SANDIA REPORT
SAND2008-5980
Unlimited Release
Printed September 2008

An Assessment of Spent Fuel Reprocessing for Actinide Destruction and Resource Sustainability

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Abstract

The reprocessing and recycling of spent nuclear fuel can benefit the nuclear fuel cycle by destroying actinides or extending fissionable resources if uranium supplies become limited. The purpose of this study was to assess reprocessing and recycling in both fast and thermal reactors to determine the effectiveness for actinide destruction and resource utilization. Fast reactor recycling will reduce both the mass and heat load of actinides by a factor of 2, but only after 3 recycles and many decades. Thermal reactor recycling is similarly effective for reducing actinide mass, but the heat load will increase by a factor of 2. Economically recoverable reserves of uranium are estimated to sustain the current global fleet for the next 100 years, and undiscovered reserves and lower quality ores are estimated to contain twice the amount of economically recoverable reserves—which delays the concern of resource utilization for many decades. Economic analysis reveals that reprocessed plutonium will become competitive only when uranium prices rise to about $360 per kg. Alternative uranium sources are estimated to be competitive well below that price. Decisions regarding the development of a near term commercial-scale reprocessing fuel cycle must partially take into account the effectiveness of reactors for actnides destruction and the time scale for when uranium supplies may become limited. Long-term research and development is recommended in order to make more dramatic improvements in actinide destruction and cost reductions for advanced fuel cycle technologies.

The original scope of this work was to optimize an advanced fuel cycle using a tool that couples a reprocessing plant simulation model with a depletion analysis code. Due to funding and time constraints of the late start LDRD process and a lack of support for follow-on work, the project focused instead on a comparison of different reprocessing and recycling options. This optimization study led to new insight into the fuel cycle.

Acknowledgement

The authors would like to acknowledge the support of Laboratory Directed Research and Development Project 125862 for funding this research.

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Executive Summary

Reprocessing and recycling of actinides has seen a resurgence of interest due to the anticipated growth of nuclear energy and the uncertainty associated with the licensing of the Yucca Mountain repository. Reprocessing has been justified on the basis of two main arguments: (1) reducing radiotoxic and heat-producing waste, and (2) extending uranium resources. The original goal of this work was to optimize a simpler fuel cycle by developing a tool for reprocessing and recycling analysis. However, given funding constraints, the tool development was dropped in an effort to focus on the bigger picture of providing an assessment of reprocessing and recycling options.

Waste reduction is accomplished by separating the long-lived actinides from spent fuel and recycling them back into reactors to be burned up. The fission products produced from burning the actinides on average have much shorter half-lives so will decay to benign elements much sooner. This paper investigated the actual actinide destruction effectiveness of reactors once those elements are recycled back into the fuel cycle.

This study investigated both the use of fast reactors and existing thermal reactors for burning actinides. Both fast and thermal reactors will take 3 recycles to reduce the mass of actinides by a factor of 2. The heat load of the recycled spent fuel from fast recycle will also be reduced by a factor of 2, while that from thermal recycle will have increased by a factor of 2. Therefore, fast reactors are effective at reducing the heat load, while thermal reactors are not.

A literature review was conducted to investigate the availability of uranium resources. Currently known, economically recoverable reserves will be able to fuel the existing global fleet of reactors for the next 100 years. Uranium resource estimates from undiscovered sources and more expensive sources are twice the economic reserves. Re-enrichment of depleted uranium will also become an economically feasible source as prices rise. According to one report, the price of uranium would need to rise to $360 per kg in order for reprocessed plutonium to compete economically. Therefore, reprocessing may not be required (solely for the purpose of resource sustainability) for many decades.

Ultimately, fast reactors provide an advantage over thermal reactors in being able to burn all actinides without creating more heat load. In the future, they can be used for breeding fuel if uranium resources become limited. The cost of reprocessing and fast reactors will likely need to be reduced considerably before this fuel cycle becomes economically attractive. A vigorous research program investigating advances in actinide destruction and cost reductions of fuel cycle facilities by a wide variety of reprocessing and recycling techniques should be encouraged.

Acronyms

AFCI	Advanced Fuel Cycle Initiative
CR	Conversion Ratio
FP	Fission Product
GNEP	Global Nuclear Energy Partnership
GWD	Giga-Watt Day
HLW	High Level Waste
HM	Heavy Metal
LLW	Low Level Waste
LWR	Light Water Reactor
MA	Minor Actinides
MOX	Mixed Oxide
MT	Metric Ton
ORIGEN	Depletion Analysis Code
PUREX	Plutonium-Uranium Extraction
PWR	Pressurized Water Reactor
RE	Rare Earth
TRU	Transuranic Isotopes (Np, Pu, Am, Cm)
UREX	Uranium Extraction (Aqueous Processing of Spent Fuel)
UOX	Uranium Oxide

An Assessment of Spent Fuel Reprocessing for Actinide Destruction and Resource Sustainability

1.0 Introduction

The recent interest in expanding nuclear energy has initiated new debate regarding the need for an advanced nuclear fuel cycle. Proponents of reprocessing and recycling of spent fuel suggest that these technologies are needed for reducing the amount of nuclear waste and extending uranium resources when supplies become scarce. Given the current difficulties with building a deep geologic repository, an advanced fuel cycle may provide other options. Opponents argue that an advanced fuel cycle will lead to high costs, greater proliferation risk, and greater safety risks.

