Transmutation Performance Analysis for Inert Matrix Fuels in Light Water Reactors and Computational Neutronics Methods Capabilities at INL

Advanced Fuel Cycle Initiative

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SUMMARY

A task was undertaken at INL to establish specific technical capabilities to perform neutronics analyses in order to further assess several key issues related to the viability of thermal recycling. The initial computational study reported here is focused on direct thermal recycling of IMF fuels in a heterogeneous Pressurized Water Reactor (PWR) bundle design in a multi-recycle strategy using legacy 5 year cooled LWR SNF. These analyses provide comparison of direct thermal recycling of four actinide partitioning options: PuNpAmCmCf, PuNpAm, PuNp, and Pu. The TRITON depletion code (a component of the SCALE5.1 suite) was used to simulate depletion of an infinite-lattice (2-D) PWR fuel assembly, containing both IMF and UO₂ pins. The TRU loading in the IMF pins was adjusted to ensure a pin power peaking factor no greater than 1.2. The enrichment of the uranium in the UO₂ pins was adjusted to achieve a 1500 day fuel life in a 3-batch strategy. Transuranic recycling was assumed where the selected TRU elements of the given strategy are recycled from UO₂ and IMF pins in the previous cycle and loaded into IMF pins of the current cycle. In the cases where the bundle design was constrained to have a constant number of IMF pins (44 pins), some of the partitioning scenarios required that a portion of the transuranic mass would have to be discarded to repository storage. The reasons for this mass expulsion from an otherwise closed fuel cycle was the requirement to maintain a peaking factor no greater than 1.2. Additional calculations described in Section 5.3 allowed variation of the number of IMF pins between 44 and 60 per assembly as needed in each pass in order to accommodate all TRU in the fuel cycle with no material (aside from separation losses) being discarded.

The results of this study indicate that in the case of Pu-only or NpPu recycling, more IMF pins were required in the first pass to avoid exceeding the peaking limits. After multiple passes, the TRU vector is less reactive and fewer pins can then accommodate this material. The opposite trend was observed when the higher actinides were carried in the recycle stream (PuNpAm and PuNpAmCmCf). In these cases, the number of pins had to be increased with increasing recycle pass to accommodate all TRU in the fuel cycle. It should be noted that these results indicated that 60 pins were sufficient to carry the transuranics in all of these cases on the basis of a power peaking constraint. Additionally, 44 pins was not necessarily the minimum number of IMF pins which could be used to carry the TRU. From a power peaking basis, less than 44 pins could possibly be used for some cases. However, further analyses of other factors, such as gas generation and pellet integrity, in addition to whole core analyses would be needed to make a determination of the minimum or maximum number of IMF pins in the design.

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ACRONYMS

AFCI	Advanced Fuel Cycle Initiative
ANL	Argonne National Laboratories
BOL	Beginning of Life
CONFU	Combined Non-Fertile and Uranium
SNF	Spent Nuclear Fuel
DOE	Department of Energy
EOL	End of Life
GT	Guide Tube
HM	Heavy Metal
IMF	Inert Matrix Fuel
IMF-PuNpAmCm	Inert Matrix Fuel with Plutonium, Neptunium, Americium, & Curium
IMF-PuNpAm	Inert Matrix Fuel with Plutonium, Neptunium, Americium
IMF-PuNp	Inert Matrix Fuel with Plutonium and Neptunium
IMF-Pu	Inert Matrix Fuel with Plutonium
INL	Idaho National Laboratory
IT	Instrument Tube
LWR	Light Water Reactor
MA	Minor Actinides
MCNP	Monte Carlo Neutral Particle code
MOX	Mixed Oxide Fuel
MTHM	Metric Tons Heavy Metal
ORIGEN2	Oak Ridge Isotope Generation and Depletion code, version 2.2
OTC	Once Through Cycle
PWR	Pressurized Water Reactor
TRU	Transuranics
UO ₂	Uranium Dioxide

TRANSMUTATION PERFORMANCE ANALYSIS FOR INERT MATRIX FUELS IN LIGHT WATER REACTORS AND COMPUTATIONAL NEUTRONICS METHODS CAPABILITIES AT INL

1. INTRODUCTION

Increased concerns over repository space and growing Spent Nuclear Fuel (SNF) inventories from currently operating commercial nuclear power plants have motivated efforts to reduce transuranic (TRU) elements from the waste stream. One of the TRU destruction strategies proposed is enabled through the use of thermal recycling in commercial Light Water Reactors (LWR). In order to assess current key issues related to the viability of thermal recycling, efforts were undertaken at INL to identify and establish the specific technical capabilities required to perform the necessary neutronics analyses for LWR recycle strategies. SCALE5.1 developed by Oak Ridge National Laboratory and distributed by RSICC was implemented at INL for this purpose. This system of widely used code packages provides the necessary tools to process nuclear cross section data as well as lattice physics calculations through the TRITON module (DeHart, 2006) along with many other capabilities such as criticality safety calculations, cross section sensitivity and uncertainty analysis, cask shielding analysis and more. Utilizing this package, one can model any LWR fuel assembly and perform infinite lattice depletion calculations. The lattice cross section data as a function of depletion from the TRITON code can also subsequently be used in core follow and core simulation calculations utilizing codes such as PARCS (Downar et al, 2006). PARCS is a multigroup nodal core simulation code developed by Purdue University and is a NRC approved code for LWR applications. This code package was obtained from NRC and installed at INL for full core tracking and simulation analyses. Introduction of these two code packages to the list of the available computational tools at INL has significantly enhanced our capabilities and expertise in LWR neutronics calculations and analyses. This capability, in addition to its value per-se, will also enable studies of the entire fuel cycle strategies contemplated under GNEP by providing a tool for computation of feedstock to fast burner reactors. A brief description of the codes used in this report is presented in Section 2.

Prior to utilizing the TRITON code for transmutation analyses with LWR systems, the code package was benchmarked against MCNP (X5 Monte Carlo Team, 2003), an independent code based on the Monte Carlo methodology, as described in Section 2. The thermal transmutation analyses documented in this report are based on infinite lattice calculations utilizing the TRITON sequence in the SCALE 5.1, therefore only the TRITON sequence was benchmarked against the MCNP code at this time.

Many studies have been performed in the past to address various options of blending strategies and bundle designs for thermal recycling in the current fleet of thermal reactors (Taiwo et al, 2002; Stillman, 2003; Hoffman, 2005). Similar to the analyses reported here, the earlier studies were based on infinite lattice depletion calculation of a typical Pressurized Water Reactor (PWR) fuel assembly with a certain number of UO_2 fuel pins replaced with Inert Matrix Fuel (IMF) pins. This study focuses on a heterogeneous PWR bundle design with IMF pins loaded according to various isotopic blending strategies. In the initial analysis “reference case,” 44 pins contain transuranic vectors of Neptunium (Np), Plutonium (Pu), Americium (Am), Curium (Cm), and Californium (Cf) in a ZrO_2 matrix as would be obtained from the UREX+1a recycling process. Three other alternate fuel assembly designs with 44 IMF

pins were performed by utilizing NpPuAm (UREX+4), NpPu (UREX+2), and Pu (PUREX), respectively as the transuranic vectors in a ZrO_2 matrix in the IMF pins. For each of the four designs, a multi-pass blended transmutation recycling was analyzed. These analyses provide a comparison of direct thermal recycle of Pu, Pu+Np, Pu+Np+Am and Pu+Np+Am+Cm. In addition to the 44 IMF pin cases, in Section 5.3, cases where the number IMF pins per assembly is allowed to vary are investigated.

Section 2 of this report will introduce a brief description of the strategy and the computational codes utilized in this analysis. Section 3 presents a description of the LWR fuel assembly model used in TRITON benchmarking with MCNP. Section 4 presents the description of the fuel assembly with 44 IMF pins used in the multi-pass thermal recycling analyses with TRITON. Section 5 will provide the results from both benchmarking as well as multi-pass thermal recycling comparison. Finally, section 6 will have conclusions and recommendations for future work.

2. METHODOLOGY

The methodology used in the analyses documented in this report is based on 2-D infinite lattice neutron transport calculations for a LWR bundle of a typical 17×17 PWR fuel assembly. These calculations were performed using the TRITON control module of the ORNL SCALE 5.1 code system. Verification of the main modules used by TRITON was performed utilizing the MCNP Monte Carlo code. This additional work was done to verify the accuracy of models used by TRITON for heterogeneous pin lattice calculations. Brief description of both TRITON and MCNP are given in this section followed by a description of the recycling processes analyzed.

2.1 Triton

The TRITON, Transport Rigor Implemented with Time-dependent Operation for Neutronic depletion (DeHart, 2006a) control module is developed and maintained by Oak Ridge National Laboratory as part of the SCALE package. It was originally built around the two-dimensional arbitrary geometry discrete ordinates transport code NEWT (Dehart, 2006b). In recent years, the capabilities were also extended to the Monte Carlo code KENO. TRITON serves as a controller for the sequencing of the different modules and the data transfer between them. Different code sequences exist within TRITON; the one used in these studies was *T-DEPL*. That sequence builds on the cross-section processing and 2-D neutron transport solution, and adds depletion capabilities.

The cross-section processing sequence in TRITON uses BONAMI, CENTRM/PMC and NITAWL. BONAMI (Greene, 2006) is a module that performs the Bondarenko calculations for the resonance self-shielding. CENTRM (Williams et al, 2006) computes a continuous-energy neutron spectrum by solving the transport equation using a combination of point-wise and multigroup data, which works in combination with PMC (Williams and Hollenbach, 2006), a module that produces multigroup data from point-wise. An alternative to CENTRM/PMC is the use of NITAWL (Greene et al, 2006), a module that performs the Nordheim integral treatment for resonance self-shielding. The cross-sections generated by combinations of these modules are then passed to NEWT for the neutronics calculations.

In a *T-DEPL* calculation, NEWT is used to create a three-group weighted library based on calculated volume-averaged fluxes for each mixture. COUPLE (Gauld and Hermann, 2006) is used to update the ORIGEN-S (Gauld et al, 2006) cross-section library with cross-section data read from the weighted library. Three-group fluxes calculated by NEWT are supplied to ORIGEN-S for depletion calculations. COUPLE/ORIGEN calculations are repeated for each mixture being depleted, as specified in the input, using mixture-specific cross-section data and fluxes.

2.2 MCNP

MCNP (X5 Monte Carlo Team, 2003) is a general purpose Monte Carlo N-Particle code that can be used for neutron, photon and electron transport. In this study, MCNP was used as a verification tool for the cross-section processing and neutron transport capabilities used by the TRITON control module. The MCNP code treats arbitrary three-dimensional configurations of materials in geometric cells and uses point-wise cross-section data, which makes it a very popular choice for benchmarking and verification studies.

