The Dependence of LMFBR Fueling Requirements on Plutonium Isotopic Composition

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INTRODUCTION

When the liquid metal fast breeder reactors (LMFBRs) start up, plutonium from thermal reactors will be required to enrich the reactor fuel. Neutronics analyses performed to determine the fueling requirements for an 800 megawatt electric (MWe) breeder reactor are described in this report. This study was initiated when it was assumed that thermal reactor plutonium recycle would take place prior to the introduction of the breeder. Therefore, a range of plutonium compositions was fed into the LMFBR and the fueling requirements were determined for these various compositions. Depleted uranium was used as the diluent.

The analyses were performed for two reactor designs--a reference small fuel pin design and an advanced large fuel pin design. Burnup calculations were performed to determine the compositions of the discharge plutonium. The instantaneous breeding ratio at mid-cycle was calculated for each plutonium composition. Plutonium isotopic coefficients were determined so that fueling requirements could be predicted without having to analyze every particular plutonium composition in question. As a comparison, analyses were also done for an LMFBR fueled with uranium enriched in ^{235}U rather than plutonium.

This study was funded under the Fuels Refabrication and Development Program and related Nuclear Fuel Cycle and Production Division Programs.

SUMMARY AND CONCLUSIONS

Neutronics analyses were performed for two LMFBR designs to determine the fueling requirements, mass flows, and breeding ratios using various plutonium compositions. Correlation coefficients relating the fueling requirements to isotopic compositions were also determined.

As the ^{242}Pu content of the plutonium increases, the fueling requirement increases because ^{242}Pu neither fissions appreciably nor forms another fissile isotope upon neutron capture. Because of its low capture-to-fission ratio, ^{241}Pu is the most valuable isotope. The fertile isotopes ^{238}Pu and ^{240}Pu are also valuable because they fission as well as create a fissile isotope upon neutron capture. As the ^{238}Pu and ^{240}Pu content of the plutonium increases, the fueling requirement increases. For plutonium compositions with high ^{238}Pu and ^{240}Pu contents, the breeding ratio is very high.

The results for the advanced large pin design are nearly the same as the results for the small pin design because the fuel, structural, and sodium volume fractions are nearly identical. The largest cause of the differences in results between the two designs is the longer residence times of the core and blankets for the advanced large pin design.

If the uranium is enriched with ^{235}U rather than plutonium, the fissile fraction required is about 17%. The conversion ratio drops to 0.96 for these cases.

DESCRIPTION OF REACTORS

Calculations were done for two LMFBR designs using advanced oxide fuel. The designs are based on a reference small fuel pin and on an advanced large fuel pin. The reactor data developed by HEDL⁽¹⁾ are given in Table 1 for the cores and axial blankets and Table 2 for the radial blankets.

The designs are symmetrical about the midplane. The core is divided into two enrichment regions in order to reduce power peaking. The axial blanket is 18 in. thick on each end of the core. The primary difference between the two cores is the size of the fuel pins. Additional design parameters are given in Reference 1.

One-half of the core and one-fourth of the radial blanket are replaced each year in the small pin design. In the advanced large pin design, one-third of the core and one-sixth of the radial blanket are replaced each year. The uranium in the core and blankets was depleted to 0.2 atom percent ^{235}U . The structural material was assumed to be 316 stainless steel with atom percentages of 69, 18, 11, and 2 for iron, chromium, nickel, and molybdenum, respectively.

The isotopic compositions of the different types of plutonium are listed in Table 3. The LMFBR type (as calculated by HEDL⁽¹⁾) is a mixture of the plutonium discharged from the inner core, outer core, axial blanket, and radial blanket of an LMFBR with the small pin design. The other plutonium types were obtained from light water reactor discharged fuel.⁽²⁾ The first UO_2 plutonium is recovered from fuel used to start up a PWR and is discharged after one cycle or at 15 GWd/T. The equilibrium UO_2 plutonium is recovered from a PWR on an equilibrium once-through cycle discharged at 33 GWd/T. The second U plutonium is obtained from a BWR after the uranium is recovered, re-enriched, and re-irradiated twice. The third U plutonium results from the same sequence, three times in a PWR. The first Pu plutonium is recovered from PWR mixed oxide fuel after the plutonium has been recycled through the reactor once. The third Pu plutonium is recovered after it has been recycled through the PWR three times.

TABLE 1. Core and Axial Blanket Design Parameters
Using Advanced Oxide Fuel

<u>Design Characteristic</u>	<u>Small Pin</u>	<u>Advanced Large Pin</u>
Core radius, in.	58.9	60.1
Active fuel length, in.	36.0	36.0
Axial blanket thickness, in.	36.0	36.0
Pin outer diameter, in.	0.23	0.30
Cladding thickness, in.	0.010	0.013
Pins per subassembly	271	271
Subassembly pitch, in.	4.886	6.3217
Number of subassemblies	527	328
Mass of fuel in core, kg	23968	25388
Mass of fuel in axial blanket, kg	23968	25388
Fuel volume fraction	0.4237	0.4340
Steel volume fraction	0.1668	0.1693
Sodium volume fraction	0.3775	0.3690
Control volume fraction	0.0272	0.0277
Average coolant temperature, °C	470	438

