Mass Flows for LMFBRs Fueled with Various Types of Plutonium and Fertile Material

U. P. Jenquin

December 1979

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INTRODUCTION

Under the current policy of operating light water reactors on a once-through cycle until the breeder reactor is introduced, breeder reactors must obtain their plutonium initially from the spent UO_2 fuel. This report presents results of neutronics analyses performed to determine fueling requirements and mass flows for a typical 1200 megawatt electric (MWe) liquid metal fast breeder reactor (LMFBR). This information could be used in future analyses of requirements for particular generating scenarios.

In performing the analyses, three plutonium compositions were considered to fuel the reactor. The composition depended on the amount of irradiation either a UO_2 or $\text{PuO}_2\text{-ThO}_2$ fuel had received in a light water reactor (LWR). Uranium and thorium fertile materials were considered. Calculations were performed to determine the cross sections, reactivity, and burnup for each fuel-fertile material configuration. Based on these calculations, the mass flows, plutonium enrichment requirements, and breeding ratios for each configuration were determined.

This study was prompted by the potential symbiotic relationship between LWRs and LMFBRs. For instance, the fuel produced by the LMFBR will have a very high fissile content. Thus, it may be more useful to use this bred fuel in LWRs and continue to fuel LMFBRs with plutonium discharged from LWRs. When using thorium fertile material in the LMFBR, the discharged uranium will have a very high ^{233}U content. When using uranium fertile material in the LMFBR blankets, the discharged plutonium will have a very high ^{239}Pu content. However, uranium fertile material in the LMFBR core will produce plutonium containing a large percentage of ^{240}Pu . This plutonium is used more efficiently in the LMFBR than the LWR. As ^{233}U is recycled in LWRs, it may be desirable to recycle LWR-discharged plutonium back in the LWR if the LMFBRs cannot use all of the plutonium. This is the main reason LMFBR calculations were done with plutonium obtained from a Pu-Th fueled LWR. This study does not address the use of the bred fuel in LWRs.

This study was funded under the Fuels Refabrication and Development Program. It parallels a study done by HEDL⁽¹⁾ and reported in Nuclear Technology (February 1979). The HEDL report was focused upon the effect of

various blanket materials as well as use of both ^{233}U and plutonium to fuel the LMFBR. The HEDL study was directed toward the objectives under the Non-proliferation Alternative Systems Assessment Program (NASAP). In contrast to this study, the HEDL study included only one plutonium composition--that of UO_2 fuel discharged at 30,000 MWd/MTM and evaluation of thorium data. This study utilized more recent thorium data in which the absorption cross sections are significantly different from those used by HEDL.

SUMMARY

Plutonium enrichment requirements, mass flows, and breeding ratios are presented for a 1,200 MWe LMFBR using plutonium with one of three isotopic compositions and either uranium or thorium fertile materials in the blankets and the core.

The mass-flow data for the LMFBR were obtained through calculation of cross sections, flux, reactivity, burnup and breeding ratios for each fuel-fertile material configuration. The amount of plutonium required to fuel an LMFBR is most sensitive to the isotopic composition of the plutonium and the type of fertile material used in the core. When the fissile fraction of the plutonium decreases, the total plutonium requirement increases but the fissile plutonium requirement decreases. The highest breeding ratios are obtained using the plutonium with the lowest fissile fraction. A change from uranium to thorium in the axial or radial blankets has little effect on enrichment requirements. However, changing the fertile material in the core from uranium to thorium increases the enrichment requirement by 25%.

The LMFBR mass-flow data generated in this study may be used to analyze symbiotic relationships with LWRs. It may be more beneficial to use the bred ^{233}U and ^{239}Pu to fuel LWRs because of the high fissile fraction of the product. The plutonium generated by LWRs has a lower fissile fraction; hence, it may be more beneficial to use it to fuel LMFBRs.

REACTOR DESCRIPTION

The study was performed for a reactor based on the General Electric 1200 MWe advanced oxide design.⁽²⁾ The reactor operates at full power for 315 days per year. Three plutonium compositions were considered as fuel for the reactor and uranium and thorium were considered as fertile materials.

The core and axial blanket parameters for the reference reactor are given in Table 1. The radial blanket parameters are also given in Table 1. A radial reflector, made of Inconel, was assumed to be 13.2 in. thick. The design did not include an axial reflector. The core and axial blanket are replaced every two years while the radial blanket is replaced every five years.