2.3 Recycling strategies

Four different separations strategies were studied in this report for the fabrication of the IMF pins. These recycling strategies include the PUREX process and three different levels of UREX processes.

The PUREX process is an aqueous extraction method used to reprocess SNF. It extracts the uranium and the plutonium independently from each other. PUREX also extracts fission products and other minor actinides from SNF. This process is currently the most widespread and mature recycling strategy.

The UREX process is also an aqueous extraction method but offers greater proliferation resistance by not having separated plutonium at any stage of the process. Different levels of separation have been tested at the laboratory scale. Each level allows for different groupings of transuranics to be extracted. In this report, three different variations were looked into: UREX+1a, UREX+2 and UREX+4. UREX+1a separates all the TRU from the fission products. UREX+2 allows the Np and Pu to be extracted simultaneously, while UREX+4 has additional separation stages to extract the americium and the curium, independently from each other.

Two approaches to mass balance from recycle-to-recycle were evaluated. First, the blending strategies described above are evaluated for a heterogeneous fuel bundle containing a *fixed* number of 44 IMF pins. In this case, some recycle TRU from the previous cycle is allowed to be discharged from the fuel cycle (for repository disposal) if the design constraints of the fixed 44-pin bundle does not allow for that mass to be included. A second case is evaluated where the number of IMF pins is allowed to *vary* from recycle-to-recycle, thus ensuring no TRU goes to the repository other than reprocessing losses (i.e., self-consistent fuel cycle)

3. BENCHMARK MODEL

Prior to performing the IMF transmutation analysis, two benchmark verification studies were performed. The first compares the TRITON control module with the MCNP/MONTEBURNS (Poston and Trellue, 1999) depletion sequence for the reference PWR bundle with all pins composed of UO_2 . The second benchmark study compares the cross-section processing and neutronic calculation capabilities of TRITON with MCNP for a fuel bundle composed of UO_2 and IMF fuel pins. The sections below describe the benchmarking activities.

3.1 Reference Benchmark Model

The prototype LWR bundle consists of a typical 17×17 PWR fuel assembly. The reference assembly design has 24 guide tubes, 1 instrumentation tube and 264 fuel pins. The detailed parameters of this fuel bundle are described in the following table.

Table 3-1. Benchmark problem design parameters.

	UO ₂
Assembly Size	17 × 17
Number of Fuel Pins	264
Number of Guide Tubes (GT)	24
Number of Instrumentation Tubes (IT)	1
Fuel Rod Pitch (cm)	1.26
Inter-assembly Gap (cm)	0.08
Fuel Pellet Material	UO ₂
Fuel Pellet Radius (cm)	0.4096
Clad Inner Radius (cm)	0.4178
Clad Outer Radius (cm)	0.4750
Fuel Density (g/cc)	10.76
Fuel Mass (kg HM/assembly)	483
Clad Density (g/cc)	6.5522
GT/IT Inner Radius (cm)	0.5715
GT/IT Outer Radius (cm)	0.6121
Discharge Burnup (GWd/MTHM)	51
Fuel Temperature (K)	900.0
Cladding Temperature (K)	581.0
Bulk Coolant Temperature (K)	581.0
Nominal Coolant Density (g/cc)	0.72

The initial fuel loading was assumed to be 4.23% enriched UO₂ burned for 1500 days with a specific power of 34.0 MW/MTHM (assembly power of 16.4 MW). An input file representing this prototype fuel assembly was developed for the TRITON control module to perform the lattice depletion and decay calculations. The TRITON results were then compared to the MCNP/MONTEBURNS depletion sequence. The details of this comparison are documented in Section 5.1.

Figure 3-1. Reference PWR bundle.

3.2 IMF Benchmark Model

The second benchmark study compared the cross-section processing and neutronic calculation capabilities of TRITON with MCNP for a fuel bundle composed of UO_2 and IMF fuel pins. The geometry of this benchmark is identical to the base case of Section 3.1, with the exception that 60 of the 264 fuel pins are loaded with IMF fuel. The model was taken from Goldmann (2005) in which the fuel loading was 9.7% $\text{TRU}(\text{O}_2)$ with an inert fuel matrix of MgO-ZrO_2 . The composition of the TRU vector was taken from the reference benchmark model after 1500 days of irradiation and 5 years of cooling. The $\frac{1}{4}$ PWR fuel bundle with 60 IMF pins is illustrated in Figure 3-2. Considering that the benchmarking calculations were performed as part of a separate and earlier task, the model used in benchmarking is somewhat different from the model used in the fixed 44 IMF pin heterogeneous bundle described in Section 4 and Section 5.2. For the variable-pin bundle analysis, with results given in Section 5.3, the bundle design varies from 44 to 60 pins. The 60 IMF pin bundle design is reflected by Figure 3-2.

Figure 3-2. Quarter representation of 60 pin IMF fuel bundle.

4. IMF MODEL DESCRIPTIONS

The fuel assembly model used in the study reported here for LWR transmutation performance is a typical 17X17 PWR fuel assembly with IMF pins in the assembly periphery as shown in Figure 4-1 (44 IMF pin case). Consistent with a previous study by Hoffman (2005) the IMF pins were located on the first row of the fuel assembly in order to maintain BOL peak IMF pin to assembly average power ratio below 1.20. The IMF pins have ZrO_2 as the inert fuel matrix. As suggested by Stillman (2003) and Hoffman (2005), the pin has an annular design to compensate for the low thermal conductivity of the zirconium oxide. As was assumed in Stillman (2003) and Hoffman (2005) the key measure for the cycle sustainability was determined by the fuel assembly reactivity at a point equivalent to 2/3 of the discharge burnup. The target assembly reactivity at the 2/3 of the discharged burnup was selected to be $k \sim 1.035$ similar to Hoffman study (2005). Also, all the IMF pins were loaded with the same TRU enrichment and without any optimization of the IMF pin location or TRU enrichment variation among different pins. Figure 4-1 shows the arrangement in the 44 IMF pin case. Later in this report, other numbers of IMF pins will be used and their arrangements will be given in their respective sections.

In this study, four different recycling strategies were considered to analyze the effect of the TRU composition in the fuel on repository benefit and impact on discharged IMF neutron and gamma emission. All the fuel pins in the bundle were processed together (i.e. co-processing). After each irradiation cycle of 1500 days, it was assumed that the fuel bundle was cooled for 5 years, followed by a 2 year delay for fuel processing.

Figure 4-1. Quarter representation of the 44 pin IMF bundle design

5. RESULTS

This section will present the results of the benchmarking studies and the subject multi-recycle problems of various types. Four different recycling schemes were analyzed in a 44 pin IMF configuration: Pu recycling (PUREX), Np-Pu recycling (UREX+2), Np-Pu-Am recycling (UREX+4) and Np-Pu-Am-Cm recycling (UREX+1a). Section 5.2 will give results from the cases where the number of IMF pins is fixed at 44 and Section 5.3 will give the results from the cases where the number of IMF pins was allowed to change.

5.1 Benchmark Problems

The TRITON code was compared to MCNP/MONTEBURNS for a base case that consisted of depleting a PWR bundle with 4.3% enrichment. The MCNP/MONTEBURNS results were those provided by Goldmann (2005). The eigenvalue results are presented in Figure 5-1. At the Beginning of life (BOL) the difference between the two methodologies is 0.4%. The TRITON results are slightly lower than the MCNP and MONTEBURNS results as a function of cycle time. However, the uncertainty of the MCNP results is not presented in the figure and most importantly is not propagated in the MONTEBURNS algorithm. Thus, as the depletion progresses, the uncertainty keeps increasing and might account for this difference.

Figure 5-1. Eigenvalue comparison between MCNP/MONTEBURNS and TRITON.

In addition to the comparison with published data reported above, a comparison of eigenvalue and pin powers was also made between locally-computed results from MCNP and TRITON for the base case and a case that included IMF pins. The eigenvalue computed with MCNP for the base case is 1.4014 ± 0.0004 , while TRITON yielded a value of 1.3985. A difference of about 3 mk or 0.2% between the two codes. This difference is understandable when one considers that the codes use different cross section libraries and different methods to solve the problem. Another comparison of interest between the codes is the pin power distribution (e.g. fission density). The results are presented in Figure 5-2 for 1/8 of the bundle. The maximum pin power error is 0.7 % with an average of 0.2 %.

The second case of interest is the fuel bundle containing IMF pins because of its high heterogeneity. The comparison is based on the fuel composition of Recycle 1. The eigenvalue obtained with MCNP is 1.3701 ± 0.0004 and with TRITON an eigenvalue of 1.3729 was obtained. Once again, the difference between both codes is about 3 mk or 0.2%. Figure 5-3 presents the pin power results and comparison for

1/8 of the bundle for the first recycle case. The pin power errors are slightly higher than the base case but still acceptable considering that the bundle is much more heterogeneous. The maximum pin power error is 1.1 % with an average of 0.4 %.

<div> MCNP result $\frac{(\text{TRITON}-\text{MCNP})}{\text{MCNP}}$ </div>								0.901 0.1 %
								0.916 0.0 %
								0.908 0.1 %
								0.920 -0.1 %
								0.970 0.0 %
								0.932 0.2 %
								0.920 -0.1 %
								1.031 -0.2 %
								0.956 0.1 %
								0.932 -0.1 %
								1.053 -0.3 %
								1.077 -0.4 %
								1.059 -0.7 %
								0.980 0.0 %
								0.943 0.3 %
								1.069 -0.1 %
								1.066 0.1 %
								1.015 0.3 %
								0.956 0.2 %
								1.017 -0.1 %
								1.057 0.1 %
								1.023 0.1 %
								1.023 -0.3 %
								1.043 0.1 %
								0.987 0.1 %
								0.954 0.1 %
								0.992 0.0 %
								1.010 -0.1 %
								1.054 0.0 %
								1.021 -0.2 %
								1.017 -0.2 %
								1.041 0.1 %
								0.988 -0.1 %
								0.955 0.1 %
								0.997 0.5 %
								1.038 0.4 %
								1.054 0.1 %
								1.052 0.0 %
								1.016 0.2 %
								0.959 0.3 %

Figure 5-2. Pin power comparison between MCNP and TRITON for PWR base case.