TABLE 2. Radial Blanket Design Parameters

<u>Design Characteristic</u>	<u>Small Pin</u>	<u>Advanced Large Pin</u>
Blanket thickness, in.	16.3	16.6
Pin outer diameter, in.	0.519	0.662
Cladding thickness, in.	0.015	0.015
Pins per subassembly	61	61
Number of subassemblies	331	206
Mass of fuel in blanket, kg	39190	40953
Fuel volume fraction	0.5532	0.5532
Steel volume fraction	0.1697	0.1697
Sodium volume fraction	0.2771	0.2771
Average coolant temperature, °C	315	315

TABLE 3. Plutonium Isotopics Used to Fuel the LMFBR

<u>Isotope</u>	<u>Composition, atom per cent</u>						
	<u>1st UO₂</u>	<u>Equil. UO₂</u>	<u>2nd U</u>	<u>3rd U</u>	<u>1st Pu</u>	<u>3rd Pu</u>	<u>LMFBR</u>
Pu-238	0.39	1.55	15.00	35.75	2.21	3.74	0
Pu-239	66.81	55.13	56.92	50.70	39.23	27.17	70.7
Pu-240	21.73	23.89	16.98	7.50	30.51	28.34	24.8
Pu-241	9.34	14.17	9.14	5.47	17.87	21.47	3.0
Pu-242	1.73	5.26	1.96	0.58	10.18	19.28	1.5

CALCULATIONAL METHODS

To determine the fueling requirements and mass flows for the LMFBR designs, cross sections, reactivity, and burnup were calculated. The calculational methods are described below.

CROSS SECTIONS

Four-group cross sections were generated with 1DX⁽³⁾ by collapsing 30-group cross sections over spectra representing a core and radial blanket. Most of the 30-group cross sections are composed of the FTR Set 300⁽⁴⁾ data, which are based on ENDF/B-II data. Version IV data were used for Fe, Ni, and ²³⁸Pu. For ²⁴¹Am, preliminary Version V data^(5,6) were used. Version IV data for Fe and Ni are substantially different than Version II data. For ²³⁸Pu and ²⁴¹Am, no data existed on the FTR Set 300 library. The half-life of ²⁴¹Pu was assumed to be 14.5 years. Energy boundaries of the four broad groups are given in Table 4.

TABLE 4. 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

The 1DX code performs a one-dimensional diffusion theory calculation in 30 energy groups. The core consists of a uniform fuel mixture at a typical plutonium enrichment with appropriate isotopics. The radial blanket mixture was represented with appropriate volume-weighted isotopics of fuel, structural, and coolant materials. Cross sections were averaged over the core and over the radial blanket for several core enrichments using various plutonium isotopics.

REACTIVITY AND BURNUP

Reactivity and burnup calculations were performed with the 2DB⁽⁷⁾ code using the 4-group cross sections generated with 1DX. The reactors were modeled as right cylinders assuming axial symmetry. The cores were divided into two enrichment regions as shown in Figures 1 and 2. The number of mesh intervals used to represent each region is indicated in Figure 1 for the small pin design and Figure 2 for the advanced large pin design.

Each region was divided into multiple zones to represent fuel at different exposures. For the small pin design, four zones were used for the radial blanket and two zones were used for each of the other regions. For the advanced large pin design, six zones were used for the radial blanket and three zones were used for each of the other regions. Within each region these multiple zones were arrayed in a checkerboard type of pattern in order to approximate homogeneity.

The 2DB code also performs the burnup calculation on a zone basis. One-group cross sections are 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 1800 MWt. This corresponds to a full power of 2500 MWt with a capacity factor of 72%.

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 instantaneous breeding ratio (BR) were calculated before and after the fresh fuel was charged. The instantaneous breeding ratio is defined as:

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

where

$\sum$ is the macroscopic cross section
subscript c refers to capture
subscript a refers to absorption.

FIGURE 1. Small Pin Design Mesh Layout

FIGURE 2. Advanced Large Pin Design Mesh Layout

RESULTS

Based on the calculational methods described in the previous section, cross-section comparisons were made for several of the plutonium types listed in Table 3. Plutonium enrichment requirements for the small pin and advanced large pin designs were calculated and correlated with the various plutonium isotopics. A comparative calculation was also performed for uranium fuel enriched in ^{235}U .

CROSS-SECTION COMPARISONS

Four-group microscopic cross sections were generated with 1DX using the plutonium types listed in Table 3 except for the first UO_2 and first Pu. In Table 5, values of the actinide cross sections are compared for three of the plutonium types. The values are nearly independent of the plutonium isotopic composition. Thus, using cross sections generated with other types of plutonium for the first UO_2 and first Pu cases does not significantly affect the calculated reactivity and burnup.

A potential error results from using cross sections derived with an enrichment different than the enrichment converged on in 2DB. Table 6 shows the sensitivity of the 4-group microscopic cross sections to plutonium enrichment using equilibrium UO_2 plutonium. The differences are small. If the enrichment used in 2DB is within 1% of the enrichment used in 1DX, the error should be negligible.

The worth of the primary elements of 316 stainless steel structural material was estimated by comparing the reaction rate of each element to the total reaction rate in the reactor. The results are presented in Table 7. As Table 7 shows, the total worth of the structural material is 44 mk or 4.4% in k. Each component contributes significantly to the total.

