per year for the multiple-plutonium-recycle gas-cooled reactors, and 8,800 curies per gigawatt per year for the once-through-plutonium-recycle gas-cooled reactors.[a] Thus, even though the amount of americium reprocessed per gigawatt per year of operation is larger for the once-through-plutonium-recycle gas-cooled reactors[a] than the AIFO fast reactors, 22.4 Kilograms compared with 6.04 Kilograms, the activity of the americium at the time of reprocessing is larger for the AIFO fast reactors. This is because of the larger amount of the more active ^{241}Am in the AIFO fast-reactor fuel being reprocessed, 4.05 Kilogram per gigawatt per year compared with 1.31 Kilogram per gigawatt per year for the once-through-plutonium recycle gas-cooled reactor[a] fuel being reprocessed. The yearly and cumulative amounts of americium activity reprocessed for each of the six cases studied are shown in Figs. 48 and 49. It can be seen that the amounts of americium activity reprocessed yearly are initially larger for Cases 5 and 6 than for Case 2 because of the larger installed capacities of plutonium-fueled gas-cooled reactors, but at about the year 1993, the americium activity

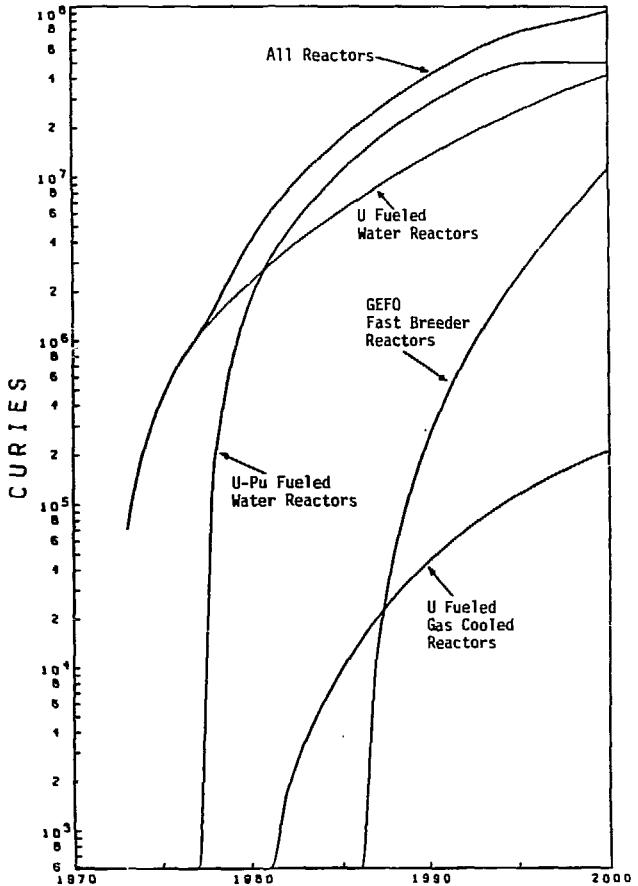
(a) The plutonium is not multiply recycled in these gas-cooled reactors.

Fig. 46



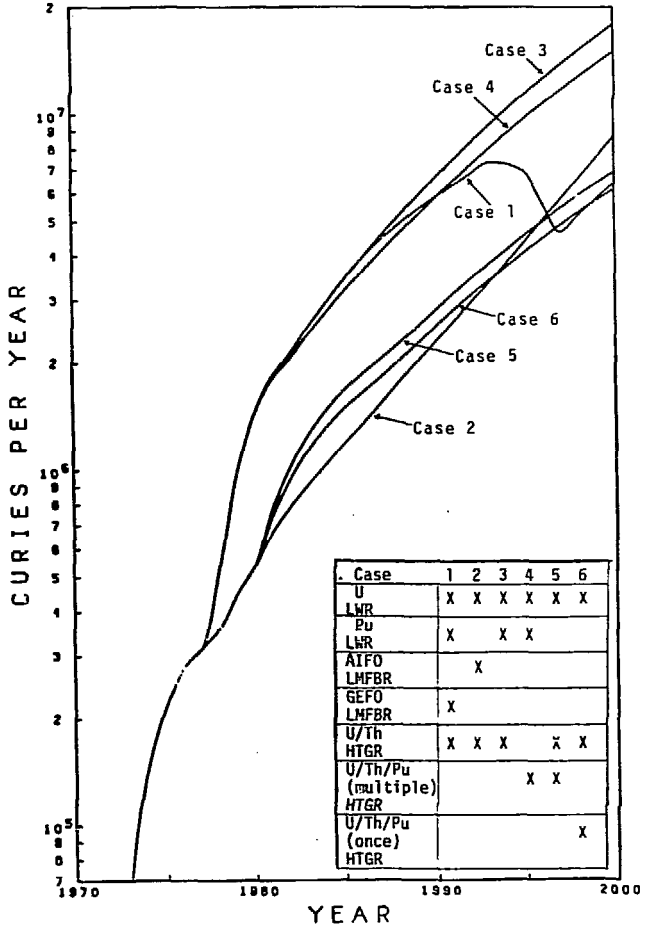
Americium Activity Reprocessed Yearly
(Case 1)

Fig. 47



Total Americium Activity Reprocessed
(Case 1)

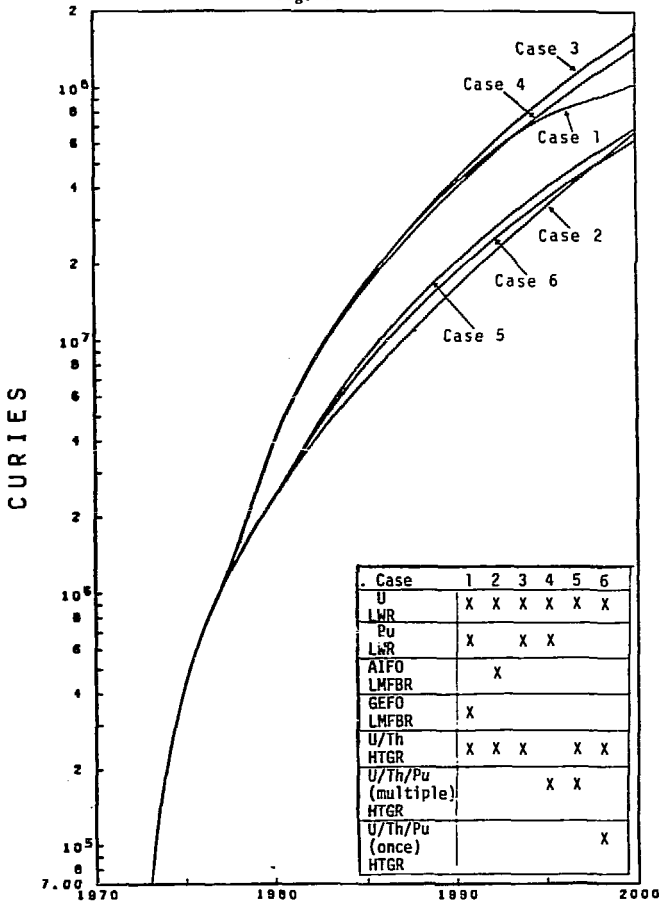
Fig. 48



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Americium Activity Reprocessed Yearly

Fig. 49



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

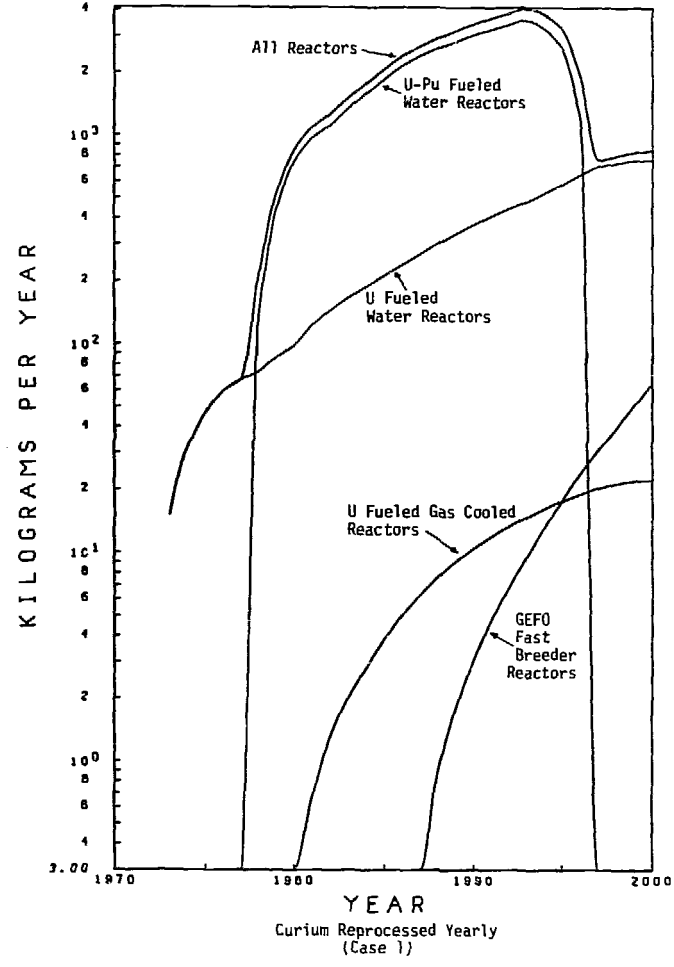
Total Americium Activity Reprocessed

reprocessed yearly becomes larger for Case 2 than for Case 6. In the year 2000, the americium activity reprocessed is larger for Case 2 than for Cases 1, 5, and 6. The cumulative americium activities reprocessed by the year 2000 are 165 million curies for Case 3, 103 million curies for Case 1, 68.5 million curies for Case 5, 66.2 million curies for Case 2, and 61.7 million curies for Case 6.