<div> MCNP result <u>(TRITON-MCNP)</u> MCNP </div>								0.754 1.3 %
								0.794 0.8 %
								0.921 0.6 %
								0.836 1.1 %
								0.909 0.1 %
								1.005 0.3 %
								0.875 0.7 %
								0.938 -0.7 %
								1.095 -0.8 %
								1.102 -0.5 %
								1.046 -0.3 %
								0.905 0.6 %
								0.953 -0.1 %
								1.119 -0.4 %
								1.098 -0.2 %
								0.943 0.8 %
								0.968 -0.1 %
								1.080 -0.4 %
								1.120 -0.4 %
								1.075 -0.4 %
								1.052 -0.1 %
								1.038 0.2 %
								0.914 0.8 %
								0.967 -0.1 %
								1.053 -0.1 %
								1.075 -0.4 %
								1.118 -0.5 %
								1.072 -0.3 %
								1.049 -0.2 %
								1.038 0.1 %
								0.914 0.8 %
								0.966 0.0 %
								1.067 -0.1 %
								1.104 0.0 %
								1.110 -0.4 %
								1.087 -0.2 %
								0.948 0.5 %
								0.974 -0.3 %

Figure 5-3. Pin power comparison between MCNP and TRITON for 60 pin IMF.

5.2 Recycling Strategies with 44 IMF Pins

This section gives results from the study assuming a fixed number (44) of IMF pins. The initial TRU vector was generated by the base case PWR bundle calculation that was defined in Section 2. The discharged base case TRU vector was burned to 51 GWd/MTHM and subsequently decayed for 5 years. In the first four recycles of each strategy, the TRU loading and uranium enrichment are adjusted to meet the simulations criteria mentioned previously (k_{inf} greater than 1.035 after 1000 days of irradiation and peak pin below 1.2 at BOL). From the 5th recycle, the TRU loading is kept constant and the uranium enrichment is increased, if necessary, so that k_{inf} is greater than 1.035 after 1000 days irradiation at equilibrium. Equilibrium is considered to be reached when k_{inf} at 1000 days varies by less than 10^{-6} between consecutive recycle stages. An important point to mention is that at equilibrium the amount of TRU loaded doesn't necessarily match the amount of TRU recycled. Currently, the excess TRU recycled is assumed to be sent to the repository. However this excess could be used as fuel for different bundle designs with more IMF pins that are not necessarily self-sufficient.

5.2.1 Pu-only Recycling

Table 5-1 presents a summary of the results for the first four recycling passes of Pu recycling as well as the equilibrium.

Table 5-1. Pu Recycling Data with 44 IMF pins.

		Initial	1 st pass	2 nd pass	3 rd pass	4 th pass	Eq.
Number of IMF pins		0	44	44	44	44	44
Uranium Enrichment		4.23	4.25	4.35	4.36	4.36	4.44
HM loading (kg/assembly)	UO ₂	461.3	384.43	384.43	384.43	384.43	384.43
	IMF	—	4.88	5.85	6.72	7.42	11.92
Charge - Peak Pin	UO ₂	1.072	1.0796	1.0924	1.0939	1.0949	1.1002
	IMF	—	1.1966	1.1343	1.1469	1.1559	1.1779
Charge k-inf		1.3984	1.4057	1.3922	1.3884	1.3855	1.3754
1000 days k-inf		1.0377	1.0358	1.0357	1.0357	1.0352	1.0350
TRU Discharge (kg/assembly)	UO ₂	5.94	4.94	4.99	5.01	5.03	5.11
	IMF	—	1.75	2.71	3.47	4.10	8.34
ΔTRU (kg/assembly)	UO ₂	5.94	4.94	4.99	5.01	5.03	5.11
	IMF	—	-3.13	-3.14	-3.25	-3.32	-3.58
	Total	5.94	1.81	1.85	1.76	1.71	1.53
Pu Discharge (kg/assembly)	UO ₂	5.26	4.35	4.40	4.42	4.44	4.52
	IMF	—	1.51	2.34	3.01	3.57	7.43
Available Pu not Recycled		0.37	0.00	0.00	0.00	0.00	0.00
Pu loss in reprocessing		0.01	0.01	0.01	0.01	0.02	0.02
Unused TRU to repository		1.05	0.84	0.96	1.05	1.12	1.50

In order to respect the peak pin limit at BOL of 1.20 in the first recycle, an excess of 0.37 kg/assembly of Pu must be disposed of by alternate means. All other recycles use the entire amount of Pu available. At equilibrium, 1.50 kg of TRU (non-Pu) per assembly is sent to the repository. The uranium enrichment had to be increased to 4.44% in order to meet the required criterion of cycle length. The peaking factor in all cycles other than the first one is well below the imposed 1.20 BOL limit. Table 5-2 presents the mass of each isotope at equilibrium supplied to the VISION code (Piet, 2009). The values presented in this table correspond to charged, discharged and five year cooling period after discharge. Some of these isotopes were lumped according to the definitions presented in Appendix A. All results are normalized to a metric ton of heavy metal (MTHM) charged in the fuel bundle.

Table 5-2. Mass of each isotope for Pu recycling at equilibrium (grams/MTHM).^a

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
He-4	2.60E-01	1.44E+01	1.85E+01	Cf-251	0.00E+00	6.72E-05	6.69E-05
Pb-206	0.00E+00	1.04E-11	7.15E-11	Cf-252	0.00E+00	5.48E-05	1.48E-05
Pb-207	3.72E-11	1.58E-09	1.25E-08	H-3	6.10E-08	1.07E-01	8.05E-02
Pb-208	0.00E+00	4.22E-06	5.54E-05	C14	2.82E-09	5.26E-03	5.26E-03

a. Note that many of these isotope groups include other isotopes than those shown. In several cases, information was omitted from these tables for brevity. See Appendix A for a more detailed listing of isotope groups.

Table 5-2. (continued).

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
Pb-210	4.59E-12	2.75E-10	5.81E-10	C-other	1.06E-05	1.98E+01	1.98E+01
Bi-209	0.00E+00	1.82E-09	5.40E-09	Kr-81	4.47E-12	2.37E-05	2.37E-05
Ra-226	1.76E-08	1.01E-07	2.87E-07	Kr-85	3.41E-06	3.85E+01	2.78E+01
Ra-228	0.00E+00	2.73E-14	1.78E-13	Other Inert Gases	6.15E-03	9.96E+03	9.96E+03
Ac-227	1.71E-09	1.73E-08	1.27E-07	Rb	1.18E-03	5.49E+02	5.59E+02
Th-228	0.00E+00	9.99E-06	4.77E-05	Sr-90	8.13E-05	8.38E+02	7.41E+02
Th-229	0.00E+00	3.61E-06	3.69E-06	Sr-other	3.09E-03	5.67E+02	5.39E+02
Th-230	1.96E-03	2.76E-03	5.58E-03	Zr-93	1.32E-07	1.16E+03	1.16E+03
Th-232	3.51E-08	4.26E-04	1.28E-03	Zr-95	5.15E-05	7.51E+01	1.97E-07
Pa-231	8.40E-05	1.15E-03	1.19E-03	Zr-other	2.70E-03	4.67E+03	4.81E+03
U-232	5.42E-10	2.90E-03	2.79E-03	Tc-99	3.90E-08	1.33E+03	1.34E+03
U-233	8.54E-08	2.99E-03	4.19E-03	Tc-other	8.29E-04	3.64E-01	0.00E+00
U-234	3.61E+02	1.87E+02	2.21E+02	Ru-106	1.22E-04	2.75E+02	9.11E+00
U-235	4.31E+04	7.83E+03	7.83E+03	Pd-107	2.32E-07	5.02E+02	5.02E+02
U-236	1.22E+00	5.87E+03	5.87E+03	Other Ru, Rh, Pd	5.24E-04	7.37E+03	7.63E+03
U-238	9.26E+05	8.91E+05	8.91E+05	Mo-Other	5.08E-03	5.72E+03	5.84E+03
Np-237	3.20E-01	7.37E+02	7.40E+02	Se-79	2.08E-08	7.84E+00	7.84E+00
Pu-238	8.48E+02	8.30E+02	8.63E+02	Cd-113m	3.28E-11	4.41E-03	3.52E-03
Pu-239	6.21E+03	6.22E+03	6.22E+03	Sn-126	1.86E-05	3.48E+01	3.48E+01
Pu-240	5.82E+03	5.70E+03	5.83E+03	Sb-125	3.65E-07	1.29E+01	3.66E+00
Pu-241	1.95E+03	2.74E+03	2.15E+03	Other Trans. Met.	7.27E-03	1.45E+03	1.41E+03
Pu-242	1.50E+04	1.51E+04	1.51E+04	I-129	4.36E-09	2.78E+02	2.80E+02
Pu-244	1.10E-10	2.00E-01	2.00E-01	Other Halogens	3.23E-03	1.28E+02	1.19E+02
Am-241	1.97E+02	1.54E+02	7.37E+02	Cs-134	1.14E-08	2.33E+02	4.35E+01
Am-242m	3.75E-05	3.53E+00	3.45E+00	Cs-135	3.22E-07	8.12E+02	8.13E+02
Am-243	1.16E-03	1.61E+03	1.61E+03	Cs-137	1.85E-04	2.14E+03	1.91E+03
Cm-242	1.60E-04	6.85E+01	3.82E-02	Cs-other	2.38E-03	1.91E+03	1.92E+03
Cm-243	0.00E+00	3.39E+00	3.01E+00	Ba	3.73E-03	2.61E+03	3.01E+03
Cm-244	0.00E+00	7.84E+02	6.47E+02	Ce-144	5.56E-04	4.39E+02	5.18E+00
Cm-245	0.00E+00	4.00E+01	4.00E+01	Pm-147	9.02E-09	2.31E+02	6.38E+01
Cm-246	0.00E+00	8.28E+00	8.28E+00	Sm-146	0.00E+00	1.64E-02	1.66E-02
Cm-247	0.00E+00	1.72E-01	1.72E-01	Sm-147	5.97E-09	1.32E+02	3.07E+02
Cm-248	0.00E+00	1.73E-02	1.73E-02	Sm-151	5.81E-09	2.36E+01	2.30E+01
Cm-250	0.00E+00	1.11E-08	1.11E-08	Eu-154	5.41E-10	5.10E+01	3.41E+01
Bk-249	0.00E+00	2.50E-04	4.81E-06	Eu-155	1.34E-07	1.17E+01	5.56E+00
Cf-249	0.00E+00	5.39E-05	2.97E-04	Ho-166m	5.31E-12	7.59E-04	7.57E-04
Cf-250	0.00E+00	1.09E-04	8.36E-05	Other Lanthanides	6.86E-03	1.72E+04	1.76E+04

5.2.2 Np-Pu Recycling (UREX+2)

Table 5-3 shows the results for the Np-Pu recycling strategy for the first four transition recycles and the equilibrium case. In each recycle, all of the Am, Cm and Cf isotopes are sent directly to the repository.

Table 5-3. Np-Pu recycling with 44 IMF pins.