TABLE 5. Sensitivity of the Microscopic Cross Sections to the Plutonium Composition (Small Pin Design)

Group No.		Fission, Barns			Absorption, Barns		
		Equil. UO ₂ ; 16.5%Pu ²	3rd U; 16.0%Pu	3rd Pu; 20.0%Pu	Equil. UO ₂ ; 16.5%Pu ²	3rd U; 16.0%Pu	3rd Pu; 20.0%Pu
U-238	1	0.3209	0.3215	0.3211	0.3786	0.3791	0.3789
	2	0.0004	0.0004	0.0004	0.1398	0.1399	0.1398
	3	0	0	0	0.3646	0.3653	0.3653
	4	0	0	0	0.8739	0.8782	0.8814
Pu-238	1	2.220	2.220	2.220	2.247	2.247	2.246
	2	0.9972	0.9970	0.9972	1.118	1.117	1.118
	3	0.6283	0.6289	0.6287	0.9896	0.9909	0.9905
	4	1.695	1.550	1.674	3.539	3.133	3.465
Pu-239	1	1.870	1.870	1.870	1.881	1.881	1.881
	2	1.553	1.553	1.553	1.722	1.722	1.722
	3	1.702	1.702	1.702	2.159	2.160	2.160
	4	3.144	3.210	3.161	5.519	5.632	5.559
Pu-240	1	1.533	1.534	1.533	1.595	1.595	1.595
	2	0.2613	0.2613	0.2613	0.4441	0.4441	0.4441
	3	0.0889	0.0889	0.0889	0.5063	0.5071	0.5067
	4	0.1321	0.1354	0.1308	1.670	1.787	1.634
Pu-241	3	2.579	2.581	2.580	3.140	3.142	3.141
	4	5.755	5.878	5.729	7.134	7.290	7.103
Pu-242	3	0.0398	0.0399	0.0399	0.3680	0.3687	0.3684
	4	0.0194	0.0194	0.0196	1.432	1.520	1.315

TABLE 6. Sensitivity of the Microscopic Cross Sections to the Equilibrium UO₂ Plutonium Enrichment

	Group No.	Fission, Barns		Absorption, Barns	
		16.5%Pu	15.3%Pu	16.5%Pu	15.3%Pu
U-238	1	0.3209	0.3208	0.3786	0.3786
	2	0.0004	0.0004	0.1398	0.1399
	3	0	0	0.3646	0.3651
	4	0	0	0.8739	0.8759
Pu-238	1	2.220	2.220	2.247	2.247
	2	0.9972	0.9961	1.118	1.117
	3	0.6283	0.6288	0.9896	0.9907
	4	1.695	1.708	3.539	3.605
Pu-239	1	1.870	1.870	1.881	1.881
	2	1.553	1.552	1.722	1.722
	3	1.702	1.702	2.159	2.160
	4	3.144	3.197	5.519	5.610
Pu-240	1	1.533	1.533	1.595	1.595
	2	0.2613	0.2608	0.4441	0.4436
	3	0.0889	0.0889	0.5063	0.5069
	4	0.1321	0.1329	1.670	1.705
Pu-241	3	2.579	2.581	3.140	3.142
	4	5.755	5.846	7.134	7.249
Pu-242	3	0.0398	0.0399	0.3680	0.3686
	4	0.0197	0.0194	1.432	1.463

TABLE 7. Reactivity Worth of Steel Components

<u>Element</u>	<u>Worth, mk</u>
Fe	19
Cr	8
Ni	9
Mo	8
Total	44

SMALL PIN DESIGN

The plutonium enrichment required for fueling the small pin design is summarized in Table 8 for the various types of plutonium. Large amounts of ^{238}Pu and ^{240}Pu do not force the enrichment up because these isotopes have relatively large fission cross sections and readily transmute into fissile isotopes (^{239}Pu and ^{241}Pu). The enrichment does increase with increasing ^{242}Pu content because ^{242}Pu does not fission appreciably and does not form another fissile isotope upon neutron capture.

TABLE 8. Plutonium Enrichment as a Function of Isotopics for the Small Pin Design

<u>Parameter</u>	<u>1st UO₂</u>	<u>Equil. UO₂</u>	<u>3rd U</u>	<u>1st Pu</u>	<u>3rd Pu</u>	<u>2nd U</u>	<u>LMFBR</u>
Enrichment, %Pu	14.88	15.62	15.24	17.48	19.06	15.12	15.50
Reactivity Swing, mk	-9.8	-13.1	+3.6	-13.7	-18.7	-3.8	-2.1
BR (2nd yr)	1.386	1.423	1.724	1.498	1.554	1.530	1.390
BR (4th yr)	1.383	1.420	1.721	1.495	1.551	1.527	1.387

The calculations using plutonium with a high ^{242}Pu content may be somewhat in error because of the omission of ^{243}Am from the calculation. In two years about 8% of the ^{242}Pu is converted to ^{243}Am . For the third Pu case where 19% of the plutonium is ^{242}Pu , this means that the ^{243}Am content of the discharged fuel is 1-1/2% of the total actinides. The reactivity effect of not including ^{243}Am in the calculation is expected to be of the order of mk because of fast fissions; however, the isotope should be included in the calculation to accurately assess its value.

Also shown in Table 8 is the reactivity change over a cycle for equilibrium conditions. The minimum reactivity generally occurs at the end of the second year. Thereafter, the end-of-cycle reactivity increases slightly because of plutonium buildup in the radial blanket. The minimum reactivity

using the third U type of plutonium occurs at the initial loading. Thereafter, the reactivity increases because of the high breeding ratio.