TABLE 1. Design Parameters

	<u>Core and Axial Blanket</u>	<u>Radial Blanket</u>
Electric Power (MWe) ^(a)	1200	
Thermal Power (MWt) ^(a)	3736	
Core Radius (in.)	65.3	
Core Height (in.)	46.8	
Blanket Thickness (in.)	13.0	13.6
Number of Fuel Assemblies	380	331
Number of Control Assemblies	20	
Fuel Pin Diameter (in.)	0.286	0.519
Pins Per Assembly	271	61
Cladding Thickness (in.)	0.012	0.015
Fuel Smear Density (% TD) ^(b)	88	91
Core Composition (Vol. %)		
Fuel	41.43	55.32
Structure	14.96	16.97
Sodium	43.61	27.71
Average Coolant Temperature (°C)	470	315

(a) 315 Full Power Days/Year

(b) Percent of Theoretical Density

The structural material is assumed to be 316 stainless steel with elemental percentages of 68.5, 17, 12, and 2.5 for iron, chromium, nickel, and molybdenum, respectively. The fertile uranium used in the core and blankets was assumed to be 0.3% depleted, i.e. 99.7% ^{238}U and 0.3% ^{235}U .

The plutonium enrichment required to maintain a critical reactor from startup through equilibrium was determined for three isotopic compositions of plutonium. The isotopics are identified in Table 2. The material referred to as LEU @ 30 is the plutonium discharged from an LWR after 30 GWd/MTM exposure, where the fuel initially consisted of low-enriched UO_2 . The LEU @ 50 plutonium is similarly described but discharged after 50 GWd/MTM exposure. The plutonium referred to as Pu-Th @ 55 is the discharge from an LWR fueled with plutonium and thorium and irradiated to 55 GWd/MTM. For this latter case, the plutonium charged to the LWR in the form of a $\text{ThO}_2\text{-PuO}_2$ fresh fuel was type LEU @ 30.

TABLE 2. Plutonium Compositions(3)

Isotope	Composition, atom %		
	LEU @ 30	LEU @ 50	Pu-Th @ 55
^{238}Pu	1.28	3.02	4.75
^{239}Pu	58.83	50.96	20.73
^{240}Pu	22.84	24.19	35.62
^{241}Pu	12.94	14.69	24.41
^{242}Pu	4.11	7.14	14.49

The reactor composition will be identified by nomenclature such as Pu-U8/U8/Th. The first item in this nomenclature refers to the enriching material in the core. Throughout this study, Pu is the only material used. The second, third, and fourth items in the nomenclature refer to the fertile materials in the core, axial blanket, and radial blanket, respectively. These will be either depleted uranium (U8) or thorium (Th).

CALCULATIONAL MODEL

The analytical approach taken in this study included generation of broad-group cross sections, which were then used in a reactivity and burnup calculation. Results of these calculations consisted of enrichment requirements, mass flows, and breeding ratios. The calculational methods are described below. The results of the calculations are presented in the next section.

CROSS SECTIONS

Four-group cross sections were generated with 1DX⁽⁴⁾ by collapsing 42-group cross sections over both the core and blanket neutron spectra individually. The 1DX code was used to perform a one-dimensional two-region multi-group diffusion theory calculation to generate neutron spectra for collapsing the cross-section data. The core consists of a uniform fuel mixture at a typical plutonium enrichment with appropriate isotopics. The radial blanket mixture was homogenized with appropriate volume fractions of fuel, structural, and coolant materials. Four-group cross sections were averaged over the core and over the radial blanket for several core enrichments using various plutonium isotopics. The four groups are described in Table 3.

The bulk of the 42-group cross sections were derived from ENDF/B-IV data by HEDL. For ²³²Th, preliminary Version V data, which are substantially more accurate than Version IV data, were used. The half-life of ²⁴¹Pu was taken as 14.5 years. The results are insensitive to the half-lives of the other isotopes.

TABLE 3. Energy Boundaries for Broad-Group Cross Sections

<u>Group No.</u>	<u>Lethargy Width</u>	<u>Energy Boundaries, eV</u>
1	2.5	8.209×10^5 to 1.0×10^7
2	2.0	1.111×10^5 to 8.209×10^5
3	2.0	1.503×10^4 to 1.111×10^5
4	-	0.0 to 1.503×10^4

REACTIVITY AND BURNUP

Reactivity and burnup calculations were based on the 4-group cross sections generated with 2DB. Two-dimensional R-Z diffusion theory calculations were performed with 2DB⁽⁵⁾ to determine the spatial neutron flux distribution. The core was divided into two enrichment regions (an inner and outer core) of equal volume to flatten the power. Axial symmetry was assumed. The number of mesh intervals used to represent each region are indicated in Figure 1.

FIGURE 1. 2DB Model for the Reactor

Multiple zones were used to represent fuel at different exposures within each region. Five zones were used for the radial blanket and two zones were used for each of the other regions. In the radial blanket the five zones are not all the same volume. In the other regions the zones are of equal volume. Within each region these multiple zones were arrayed in a checkerboard-type of pattern in order to approximate homogeneity.

The 2DB code was used to perform the burnup calculation on a zone basis. One-group cross sections were obtained by flux and volume weighting the four-group cross sections over each zone. The isotopics in each zone were updated

every 182.5 days based on a total power of 3224 MWt. This represents full reactor power of 3736 MWt with a capacity factor of 86%. After each year of exposure the appropriate fraction of fuel in each region was replaced by fresh fuel. Flux distributions, power distributions, mass inventories, reaction rates, and the breeding ratio were calculated before and after the fresh fuel was charged.