		Initial	1 st pass	2 nd pass	3 rd pass	4 th pass	Eq.
Number of IMF pins		0	44	44	44	44	44
Uranium Enrichment		4.23	4.30	4.42	4.43	4.43	4.49
HM loading (kg/assembly)	UO ₂	461.3	384.43	384.43	384.43	384.43	384.43
	IMF	—	5.38	6.55	7.62	8.47	13.97
Charge - Peak Pin	UO ₂	1.072	1.0843	1.0992	1.1013	1.1026	1.1084
	IMF	—	1.1971	1.1299	1.1469	1.1597	1.1983
Charge k-inf		1.3984	1.3991	1.3832	1.3779	1.3740	1.3602
1000 days k-inf		1.0377	1.0355	1.0354	1.0357	1.0355	1.0354
TRU Discharge (kg/assembly)	UO ₂	5.94	4.98	5.04	5.08	5.10	5.18
	IMF	—	2.14	3.27	4.18	4.93	10.07
Δ TRU (kg/assembly)	UO ₂	5.94	4.98	5.04	5.08	5.10	5.18
	IMF	—	-3.24	-3.28	-3.44	-3.54	-3.90
	Total	5.94	1.74	1.76	1.64	1.56	1.28
Np and Pu Discharge (kg/assembly)	UO ₂	5.59	4.68	4.74	4.78	4.80	4.89
	IMF	—	1.88	2.89	3.71	4.39	9.11
Available NpPu not Recycled		0.20	0.00	0.00	0.00	0.00	0.00
Np and Pu loss in reprocessing		0.01	0.01	0.02	0.02	0.02	0.03
Unused TRU to repository		0.55	0.56	0.68	0.77	0.83	1.25

At the first recycle, 0.20 kg of Np and Pu had to be disposed of to ensure that the peaking factor at BOL was below 1.20. At equilibrium, 1.25 kg per assembly of Am, Cm and Cf are sent to the repository. In order to achieve an equilibrium cycle with a k-inf above 1.035 after 1000 days of irradiation and a peaking factor below 1.20 at BOL, the uranium enrichment had to be increased to 4.49%. Table 5-4 gives the mass of all isotopes needed for VISION as described in Appendix A. The results are normalized to one MTHM charged at equilibrium.

Table 5-4. Mass of each isotope for Np-Pu recycling at equilibrium (grams/MTHM)

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
He-4	5.27E-01	1.55E+01	2.03E+01	Cf-251	0.00E+00	4.74E-05	4.72E-05
Pb-206	0.00E+00	1.75E-11	1.09E-10	Cf-252	0.00E+00	2.99E-05	8.07E-06
Pb-207	3.74E-11	2.27E-09	1.42E-08	H-3	6.07E-08	1.06E-01	7.97E-02
Pb-208	0.00E+00	9.62E-06	1.14E-04	C14	2.78E-09	5.24E-03	5.24E-03

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Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
Pb-210	4.62E-12	4.80E-10	7.84E-10	C-other	1.07E-05	1.98E+01	1.98E+01
Bi-209	0.00E+00	3.74E-09	1.12E-08	Kr-81	4.37E-12	2.36E-05	2.36E-05
Ra-226	1.78E-08	1.06E-07	3.17E-07	Kr-85	3.38E-06	3.82E+01	2.76E+01
Ra-228	0.00E+00	2.73E-14	1.77E-13	Other Inert Gases	6.11E-03	9.86E+03	9.86E+03
Ac-227	1.72E-09	1.95E-08	1.39E-07	Rb	1.17E-03	5.45E+02	5.55E+02
Th-228	0.00E+00	2.09E-05	9.98E-05	Sr-90 w/Y-90 decay	8.07E-05	8.32E+02	7.36E+02
Th-229	3.20E-09	7.55E-06	7.66E-06	Sr-other	3.06E-03	5.63E+02	5.35E+02
Th-230	2.00E-03	2.98E-03	6.56E-03	Zr-93	1.30E-07	1.15E+03	1.15E+03
Th-232	4.11E-08	4.25E-04	1.28E-03	Zr-95	5.11E-05	7.48E+01	1.96E-07
Pa-231	8.45E-05	1.25E-03	1.29E-03	Zr-other	2.68E-03	4.64E+03	4.77E+03
U-232	6.17E-09	6.36E-03	6.12E-03	Tc-99	3.89E-08	1.33E+03	1.33E+03
U-233	8.17E-04	4.20E-03	6.18E-03	Tc-other	8.27E-04	3.63E-01	0.00E+00
U-234	3.74E+02	2.22E+02	2.95E+02	Ru-106	1.22E-04	2.74E+02	9.08E+00
U-235	4.33E+04	8.44E+03	8.44E+03	Pd-107	2.32E-07	5.02E+02	5.02E+02
U-236	1.42E+00	5.86E+03	5.86E+03	Other Ru, Rh, Pd	5.25E-04	7.33E+03	7.60E+03
U-238	9.21E+05	8.87E+05	8.87E+05	Mo-Other	5.06E-03	5.69E+03	5.80E+03
Np-237	1.22E+03	1.22E+03	1.22E+03	Se-79	2.06E-08	7.81E+00	7.81E+00
Pu-238	1.83E+03	1.86E+03	1.86E+03	Cd-113m	3.31E-11	5.02E-03	3.99E-03
Pu-239	6.78E+03	6.80E+03	6.80E+03	Sn-126	1.85E-05	3.48E+01	3.48E+01
Pu-240	6.81E+03	6.71E+03	6.83E+03	Sb-125	3.62E-07	1.29E+01	3.66E+00
Pu-241	2.23E+03	3.13E+03	2.46E+03	Other Trans. Met.	7.22E-03	1.44E+03	1.40E+03
Pu-242	1.59E+04	1.60E+04	1.60E+04	I-129	4.36E-09	2.78E+02	2.80E+02
Pu-244	1.07E-10	1.80E-01	1.80E-01	Other Halogens	3.21E-03	1.28E+02	1.19E+02
Am-241	2.25E+02	2.03E+02	8.70E+02	Cs-134	1.12E-08	2.28E+02	4.25E+01
Am-242m	3.91E-05	4.96E+00	4.84E+00	Cs-135	3.18E-07	8.48E+02	8.49E+02
Am-243	1.16E-03	1.60E+03	1.60E+03	Cs-137	1.84E-04	2.13E+03	1.90E+03
Cm-242	1.67E-04	7.60E+01	4.50E-02	Cs-other	2.37E-03	1.91E+03	1.92E+03
Cm-243	0.00E+00	3.82E+00	3.38E+00	Ba	3.71E-03	2.59E+03	2.98E+03
Cm-244	0.00E+00	7.32E+02	6.04E+02	Ce-144	5.53E-04	4.36E+02	5.15E+00
Cm-245	0.00E+00	4.26E+01	4.26E+01	Pm-147	9.01E-09	2.34E+02	6.47E+01
Cm-246	0.00E+00	6.86E+00	6.86E+00	Sm-146	0.00E+00	1.65E-02	1.67E-02
Cm-247	0.00E+00	1.40E-01	1.40E-01	Sm-147	5.97E-09	1.34E+02	3.11E+02
Cm-248	0.00E+00	1.25E-02	1.25E-02	Sm-151	5.81E-09	2.56E+01	2.49E+01
Cm-250	0.00E+00	7.48E-09	7.48E-09	Eu-154	5.40E-10	5.25E+01	3.51E+01
Bk-249	0.00E+00	1.97E-04	3.78E-06	Eu-155	1.34E-07	1.16E+01	5.55E+00
Cf-249	0.00E+00	4.66E-05	2.38E-04	Ho-166m	5.39E-12	6.88E-04	6.86E-04
Cf-250	0.00E+00	7.40E-05	5.68E-05	Other Lanthanides	6.82E-03	1.71E+04	1.75E+04

5.2.3 Np-Pu-Am Recycling (UREX+4)

A summary of the first four transition recycles and equilibrium of the Np-Pu-Am recycling strategy is presented in

Table 5-5. For this strategy, the Cm and Cf isotopes are sent directly to the repository.

Table 5-5. Np-Pu-Am Recycling with 44 IMF pins.

		Initial	1 st pass	2 nd pass	3 rd pass	4 th pass	Eq.
Number of IMF pins		0	44	44	44	44	44
Uranium Enrichment		4.23	4.33	4.48	4.50	4.52	4.63
HM loading (kg/assembly)	UO ₂	461.3	384.4	384.4	384.4	384.4	384.4
	IMF	—	5.89	7.37	8.79	10.00	17.35
Charge - Peak Pin	UO ₂	1.072	1.0927	1.1120	1.1162	1.1192	1.1319
	IMF	—	1.1901	1.1109	1.1283	1.1411	1.1879
Charge k-inf		1.3984	1.3858	1.3647	1.3561	1.3499	1.3244
1000 days k-inf		1.0377	1.0360	1.0353	1.0353	1.0355	1.0355
TRU Discharge (kg/assembly)	UO ₂	5.94	5.02	5.09	5.14	5.17	5.29
	IMF	—	2.53	3.96	5.20	6.27	13.1
Δ TRU (kg/assembly)	UO ₂	5.94	5.02	5.09	5.14	5.17	5.29
	IMF	—	-3.36	-3.41	-3.59	-3.73	-4.25
	Total	5.94	1.66	1.68	1.55	1.44	1.04
Np, Pu and Am Discharged (kg/assembly)	UO ₂	5.90	4.98	5.06	5.11	5.14	5.26
	IMF	—	2.40	3.75	4.92	5.94	12.5
Available NpPuAm not Recycled		0.00	0.00	0.00	0.00	0.00	0.38
Np, Pu and Am loss in reprocessing		0.01	0.02	0.02	0.02	0.02	0.03
Unused TRU to repository		0.04	0.16	0.25	0.31	0.36	1.01

At equilibrium, 1.01 kg per assembly of Cm and Cf are sent to the repository in order to respect the pin peaking limit. A surplus of 0.38 kg of Np, Pu and Am is also present at equilibrium that could be used elsewhere in the fuel cycle, but is assumed to be sent to the repository. In the initial transitional recycle and at equilibrium, the peaking factor of the IMF pins stays just below the 1.20 BOL limit. In the transitional cycles (2 to 4), the peaking factor is well below the prescribed limit. The uranium enrichment was also increased to 4.63% at equilibrium. Table 5-6 gives the mass of all isotopes needed for VISION as described in Appendix A. The results are normalized to one MTHM charged at equilibrium.