Thus americium production is dominated by the uranium-plutonium-fueled water reactors. The effect of the introduction of breeders is to reduce the total amount of americium reprocessed, as shown in Figs. 44 and 45. However, the total amounts of americium activity reprocessed can also be reduced by recycling plutonium as fuel for the gas-cooled reactors as shown in Figs. 48 and 49.

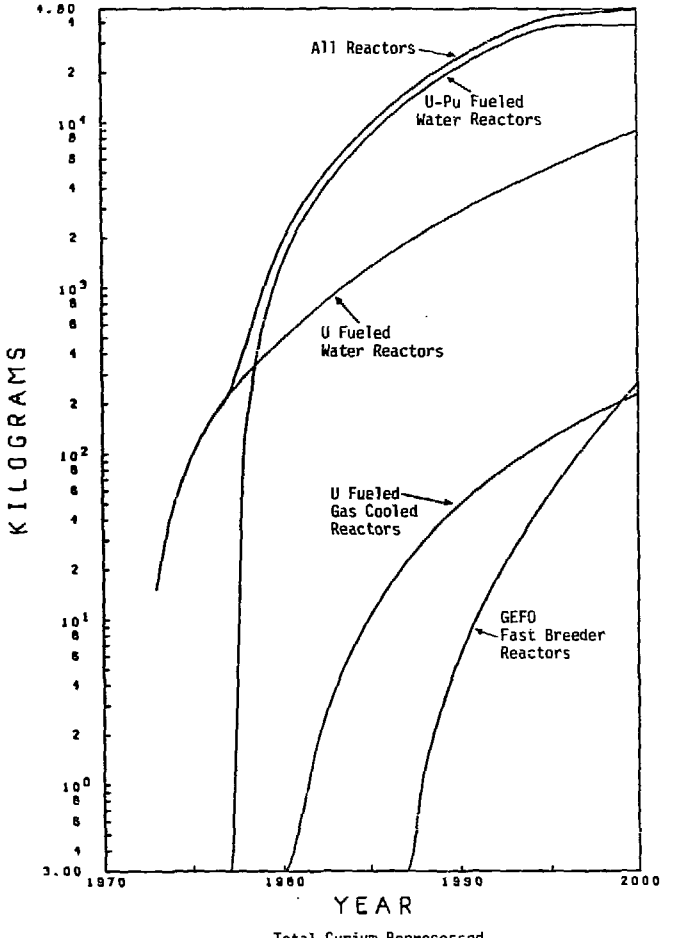
The estimated yearly and integrated quantities of curium reprocessed are shown in Figs. 50 and 51 for Case 1, and its yearly and integrated activities of curium reprocessed are shown in Figs. 52 and 53. The greatest amounts of curium production result from the uranium-plutonium-fueled water reactors. The effect of developing nuclear power without breeders is to increase the curium production, as shown in Figs. 54 and 55. Even though curium production is greatest from the uranium-plutonium-fueled water reactors, Figs. 54 and 55 show that the total yearly and integrated amounts of curium reprocessed is larger for Case 5, where all plutonium is recycled in gas-cooled reactors, than for Case 3, where all plutonium is recycled in water reactors. This is because more gigawatts of generating capacity are fueled with plutonium in Case 5 than in Case 3 due to the large inventories of plutonium required by the uranium-plutonium-fueled water reactors. 53.4 Kilograms of curium are produced per gigawatt per year of operation from the uranium-plutonium-fueled water reactors

Fig. 50



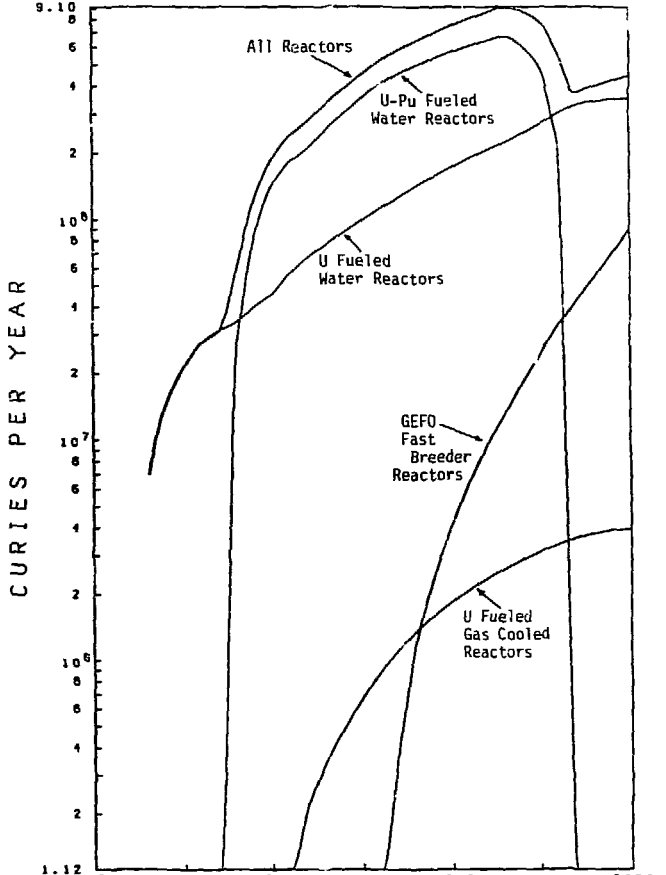
Curium Reprocessed Yearly
(Case 1)

Fig. 51



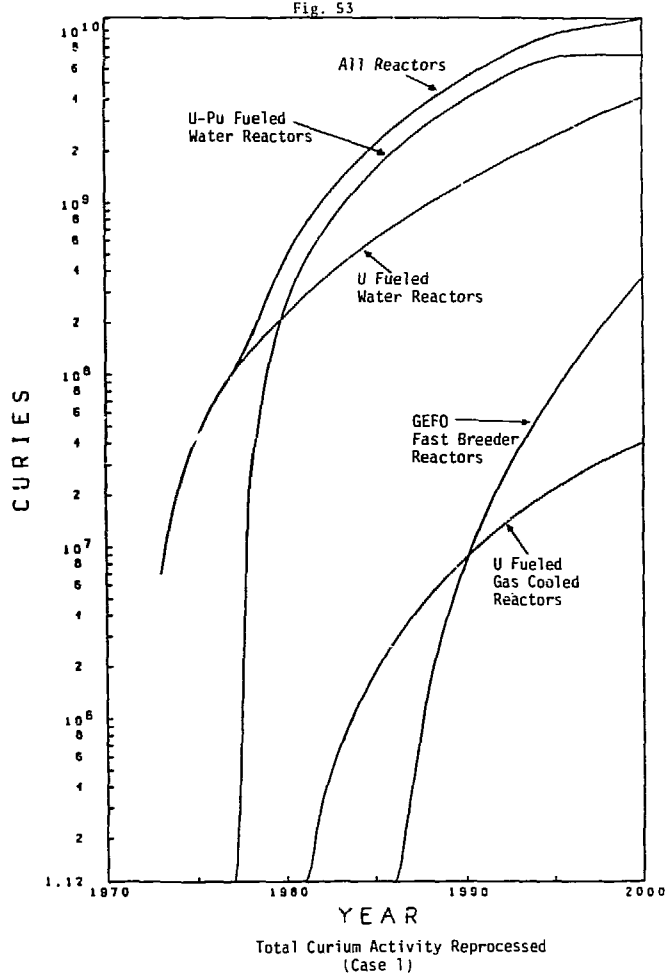
Total Curium Reprocessed
(Case 1)

Fig. 52



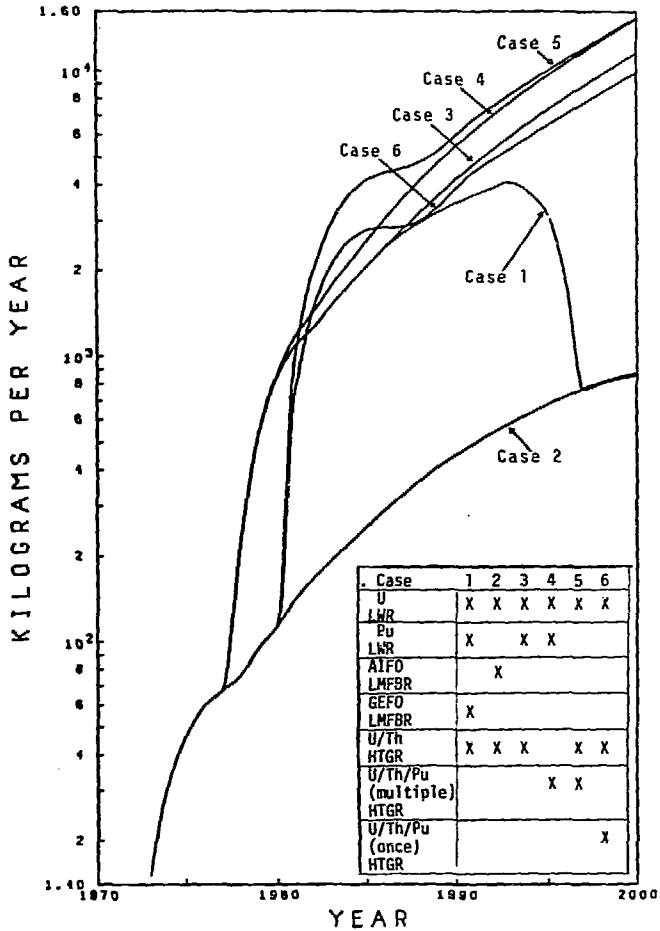
Curium Activity Reprocessed Yearly
(Case 1)