The instantaneous breeding ratios for the second year and the fourth year are also given in Table 8. The difference in the two values is caused by the buildup of fissile material in the radial blanket. Generally, the lower the percentage of fissile isotopes in the plutonium, the higher the breeding ratio. A high percentage of ^{238}Pu also pushes the breeding ratio up, while a high percentage of ^{242}Pu holds the breeding ratio down because ^{242}Pu is not a fertile isotope.

The sensitivity of reactivity and breeding ratio to the enrichment requirement is given in Table 9 for some of the plutonium types.

TABLE 9. Sensitivity of Reactivity and Breeding Ratio to Enrichment for the Small Pin Design

Type	$\Delta k/\Delta E$, mk/% Pu	$\Delta BR/\Delta E$, (% Pu) $^{-1}$
1st UO_2	24	0.068
Equil. UO_2	25	0.071
3rd U Recycle	38	0.079
1st Pu Recycle	21	0.055
3rd Pu Recycle	20	0.054

The annual feed and discharge masses by isotope are given for the various types of plutonium in Appendix A, Tables A.1 to A.7 for the small pin design. The values given are for the equilibrium situation.

ADVANCED LARGE PIN DESIGN

The plutonium enrichment required for the advanced large pin design is summarized in Table 10 for the various types of plutonium. The fueling requirements are very close to those of the small pin design because, as noted earlier, the volume fractions of the fuel, structure, and moderator are nearly the same. The reactivity swing for the equilibrium cycle is also given in Table 10. The values are nearly the same as for the small pin design.

TABLE 10. Plutonium Enrichment as a Function of Isotopics for the Advanced Large Pin Design

<u>Parameter</u>	<u>1st UO₂</u>	<u>Equil. UO₂</u>	<u>3rd U</u>	<u>1st Pu</u>	<u>3rd Pu</u>	<u>2nd U</u>	<u>LMFBR</u>
Enrichment, %Pu	14.84	15.60	15.09	17.47	19.11	15.02	15.37
Reactivity Swing, mk	-9.7	-12.5	+1.5	-12.7	-17.2	-4.7	-3.1
BR (3rd yr)	1.367	1.400	1.663	1.469	1.520	1.499	1.372
BR (6th yr)	1.363	1.397	1.659	1.465	1.515	1.495	1.369

The breeding ratio is given for the third year, the time period in which the minimum reactivity is attained, and for the sixth year, the equilibrium situation case. The values for the sixth year are slightly lower than the values for the third year because of plutonium buildup in the radial blanket. Compared to the small pin design, the breeding ratios are a little lower because of the longer residence time.

The annual feed and discharge masses by isotope are given for the various types of plutonium in Tables A.8 to A.14 for the advanced large pin design.

CORRELATION OF ENRICHMENT WITH PLUTONIUM ISOTOPICS

The calculated feed requirements were least-squares fitted to the plutonium isotopic compositions with the following equation:

$$\text{Atom Fraction Pu} = \sum_i A_i (\text{Pu Isotopic Fraction})$$

where

A_i are the correlation coefficients.

The smaller the value of the coefficient, the more valuable the isotope. One should consider the value of the coefficients to be valid only within the range of isotopics used in this study.

The coefficients are listed in Table 11 for both designs. The coefficients are nearly the same for both designs except for ^{241}Pu . The coefficient for ^{241}Pu is higher for the advanced large pin design because the longer core residence time results in more ^{241}Am buildup. The effect of increased ^{241}Pu decays is a decrease in the fraction of plutonium atoms available for fissioning, and an increase in fissile content necessary to overcome the lesser reactivity of ^{241}Am . These results have also been reported in Reference 8.

TABLE 11. Correlation Coefficients for Plutonium Requirements

<u>Isotope</u>	<u>Small Pin</u>	<u>Advanced Large Pin</u>
Pu-238	0.186 ± 0.005	0.182 ± 0.005
Pu-239	0.121 ± 0.004	0.121 ± 0.004
Pu-240	0.254 ± 0.014	0.247 ± 0.016
Pu-241	0.061 ± 0.013	0.070 ± 0.015
Pu-242	0.342 ± 0.017	0.344 ± 0.020

ENRICHED UO_2 CORES

Burnup calculations were also performed for both designs when a uranium core is enriched with ^{235}U . The results are summarized in Table 12. Both reactor designs require almost 17% ^{235}U . The breeding ratio is slightly less than unity for each reactor. The reactivity swing during a cycle is over 2% $\Delta k/k$, which is much larger than the reactivity swing for the plutonium enriched systems.

The annual feed and discharge masses by isotope are given in Table A.15 for the small pin design and Table A.16 for the advanced large pin design. The plutonium bred in the core consists of mostly ^{239}Pu . The longer the core residence time, the more ^{240}Pu builds into the plutonium.