Table 5-6. Mass of each isotope for Np-Pu-Am recycling at equilibrium (grams/MTHM)

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
He-4	1.01E+00	2.91E+01	3.92E+01	Cf-251	0.00E+00	1.17E-04	1.16E-04
Pb-206	0.00E+00	1.99E-11	1.25E-10	Cf-252	0.00E+00	5.62E-05	1.52E-05
Pb-207	3.83E-11	2.65E-09	1.62E-08	H-3	6.01E-08	1.04E-01	7.83E-02
Pb-208	0.00E+00	1.14E-05	1.39E-04	C14	2.69E-09	5.15E-03	5.15E-03
Pb-210	4.65E-12	5.58E-10	8.94E-10	C-other	1.08E-05	1.97E+01	1.97E+01
Bi-209	0.00E+00	4.21E-09	1.33E-08	Kr-81	4.04E-12	2.32E-05	2.32E-05
Ra-226	1.80E-08	1.14E-07	3.65E-07	Kr-85	3.35E-06	3.79E+01	2.74E+01
Ra-228	0.00E+00	2.75E-14	1.79E-13	Other Inert Gases	6.06E-03	9.69E+03	9.69E+03
Ac-227	1.76E-09	2.33E-08	1.57E-07	Rb	1.17E-03	5.41E+02	5.51E+02
Th-228	0.00E+00	2.51E-05	1.23E-04	Sr-90	8.00E-05	8.26E+02	7.30E+02
Th-229	3.46E-09	8.74E-06	8.87E-06	Sr-other	3.04E-03	5.58E+02	5.31E+02
Th-230	2.04E-03	3.34E-03	8.12E-03	Zr-93	1.27E-07	1.14E+03	1.14E+03
Th-232	5.25E-08	4.28E-04	1.29E-03	Zr-95	5.05E-05	7.43E+01	1.95E-07
Pa-231	8.64E-05	1.40E-03	1.45E-03	Zr-other	2.66E-03	4.60E+03	4.73E+03
U-232	7.45E-09	7.96E-03	7.66E-03	Tc-99	3.88E-08	1.33E+03	1.33E+03
U-233	8.85E-04	5.22E-03	7.41E-03	Tc-other	8.14E-04	3.60E-01	0.00E+00
U-234	3.95E+02	2.77E+02	4.13E+02	Ru-106	1.19E-04	2.70E+02	8.97E+00
U-235	4.43E+04	9.53E+03	9.54E+03	Pd-107	2.24E-07	4.97E+02	4.97E+02
U-236	1.81E+00	5.93E+03	5.93E+03	Other Ru, Rh, Pd	5.18E-04	7.25E+03	7.51E+03
U-238	9.12E+05	8.78E+05	8.78E+05	Mo-Other	5.00E-03	5.64E+03	5.75E+03
Np-237	1.32E+03	1.34E+03	1.35E+03	Se-79	2.01E-08	7.77E+00	7.77E+00
Pu-238	3.31E+03	3.42E+03	3.44E+03	Cd-113m	3.34E-11	6.77E-03	5.37E-03
Pu-239	7.65E+03	7.84E+03	7.84E+03	Sn-126	1.81E-05	3.46E+01	3.46E+01
Pu-240	8.69E+03	8.62E+03	8.91E+03	Sb-125	3.57E-07	1.28E+01	3.64E+00
Pu-241	2.64E+03	3.79E+03	2.98E+03	Other Trans. Met.	7.15E-03	1.43E+03	1.39E+03
Pu-242	1.49E+04	1.53E+04	1.53E+04	I-129	4.37E-09	2.77E+02	2.79E+02
Pu-244	8.99E-11	1.43E-01	1.43E-01	Other Halogens	3.18E-03	1.27E+02	1.18E+02
Am-241	1.58E+03	5.42E+02	1.35E+03	Cs-134	1.06E-08	2.19E+02	4.07E+01
Am-242m	1.42E+01	1.50E+01	1.47E+01	Cs-135	3.06E-07	9.08E+02	9.09E+02
Am-243	2.99E+03	3.06E+03	3.06E+03	Cs-137	1.81E-04	2.11E+03	1.88E+03
Cm-242	3.63E-02	1.63E+02	1.08E-01	Cs-other	2.35E-03	1.90E+03	1.92E+03
Cm-243	3.46E-09	1.03E+01	9.11E+00	Ba	3.67E-03	2.56E+03	2.95E+03
Cm-244	1.12E-03	1.71E+03	1.41E+03	Ce-144	5.48E-04	4.33E+02	5.11E+00
Cm-245	0.00E+00	9.89E+01	9.89E+01	Pm-147	9.01E-09	2.39E+02	6.61E+01
Cm-246	0.00E+00	1.43E+01	1.43E+01	Sm-146	0.00E+00	1.67E-02	1.70E-02
Cm-247	0.00E+00	3.36E-01	3.36E-01	Sm-147	5.97E-09	1.37E+02	3.18E+02
Cm-248	0.00E+00	2.89E-02	2.89E-02	Sm-151	5.79E-09	2.92E+01	2.84E+01
Cm-250	0.00E+00	1.76E-08	1.76E-08	Eu-154	5.52E-10	5.42E+01	3.62E+01
Bk-249	0.00E+00	5.26E-04	1.01E-05	Eu-155	1.33E-07	1.16E+01	5.53E+00

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
Cf-249	0.00E+00	1.55E-04	6.66E-04	Ho-166m	6.40E-12	6.75E-04	6.73E-04
Cf-250	0.00E+00	1.70E-04	1.30E-04	Other Lanthanides	6.76E-03	1.69E+04	1.73E+04

5.2.4 Np-Pu-Am-Cm-Cf Recycling (UREX+1a)

In this recycling strategy, no transuranics are partitioned out of the fuel stream and sent to the repository. A summary of the transitional recycles and equilibrium are presented in

Table 5-7.

Table 5-7. Np-Pu-Am-Cm Recycling with 44 IMF pins.

		Initial	1 st pass	2 nd pass	3 rd pass	4 th pass	Eq.
Number of IMF pins		0	44	44	44	44	44
Uranium Enrichment		4.23	4.31	4.46	4.46	4.46	4.51
HM loading (kg/assembly)	UO ₂	461.3	384.3	384.3	384.3	384.3	384.3
	IMF	—	5.93	7.56	9.16	10.62	14.76
Charge - Peak Pin	UO ₂	1.072	1.0925	1.1120	1.1159	1.1187	1.1272
	IMF	—	1.1939	1.1157	1.1382	1.1583	1.1757
Charge k-inf		1.3984	1.3308	1.3639	1.3544	1.3470	1.3411
1000 days k-inf		1.0377	1.0353	1.0359	1.0356	1.0357	1.0357
TRU Discharge (kg/assembly)	UO ₂	5.94	5.02	5.10	5.14	5.18	5.25
	IMF	—	2.55	4.12	5.49	6.77	10.64
ΔTRU (kg/assembly)	UO ₂	5.94	5.02	5.10	5.14	5.18	5.25
	IMF	—	−3.38	−3.44	−3.67	−3.85	−4.12
	Total	5.94	1.64	1.66	1.47	1.33	1.13
TRU Recycled (kg/assembly)	UO ₂	5.94	5.02	5.10	5.14	5.18	4.89
	IMF	—	2.55	4.12	5.49	6.77	9.91
TRU loss in reprocessing		0.01	0.02	0.02	0.02	0.02	0.03
Unused TRU to repository		0.00	0.00	0.00	0.00	0.00	1.09

At equilibrium, an excess of 1.09 kg of Np, Pu, Am, Cm and Cf is produced which cannot be burned in the 44 IMF pins without violating the pin peaking factor limit of 1.2. The UO₂ enrichment was increased to 4.51% to sustain the cycle length. The initial charge of TRU in the IMF pins at equilibrium is 14.76 kg per assembly and the consumption is 4.12 kg per assembly.

Table 5-8 presents the mass of each isotope at equilibrium used by the VISION code. All results were normalized to a metric ton of heavy metal (MTHM) charged in the fuel bundle.

Table 5-8. Mass of each isotope for Np-Pu-Am-Cm recycling at equilibrium (grams/MTHM).

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
He-4	3.38E+00	3.33E+01	4.58E+01	Cf-251	4.05E-01	4.38E-01	4.36E-01
Pb-206	0.00E+00	1.82E-11	1.14E-10	Cf-252	1.44E-01	9.72E-01	2.63E-01
Pb-207	3.75E-11	2.41E-09	1.51E-08	H-3	6.05E-08	1.05E-01	7.93E-02
Pb-208	0.00E+00	1.01E-05	1.23E-04	C14	2.70E-09	5.16E-03	5.16E-03
Pb-210	4.64E-12	5.05E-10	8.26E-10	C-other	1.09E-05	1.99E+01	1.99E+01
Bi-209	0.00E+00	3.84E-09	1.18E-08	Kr-81	4.08E-12	2.35E-05	2.35E-05
Ra-226	1.79E-08	1.09E-07	3.39E-07	Kr-85	3.37E-06	3.79E+01	2.75E+01
Ra-228	0.00E+00	2.73E-14	1.77E-13	Other Inert Gases	6.09E-03	9.78E+03	9.78E+03
Ac-227	1.73E-09	2.13E-08	1.47E-07	Rb	1.17E-03	5.41E+02	5.52E+02
Th-228	0.00E+00	2.22E-05	1.08E-04	Sr-90	8.05E-05	8.26E+02	7.30E+02
Th-229	3.02E-09	7.86E-06	7.98E-06	Sr-other	3.06E-03	5.58E+02	5.31E+02
Th-230	2.02E-03	3.14E-03	7.31E-03	Zr-93	1.27E-07	1.15E+03	1.15E+03
Th-232	4.71E-08	4.24E-04	1.28E-03	Zr-95	5.08E-05	7.43E+01	1.95E-07
Pa-231	8.47E-05	1.32E-03	1.36E-03	Zr-other	2.67E-03	4.60E+03	4.74E+03
U-232	6.33E-09	6.93E-03	6.67E-03	Tc-99	3.88E-08	1.33E+03	1.33E+03
U-233	7.71E-04	4.62E-03	6.62E-03	Tc-other	8.19E-04	3.61E-01	0.00E+00
U-234	3.84E+02	2.48E+02	3.54E+02	Ru-106	1.20E-04	2.75E+02	9.12E+00
U-235	4.34E+04	8.82E+03	8.83E+03	Pd-107	2.27E-07	5.07E+02	5.07E+02
U-236	1.63E+00	5.85E+03	5.85E+03	Other Ru, Rh, Pd	5.35E-04	7.34E+03	7.60E+03
U-238	9.19E+05	8.85E+05	8.85E+05	Mo-Other	5.03E-03	5.66E+03	5.77E+03
Np-237	1.15E+03	1.23E+03	1.24E+03	Se-79	2.02E-08	7.78E+00	7.78E+00
Pu-238	2.47E+03	2.67E+03	2.70E+03	Cd-113m	4.17E-10	7.09E-03	5.63E-03
Pu-239	6.76E+03	7.28E+03	7.28E+03	Sn-126	1.83E-05	3.49E+01	3.49E+01
Pu-240	7.90E+03	7.86E+03	8.34E+03	Sb-125	3.60E-07	1.30E+01	3.68E+00
Pu-241	2.33E+03	3.51E+03	2.76E+03	Other Trans. Met.	7.19E-03	1.46E+03	1.42E+03
Pu-242	1.04E+04	1.12E+04	1.12E+04	I-129	4.56E-09	2.79E+02	2.81E+02
Pu-244	1.19E-04	1.31E-01	1.31E-01	Other Halogens	3.20E-03	1.28E+02	1.19E+02
Am-241	1.30E+03	4.03E+02	1.15E+03	Cs-134	1.11E-08	2.23E+02	4.16E+01
Am-242m	9.69E+00	1.08E+01	1.05E+01	Cs-135	3.12E-07	8.76E+02	8.77E+02
Am-243	2.11E+03	2.27E+03	2.27E+03	Cs-137	1.83E-04	2.12E+03	1.89E+03
Cm-242	2.87E-02	1.41E+02	8.76E-02	Cs-other	2.36E-03	1.91E+03	1.92E+03
Cm-243	7.36E+00	9.39E+00	8.31E+00	Ba	3.70E-03	2.58E+03	2.97E+03
Cm-244	2.00E+03	2.81E+03	2.32E+03	Ce-144	5.52E-04	4.35E+02	5.13E+00
Cm-245	1.54E+02	1.65E+02	1.65E+02	Pm-147	9.02E-09	2.37E+02	6.56E+01
Cm-246	2.74E+02	2.95E+02	2.95E+02	Sm-146	0.00E+00	1.68E-02	1.70E-02
Cm-247	2.36E+01	2.54E+01	2.54E+01	Sm-147	5.97E-09	1.36E+02	3.16E+02
Cm-248	3.24E+01	3.41E+01	3.48E+01	Sm-151	5.93E-09	2.77E+01	2.70E+01
Cm-250	0.00E+00	9.47E-05	9.49E-05	Eu-154	6.77E-10	5.41E+01	3.62E+01
Bk-249	4.14E-06	8.98E-01	1.73E-02	Eu-155	1.40E-07	1.18E+01	5.63E+00