Fig. 53



Total Curium Activity Reprocessed
(Case 1)

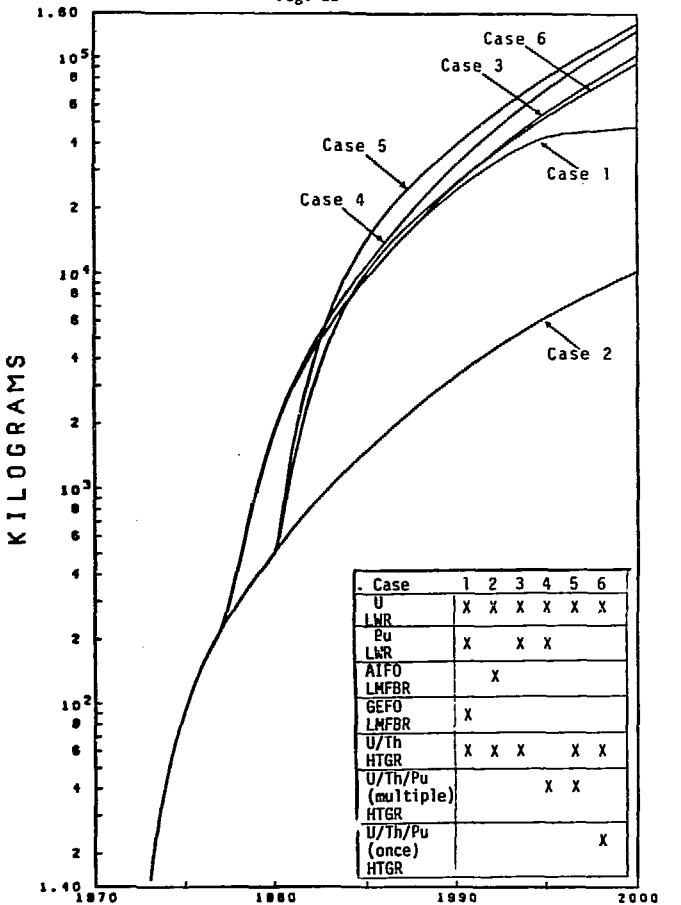
Fig. 54



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Curium Reprocessed Yearly

Fig. 55



Total Curium Reprocessed

compared with 48.9 Kilograms from the multiple-plutonium-recycle gas-cooled reactors. The total yearly and integrated amounts of curium reprocessed in Case 6 are much less than in Cases 3, 4, and 5, because only 31.6 Kilograms of curium are produced per gigawatt per year of operation of the once-through-plutonium-recycle gas-cooled reactors.(a) Figures 56 and 57 show the total yearly and integrated amounts of curium activity reprocessed. Even though the quantities of curium reprocessed are less for Case 3 than for Cases 4 and 5, the total curium activity reprocessed is larger for Case 3 than for Cases 4 and 5 because of the high concentration of the 163-day ^{242}Cm in the uranium-plutonium-fueled water reactors. According to these calculations, 21.9 billion curies of curium will have been reprocessed by the year 2000 for Case 3, 11.7 billion curies for Case 1, 11.5 billion curies for Case 6, and 5.0 billion curies for Case 2.

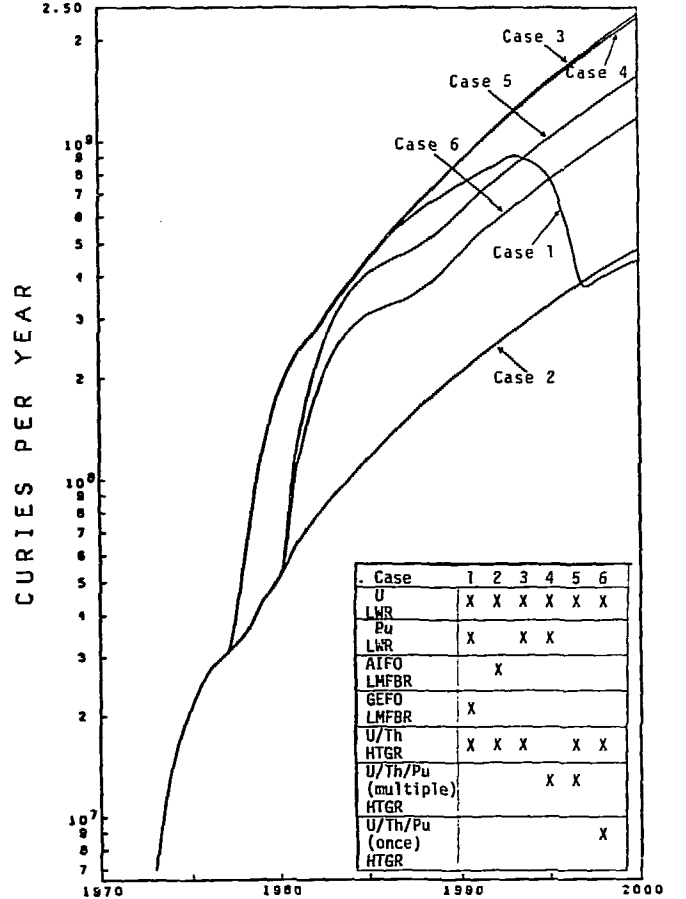
Curium is the largest source of alpha radioactivity at the time of fuel reprocessing. However, the curium radionuclides 163-day ^{242}Cm, 32-year ^{243}Cm, and 17.6-year ^{244}Cm are short-lived compared with the alpha-active radionuclides of americium and plutonium of importance here, and will not be as significant a concern in long-term waste storage.

Plutonium, Americium, and Curium in Process Wastes

The flowsheets, Figs. 3, 7, 10, 14, 16, and 19 indicate estimates of the fractional losses of plutonium to non-recoverable solid wastes in fuel-cycle operations. The indicated losses do not represent the limits of the process technologies. However, they are used here as estimates of representative losses in commercial fuel-cycle operations. These losses are not environmental releases, as acceptable environmental releases

(a) The plutonium is not multiply recycled in these gas-cooled reactors.

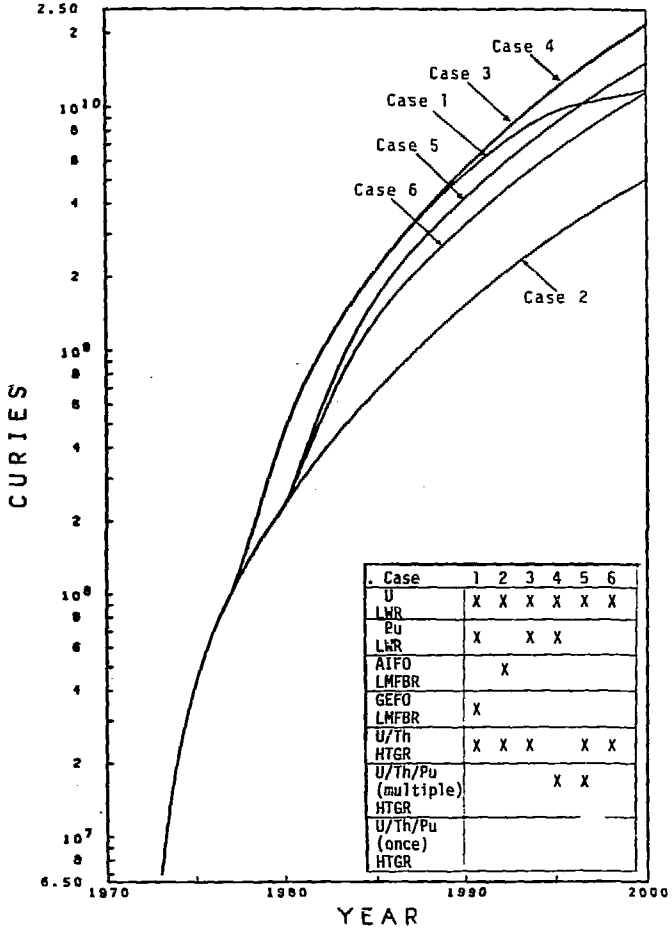
Fig. 56



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Curium Activity Reprocessed Yearly

Fig. 57



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						

Total Curium Activity Reprocessed

must be many orders of magnitude less than the losses to wastes. Therefore, the wastes associated with these process losses must be subjected to permanently protected storage or disposal. The quantities of plutonium and its alpha and beta activities in the high-level and low-level wastes generated in one year of operation for one gigawatt of generating capacity for each type of fuel cycle are summarized in Table 36.

The values in Table 36 were used to estimate the total yearly and cumulative quantities of plutonium in the low-level and high-level wastes for the six cases considered and are shown in Figs. 58 to 69.