TABLE 12. Uranium Enrichment for LMFBRs

	<u>Small Pin Design</u>	<u>Advanced Large Pin Design</u>
% U-234	0.156	0.157
% U-235	16.78	16.92
% U-238	83.06	82.92
Reactivity Swing, mk	-23.6	-22.5
BR	0.955	0.957

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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 of Isotopes for First UO₂ With the Small Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u>	<u>Outer</u>	<u>Axial</u>	<u>Radial</u>	<u>Total</u>
<u>Feed</u>	<u>Core</u>	<u>Core</u>	<u>Blanket</u>	<u>Blanket</u>	
U-235	10.28	9.84	23.58	19.32	63.02
U-238	5188	4976	11,942	9748	31,890
Pu-238	3.04	3.88			6.92
Pu-239	527.8	668.0			1195.8
Pu-240	172.4	218.2			390.6
Pu-241	74.42	94.16			168.6
Pu-242	13.82	17.50			
Total Fissile	1384.6 ^(a)		42.90 ^(b)		1427.4
Total Heavy Metal	11,978 ^(a)		21.768 ^(b)		33,746
<u>Discharge</u>					
U-235	5.48	6.58	20.28	17.24	49.58
U-238	4778	4720	11748	9664	30,910
Pu-238	2.10	3.04	0	0	5.14
Pu-239	572.0	647.8	174.6	110.58	1505.0
Pu-240	204.8	242.8	3.70	1.78	456.6
Pu-241	46.44	65.46	0.08	0.02	112.0
Pu-242	17.74	20.94	-	-	38.68
Am-241	4.32	6.38	-	-	10.70
Total Fissile	1343.8		322.82		1666.6
Total Heavy Metal	11,348		21,740		33,088

(a) These values are the sum of the inner core and the outer core.

(b) These values are the sum of the axial blanket and the radial blanket.

TABLE A.2. Annual Mass Flow of Isotopes for Equilibrium UO₂
With the Small Pin Design

Isotope	Kilograms/Year				
	Inner Core	Outer Core	Axial Blanket	Radial Blanket	Total
U-235	10.16	9.78	23.58	19.32	62.84
U-238	5148	4926	11,942	9784	31,800
Pu-238	12.84	16.18			29.02
Pu-239	457.2	578.0			1035.2
Pu-240	198.9	251.6			450.5
Pu-241	118.48	149.84			268.3
Pu-242	44.18	55.84			100.02
Total Fissile	1323.4		42.90		1366.4
Total Heavy Metal	11,978		21,768		33,746
<u>Discharge</u>					
U-235	5.40	6.54	20.28	17.24	49.46
U-238	4742	4674	11,748	9664	30,828
Pu-238	8.88	12.74	0	0	21.62
Pu-239	530.6	584.4	174.5	110.44	1399.8
Pu-240	224.2	266.8	3.70	1.76	496.5
Pu-241	67.36	98.80	0.08	0.02	166.3
Pu-242	46.98	58.52	-	-	105.50
Am-241	6.62	9.92	-	-	16.54
Total Fissile	1293.2		322.58		1615.6
Total Heavy Metal	11,344		21,740		33,084

TABLE A.3. Annual Mass Flow of Isotopes for Second U Recycle
With the Small Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u> <u>Core</u>	<u>Outer</u> <u>Core</u>	<u>Axial</u> <u>Blanket</u>	<u>Radial</u> <u>Blanket</u>	<u>Total</u>
<u>U-235</u>	10.22	9.84	23.58	19.32	62.96
U-238	5178	4962	11,942	9784	31,866
Pu-238	119.60	151.46			271.0
Pu-239	455.6	577.0			1032.6
Pu-240	136.5	172.9			309.4
Pu-241	73.78	93.46			167.24
Pu-242	15.88	20.14			36.02
Total Fissile	1219.8		42.90		1262.8
Total Heavy Metal	11,986		21,768		33,746
<u>Discharge</u>					
U-235	5.42	6.58	20.26	17.24	49.50
U-238	4766	4706	11,746	9664	30,882
Pu-238	83.18	119.62	0	0	202.8
Pu-239	538.0	591.2	175.0	110.8	1415.0
Pu-240	173.0	197.5	3.74	1.78	376.0
Pu-241	43.70	62.86	0.08	0.02	106.66
Pu-242	19.34	23.22	-	-	42.56
Am-241	4.18	6.24	-	-	10.42
Total Fissile	1247.8		323.32		1571.2
Total Heavy Metal	11,346		21,738		33,084

TABLE A.4. Annual Mass Flow of Isotopes for Third U Recycle
With the Small Pin Design

Isotope	Kilograms/Year				
	Inner Core	Outer Core	Axial Blanket	Radial Blanket	Total
U-235	10.22	9.78	23.58	19.32	62.90
U-238	5168	4950	11,942	9784	31,844
Pu-238	288.4	364.8			653.2
Pu-239	410.8	519.4			930.2
Pu-240	61.04	77.20			138.24
Pu-241	44.70	56.50			101.20
Pu-242	4.78	6.00			10.78
Total Fissile	1055.4		42.90		1094.4
Total Heavy Metal	11,972		21,768		33,740
<u>Discharge</u>					
U-235	5.42	6.56	20.30	17.76	50.04
U-238	4760	4698	11,748	9696	30,902
Pu-238	202.2	290.0	0	0	492.2
Pu-239	521.0	559.2	173.08	83.12	1336.4
Pu-240	107.08	109.42	3.66	1.00	221.16
Pu-241	26.00	37.28	0.08	0.02	63.38
Pu-242	7.50	8.40	-	-	15.90
Am-241	2.50	3.72	-	-	6.22
Total Fissile	1155.4		294.36		1449.8
Total Heavy Metal	11,344		21,743		33,087