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
Cf-249	1.38E+00	6.24E-01	1.49E+00	Ho-166m	4.00E-11	1.14E-03	1.14E-03
Cf-250	2.97E-01	4.62E-01	3.55E-01	Other Lanthanides	6.81E-03	1.70E+04	1.75E+04

5.2.5 44 IMF Pin Summary

Figure 5-4 presents the total decay heat in recycled fuel per mass of original fresh fuel as a function of recycle pass. Over 98% of the decay heat produced from UREX+1a recycle, “NpPuAmCmCf” is from only five isotopes of Pu238, Pu239, Am241, Am243, and Cm244. After only eight recycle pass, the decay heat produced from UREX+1a recycle case is about 13 times higher than in the case of Pu-only recycle.

Figure 5-4. Total decay heat in recycled fuel.

Figure 5-5 presents the total photon energy per mass of fresh fuel. In this case over 98% of the photon energy from UREX+1a “NpPuAmCm” recycle case is given off by only six isotopes: Pu238, Am241, Am243, Cm243, Cm244, and Cf252. The photon energy produce by Cf252 is about 4%. After only eight recycle passes the ratio of the photon energy from the UREX+1a recycle case to “NpPuAm,” “NpPu,” and “Pu” is 2, 8, and 13, respectively.

Figure 5-5. Photon energy in recycled fuel.

Figure 5-6 presents the neutron emission rate per mass of fuel. The key isotopes contributing to the neutron emission rate from “NpPuAmCm” recycle case are Cm244, Cm246, Cm247, Cm248, Cf250, and Cf252. Here after eight recycle passes the ratio of the neutron emission from the UREX+1a recycle case to “NpPuAm,” “NpPu,” and “Pu” is 3600, 4300, and 4900, respectively. The Cm/Cf recycle increases the neutron emission by four orders of magnitude.

Figure 5-6. Neutron emission in recycled fuel (neutrons/s*MTHM).

Finally, Table 5-9 presents the benefit of each recycling strategy in terms of total mass to the repository in the middle column. The far right column indicates what the total mass benefit could be if the excess recycling isotopes were used elsewhere in the fuel cycle instead of being sent to the repository. This indicates that loading this excess fuel in different bundle designs (e.g. more IMF pins) would reduce the mass to repository considerably. Another point to consider would be a synergistic approach between thermal and fast transmutation by sending the non-usable TRU from thermal recycle to the feed stream of a fast reactor.

Table 5-9. TRU to repository at equilibrium.

Recycling Strategy	TRU to repository due to separations strategy (kg/assembly)	Unrecycled TRU to repository to respect peaking limits (kg/assembly)
Once Through Cycle	5.94	—
PUREX (Pu)	1.50	0.00
UREX+2 (Np,Pu)	1.25	0.00
UREX+4 (Np,Pu,Am)	1.01	0.38
UREX+1a (Np,Pu,Am,Cm,Cf)	—	1.09

5.3 Recycling Strategies with Variable Number of IMF Pins

In the previous section, it was assumed that only 44 pins of IMF could be used per fuel assembly. Thus, in order to meet the power peaking constraint in the IMF pins, which is a function of TRU concentration or enrichment, some TRU was discarded to ensure an enrichment that respects the 1.2 pin peaking limit. In this section, the number of IMF pins was allowed to vary in order to keep all of the TRU isotopes of interest in the recycle stream. As before, four cases were analyzed; Pu-only, NpPu, NpPuAm and NpPuAmCmCf.

5.3.1 Pu-only Recycling

In the Pu-only case, the first recycle gives a high peaking factor in the IMF pins due to the relatively high reactivity Pu vector coming out of the first irradiation. Therefore, the 1st pass must use greater than 44 IMF pins in order to respect the peaking factor limit of 1.2. Here the number used was 52 (arrangement is shown in Figure 5-7. In the 2nd pass, the number of pins can be reduced to 44 again. From this point on, the recycle strategy is approximately the same as in Section 5.2.1. 44 IMF pins are used all the way to equilibrium. As can be seen in

Table 5-10 and as is consistent with expectations, the same equilibrium condition is reached as in the case where 44 pins were used throughout. A table is not given here showing isotopics of the equilibrium fuel as it would be identical to Table 5-2.

Table 5-10. Pu-only recycling with variable number of IMF pins.

	Initial	1 st pass	2 nd pass	3 rd pass	4 th pass	Eq.
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Number of IMF pins		0	52	44	44	44	44
Uranium Enrichment		4.23	4.36	4.42	4.42	4.42	4.44
HM loading (kg/assembly)	UO ₂	461.3	370.45	384.4	384.4	384.4	384.43
	IMF	—	5.25	5.70	6.68	7.42	11.92
Charge - Peak Pin	UO ₂	1.072	1.0884	1.0909	1.0903	1.0912	1.1002
	IMF	—	1.1026	1.1195	1.1560	1.1684	1.1779
Charge k-inf		1.3984	1.4113	1.3937	1.3911	1.3879	1.3754
1000 days k-inf		1.0377	1.0362	1.0373	1.0385	1.0384	1.0350
TRU Discharge (kg/assembly)	UO ₂	5.94	4.74	4.98	5.01	5.03	5.11
	IMF	—	1.82	2.68	3.47	4.11	8.34
Δ TRU (kg/assembly)	UO ₂	5.94	4.74	4.98	5.01	5.03	5.11
	IMF	—	-3.43	-3.02	-3.21	-3.31	-3.58
	Total	5.94	1.31	1.96	1.80	1.72	1.53
Pu Discharge (kg/assembly)	UO ₂	5.26	4.16	4.39	4.42	4.44	4.52
	IMF	—	1.55	2.31	3.01	3.58	7.43
Pu loss in reprocessing		0.01	0.01	0.01	0.01	0.01	0.02
Unused TRU to repository		0.68	0.85	1.04	1.04	1.11	1.50

Figure 5-7. Layout of 1/4 PWR assemblies with 52 IMF pins.

5.3.2 Np-Pu Recycling (UREX+2)

Table 5-11 shows the recycling strategy for Np-Pu recycling with variable number of IMF pins. Similar to the Pu-only scenario, the 44 IMF pin arrangement was unable to accommodate all of the Np+Pu recycled from the initial SNF without exceeding the 1.2 peaking limit. Therefore, the number of IMF pins used in the 1st pass of recycle was increased to 48. Figure 5-8 shows the arrangement of the 48 IMF pins in the fuel assembly. As in the case of the Pu-only recycle, the number of IMF pins could be reduced after the first pass back to the 44 pins. The strategy then returns to the same as in the case where the number if

IMF pins was fixed (Section 5.2.2) and the equilibrium state of both are identical. In this case, a table giving equilibrium isotopics is not given as it would be identical to Table 5-4.

Table 5-11. Np-Pu recycling with variable number of IMF pins.

		Initial	1 st pass	2 nd pass	3 rd pass	4 th pass	Eq.
Number of IMF pins		0	48	44	44	44	44
Uranium Enrichment		4.23	4.35	4.45	4.43	4.43	4.49
HM loading (kg/assembly)	UO ₂	461.3	377.44	384.43	384.43	384.43	384.43
	IMF	—	5.58	6.49	7.60	8.46	13.97
Charge - Peak Pin	UO ₂	1.072	1.0881	1.0980	1.0991	1.1026	1.1084
	IMF	—	1.1564	1.1144	1.1459	1.1590	1.1983
Charge k-inf		1.3984	1.4008	1.3836	1.3782	1.3741	1.3602
1000 days k-inf		1.0377	1.0354	1.0359	1.0355	1.0354	1.0354
TRU Discharge (kg/assembly)	UO ₂	5.94	4.88	5.04	5.08	5.10	5.18
	IMF	—	2.19	3.26	4.17	4.92	10.07
Δ TRU (kg/assembly)	UO ₂	5.94	4.88	5.04	5.08	5.10	5.18
	IMF	-	-3.41	-3.23	-3.43	-3.54	-3.90
	Total	5.94	1.47	1.81	1.65	1.56	1.28
Np and Pu Recycled (kg/assembly)	UO ₂	5.59	4.58	4.74	4.78	4.80	4.89
	IMF	—	1.92	2.88	3.71	4.39	9.11
Np and Pu loss in reprocessing		0.01	0.01	0.02	0.02	0.02	0.03
Unused TRU to repository		0.35	0.57	0.68	0.76	0.83	1.25

Figure 5-8. Layout of 1/4 PWR assemblies with 48 IMF pins.