Figures 58 and 59 show the total yearly and cumulative amounts of plutonium in the low-level wastes. The plutonium in the low-level wastes is least for Case 6 since all plutonium discharged from the gas-cooled reactors in this case is retired to the high-level wastes and the only contribution to the plutonium in low-level wastes comes from the uranium-fueled water reactors. The yearly quantities of plutonium in low-level wastes are initially low for Case 2 until the introduction of fast reactors when the yearly plutonium in low-level wastes increases rapidly and eventually surpasses all other cases. This is because of the large plutonium inventory in the AIFO fast reactor fuel cycle. By the year 2000, the total cumulative plutonium in low-level wastes is 47,600 Kilograms for Case 2, 47,000 Kilograms for Case 1, 44,600 Kilograms for Case 3, 38,000 Kilograms for for Case 4, 16,600 Kilograms for Case 5, and 8,830 Kilograms for Case 6. Because of the relatively large plutonium inventory in the uranium-plutonium-fueled water reactor fuel cycle, the amounts of plutonium in low-level wastes for Cases 1 and 3 are also relatively large.

Figures 60 and 61 show the total yearly and cumulative amounts of plutonium alpha activity in the low-level wastes. Because of the high

Table 36

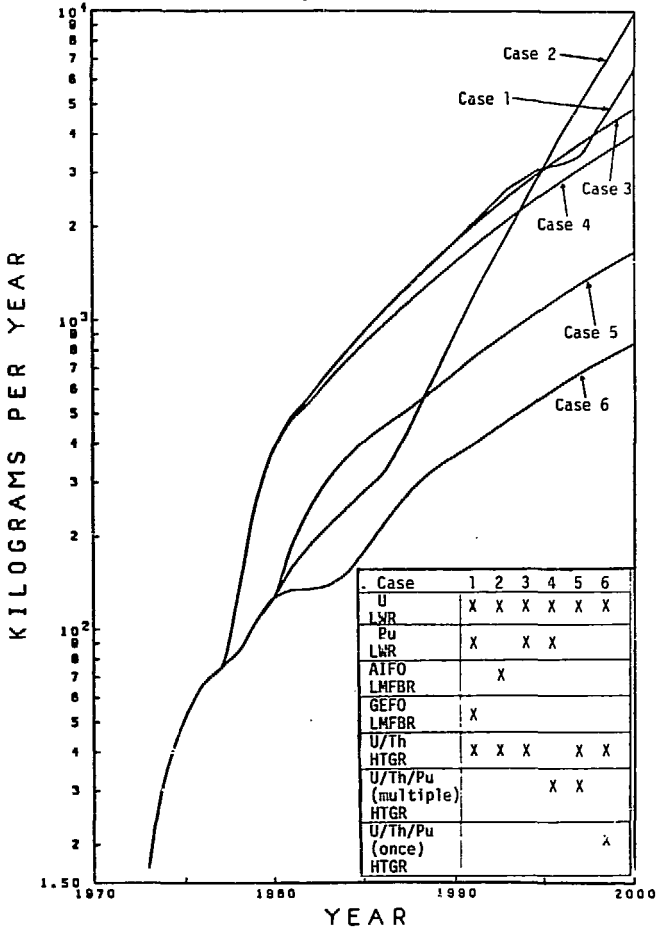
Plutonium in Low-Level and High-Level Wastes in One Year of Operation
Per Gigawatt Generating Capacity

	Low-Level Wastes			High-Level Wastes		
	Kg	α Curie	β Curie	Kg	α Curie	β Curie
U-Fueled Water Reactor	1.23	6.15×10^{2}	1.41×10^{4}	1.23	6.15×10^{2}	1.41×10^{4}
U-Pu-Fueled Water Reactor	19.6	1.42×10^{4}	3.26×10^{5}	4.96	3.93×10^{3}	9.10×10^{4}
AIFO Fast Breeder Reactor	27.8	2.99×10^{3}	6.53×10^{4}	10.3	1.08×10^{3}	2.34×10^{4}
GEFO Fast Breeder Reactor	17.3	1.82×10^{3}	3.27×10^{4}	7.35	7.70×10^{2}	1.39×10^{4}
Th-U-Fueled Gas-Cooled Reactor	0	0	0	16.1	9.90×10^{4}	1.77×10^{5}
Th-U-Pu-Fueled Gas-Cooled Reactor[a]	2.79	2.04×10^{3}	3.36×10^{4}	0.59	1.30×10^{3}	1.00×10^{4}
Th-U-Pu-Fueled Gas-Cooled Reactor[b]	0	0	0	59.8	1.33×10^{5}	1.08×10^{6}

(a) This gas-cooled reactor is fueled with plutonium from its spent fuel, as well as plutonium from the water reactors.

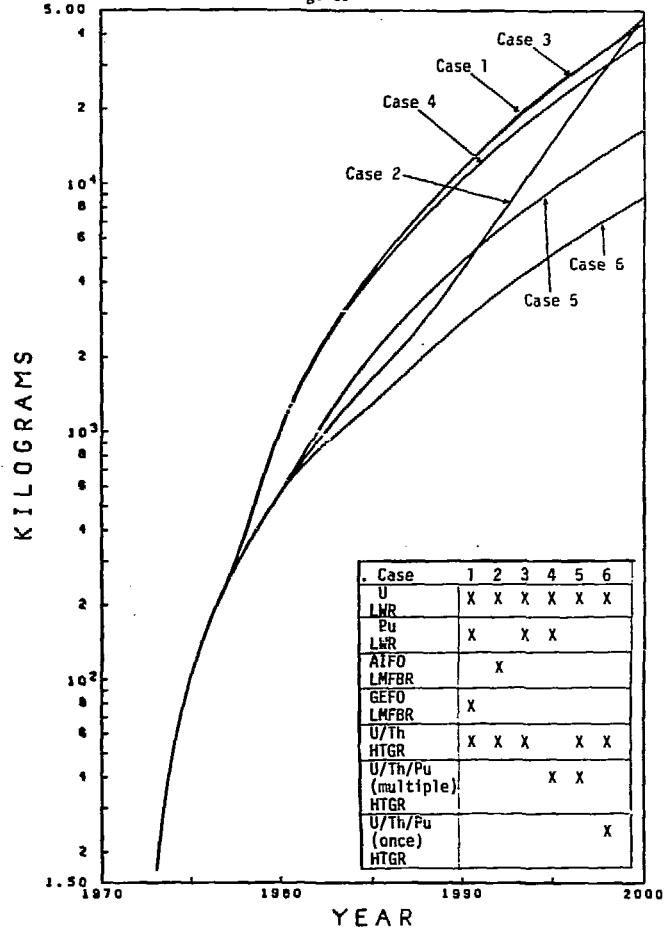
(b) This gas-cooled reactor is fueled with plutonium from water reactors, the plutonium from its spent fuel is not recycled, but is retired into the high-level wastes.

Fig. 58



Yearly Quantity of Plutonium in Low-Level Wastes

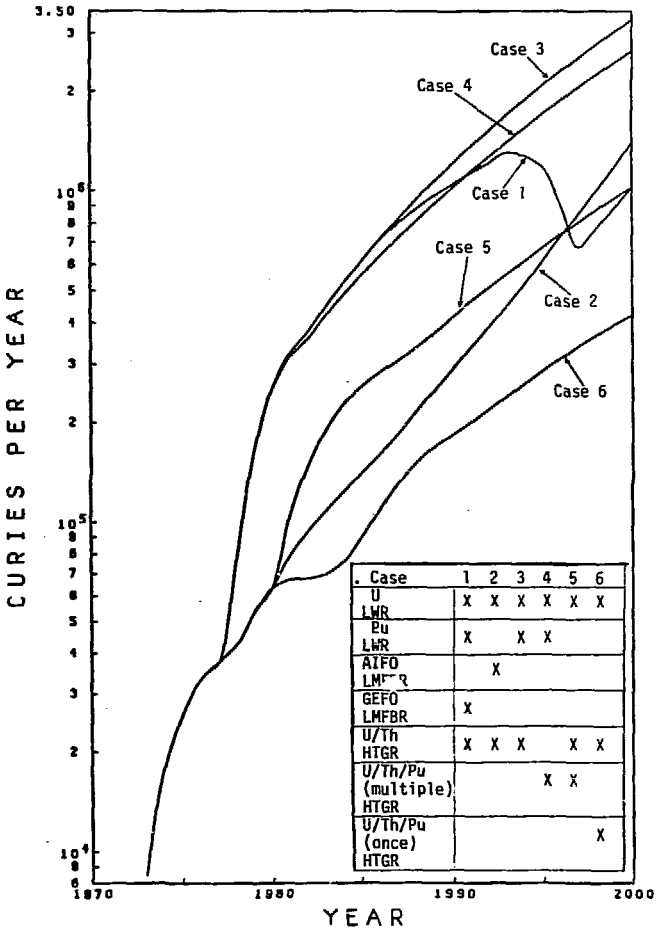
Fig. 59



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

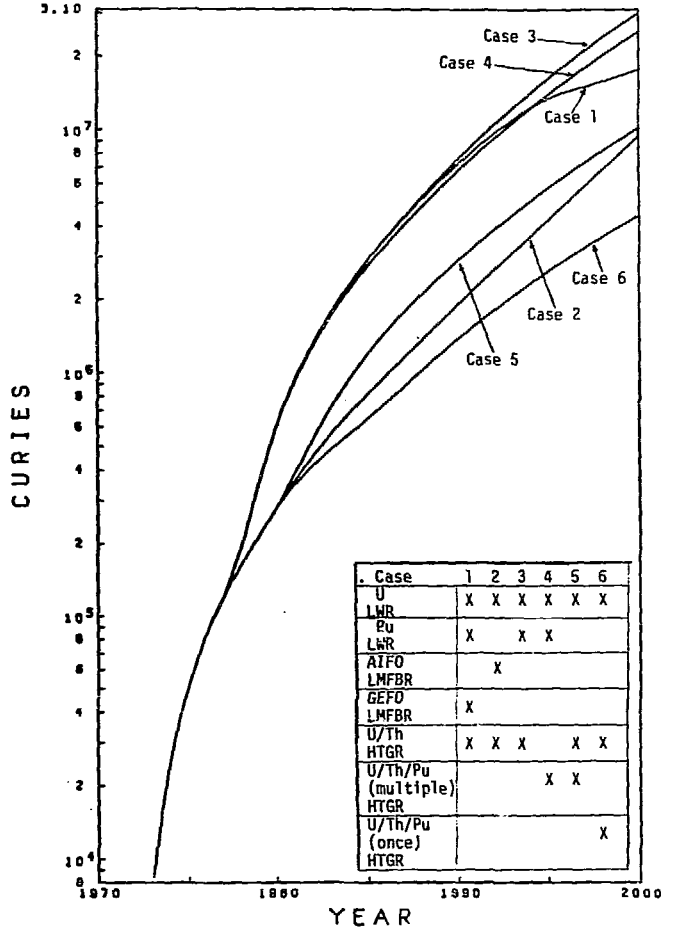
Total Quantity of Plutonium in Low-Level Wastes