TABLE A.5. Annual Mass Flow of Isotopes for Equilibrium LMFBR
With the Small Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u>	<u>Outer</u>	<u>Axial</u>	<u>Radial</u>	<u>Total</u>
<u>Feed</u>	<u>Core</u>	<u>Core</u>	<u>Blanket</u>	<u>Blanket</u>	
U-235	10.22	9.78	23.58	19.32	62.90
U-238	5156	4936	11,942	9784	31,818
Pu-238	0	0			0
Pu-239	581.6	735.0			1316.6
Pu-240	204.8	259.0			463.8
Pu-241	24.90	31.44			56.34
Pu-242	12.46	15.82			28.28
Total Fissile	1393.0		42.90		1435.8
Total Heavy Metal	11,978		21,768		33,746
<u>Discharge</u>					
U-235	5.42	6.54	20.26	17.24	49.46
U-238	4746	4682	11,746	9664	30,838
Pu-238	0	0	0	0	0
Pu-239	600.6	692.8	175.2	110.7	1579.4
Pu-240	240.2	283.2	3.74	1.78	529.0
Pu-241	26.84	31.52	0.08	0.02	58.46
Pu-242	13.32	16.36	-	-	29.68
Am-241	1.94	2.58	-	-	4.52
Total Fissile	1363.8		323.54		1687.2
Total Heavy Metal	11,350		21,740		33,088

TABLE A.6. Annual Mass Flow of Isotopes for First Pu Recycle
With the Small Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u> <u>Core</u>	<u>Outer</u> <u>Core</u>	<u>Axial</u> <u>Blanket</u>	<u>Radial</u> <u>Blanket</u>	<u>Total</u>
U-235	9.98	9.52	23.58	19.32	62.40
U-238	5050	4802	11,942	9784	31,578
Pu-238	20.46	25.84			46.30
Pu-239	364.2	460.6			824.8
Pu-240	284.4	359.8			644.2
Pu-241	167.3	211.6			379.0
Pu-242	95.72	121.02			216.7
Total Fissile	1223.2		42.90		1266.2
Total Heavy Metal	11,982		21,768		33,750
<u>Discharge</u>					
U-235	5.32	6.38	20.28	17.24	49.22
U-238	4650	4554	11,748	9664	30,616
Pu-238	14.20	20.36	0	0	34.56
Pu-239	474.0	499.4	174.42	110.58	1258.4
Pu-240	287.2	355.4	3.70	1.78	648.0
Pu-241	93.94	138.88	0.08	0.02	233.0
Pu-242	95.34	121.12	-	-	216.5
Am-241	9.30	13.98	-	-	23.28
Total Fissile	1217.8		322.65		1540.6
Total Heavy Metal	11,338		21,740		33,078

TABLE A.7. Annual Mass Flow of Isotopes for Third Pu Recycle
With the Small Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u>	<u>Outer</u>	<u>Axial</u>	<u>Radial</u>	<u>Total</u>
<u>Feed</u>	<u>Core</u>	<u>Core</u>	<u>Blanket</u>	<u>Blanket</u>	
U-235	9.84	9.28	23.58	19.28	61.98
U-238	4966	4694	11,942	9760	31,366
Pu-238	37.72	47.68			85.40
Pu-239	275.2	347.6			622.8
Pu-240	288.4	364.0			652.4
Pu-241	219.4	277.0			496.4
Pu-242	197.8	249.8			447.6
Total Fissile	1138.4		42.86		1181.2
Total Heavy Metal	11,988		21,744		33,732
<u>Discharge</u>					
U-235	5.24	6.20	20.28	17.66	49.38
U-238	4572	4456	11,748	9668	30,444
Pu-238	26.16	37.56	0	0	63.72
Pu-239	420.8	418.4	174.38	86.12	1099.7
Pu-240	282.4	352.0	3.70	1.06	639.2
Pu-241	116.88	176.4	0.04	0.02	293.4
Pu-242	187.22	241.4	-	-	428.6
Am-241	11.92	18.04	-	-	29.96
Total Fissile	1144.0		298.54		1442.6
Total Heavy Metal	11,328		21,720		33,048

TABLE A.8. Annual Mass Flow of Isotopes for First UO₂
With the Advanced Large Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u> <u>Core</u>	<u>Outer</u> <u>Core</u>	<u>Axial</u> <u>Blanket</u>	<u>Radial</u> <u>Blanket</u>	<u>Total</u>
U-235	7.22	6.96	16.72	13.48	44.38
U-238	3666	3516	8432	6808	22,422
Pu-238	2.16	2.74			4.90
Pu-239	371.2	469.4			840.6
Pu-240	121.24	153.32			274.56
Pu-241	52.32	66.16			118.48
Pu-242	9.74	12.32			22.06
Total Fissile	973.2		30.20		1003.4
Total Heavy Metal	8456		15,270		23,726
<u>Discharge</u>					
U-235	2.94	3.96	13.52	11.54	31.96
U-238	3262	3264	8240	6694	21,460
Pu-238	1.28	1.96	0	0	3.24
Pu-239	406.8	450.0	168.78	103.04	1128.6
Pu-240	156.72	176.90	5.04	2.26	341.0
Pu-241	28.54	40.48	0.14	0.04	69.20
Pu-242	13.06	15.32	-	-	28.38
Am-241	3.78	5.88	-	-	9.66
Total Fissile	932.8		297.06		1229.8
Total Heavy Metal	7834		15,238		23,072