RESULTS

Using the calculational model just described, enrichment requirements, mass flows, and breeding ratios were determined for an LMFBR using several types of fuels.

ENRICHMENT

The core enrichment was determined such that the minimum neutron multiplication (k_{eff}) was unity. The results are given in Table 4 in terms of the fraction of plutonium atoms relative to total heavy atoms in the core.

TABLE 4. Summary of Enrichment Requirements Using Various Types of Plutonium

<u>Type of Pu</u>	<u>Enrichment, Pu Fraction</u>		
	<u>Pu-U8/U8/Th</u>	<u>Pu-U8/Th/Th</u>	<u>Pu-Th/Th/Th</u>
LEU @ 30	0.1382	0.1393	0.1735
LEU @ 50	0.1447	0.1458	0.1813
Pu-Th @ 55	0.1727	0.1740	0.2144

When the axial blanket is changed from uranium to thorium, the plutonium enrichment increases slightly. Depleted uranium has a larger fission cross section than thorium; hence, the required enrichment is reduced because of the axial blanket. In the case of the radial blanket the reactivity effect is negligible. Thus, the values given in the second column of Table 4 are identical to those for the LMFBR with a depleted uranium radial blanket.

When the core diluent is changed from uranium to thorium, the enrichment increases significantly because of the larger effective capture rate of thorium. For comparison, it is noted that if ENDF/B-IV thorium data were used in the analyses, the enrichment requirement would be increased still further because the thorium capture cross section is larger in Version IV than in Version V.

In changing plutonium types from LEU @ 30 to LEU @ 50 to Pu-Th @ 55, the enrichment increases because the fraction of the plutonium that is "fissile" (isotopes ^{239}Pu and ^{241}Pu) decreases. The fertile isotopes fission at high energies but the spectrum-averaged capture-to-fission ratio is higher for these isotopes. Consequently, their reactivity worths are somewhat less than the worths for the fissile isotopes. Relative isotopic worths are discussed more fully in Reference 6.

A typical reactivity history is shown in Figure 2 where the core diluent is depleted uranium. During a cycle (each year) reactivity decreases due to the buildup of fission products. At the end of each cycle fresh fuel is added and reactivity is increased. From cycle to cycle reactivity increases because of the buildup of fissile material in the radial blanket. The minimum reactivity usually occurs at the end of the second cycle.

FIGURE 2. Reactivity of Pu-U8/U8/Th System Using LEU @ 30 Plutonium

When thorium is the core diluent, the reactivity history is quite different as shown in Figure 3. With a 27 day half-life, ^{233}Pa causes the reactivity swing during each cycle to be more drastic. Initially, the buildup of fission products, the buildup of ^{233}Pa , and the burnout of fissile Pu all have negative reactivity effects. Toward the end of the cycle the buildup of ^{233}U has a positive reactivity effect and ^{233}Pa approaches saturation so

its reactivity contribution is not changing appreciably with time. The reactivity calculated at mid-cycle was always the lowest with the minimum value occurring in of the first cycle. Finer time increments are needed to more accurately track the reactivity and determine the minimum reactivity. As in the case with uranium diluent, the cycle to cycle reactivity increases because of the buildup of fissile material in the radial blanket.

FIGURE 3. Reactivity of Pu-Th/Th/Th System Using LEU @ 30 Plutonium

MASS FLOW

The annual mass flows for the various combinations of plutonium types and fertile materials are discussed here and tabulated in Appendix A. In these analyses the feed material is assumed to be constant from year to year, except for the radial blanket in which the zone volumes differ. Since the inner core, outer core, and axial blanket are on a two-year cycle, the initial quantities of feed material are twice the values shown in Appendix A.

As a reference, data are given for the Pu-U8/U8/U8 reactor fueled with LEU @ 30 plutonium (Tables A.1 and A.2). In comparing the quantities discharged from the core and axial blanket at 2, 3, 4, and 5 years, the values calculated at 2 years can be assumed to be equilibrium discharge values. The radial blanket must be calculated out to 5 years because at equilibrium the discharged radial blanket has been in the reactor for 5 years.

Mass flows for a thorium radial blanket are shown in Table A.3. The type of plutonium used in the core has virtually no effect on the radial blanket, but there is a small effect on the radial blanket isotopics depending on the diluent material in the core. The mass flow in the radial blanket also has a slight dependence on the plutonium distribution between the inner core and the outer core. This effect has not been studied thoroughly because it is secondary compared to the overall reactor mass flows.