Fig. 60



Yearly Quantity of Plutonium Alpha Activity in Low-Level Wastes

Fig. 61



Total Plutonium Alpha Activity in Low-Level Wastes

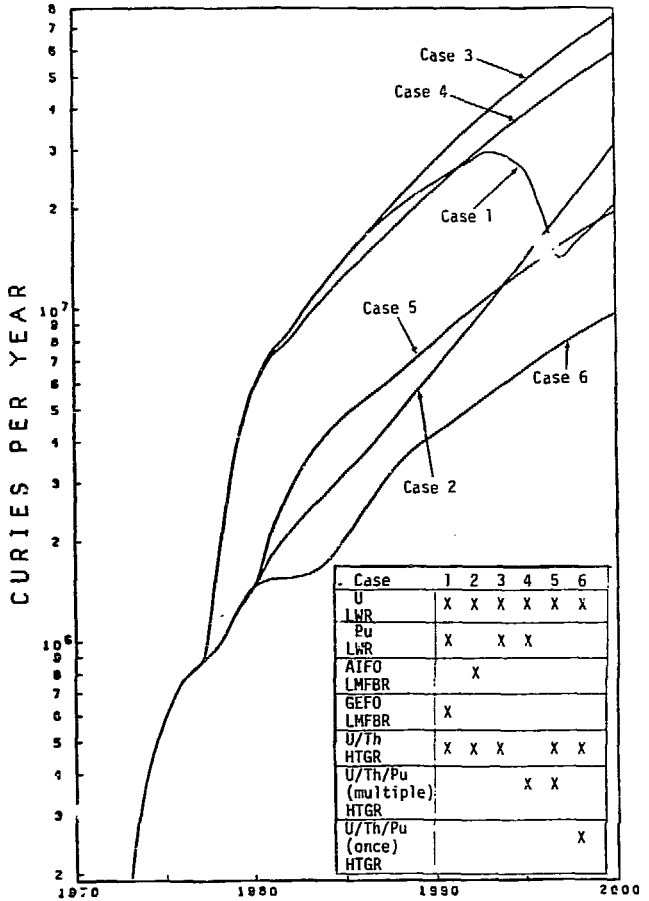
concentrations of ^{238}Pu and ^{240}Pu in the plutonium-fueled water reactors and plutonium-fueled gas-cooled reactors, the total annual and cumulative plutonium alpha activity in the low-level wastes for Cases 3 and 4 are greater than the other cases. The introduction of breeders will decrease the total annual and cumulative quantities of plutonium alpha activity in the low-level wastes as can be seen in Figs. 60 and 61 for Cases 1 and 2.

Figures 62 and 63 show the total yearly and cumulative amounts of plutonium beta activity in the low-level wastes. The trends are similar as for those found for plutonium alpha activity in the low-level wastes because the concentrations of the beta active ^{241}Pu are higher in the plutonium-fueled water reactors and plutonium-fueled gas-cooled reactors than in the fast breeder reactors.

Figures 64 and 65 show the total yearly and cumulative quantities of plutonium in the high-level wastes. Since all plutonium discharged from the gas-cooled reactors in Case 6 is not recovered for recycling but is retired with the high-level fission product wastes, the total annual and cumulative amounts of plutonium associated with the high-level fission-product wastes are greatest for Case 6. Since the plutonium from all the reactors in Case 4 is recycled, the amounts of plutonium associated with the high-level fission product wastes are least for this case. By the year 2000, the total cumulative plutonium in high-level wastes is 192,000 Kilograms for Case 6, 40,800 Kilograms for Case 2, 39,600 Kilograms for Case 1, 38,300 Kilograms for Case 3, 29,900 Kilograms for Case 5, and 17,500 Kilograms for Case 4.

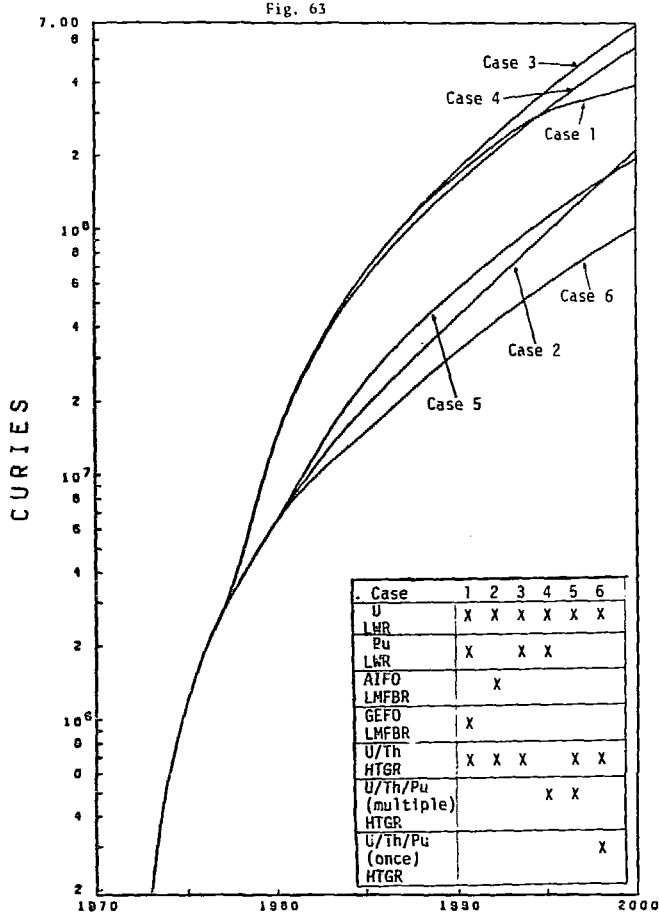
Figures 66 and 67 show the total yearly and cumulative amounts of plutonium alpha activity in the high-level wastes. Again, Cases 3 and 5 have larger amounts of plutonium alpha activity in their high-level wastes

Fig. 62



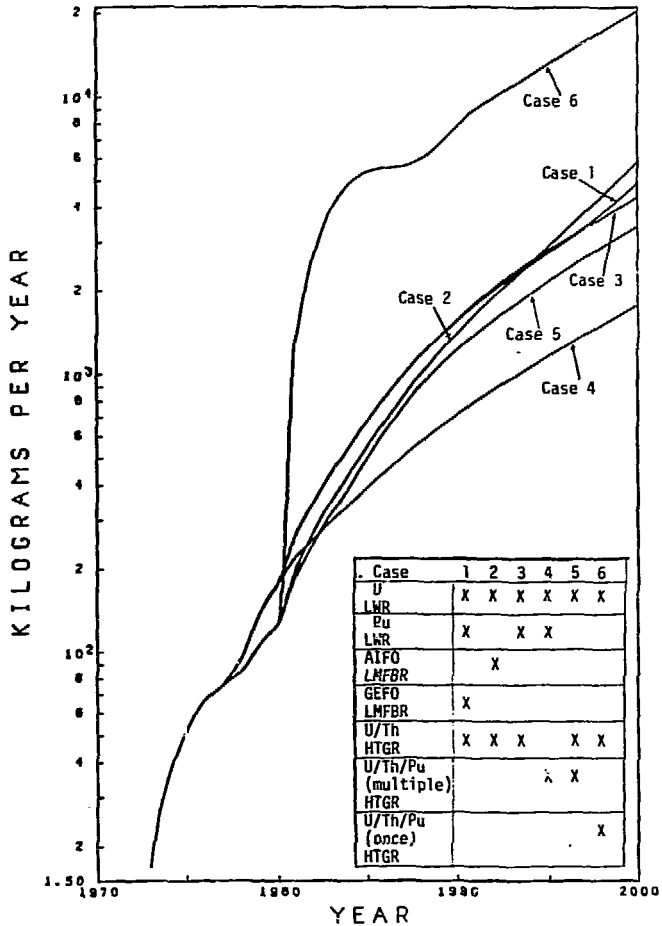
Yearly Quantity of Plutonium Beta Activity in Low-Level Wastes