TABLE A.9. Annual Mass Flow of Isotopes for Equilibrium UO₂
With the Advanced Large Pin Design

Isotope	Kilograms/Year				
	Inner Core	Outer Core	Axial Blanket	Radial Blanket	Total
U-235	7.18	6.88	16.72	13.48	44.26
U-238	3636	3480	8432	6808	22,356
Pu-238	9.04	11.42			20.46
Pu-239	322.4	407.8			730.2
Pu-240	140.30	177.42			317.7
Pu-241	83.56	105.66			189.2
Pu-242	31.14	39.40			70.54
Total Fissile	933.4		30.20		963.6
Total Heavy Metal	8458		15,270		23,728
<u>Discharge</u>					
U-235	2.94	3.90	13.52	11.54	31.90
U-238	3236	3230	8240	6694	21,400
Pu-238	5.36	8.16	0	0	13.52
Pu-239	383.8	411.8	168.52	103.00	1067.1
Pu-240	165.9	192.2	5.02	2.26	365.3
Pu-241	39.40	59.58	0.14	0.04	99.16
Pu-242	32.98	41.42	-	-	74.40
Am-241	5.66	9.06	-	-	14.72
Total Fissile	901.4		296.76		1198.2
Total Heavy Metal	7828		15,238		23,066

TABLE A.10. Annual Mass Flow of Isotopes for Second U Recycle
With the Advanced Large Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u> <u>Core</u>	<u>Outer</u> <u>Core</u>	<u>Axial</u> <u>Blanket</u>	<u>Radial</u> <u>Blanket</u>	<u>Total</u>
U-235	7.24	6.92	16.72	13.48	44.36
U-238	3660	3508	8432	6808	22,408
Pu-238	83.88	106.24			190.12
Pu-239	319.6	404.8			724.4
Pu-240	95.76	121.28			217.0
Pu-241	51.74	65.54			117.28
Pu-242	11.12	14.12			25.24
Total Fissile	855.8		30.20		886.0
Total Heavy Metal	8456		15,270		23,726
<u>Discharge</u>					
U-235	2.92	3.92	13.52	11.54	31.90
U-238	3254	3256	8240	6694	21,444
Pu-238	50.00	76.34	0	0	126.34
Pu-239	389.4	416.8	168.96	102.98	1078.2
Pu-240	132.42	145.14	5.04	2.26	284.9
Pu-241	26.24	38.26	0.14	0.04	64.68
Pu-242	13.96	16.76	-	-	30.72
Am-241	3.58	5.70	-	-	9.28
Total Fissile	877.6		297.18		1174.8
Total Heavy Metal	7832		15,238		23,070

TABLE A.11. Annual Mass Flow of Isotopes for Third U Recycle
With the Advanced Large Pin Design

<u>Isotope</u>	<u>Kiglograms/Year</u>				
	<u>Inner</u> <u>Core</u>	<u>Outer</u> <u>Core</u>	<u>Axial</u> <u>Blanket</u>	<u>Radial</u> <u>Blanket</u>	<u>Total</u>
U-235	7.24	6.92	16.72	13.48	44.36
U-238	3656	3504	8432	6808	22,400
Pu-238	201.2	254.6			455.8
Pu-239	286.6	362.4			649.0
Pu-240	42.58	53.84			96.42
Pu-241	31.18	39.42			70.60
Pu-242	3.32	4.22			7.54
Total Fissile	733.8		30.20		764.0
Total Heavy Metal	8454		15,270		23,724
<u>Discharge</u>					
U-235	2.94	3.96	13.54	11.56	32.00
U-238	3252	3256	8242	6696	21,446
Pu-238	121.46	184.68	0	0	306.14
Pu-239	381.8	398.6	167.10	101.52	1049.0
Pu-240	88.78	85.20	4.94	2.20	181.12
Pu-241	15.86	22.58	0.14	0.04	38.62
Pu-242	5.64	6.30	-	-	11.94
Am-241	2.14	3.38	-	-	5.52
Total Fissile	825.8		293.9		1119.6
Total Heavy Metal	7832		15,240		23,070

TABLE A.12. Annual Mass Flow of Isotopes for Equilibrium LMFBR
With the Advanced Large Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u> <u>Core</u>	<u>Outer</u> <u>Core</u>	<u>Axial</u> <u>Blanket</u>	<u>Radial</u> <u>Blanket</u>	<u>Total</u>
U-235	7.24	6.92	16.72	13.48	44.36
U-238	3646	3492	8432	6808	22,378
Pu-238	0	0			0
Pu-239	406.6	514.2			920.8
Pu-240	143.2	181.1			324.3
Pu-241	17.38	22.00			39.38
Pu-242	8.76	11.02			19.78
Total Fissile	974.4		30.20		1004.6
Total Heavy Metal	8456		15,270		23,726
<u>Discharge</u>					
U-235	2.92	3.92	13.50	11.52	31.86
U-238	3242	3242	8238	6694	21,416
Pu-238	0	0	0	0	0
Pu-239	421.2	475.4	169.32	103.12	1169.0
Pu-240	177.5	203.8	5.08	2.26	388.6
Pu-241	19.54	22.18	0.14	0.04	41.90
Pu-242	9.62	11.58	-	-	21.20
Am-241	1.90	2.56	-	-	4.46
Total Fissile	945.2		297.64		1242.8
Total Heavy Metal	7836		15,236		23,072