Mass flows for the Pu-U8/U8/Th, Pu-U8/Th/Th, and Pu-Th/Th/Th reactors using LEU @ 30 plutonium are given in Tables A.4, A.5, and A.6, respectively. When the axial blanket is changed from uranium to thorium, the effect on the inner core and outer core is small. When the fertile material in the inner and outer cores is changed from uranium to thorium, the plutonium enrichment must be increased by 25%.

Mass flows for the Pu-U8/U8/Th, Pu-U8/Th/Th, and Pu-Th/Th/Th reactors using LEU @ 50 plutonium are given in Tables A.7, A.8, and A.9, respectively. Mass flows for the Pu-U8/U8/Th, Pu-U8/Th/Th/, and Pu-Th/Th/Th reactors using Pu-Th @ 55 plutonium are given in Tables A.10, A.11, and A.12, respectively. As was the case for the LEU @ 30 plutonium, the effect of changing the axial blanket from uranium to thorium is small. When the fertile material in the inner and outer cores is changed from uranium to thorium, the plutonium enrichment must be increased by 25%.

In the mass-flow tables ^{233}Pa has been listed separately so that one can determine the quantity of ^{233}U not recovered for various time increments between discharge and reprocessing. For a holdup time of 3 months after discharge, 99% of the total ^{233}U potentially available from ^{232}Th captures will have been formed.

The mass-flow data given in Appendix A are needed to evaluate symbiotic relationships with LWRs as suggested in the introduction.

BREEDING RATIO

Equilibrium breeding ratios were calculated for the various reactor configurations. The breeding ratio is defined as:

$$BR = \frac{\sum_c^{Th-232} + \sum_c^{U-238} + \sum_c^{Pu-238} + \sum_c^{Pu-240}}{\sum_a^{Pa-233} + \sum_a^{U-233} + \sum_a^{U-235} + \sum_a^{Pu-239} + \sum_a^{Pu-241}}$$

where $\sum$ is the macroscopic one-group cross section, subscript c refers to capture and subscript a refers to absorptions. The values calculated at 1 1/2 years are listed in Table 5.

TABLE 5. Breeding Ratios for Plutonium-Fueled LMFBRs

Type of Pu	Breeding Ratio			
	<u>Pu-U8/U8/U8</u>	<u>Pu-U8/U8/Th</u>	<u>Pu-U8/Th/Th</u>	<u>Pu-Th/Th/Th</u>
LEU @ 30	1.353	1.347	1.332	1.170
LEU @ 50		1.383	1.367	1.204
Pu-Th @ 55		1.542	1.525	1.359

In going from a uranium blanket to a thorium blanket, the breeding ratio decreases slightly because core enrichment is slightly higher. In going from uranium to thorium fertile material in the core, the breeding ratio decreases significantly. This decrease is caused by the increased Pu enrichment and the large ^{233}U cross section.

The breeding ratio increases as the plutonium composition changes to that of LEU @ 50 and Pu-Th @ 55. One reason for the increased breeding ratio is the fractional increase of fertile isotopes in the plutonium. Since these isotopes have appreciably large fission cross sections, the quantity of fissile plutonium is reduced as shown in Table 6. The second reason for the increased breeding ratios is the increase in ^{241}Pu content and decrease in

^{239}Pu content of the plutonium. As shown in Reference 6, ^{241}Pu is worth twice as much as ^{239}Pu in terms of enrichment value. The higher worth for ^{241}Pu is due to the lower capture-to-fission ratio.

TABLE 6. Fissile Plutonium Enrichments

<u>Type of Pu</u>	<u>Enrichment</u>			
	<u>Pu-U8/U8/U8</u>	<u>Pu-U8/U8/Th</u>	<u>Pu-U8/Th/Th</u>	<u>Pu-Th/Th/Th</u>
LEU @ 30	0.0992	0.0992	0.1000	0.1245
LEU @ 50		0.0950	0.0957	0.1190
Pu-Th @ 55		0.0780	0.0785	0.0968

CONCLUSIONS

Based on the results of calculations described in previous sections, a number of conclusions about enrichment requirements and the effect of fertile material can be drawn. The enrichment requirement increases as plutonium composition changes to the higher isotopes, that is, as ^{242}Pu , ^{241}Pu , and ^{240}Pu content increase while the ^{239}Pu content decreases. In terms of only fissile plutonium isotopes, the enrichment decreases because the fertile plutonium isotopes have appreciable fission cross sections. There is also a corresponding increase in the breeding ratio when the fraction of higher plutonium isotopes increases.

When the fertile material in the blankets is changed from depleted uranium to thorium, the plutonium enrichment requirement and breeding ratio do not change significantly. However, when thorium replaces uranium in the core, the enrichment requirement increases by 25% and the breeding ratio decreases by 12%, independent of the type of plutonium.

The fissile production rate is about 10% higher in the axial and radial blankets when uranium rather than thorium is used as the fertile material. This is assumed to result from the higher flux level in the uranium blanket, which is aided by ^{235}U fissions. The axial and radial blanket produce approximately equal amounts of thorium annually.