Fig. 63



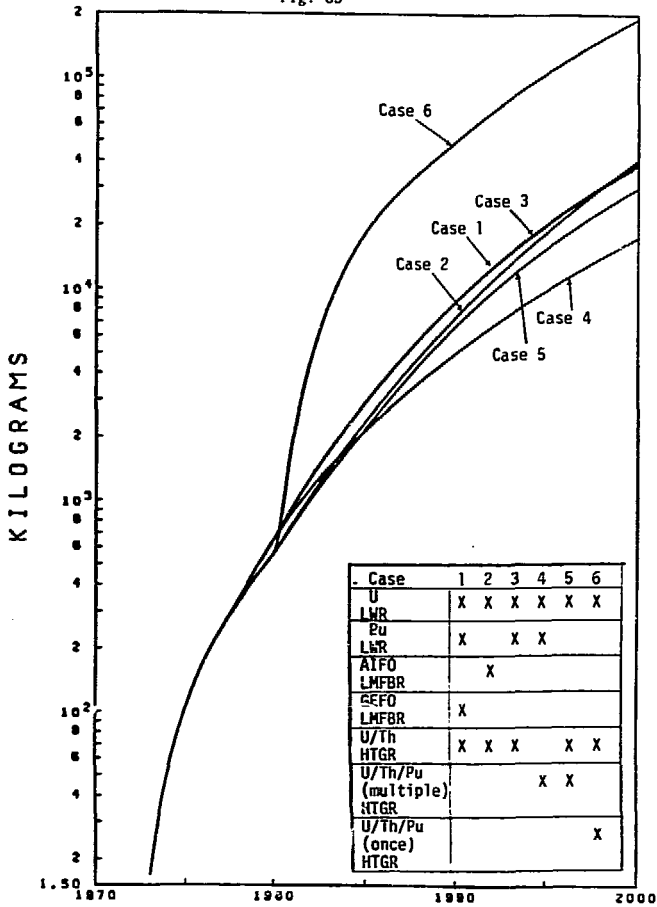
Total Plutonium Beta Activity in Low-Level Wastes

Fig. 64



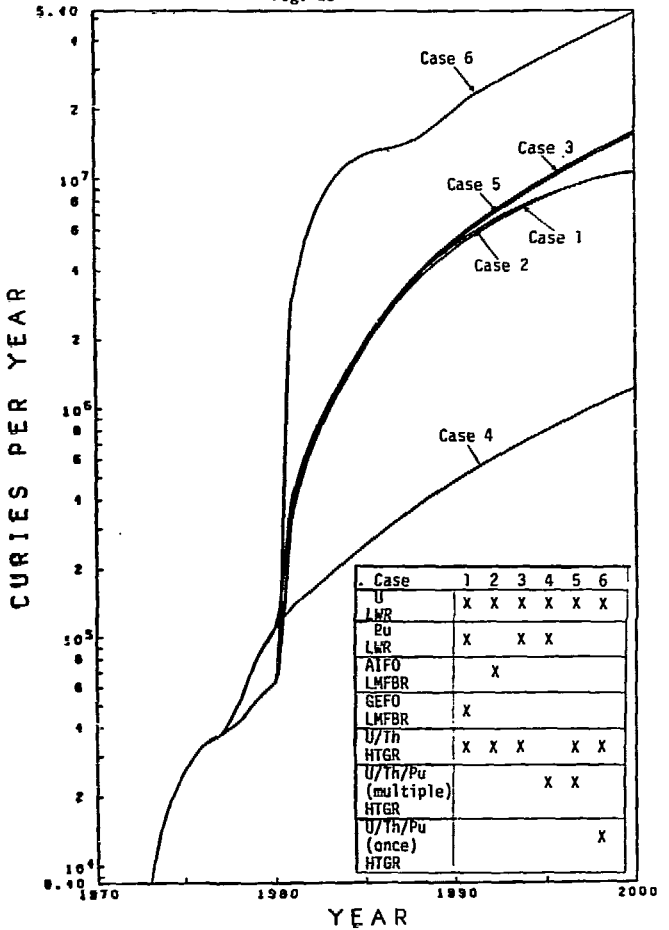
Yearly Quantity of Plutonium in High-Level Wastes

Fig. 65



Total Quantity of Plutonium in High-Level Wastes

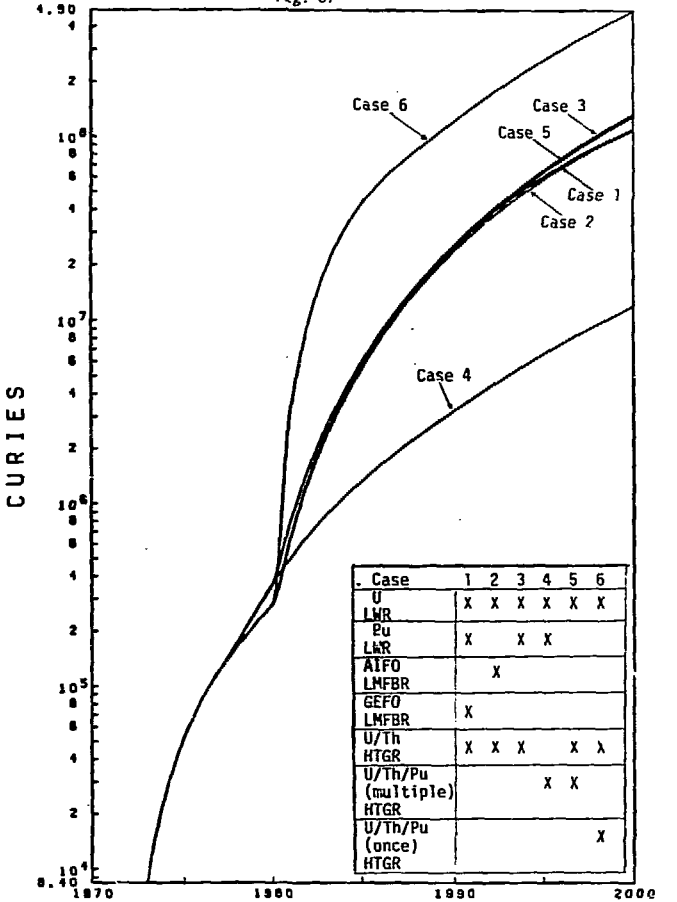
Fig. 66



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Yearly Quantity of Plutonium Alpha Activity in High-Level Wastes

Fig. 67



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Total Plutonium Alpha Activity in High-Level Wastes

than Cases 1 and 2 because of the high concentrations of ^{238}Pu and ^{240}Pu in the plutonium-fueled water reactors and plutonium-fueled gas-cooled reactors.

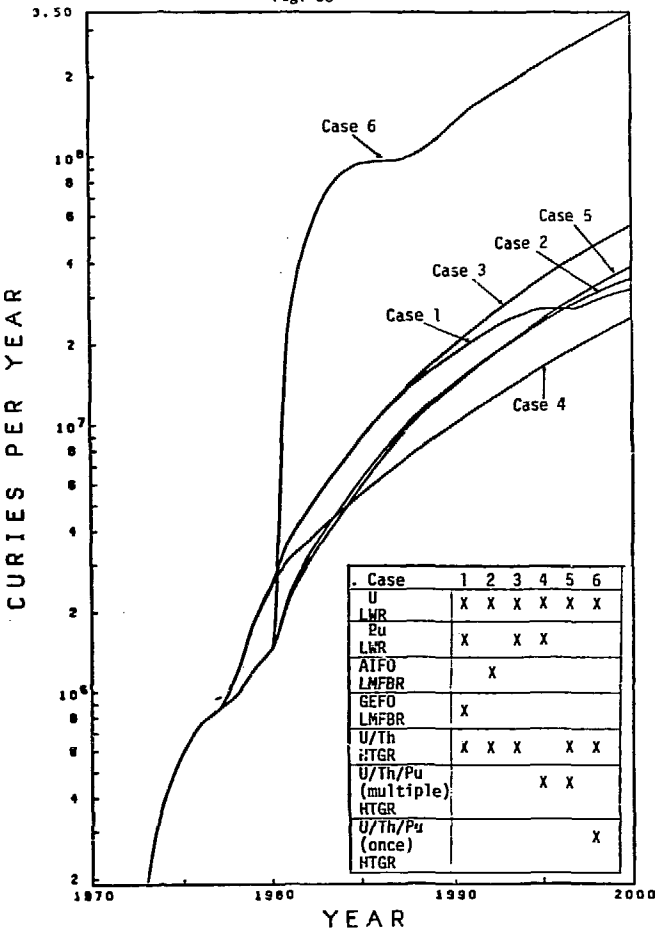
Figures 68 and 69 show the total yearly and cumulative amounts of plutonium beta activity in the high-level wastes. The trends are similar to those in Figs. 66 and 67 for the plutonium alpha activity in the high-level wastes.

According to the estimates shown in Figs. 58 and 64, the yearly amount of plutonium lost to the low-level wastes in reprocessing, fuel preparation, and fabrication operations is greater than the amount of plutonium associated with the high-level fission-product wastes in all cases, except Cases 5 and 6. However, assuming that essentially all the americium and curium follows the high-level fission-product wastes in fuel reprocessing, the total alpha activity in these high-level wastes will be far greater than that resulting directly from the plutonium losses associated with these wastes (c.f., Figs. 48, 49, 56, and 57). The amounts of plutonium in all of these wastes are significant, and it is important that careful attention be given to a waste management program which insures careful control of all of these wastes.

Uranium and Thorium Requirements

Natural uranium is required as fuel for the uranium-plutonium-fueled water reactors and as input to isotope separation plants to obtain enriched uranium for the uranium-fueled water reactors and the uranium-thorium-fueled gas-cooled reactors. Figures 70 and 71 show the total annual and cumulative natural uranium requirement for each of the six cases considered in this study. Initially natural uranium is required to obtain enriched uranium for the uranium-fueled water reactors for all six cases.