5.3.3 Np-Pu-Am Recycling (UREX+4)

In this section, the recycling of Np-Pu-Am is considered. In Section 5.2.3, recall that in the first recycle pass, the peaking limit could be respected using 44 IMF pins and without discarding any material, whereas at equilibrium, some TRU had to be discarded at each recycle in order to respect the peaking limit. Here, we start recycling in the first pass with 44 pins and then later, as equilibrium is approached, the number of IMF pins had to be increased to keep all the Np, Pu and Am without exceeding the peaking limit in these pins.

gives the mass of each isotope group at equilibrium used by the VISION code.

Table 5-12. Np-Pu-Am recycling with variable number of IMF pins

		Initial	1 st pass	2 nd pass	3 rd pass	4 th pass	Eq.
Number of IMF pins		0	44	44	44	44	48
Uranium Enrichment		4.23	4.33	4.48	4.50	4.52	4.78
HM loading (kg/assembly)	UO ₂	461.3	384.43	384.43	384.43	384.43	377.44
	IMF	—	5.89	7.37	8.79	10.00	19.17
Charge - Peak Pin	UO ₂	1.072	1.0927	1.1120	1.1162	1.1192	1.1500
	IMF	—	1.1901	1.1109	1.1283	1.1411	1.1167
Charge k-inf		1.3984	1.3858	1.3647	1.3561	1.3499	1.3183
1000 days k-inf		1.0377	1.0360	1.0353	1.0353	1.0355	1.0352
TRU Discharge (kg/assembly)	UO ₂	5.94	5.02	5.10	5.14	5.17	5.23
	IMF	—	2.53	3.97	5.20	6.27	14.71
Δ TRU (kg/assembly)	UO ₂	5.94	5.02	5.10	5.11	5.17	5.23
	IMF	—	-3.36	-3.40	-3.59	-3.73	-4.46
	Total	5.94	1.66	1.70	1.52	1.44	0.77
Np, Pu and Am Recycled (kg/assembly)	UO ₂	5.90	4.98	5.06	5.11	5.14	5.21
	IMF	—	2.40	3.75	4.92	5.94	14.02
Np, Pu and Am loss in reprocessing		0.01	0.01	0.02	0.02	0.02	0.04
Unused TRU to repository		0.04	0.17	0.26	0.31	0.36	0.71

Table 5-13. Mass of each isotope for Np-Pu-Am recycling at equilibrium (grams/MTHM)

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
He-4	1.07E+00	3.06E+01	4.18E+01	Cf-251	0.00E+00	1.43E-04	1.42E-04
Pb-206	0.00E+00	2.03E-11	1.27E-10	Cf-252	0.00E+00	7.14E-05	1.93E-05
Pb-207	3.93E-11	2.70E-09	1.65E-08	H-3	6.11E-08	1.05E-01	7.92E-02
Pb-208	0.00E+00	1.17E-05	1.43E-04	C14	2.75E-09	5.17E-03	5.17E-03
Pb-210	4.64E-12	5.66E-10	9.06E-10	C-other	1.11E-05	2.00E+01	2.00E+01
Bi-209	0.00E+00	4.32E-09	1.36E-08	Kr-81	4.31E-12	2.32E-05	2.32E-05

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
Ra-226	1.80E-08	1.14E-07	3.69E-07	Kr-85	3.36E-06	3.84E+01	2.78E+01
Ra-228	0.00E+00	2.79E-14	1.83E-13	Other Inert Gases	6.12E-03	9.80E+03	9.80E+03
Ac-227	1.81E-09	2.39E-08	1.59E-07	Rb	1.17E-03	5.48E+02	5.59E+02
Th-228	0.00E+00	2.57E-05	1.26E-04	Sr-90	8.04E-05	8.37E+02	7.40E+02
Th-229	3.62E-09	8.95E-06	9.09E-06	Sr-other	3.06E-03	5.66E+02	5.38E+02
Th-230	2.04E-03	3.37E-03	8.27E-03	Zr-93	1.30E-07	1.16E+03	1.16E+03
Th-232	5.47E-08	4.35E-04	1.32E-03	Zr-95	5.09E-05	7.53E+01	1.98E-07
Pa-231	8.87E-05	1.42E-03	1.47E-03	Zr-other	2.69E-03	4.65E+03	4.79E+03
U-232	7.79E-09	8.16E-03	7.85E-03	Tc-99	3.89E-08	1.34E+03	1.35E+03
U-233	9.24E-04	5.37E-03	7.61E-03	Tc-other	8.42E-04	3.64E-01	0.00E+00
U-234	3.96E+02	2.83E+02	4.24E+02	Ru-106	1.26E-04	2.73E+02	9.06E+00
U-235	4.55E+04	1.01E+04	1.01E+04	Pd-107	2.39E-07	5.05E+02	5.05E+02
U-236	1.89E+00	6.07E+03	6.07E+03	Other Ru, Rh, Pd	5.45E-04	7.35E+03	7.61E+03
U-238	9.06E+05	8.72E+05	8.72E+05	Mo-Other	5.08E-03	5.71E+03	5.82E+03
Np-237	1.38E+03	1.37E+03	1.38E+03	Se-79	2.05E-08	7.86E+00	7.86E+00
Pu-238	3.52E+03	3.57E+03	3.59E+03	Cd-113m	3.50E-11	7.02E-03	5.56E-03
Pu-239	7.85E+03	7.87E+03	7.87E+03	Sn-126	1.86E-05	3.49E+01	3.49E+01
Pu-240	9.07E+03	8.75E+03	9.09E+03	Sb-125	3.65E-07	1.29E+01	3.67E+00
Pu-241	2.74E+03	3.86E+03	3.03E+03	Other Trans. Met.	7.24E-03	1.45E+03	1.41E+03
Pu-242	1.84E+04	1.85E+04	1.85E+04	I-129	4.42E-09	2.80E+02	2.82E+02
Pu-244	1.09E-10	1.65E-01	1.65E-01	Other Halogens	3.22E-03	1.28E+02	1.19E+02
Am-241	1.63E+03	5.37E+02	1.36E+03	Cs-134	1.13E-08	2.21E+02	4.12E+01
Am-242m	1.43E+01	1.49E+01	1.45E+01	Cs-135	3.21E-07	9.33E+02	9.34E+02
Am-243	3.67E+03	3.68E+03	3.68E+03	Cs-137	1.84E-04	2.14E+03	1.91E+03
Cm-242	3.68E-02	1.66E+02	1.09E-01	Cs-other	2.37E-03	1.93E+03	1.94E+03
Cm-243	3.53E-09	1.06E+01	9.42E+00	Ba	3.71E-03	2.60E+03	2.99E+03
Cm-244	1.36E-03	2.04E+03	1.69E+03	Ce-144	5.53E-04	4.40E+02	5.18E+00
Cm-245	0.00E+00	1.13E+02	1.13E+02	Pm-147	9.00E-09	2.43E+02	6.72E+01
Cm-246	0.00E+00	1.69E+01	1.69E+01	Sm-146	0.00E+00	1.70E-02	1.73E-02
Cm-247	0.00E+00	3.99E-01	3.99E-01	Sm-147	5.96E-09	1.39E+02	3.23E+02
Cm-248	0.00E+00	3.51E-02	3.51E-02	Sm-151	5.94E-09	2.99E+01	2.91E+01
Cm-250	0.00E+00	2.15E-08	2.15E-08	Eu-154	5.92E-10	5.51E+01	3.68E+01
Bk-249	0.00E+00	6.33E-04	1.22E-05	Eu-155	1.38E-07	1.17E+01	5.59E+00
Cf-249	0.00E+00	1.86E-04	8.00E-04	Ho-166m	6.89E-12	6.98E-04	6.96E-04
Cf-250	0.00E+00	2.06E-04	1.58E-04	Other Lanthanides	6.84E-03	1.71E+04	1.76E+04

5.3.4 Np-Pu-Am-Cm Recycling (UREX+1)

In this section, the recycling of Np+Pu+Am+Cm was considered. When all of these TRU isotopes were recycled, 44 IMF pins was sufficient to carry all of the TRU recycled in the 1st pass without exceeding the peaking limit. At equilibrium, however, one must either discard some TRU at each recycle, as was done in Section 5.2.4, or the number of IMF pins has to be increased in order to accommodate the TRU without too high a peaking factor. As equilibrium is approached, the number of IMF pins was increased to 60, as is shown in **Error! Reference source not found.**

gives the mass of each isotope group at equilibrium used by the VISION code.

Table 5-14. Np-Pu-Am-Cm recycling with variable number of IMF pins.

		Initial	1 st pass	2 nd pass	3 rd pass	4 th pass	Eq.
Number of IMF pins		0	44	44	44	44	60
Uranium Enrichment		4.23	4.36	4.49	4.49	4.49	4.95
HM loading (kg/assembly)	UO ₂	461.3	384.43	384.43	384.43	384.43	356.47
	IMF	—	5.93	7.56	9.21	10.66	20.30
Charge - Peak Pin	UO ₂	1.072	1.0911	1.1121	1.1161	1.1190	1.1746
	IMF	—	1.1860	1.1147	1.1380	1.1570	0.9482
Charge k-inf		1.3984	1.3865	1.3647	1.3550	1.3476	1.3147
1000 days k-inf		1.0377	1.0380	1.0371	1.0368	1.0368	1.0341
TRU Discharge (kg/assembly)	UO ₂	5.94	5.02	5.10	5.15	5.18	4.94
	IMF	—	2.56	4.13	5.53	6.81	15.43
ΔTRU (kg/assembly)	UO ₂	5.94	5.02	5.10	5.15	5.18	4.94
	IMF	—	-3.37	-3.43	-3.68	-3.85	-4.87
	Total	5.94	1.65	1.67	1.47	1.33	0.07
TRU Recycled (kg/assembly)	UO ₂	5.94	5.02	5.10	5.15	5.18	4.94
	IMF	—	2.56	4.13	5.53	6.81	15.43
Np, Pu and Am loss in reprocessing		0.01	0.02	0.02	0.02	0.02	0.04
Unused TRU to repository		0.00	0.00	0.00	0.00	0.00	0.00

Table 5-15. Mass of each isotope for Np-Pu-Am recycling at equilibrium (grams/MTHM).