The amount of ^{233}U produced in the core is about twice that produced in the blankets if thorium fertile material is used in the core as well as the blankets. Thus, with a 25% plutonium enrichment penalty, one can triple the ^{233}U production rate.

A negative reactivity slope occurs when uranium is the fertile material in the core. When thorium is the fertile material in the core, the reactivity behavior goes through a minimum at mid-cycle and gains reactivity from mid-cycle until fuel discharge occurs. Thus, it is important to track the reactivity behavior of the fuel during burnup so that a neutron multiplication of unity or greater is always maintained during the burnup.

The rise in reactivity near the end of the cycle for the core containing thorium fertile material is due to the relative reactivity worth of plutonium

fissile isotopes that are consumed compared to the ^{233}U that is formed. The amount of reactivity that is held out by protactinium with a 27-day half-life, reappears after decay.

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APPENDIX A

MASS-FLOW DATA

APPENDIX A
MASS-FLOW DATA

This appendix contains the tables of mass-flow data.

TABLE A.1. Annual Mass Flow for Pu-U8/U8/U8 Reactor
Using LEU @ 30 Discharge Plutonium

	Kilograms/Year			
	<u>Isotope</u>	<u>Inner Core</u>	<u>Outer Core</u>	<u>Axial Blanket</u>
<u>Feed</u>				
	U-235	23.8	22.8	31.0
	U-238	7988.4	7652.8	10,239.0
	Pu-238	13.9	18.3	
	Pu-239	643.7	842.6	
	Pu-240	250.9	328.5	
	Pu-241	142.8	186.9	
	Pu-242	45.5	59.6	
<u>Discharge @ 1 Year</u>				
	U-235	16.2	17.3	28.0
	U-236	1.7	1.2	
	U-238	7605.0	7387.6	10,132.0
	Pu-238	11.0	15.4	
	Pu-239	741.3	860.2	42.6
	Pu-240	273.8	344.5	0.4
	Pu-241	103.5	145.0	0
	Pu-242	49.9	63.7	
	Am-241	5.1	7.2	
<u>Discharge @ 2 Years</u>				
	U-235	11.0	13.4	25.4
	U-236	2.6	2.0	
	U-238	7234.6	7141.8	10,025.2
	Pu-238	8.7	13.1	
	Pu-239	796.3	866.9	185.9
	Pu-240	299.6	359.3	5.7
	Pu-241	80.9	117.5	0.1
	Pu-242	51.7	65.8	
	Am-241	7.7	11.7	

TABLE A.1 (contd)

<u>Isotope</u>	<u>Kilograms/Year</u>		
	<u>Inner Core</u>	<u>Outer Core</u>	<u>Axial Blanket</u>
<u>Discharge @ 3 Years</u>			
U-235	11.0	13.5	25.4
U-236	2.7	2.0	
U-238	7232.4	7151.4	10,024.6
Pu-238	87	13.2	
Pu-239	796.1	66.9	186.0
Pu-240	299.5	58.8	5.7
Pu-241	80.8	18.3	0.1
Pu-242	51.7	65.7	
Am-241	7.7	11.8	
<u>Discharge @ 4 Years</u>			
U-235	11.0	13.5	25.6
U-236	2.6	2.0	
U-238	7237.8	150.8	10,025.4
Pu-238	8.7	13.2	
Pu-239	795.5	866.9	185.4
Pu-240	299.1	358.8	5.7
Pu-241	81.0	118.2	0.1
Pu-242	51.7	65.7	
Am-241	7.7	11.8	
<u>Discharge @ 5 Years</u>			
U-235	11.1	13.5	25.4
U-236	2.6	2.0	
U-238	7241.0	7150.6	10,025.8
Pu-238	8.7	13.2	185.0
Pu-239	795.2	866.9	5.6
Pu-240	298.9	358.8	0.1
Pu-241	81.1	118.2	
Pu-242	51.7	65.7	
Am-241	7.7	11.8	

TABLE A.2 Annual Mass Flow for Uranium Radial Blanket of Pu-U8/U8/U8
Reactor Using LEU @ 30 Discharge Plutonium

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Zone 7</u>	<u>Zone 8</u>	<u>Zone 9</u>	<u>Zone 10</u>	<u>Zone 11</u>
<u>Feed</u>					
U-235	22.2	22.2	22.2	22.2	22.2
U-238	7366.2	7371.8	7377.4	7383.0	7388.6
<u>Discharge</u>					
U-235	20.9	19.8	18.6	17.7	16.7
U-238	7320.4	7283.0	7243.0	7207.6	7168.8
Pu-239	42.6	80.6	118.5	151.1	184.2
Pu-240	0.4	1.5	3.2	5.4	8.2
Pu-241	0	0	0.1	0.1	0.2
<u>Irradiation time, years</u>					
	1	2	3	4	5