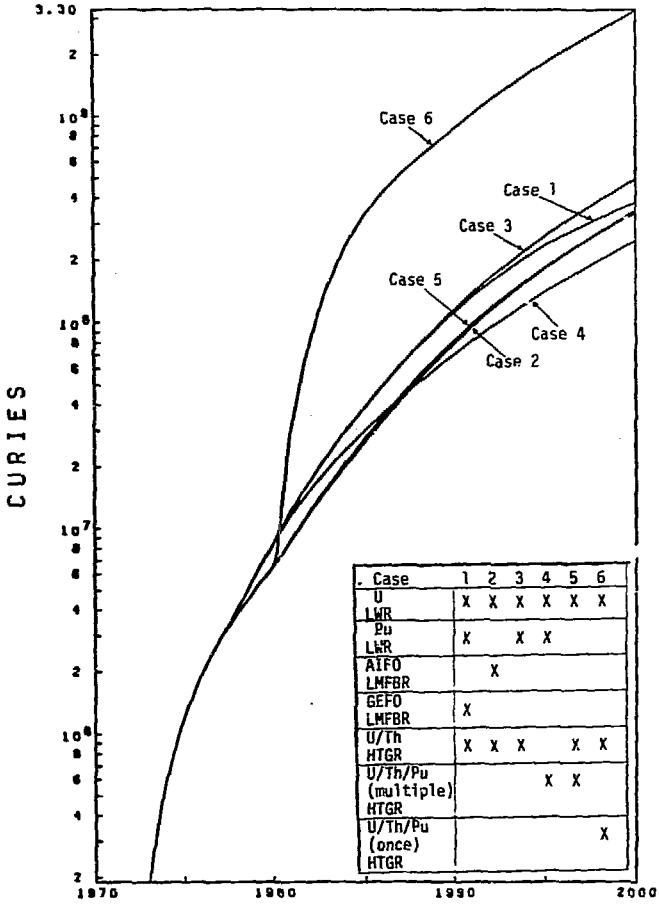
Fig. 68



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Yearly Quantity of Plutonium Beta Activity in High-Level Wastes

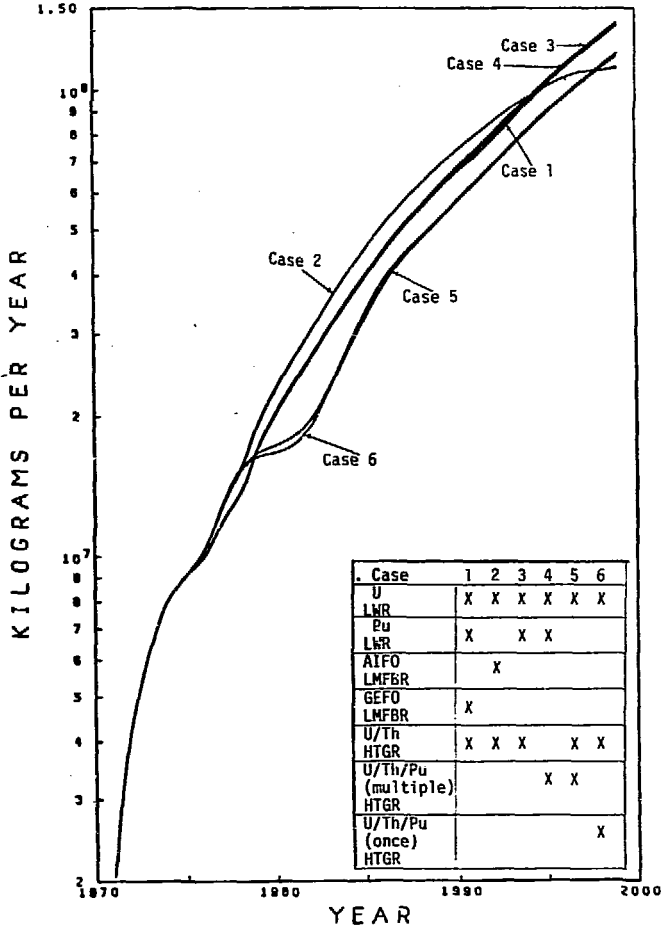
Fig. 69



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Total Plutonium Beta Activity in High-Level Wastes

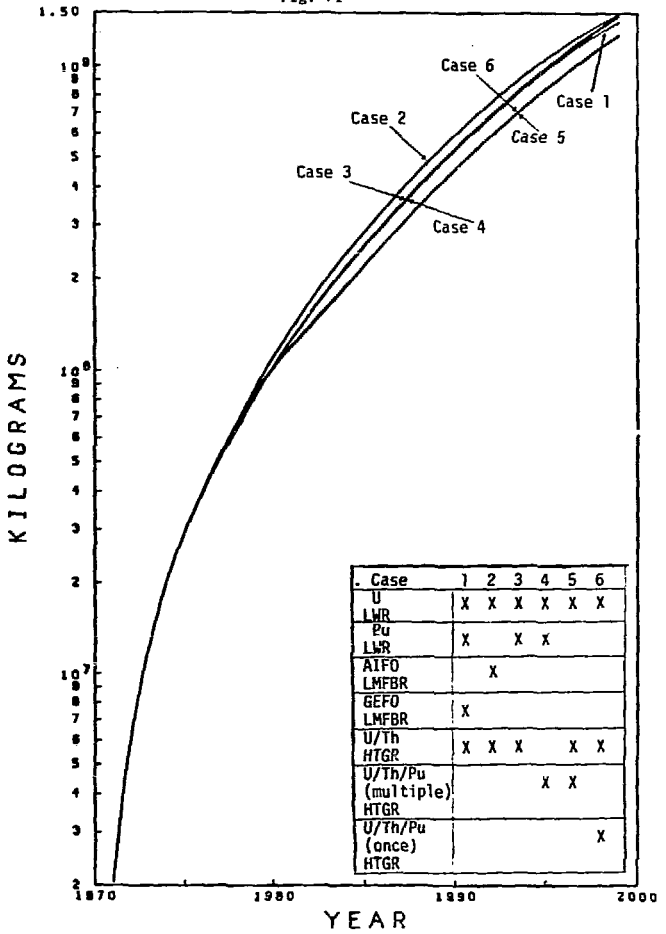
Fig. 70



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Yearly Quantity of Natural Uranium Required

Fig. 71



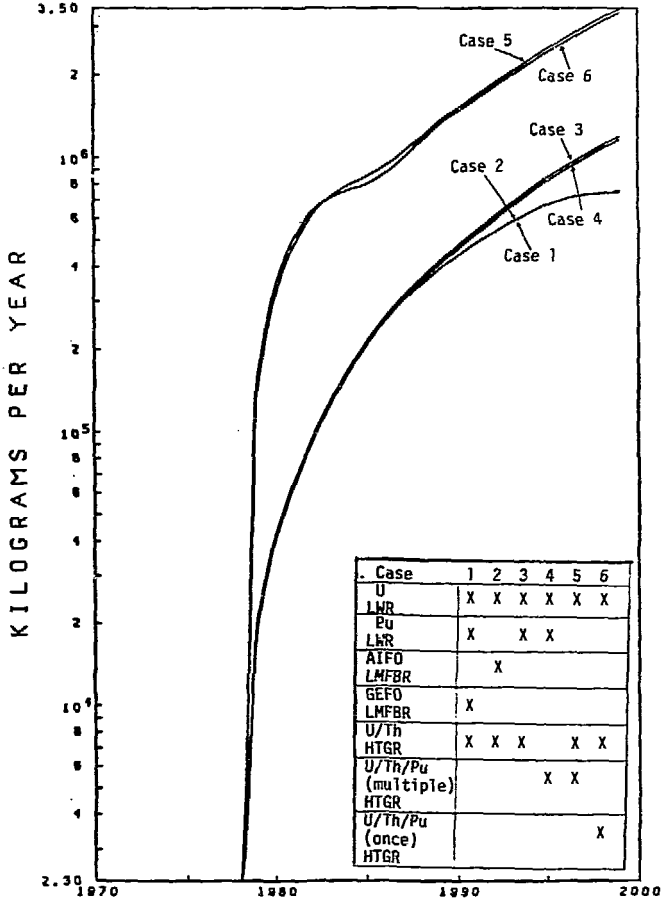
Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Total Natural Uranium Required

With the introduction of uranium-plutonium-fueled water reactors, as in Cases 1, 3, and 4, the annual natural uranium requirement for these cases is less than for Cases 2, 5, and 6, as shown in Fig. 70. In the year 1980, with the introduction of plutonium-fueled gas-cooled reactors in Cases 5 and 6, the annual natural uranium requirement for these cases become less than for all other cases. When fast breeder reactors are introduced in 1986, initially their total generating capacity is a small fraction of the total nuclear generating capacity. The main contribution to the total nuclear generating capacity is still from the water reactors, thus the total annual natural uranium requirement for Cases 1 and 2 remain greater than for all other cases. However, towards the end of the century, the total generating capacity of the fast breeders becomes a significant fraction of the total nuclear generating capacity and the annual natural uranium requirement is smaller for Cases 1 and 2 than for all other cases. Figure 71 shows that by the year 1999, the total cumulative natural uranium requirement is 1.49 billion Kilograms for Cases 2 and 3, 1.47 billion Kilograms for Case 4, 1.41 billion Kilograms for Case 1, 1.28 billion Kilograms for Case 6, and 1.26 billion Kilograms for Case 5. According to these estimates, the introduction of breeder reactors without plutonium recycling in water reactors will require an equal cumulative amount of natural uranium, by the year 1999, as a nuclear power-growth plan which only recycles its plutonium in water reactors. The cumulative natural uranium requirement can be reduced either by a nuclear power-growth plan which recycles plutonium in water reactors and breeder reactors or by a nuclear power-growth plan which recycles plutonium in gas-cooled reactors.