TABLE A.13. Annual Mass Flow of Isotopes for First Pu Recycle
With the Advanced Large Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u> <u>Core</u>	<u>Outer</u> <u>Core</u>	<u>Axial</u> <u>Blanket</u>	<u>Radial</u> <u>Blanket</u>	<u>Total</u>
U-235	7.06	6.70	16.72	13.48	43.96
U-238	3568	3392	8432	6808	22,200
Pu-238	14.38	18.20			32.58
Pu-239	256.4	324.4			580.8
Pu-240	200.2	253.4			453.6
Pu-241	117.8	149.0			266.8
Pu-242	67.40	85.26			152.66
Total Fissile	861.4		30.20		891.6
Total Heavy Metal	8460		15,270		23,730
<u>Discharge</u>					
U-235	2.88	3.80	13.52	11.52	31.72
U-238	3174	3148	8240	6694	21,256
Pu-238	8.54	13.02	0	0	21.56
Pu-239	351.0	358.8	168.66	103.20	981.6
Pu-240	205.0	249.8	5.02	2.26	462.0
Pu-241	53.94	83.16	0.14	0.04	137.28
Pu-242	65.72	84.50	-	-	150.22
Am-241	7.90	12.72	-	-	20.62
Total Fissile	853.6		297.08		1150.6
Total Heavy Metal	7822		15,238		23,060

TABLE A.14. Annual Mass Flow of Isotopes for Third Pu Recycle
With the Advanced Large Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u>	<u>Outer</u>	<u>Axial</u>	<u>Radial</u>	<u>Total</u>
<u>Feed</u>	<u>Core</u>	<u>Core</u>	<u>Blanket</u>	<u>Blanket</u>	
U-235	6.92	6.58	16.72	13.48	43.70
U-238	3506	3316	8432	6808	22,062
Pu-238	26.66	33.68			60.34
Pu-239	194.7	245.6			440.2
Pu-240	203.8	257.4			461.2
Pu-241	155.1	195.8			350.9
Pu-242	139.9	176.5			316.4
Total Fissile	804.6		30.20		835.0
Total Heavy Metal	8464		15,270		23,734
<u>Discharge</u>					
U-235	2.84	3.72	13.52	11.54	31.62
U-238	3118	3078	8240	6694	21,130
Pu-238	15.86	24.08	0	0	39.94
Pu-239	320.4	309.2	168.34	103.06	901.0
Pu-240	200.8	246.6	5.00	2.26	454.6
Pu-241	65.58	104.3	0.14	0.04	169.9
Pu-242	127.7	167.1	-	-	294.8
Am-241	10.06	24.08	-	-	34.14
Total Fissile	806.0		296.64		1102.6
Total Heavy Metal	7818		15,238		23,056

TABLE A.15. Annual Mass Flow of Isotopes for Enriched UO₂
With the Small Pin Design

<u>Isotope</u>	<u>Kilograms/Year</u>				
	<u>Inner</u> <u>Core</u>	<u>Outer</u> <u>Core</u>	<u>Axial</u> <u>Blanket</u>	<u>Radial</u> <u>Blanket</u>	<u>Total</u>
U-234	7.92	10.42	0	0	18.34
U-235	860.4	1122.0	23.58	19.32	2025.3
U-238	5106	4834	11,942	9784	31,666
Total Fissile	1982.4		42.90		2,025.3
Total Heavy Metal	11,941		21,769		33,710
<u>Discharge</u>					
U-234	6.76	9.36	0	0	16.12
U-235	536.0	827.0	20.84	17.58	1401.4
U-238	4796	4642	11,780	9684	30,902
Pu-238	0.18	0.04	0	0	0.22
Pu-239	216.6	141.5	146.10	93.56	597.7
Pu-240	10.10	4.04	2.48	1.22	17.84
Pu-241	0.24	0.06	0.04	0.02	0.36
Pu-242	-	-	-	-	-
Total Fissile	1721.4		278.14		1999.5
Total Heavy Metal	11,190		21,746		32,936

TABLE A.16. Annual Mass Flow of Isotopes for Enriched UO₂
With the Advanced Large Pin Design

Isotope	Kilograms/Year				
	Inner Core	Outer Core	Axial Blanket	Radial Blanket	Total
U-234	5.64	7.42	0	0	13.06
U-235	610.6	796.0	16.72	13.48	1436.8
U-238	3602	3410	8432	6808	22,252
Total Fissile	1406.6		30.20		1436.8
Total Heavy Metal	8432		15,270		23,702
<u>Discharge</u>					
U-234	4.48	6.34	0	0	10.82
U-235	309.6	510.8	14.04	11.80	846.2
U-238	3294	3214	8270	6710	21,488
Pu-238	0.34	0.10	0	0	0.44
Pu-239	198.2	135.2	143.28	89.42	566.1
Pu-240	13.50	5.68	3.44	1.62	24.24
Pu-241	0.42	0.12	0.08	0.02	0.64
Pu-242	.02	-	-	-	0.02
Total Fissile	1154.3		258.64		1412.9
Total Heavy Metal	7693		15,244		22,937

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