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
He-4	6.13E+00	4.54E+01	6.53E+01	Cf-251	1.59E+00	1.61E+00	1.60E+00
Pb-206	0.00E+00	1.96E-11	1.22E-10	Cf-252	6.19E-01	3.89E+00	1.05E+00
Pb-207	4.04E-11	2.59E-09	1.58E-08	H-3	6.48E-08	1.11E-01	8.37E-02
Pb-208	0.00E+00	1.12E-05	1.35E-04	C14	2.89E-09	5.27E-03	5.27E-03
Pb-210	4.60E-12	5.44E-10	8.70E-10	C-other	1.19E-05	2.14E+01	2.14E+01
Bi-209	0.00E+00	4.23E-09	1.31E-08	Kr-81	4.89E-12	2.43E-05	2.43E-05
Ra-226	1.78E-08	1.11E-07	3.52E-07	Kr-85	3.48E-06	4.00E+01	2.89E+01

Isotope Group	Charge	Discharge	5 Year Decay	Isotope Group	Charge	Discharge	5 Year Decay
Ra-228	0.00E+00	2.89E-14	1.89E-13	Other Inert Gases	6.40E-03	1.03E+04	1.03E+04
Ac-227	1.86E-09	2.24E-08	1.53E-07	Rb	1.21E-03	5.70E+02	5.81E+02
Th-228	0.00E+00	2.44E-05	1.19E-04	Sr-90	8.34E-05	8.71E+02	7.70E+02
Th-229	3.48E-09	8.65E-06	8.78E-06	Sr-other	3.18E-03	5.89E+02	5.60E+02
Th-230	2.02E-03	3.23E-03	7.76E-03	Zr-93	1.36E-07	1.21E+03	1.21E+03
Th-232	5.88E-08	4.51E-04	1.37E-03	Zr-95	5.31E-05	7.85E+01	2.06E-07
Pa-231	9.14E-05	1.37E-03	1.42E-03	Zr-other	2.81E-03	4.85E+03	4.99E+03
U-232	7.44E-09	7.69E-03	7.40E-03	Tc-99	3.92E-08	1.40E+03	1.41E+03
U-233	8.90E-04	5.06E-03	7.21E-03	Tc-other	9.18E-04	3.81E-01	0.00E+00
U-234	3.88E+02	2.64E+02	3.89E+02	Ru-106	1.41E-04	2.92E+02	9.69E+00
U-235	4.68E+04	1.01E+04	1.01E+04	Pd-107	2.74E-07	5.47E+02	5.47E+02
U-236	2.04E+00	6.29E+03	6.29E+03	Other Ru, Rh, Pd	6.43E-04	7.80E+03	8.09E+03
U-238	8.99E+05	8.65E+05	8.65E+05	Mo-Other	5.36E-03	5.97E+03	6.08E+03
Np-237	1.33E+03	1.32E+03	1.33E+03	Se-79	2.17E-08	8.14E+00	8.14E+00
Pu-238	3.12E+03	3.16E+03	3.18E+03	Cd-113m	8.37E-10	8.86E-03	7.02E-03
Pu-239	7.30E+03	7.32E+03	7.32E+03	Sn-126	2.00E-05	3.66E+01	3.66E+01
Pu-240	9.95E+03	8.79E+03	9.67E+03	Sb-125	3.92E-07	1.36E+01	3.85E+00
Pu-241	2.75E+03	3.87E+03	3.04E+03	Other Trans. Met.	7.60E-03	1.58E+03	1.54E+03
Pu-242	1.88E+04	1.89E+04	1.89E+04	I-129	5.13E-09	2.93E+02	2.95E+02
Pu-244	4.93E-04	2.02E-01	2.03E-01	Other Halogens	3.39E-03	1.34E+02	1.25E+02
Am-241	1.52E+03	4.28E+02	1.25E+03	Cs-134	1.37E-08	2.36E+02	4.39E+01
Am-242m	1.11E+01	1.15E+01	1.13E+01	Cs-135	3.59E-07	9.54E+02	9.55E+02
Am-243	3.79E+03	3.81E+03	3.81E+03	Cs-137	1.96E-04	2.25E+03	2.00E+03
Cm-242	3.31E-02	1.59E+02	9.72E-02	Cs-other	2.50E-03	2.01E+03	2.03E+03
Cm-243	9.29E+00	1.11E+01	9.79E+00	Ba	3.89E-03	2.73E+03	3.15E+03
Cm-244	3.95E+03	5.17E+03	4.27E+03	Ce-144	5.79E-04	4.63E+02	5.46E+00
Cm-245	2.73E+02	2.74E+02	2.74E+02	Pm-147	9.01E-09	2.52E+02	6.98E+01
Cm-246	8.25E+02	8.29E+02	8.29E+02	Sm-146	0.00E+00	1.81E-02	1.83E-02
Cm-247	7.06E+01	7.10E+01	7.10E+01	Sm-147	5.95E-09	1.44E+02	3.36E+02
Cm-248	1.34E+02	1.32E+02	1.35E+02	Sm-151	6.56E-09	3.01E+01	2.92E+01
Cm-250	1.38E-12	3.68E-04	3.69E-04	Eu-154	9.22E-10	5.86E+01	3.92E+01
Bk-249	1.68E-05	3.27E+00	6.29E-02	Eu-155	1.66E-07	1.27E+01	6.06E+00
Cf-249	5.31E+00	2.20E+00	5.37E+00	Ho-166m	7.57E-11	1.67E-03	1.67E-03
Cf-250	1.18E+00	1.72E+00	1.32E+00	Other Lanthanides	7.19E-03	1.80E+04	1.85E+04

5.3.5 Variable IMF Pins Summary

The heat, gamma and neutron emission plots for each recycling strategy are quite similar in behavior as those for the cases where the number of IMF pins was fixed strictly at 44. The magnitudes of these values

are higher in cases where material was being discarded at equilibrium due to the limited number of IMF pins. These are the Np-Pu-Am and Np-Pu-Am-Cm-Cf cases.

Table 5-16 shows the amount of TRU sent to the repository for each of the recycling strategies described in this section. In this case, there is no transuranics sent to the repository except that due to the selection of which separations technology to use. As expected, with each additional nuclide included in the recycle stream, the amount sent to the repository is reduced.

Figure 5-9. Decay heat of recycled fuel for each recycle step (in W/ MTHM).

Figure 5-10. Photon energy of recycled fuel for each recycle step (in W/ MTHM).

Figure 5-11. Neutron emission rate of recycled fuel for each recycle step (in n/MTHM).

Table 5-16. TRU to repository for cases with variable number of IMF pins.

Recycling Strategy	Unrecycled TRU to repository due to recycling strategy (kg/assembly)
Once Through Cycle	5.94
PUREX (Pu)	1.50
UREX+2 (Np,Pu)	1.25
UREX+4 (Np,Pu,Am)	1.01
UREX+1a (Np,Pu,Am,Cm,Cf)	—

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The goal of the effort summarized in this report, was to establish the specific technical capabilities for neutronics calculations relevant to thermal reactor fuel cycle analyses along with the application of such capabilities to transmutation analysis for a typical LWR. The new study reported here focused on the direct thermal recycling of IMF fuels in a multi-pass strategy using 5 year cooled LWR fuel. The PUREX recycling strategy was studied as well as the more proliferation resistant UREX recycling process. Different levels of separation were analyzed to assess the impact of each isotope group on the recycling: Pu (PUREX), Np-Pu (UREX+2), Np-Pu-Am (UREX+4) and Np-Pu-Am-Cm (UREX+1a).

The study focused on an IMF fuel based on a ZrO_2 inert matrix. The IMF pins were inserted in the last row of a PWR bundle, while the remaining UO_2 fuel pins were typical UO_2 fuel. An infinite lattice calculation with depletion was performed using the TRITON control module to assess the feasibility of the IMF bundle. The TRITON control module was initially verified through comparisons with MCNP and MONTEBURNS. The initial spent nuclear fuel was processed according to the four recycling strategies and the TRU was recycled in the IMF fuel pins. After each thermal recycle, all the fuels pins were reprocessed together (i.e. coprocessing of UO_2 and IMF pins). The enrichment of the UO_2 pins and the IMF pins were adjusted to meet the simulations criterion: k_{inf} greater than 1.035 after 1000 days of irradiation and peak pin relative power below 1.2 at the beginning of life).

The results show that by recycling increasing groupings of transuranics (i.e., UREX+4 going to UREX+1a), less transuranics are sent to the repository. However, recycling all TRU also sends very little TRU to the repository and this reference is very sensitive to assumptions made to obtain the equilibrium scenario. When recycling all TRU, the decay heat, the total photon energy and the neutron emission rate of the recycle fuel elements increase considerably. These issues can obviously be seen as proliferation resistance benefits, but would also be a cause for concern for the fuel fabrication and fuel handling. The other recycling strategies all offer benefits to the repository in terms of total mass and also offer much lower values of decay heat, total photon energy and neutron emission rate.

Based on the single-assembly infinite lattice calculations performed in this work, using IMF pins within an otherwise typical PWR assembly in order to burn TRU is feasible. Further work is needed in order to verify this using more detailed full-core analysis with attention to safety characteristics such as delayed neutron fraction, control rod worth, etc.

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Appendix A

Description of Isotopic Grouping Used in VISION and Given in Tables in this Report (Piet, 209)

A-1. Description of isotopic grouping used in VISION and given in tables in this report (Piet, 2009)

Actinides and Decay Chain		Fission Products	
He4 (stable)		H3	Other gases
Pb206	Transition metals	C14	
Pb207		C-other	
Pb208		Kr81	Inert gases (Group 0)
Pb210		Kr85	
Bi209		Inert gas other (Kr, Xe)	
Ra226	Group 2A	Rb	Group 1A/2A
Ra228		Sr90 w/Y90 decay	
Ac227	Actinides	Sr-other	Zirconium
Th228		Zr93 w/Nb93m decay	
Th229		Zr95 w/Nb95m decay	
Th230		Zr-other	Technetium
Th232		Tc99	
Pa231		Tc-other	
U232	Uranium	Ru106 w/Rh106 decay	Transition metals that constrain glass waste forms
U233		Pd107	
U234		Mo-Ru-Rh-Pd-other	
U235		Se79	Other transition metals
U236		Cd113m	
U238		Sn126 w/Sb126m/Sb126	
Np237	Neptunium	Sb125 w/Te125m decay	
Pu238	Plutonium	TM-other (Co-Se, Nb, Ag-Te)	Halogens (Group 7)
Pu239		I129	
Pu240		Halogen-other (Br, I)	
Pu241		Cs134	Group 1A/2A
Pu242		Cs135	
Pu244		Cs137 w/Ba137m decay	
Am241	Americium	Cs-other	Lanthanides (plus Y)
Am242m		Ba	
Am243		Ce144 w/Pr144m/Pr144 decay	
Cm242	Curium	Pm147	
Cm243		Sm146	
Cm244		Sm147	
Cm245		Sm151	

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Actinides and Decay Chain		Fission Products	
Cm246		Eu154	
Cm247		Eu155	
Cm248		Ho166m	
Cm250		Other Lanthanides (plus Yttrium)	
Bk249	Berkelium		
Cf249	Californium		
Cf250			
Cf251			
Cf252			