Figures 72 and 73 show the total annual and cumulative amounts of

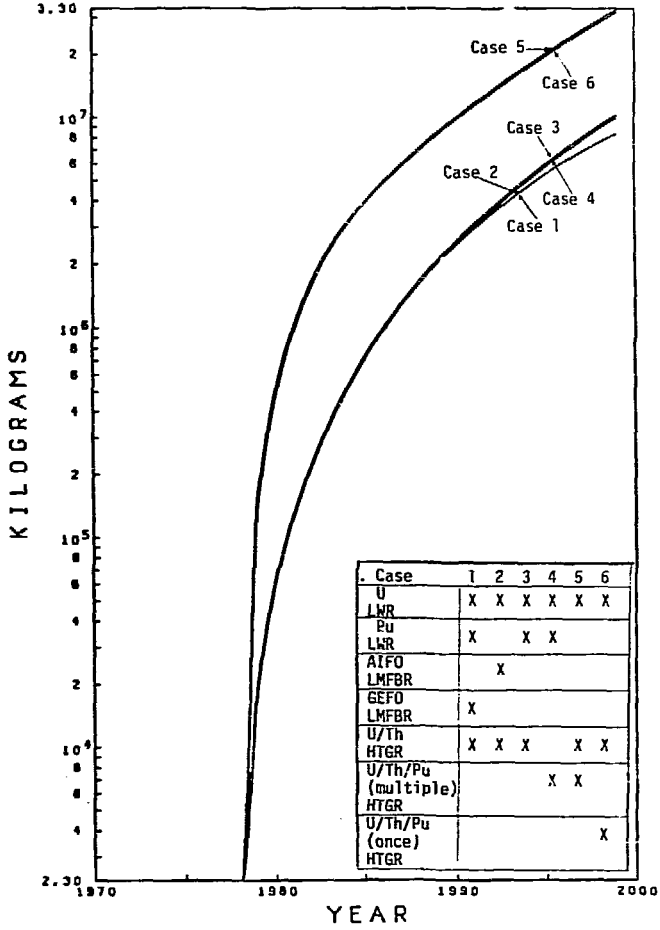
Fig. 72



Case	1	2	3	4	5	6
U LWR	X	X	X	X	X	X
Pu LWR	X		X	X		
AIFO LMFBR		X				
GEFO LMFBR	X					
U/Th HTGR	X	X	X		X	X
U/Th/Pu (multiple) HTGR				X	X	
U/Th/Pu (once) HTGR						X

Yearly Quantity of Natural Thorium Required

Fig. 73



Total Natural Thorium Required

natural thorium required as fuel for gas-cooled reactors. Cases 1 and 2 have the least amounts of natural thorium requirements since the total generating capacities of gas-cooled reactors in these two cases are less than all the other cases because of the assumption that gas-cooled reactors will penetrate only the non-breeder portion of the nuclear power market. Because the growth of gas-cooled reactors' generating capacities in Cases 5 and 6 is not limited by the AEC assumptions, but by the availability of plutonium, their generating capacities are higher than all the other cases, thus Cases 5 and 6 have the highest amounts of natural thorium requirements of all cases studied. By the year 1999, the total cumulative natural thorium required is 32.5 million Kilograms for Case 5, 31.6 million Kilograms for Case 6, 10.1 million Kilograms for Case 3, 9.87 million Kilograms for Case 4, 8.24 million Kilograms for Case 2, and 8.23 million Kilograms for Case 1.

Summary and Conclusions

This study illustrates the characteristics of plutonium production and utilization in the United States nuclear power industry for the remainder of this century. Representative material quantities and radioactivity amounts of actinides in uranium-fueled water reactors, plutonium-recycle water reactors, fast breeder reactors, thorium-uranium-fueled gas-cooled reactors, and plutonium-recycle gas-cooled reactors are calculated for each of these reactors, for each of the associated fuel-cycle process operations, and for the high-level and low-level wastes therefrom. The actual numerical values will vary with fuel burnup in the reactors, neutron spectrum, hold-up times in the fuel cycle, and the extend of process control applied to wastes from reprocessing, conversion, and fabrication. The quantities associated with plutonium recycle in water reactors are

illustrated for a water reactor[a] in which all the fuel is recycled mixed plutonium-uranium oxide and which obtains makeup plutonium from non-recycle uranium-fueled water reactors. To a good approximation, and ignoring changes in neutron spectrum these results can be used to estimate the material and radioactive quantities for recycling self-generated plutonium. A portion of such a reactor is fueled with enriched uranium and other portions are fueled with natural uranium and recycled plutonium. The material quantities associated with each type of fuel can then be scaled according to the power generated in each region. To this approximation, the total quantities of plutonium, americium, and curium for the total reactors in the United States power industry will be governed by the time-dependent material balance of total plutonium and will be the same whether the water reactors utilize plutonium on a self-generated basis or as plutonium burners.

Based upon the results presented herein, it is concluded that:

1. Significant quantities of plutonium will be utilized as water-reactor fuel, beginning in the near future and increasing rapidly through the 1980's. Using the AEC estimates for the introduction of breeders in 1986 and the very rapid growth thereafter, the breeders will not compete significantly for plutonium produced in uranium-fueled water reactors until the early 1990's. Thereafter, relatively little plutonium can be recycled in water reactors because of the demand for plutonium as start-up inventory for the rapidly growing fast-breeder industry.

2. The material quantities of plutonium to be reprocessed and fabricated for recycle fuel, compared on the basis of the same quantity of electrical energy generated from plutonium-uranium mixed-oxide fuel,

(a) This reactor concept is sometimes referred to as a "plutonium burner" or as a "dedicated" plutonium recycle reactor.

are comparable for water reactors and breeder reactors.

3. Recycling plutonium in water reactors builds greater quantities of higher-mass plutonium isotopes and significantly greater quantities of americium and curium than in the case of fast breeders, if compared on the basis of the same quantity of electrical energy produced from the mixed-oxide fuel. On this basis, recycled plutonium fuel in water reactors produces about four times as much americium alpha activity and 26 times as much curium alpha activity in high-level reprocessing wastes at the time of reprocessing as does recycled plutonium fuel in the breeder reactors.

4. The fractional fissile content in plutonium reprocessed from the breeder core and blanket discharge fuel is slightly greater than that in plutonium reprocessed from uranium-fueled water reactors and is significantly greater than that reprocessed from mixed-oxide fuel from water reactors.

5. The fuel value of plutonium produced in the uranium-fueled water reactors can be realized, and a significant reduction in the amount of plutonium to be processed in the nuclear fuel cycles can be obtained, by designing gas-cooled reactors to operate on fuel cycles which do not involve the multiple recycle of plutonium. The plutonium recovered from discharge fuel from uranium-fueled water reactors could replace the highly enriched ^{235}U make-up fissile material in the uranium-thorium fuel cycle.

6. Compared on the basis of the same quantity of electrical energy produced from the plutonium-uranium-thorium fuel, multiply-recycled plutonium fuel in gas-cooled reactors produces about 20% more americium alpha activity and 40% more curium alpha activity in high-level reprocessing wastes than the plutonium fuel in gas-cooled reactors where plu-

tonium is not multiply recycled.

7. The introduction of the breeder reactor in the context of the expanding nuclear power industry can reduce the total amount of alpha-emitting actinides processed yearly in the total of all reactor fuel cycles, as compared with a water-reactor system of the same total electrical power capability but without breeders. Similarly, the introduction of the plutonium-fueled gas-cooled reactor without the multiple recycle of plutonium in the context of the expanding nuclear power industry can reduce the total amount of alpha-emitting actinides processed yearly in the total of all reactor fuel cycles, as compared with a water-reactor system of the same total electrical power capability, but without plutonium recycle in the gas-cooled reactors.

8. On the basis of the fractional losses to process wastes used in this analysis, the amount of plutonium present in the low-level solid wastes from reprocessing, conversion, and fabrication will be greater than that in the high-level fission-product-actinide wastes at the time of reprocessing, for the fuel cycles of the uranium-plutonium-fueled water reactor, the fast-breeder reactor, and the thorium-uranium-plutonium-fueled gas-cooled reactor with multiple plutonium recycle. Permanent isolation of the plutonium from the environment is as important for the low-level wastes as it is for the high-level reprocessing wastes.

9. It is estimated that in the year 2000 the total actinides reprocessed yearly in the United States power industry will amount to approximately 620 metric tons of plutonium containing 149 million curies of alpha-active plutonium and 2.8 billion curies of beta-active plutonium. Approximately 6 million curies of alpha-active americium, and 446 million curies of alpha-active curium will be reprocessed yearly.

10. It is also estimated that in the year 2000 the yearly total natural uranium requirement for the United States power industry will be approximately 111,000 metric tons and the natural thorium requirement will be approximately 636 metric tons.

LIST OF APPENDICES

1. Listing of the ORIGEN Code (on microfiche)

2. Nuclear Data Library for the ORIGEN Code (on microfiche)

(See microfiche located in inside back cover)

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