TABLE A.3 Annual Mass Flow for Thorium Radial Blanket

Isotope	Kilograms/Year				
	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11
<u>Feed</u>					
Th-232	6623.0	6628.2	6633.2	6638.2	6643.2
<u>Discharge for Uranium Diluent in Core</u>					
Th-232	6582.8	6550.0	6514.8	6483.4	6449.0
Pa-233	4.1	3.9	4.1	4.0	4.0
U-233	34.8	69.1	102.8	131.8	160.8
U-234	0.1	0.4	1.0	1.7	2.7
U-235	0	0	0	0	0.1
<u>Discharge for Thorium Diluent in Core</u>					
Th-232	6580.0	6544.8	6507.0	6473.2	6436.4
Pa-233	4.5	4.2	4.3	4.2	4.3
U-233	37.1	73.5	109.0	139.4	169.7
U-234	0.1	0.5	1.1	1.9	3.0
U-235	0	0	0	0	0.1
<u>Irradiation time, years</u>					
	1	2	3	4	5

TABLE A.4 Annual Mass Flow for Pu-U8/U8/Th Reactor
Using LEU @ 30 Discharge Plutonium

<u>Isotope</u>	<u>Kilograms/Year</u>		
	<u>Inner Core</u>	<u>Outer Core</u>	<u>Axial Blanket</u>
<u>Feed</u>			
U-235	23.8	22.8	31.0
U-238	7988.4	7652.8	10,239.0
Pu-238	13.9	18.3	
Pu-239	643.7	842.6	
Pu-240	250.9	328.5	
Pu-241	142.8	186.9	
Pu-242	45.5	59.6	
<u>Discharge @ 1 Year</u>			
U-235	16.1	17.3	28.5
U-236	1.7	1.2	
U-238	7597.7	7386.2	10,132.6
Pu-238	11.0	15.4	
Pu-239	742.8	860.4	97.2
Pu-240	275.0	345.3	1.0
Pu-241	102.9	144.8	0
Pu-242	50.0	63.7	
Am-241	5.0	7.2	
<u>Discharge @ 2 Years</u>			
U-235	10.9	13.4	26.2
U-236	2.7	2.0	
U-238	7219.2	7141.2	10,026.6
Pu-238	8.6	13.1	
Pu-239	798.0	867.2	186.9
Pu-240	302.2	360.6	3.9
Pu-241	80.1	117.3	0
Pu-242	51.9	65.8	
Am-241	7.6	11.7	

TABLE A.5 Annual Mass Flow for Pu-U8/Th/Th Reactor
Using LEU @ 30 Discharge Plutonium

Isotope	Kilograms/Year		Isotope	Axial Blanket
	Inner Core	Outer Core		Kilograms/Year
<u>Feed</u>				
U-235	23.8	22.8	Th-232	9207.6
U-238	7979.4	7641.8		
Pu-238	14.1	18.4		
Pu-239	649.1	849.1		
Pu-240	253.1	331.1		
Pu-241	143.9	188.3		
Pu-242	45.9	60.1		
<u>Discharge @ 1 Year</u>				
U-235	16.1	17.3	Th-232	9112.8
U-236	1.7	1.2	Pa-233	10.0
U-238	7587.8	7374.2	U-233	79.5
Pu-238	11.1	15.5	U-234	0.4
Pu-239	746.5	865.2	U-235	0
Pu-240	277.3	348.0		
Pu-241	103.6	145.7		
Pu-242	50.4	64.3		
Am-241	5.1	7.2		
<u>Discharge @ 2 Years</u>				
U-235	10.9	13.4	Th-232	9018.2
U-236	2.7	2.0	Pa-233	10.0
U-238	7209.6	7128.8	U-233	158.9
Pu-238	8.8	13.2	U-234	1.8
Pu-239	800.3	870.7	U-235	0
Pu-240	304.4	363.3		
Pu-241	80.7	118.0		
Pu-242	52.3	66.4		
Am-241	7.7	11.8		

TABLE A.6 Annual Mass Flow for Pu-Th/Th/Th Reactor
Using LEU @ 30 Discharge Plutonium

<u>Feed</u>	<u>Isotope</u>	<u>Kilograms/Year</u>		
		<u>Inner Core</u>	<u>Outer Core</u>	<u>Axial Blanket</u>
	Th-232	7037.4	6653.4	9207.6
	Pu-238	16.3	21.4	
	Pu-239	754.5	987.4	
	Pu-240	294.1	384.9	
	Pu-241	167.4	219.0	
	Pu-242	53.4	69.9	
<u>Discharge @ 1 Year</u>				
	Th-232	6715.4	6433.2	9108.8
	Pa-233	31.7	21.6	10.2
	U-233	226.4	163.1	82.7
	U-234	4.2	2.2	0.4
	U-235	0.1	0	0
	Pu-238	13.0	18.1	
	Pu-239	534.9	768.0	
	Pu-240	306.1	395.9	
	Pu-241	120.4	168.8	
	Pu-242	58.3	74.6	
	Am-241	6.0	8.4	
<u>Discharge @ 2 Years</u>				
	Th-232	6411.8	6232.4	9012.6
	Pa-233	30.2	19.6	10.0
	U-233	378.8	285.9	163.4
	U-234	15.2	7.9	1.8
	U-235	0.8	0.3	0
	Pu-238	10.4	15.4	
	Pu-239	380.6	606.2	
	Pu-240	302.8	396.0	
	Pu-241	92.1	135.8	
	Pu-242	60.3	76.9	
	Am-241	9.1	13.7	

TABLE A.7 Annual Mass Flow for Pu-U8/U8/Th Reactor
Using LEU @ 50 Discharge Plutonium

	Kilograms/Year			
	<u>Isotope</u>	<u>Inner Core</u>	<u>Outer Core</u>	<u>Axial Blanket</u>
<u>Feed</u>				
	U-235	23.6	22.6	31.0
	U-238	7936.6	7586.6	10,239.0
	Pu-238	34.5	45.1	
	Pu-239	584.1	763.9	
	Pu-240	278.4	364.1	
	Pu-241	169.8	222.1	
	Pu-242	82.9	108.4	
<u>Discharge @ 1 Year</u>				
	U-235	16.0	17.2	28.5
	U-236	1.7	1.2	
	U-238	7548.2	7322.4	10,132.6
	Pu-238	27.3	38.1	
	Pu-239	700.3	798.5	97.2
	Pu-240	295.2	373.9	1.0
	Pu-241	120.6	170.5	0
	Pu-242	85.6	110.8	
	Am-241	6.0	8.5	
<u>Discharge @ 2 Years</u>				
	U-235	10.8	17.4	26.2
	U-236	2.6	2.0	
	U-238	7172.0	7079.8	10,026.6
	Pu-238	21.4	32.4	
	Pu-239	767.5	817.7	186.9
	Pu-240	316.9	383.8	3.9
	Pu-241	91.8	136.6	0
	Pu-242	85.2	111.1	
	Am-241	8.9	13.8	

TABLE A.8 Annual Mass Flow for Pu-U8/Th/Th Reactor
Using LEU @ 50 Discharge Plutonium

	Kilograms/Year		Isotope	Axial Blanket	
	Inner core	Outer Core		Kilograms/Year	
<u>Feed</u>					
	U-235	23.6	22.6	Th-232	9207.6
	U-238	7928.4	7574.8		
	Pu-238	34.7	45.5		
	Pu-239	588.3	770.0		
	Pu-240	280.4	367.0		
	Pu-241	171.1	223.8		
	Pu-242	83.5	109.2		
<u>Discharge @ 1 Year</u>					
	U-235	16.0	17.2	Th-232	9112.8
	U-236	1.7	1.2	Pa-233	10.0
	U-238	7539.8	7309.0	U-233	79.5
	Pu-238	27.4	38.4	U-234	0.4
	Pu-239	703.1	803.1	U-235	0
	Pu-240	297.2	376.8		
	Pu-241	121.4	171.6		
	Pu-242	86.2	111.7		
	Am-241	6.0	8.5		
<u>Discharge @ 2 Years</u>					
	U-235	10.8	13.2	Th-232	9018.2
	U-236	2.6	2.0	Pa-233	9.9
	U-238	7164.0	7065.6	U-233	158.9
	Pu-238	21.6	32.7	U-234	1.8
	Pu-239	769.1	821.0	U-235	0
	Pu-240	318.9	386.7		
	Pu-241	92.4	137.3		
	Pu-242	85.9	111.9		
	Am-241	9.0	13.9		

TABLE A.9 Annual Mass Flow for Pu-Th/Th/Th Reactor
Using LEU @ 50 Discharge Plutonium

	Isotope	Kilograms/Year		
		Inner Core	Outer Core	Axial Blanket
<u>Feed</u>	Th-232	6981.2	6580.4	9207.6
	Pu-238	40.3	52.7	
	Pu-239	683.1	893.5	
	Pu-240	325.6	426.0	
	Pu-241	198.6	259.8	
	Pu-242	96.9	126.8	
<u>Discharge @ 1 Year</u>				
	Th-232	6659.6	6363.6	9108.6
	Pa-233	31.5	21.4	10.2
	U-233	225.9	160.7	82.9
	U-234	4.2	2.1	0.4
	U-235	0.1	0	0
	Pu-238	32.0	44.5	
	Pu-239	484.5	697.0	
	Pu-240	329.5	428.9	
	Pu-241	140.9	198.8	
	Pu-242	99.9	129.4	
	Am-241	7.0	9.9	
<u>Discharge @ 2 Years</u>				
	Th-232	6358.2	6164.8	9012.2
	Pa-233	30.0	19.4	10.0
	U-233	376.7	282.5	163.6
	U-234	15.2	7.8	1.9
	U-235	0.8	0.3	0
	Pu-238	25.6	38.0	
	Pu-239	345.6	551.0	
	Pu-240	320.4	423.2	
	Pu-241	105.9	158.1	
	Pu-242	99.4	129.5	
	Am-241	10.6	16.2	

TABLE A.10 Annual Mass Flow for Pu-U8/U8/Th Reactor
Using Pu-Th @ 55 Discharge Plutonium

	Kilograms/Year			
	<u>Isotope</u>	<u>Inner Core</u>	<u>Outer Core</u>	<u>Axial Blanket</u>
<u>Feed</u>				
	U-235	23.0	21.6	31.0
	U-238	7717.0	7298.0	10,239.0
	Pu-238	64.7	84.7	
	Pu-239	283.5	371.0	
	Pu-240	489.1	640.1	
	Pu-241	336.6	440.5	
	Pu-242	200.7	262.6	
<u>Discharge @ 1 Year</u>				
	U-235	15.6	16.5	28.5
	U-236	1.6	1.1	
	U-238	7340.8	7043.8	10,132.8
	Pu-238	51.2	71.2	
	Pu-239	482.3	486.6	97.0
	Pu-240	459.8	605.8	1.0
	Pu-241	233.2	333.2	0
	Pu-242	202.5	264.2	
	Am-241	11.7	16.7	
<u>Discharge @ 2 Years</u>				
	U-235	10.5	12.7	26.2
	U-236	2.6	1.9	
	U-238	6975.6	6810.2	10,026.8
	Pu-238	40.2	61.0	
	Pu-239	609.0	566.1	186.8
	Pu-240	446.0	581.2	3.8
	Pu-241	168.4	260.1	0
	Pu-242	198.2	261.5	
	Am-241	17.2	26.9	

TABLE A.11 Annual Mass Flow for Pu-U8/Th/Th Reactor
Using Pu-Th @ 55 Discharge Plutonium

	Kilograms/Year		Isotope	Axial Blanket	
	Inner core	Outer Core		Kilograms/Year	
<u>Feed</u>					
	U-235	22.9	21.6	Th-232	9207.6
	U-238	7707.0	7284.4		
	Pu-238	65.2	85.3		
	Pu-239	285.5	373.8		
	Pu-240	492.7	645.0		
	Pu-241	339.0	443.9		
	Pu-242	202.1	264.6		
<u>Discharge @ 1 Year</u>					
	U-235	15.5	16.5	Th-232	9112.8
	U-236	1.6	1.1	Pa-233	10.0
	U-238	7330.6	7029.0	U-233	79.4
	Pu-238	51.5	72.0	U-234	0.4
	Pu-239	483.8	489.1	U-235	0
	Pu-240	463.0	610.2		
	Pu-241	234.7	335.2		
	Pu-242	203.9	266.1		
	Am-241	11.8	16.8		
<u>Discharge @ 2 Years</u>					
	U-235	10.5	12.7	Th-232	9018.4
	U-236	2.6	1.9	Pa-233	9.9
	U-238	6965.6	6794.6	U-233	158.8
	Pu-238	40.5	61.2	U-234	1.8
	Pu-239	609.7	568.0	U-235	0
	Pu-240	448.9	585.2		
	Pu-241	169.6	261.5		
	Pu-242	199.6	263.4		
	Am-241	17.3	27.1		

TABLE A.12 Annual Mass Flow for Pu-Th/Th/Th Reactor
Using Pu-Th @ 55 Discharge Plutonium

	<u>Isotope</u>	<u>Inner Core</u>	<u>Outer Core</u>	<u>Axial Blanket</u>
<u>Feed</u>				
	Th-232	6745.0	6268.2	9207.6
	Pu-238	74.9	98.2	
	Pu-239	328.3	430.2	
	Pu-240	566.4	742.3	
	Pu-241	389.8	510.8	
	Pu-242	232.4	304.5	
<u>Discharge @ 1 Year</u>				
	Th-232	6434.2	6060.2	9108.4
	Pa-233	30.5	20.5	10.3
	U-233	218.4	153.9	83.1
	U-234	4.1	2.0	0.5
	U-235	0.1	0	0
	Pu-238	59.6	82.9	
	Pu-239	235.5	337.7	
	Pu-240	519.2	695.2	
	Pu-241	270.2	384.8	
	Pu-242	234.3	306.0	
	Am-241	13.6	19.4	
<u>Discharge @ 2 Years</u>				
	Th-232	6142.0	5869.2	9011.6
	Pa-233	29.1	18.6	10.1
	U-233	364.3	270.6	164.1
	U-234	14.7	7.5	1.9
	U-235	0.8	0.3	0
	Pu-238	47.5	70.6	
	Pu-239	170.0	268.6	
	Pu-240	472.2	650.6	
	Pu-241	195.1	298.9	
	Pu-242	229.5	302.5	
	Am-241	20.3	31.2	

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