A number of different recycling scenarios have been proposed in the past. A reprocessing plant is the first step to separate various constituents from spent fuel, but the complexity of the plant depends on the recycling strategy. The simplest option with the most commercial experience would be an aqueous reprocessing plant designed simply to remove uranium and plutonium from spent fuel. A more complex option may separate out all minor actinides (including neptunium, americium, and curium) and possibly select fission products (cesium and strontium).

Actinides can be recycled as a fuel in either existing light water reactors or advanced fast reactors. The other wastes generated from reprocessing will need to go to various storage facilities—again, the number of waste forms and complexity of the waste storage solutions depends on the fuel cycle.

Regardless of the recycling scenario, the building of a reprocessing plant, fuel fabrication facility, and possibly fast reactors will be expensive and require extensive development to support license applications. The need for reprocessing must be clearly established in order to justify the expense. The purpose of this study was to assess spent fuel reprocessing and recycling for destroying actinides and extending uranium resources.

A literature review of the past work on fast and thermal reactor transmutation was first conducted. Then an independent assessment of fast versus thermal recycling was performed using ORIGEN2.2 in order to assess the relative rates of actinide destruction. This analysis is shown in Section 4.

2.0 Reprocessing & Recycling Spent Fuel

Two main justifications for reprocessing and recycling of spent nuclear fuel are: 1) to destroy long-lived actinides, and 2) to extend uranium resources. Reprocessing by itself only segregates spent fuel into different products. To truly reduce the waste, some of the products must be sent to reactors to be burned up or transmuted.

2.1 Spent Fuel Composition

The current fleet of roughly 100 light water reactors in the United States produces about 2,200 metric tons of spent fuel per year. Extrapolating from reference [1], roughly 58,000 metric tons of spent fuel have accumulated around the country to date. Most of this fuel is sitting at the individual reactor sites either in cooling pools or dry casks.

The vast majority of the mass and volume of spent fuel assemblies is uranium oxide, zirconium in the cladding, and steel in the support structure. While typical fresh fuel may have a ^{235}U enrichment of 4-5%, the spent fuel has an enrichment of about 1% or less. The plutonium content in spent fuel is also about 1%. This fissionable material can be recycled as a fuel if it is economically desirable to do so. Separated plutonium can be directly used as a reactor fuel for existing light water reactors or advanced fast reactors when fabricated into a mixed oxide (MOX) fuel. Reprocessed uranium could also be re-enriched.

The vast majority of the heat load and radiotoxicity of spent fuel comes from the rather small percentage of transuranic (TRU) actinides and two fission products. Figure 1 shows the major heat-producing elements in typical spent fuel.

Plutonium, americium, and curium generate about half of the heat load and along with neptunium are also responsible for most of the long-term radiotoxicity of spent fuel (due to their long half-lives). Cesium and strontium generate the other half of the heat load, but with 30-year half-lives they do not make a long-term impact.

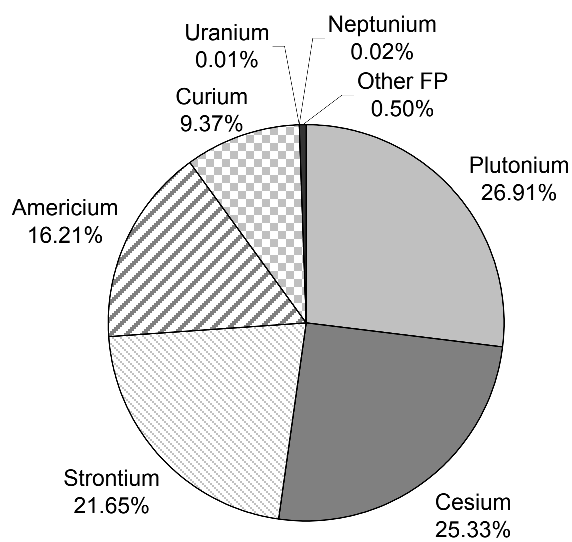

Figure 1: Heat-producers in 50-year-old, 60 GWD burnup fuel

The heat load of spent fuel limits how closely the waste can be packed into the Yucca Mountain Repository. One option for extending repository capacity is to remove these major heat-producers so that the waste can be placed closer together, thus expanding the repository capacity. However, this issue faces legal and political challenges as legislated limits currently cap the amount of waste that can be emplaced. Though the current legal limit for the repository capacity is 70,000 metric tons, another study has shown that the mountain could hold up to 570,000 metric tons of spent fuel [2].

2.2 Reprocessing Plant Options

An advanced fuel cycle must include a reprocessing plant to separate components in spent fuel. Existing reprocessing plants throughout the world use the PUREX technology which separates out plutonium and uranium oxide products. The products can then be blended to form a desired MOX fuel. It is also possible to pull out the uranium and plutonium together so as not to generate a pure plutonium stream (for proliferation concerns). Figure 2 shows the PUREX concept.

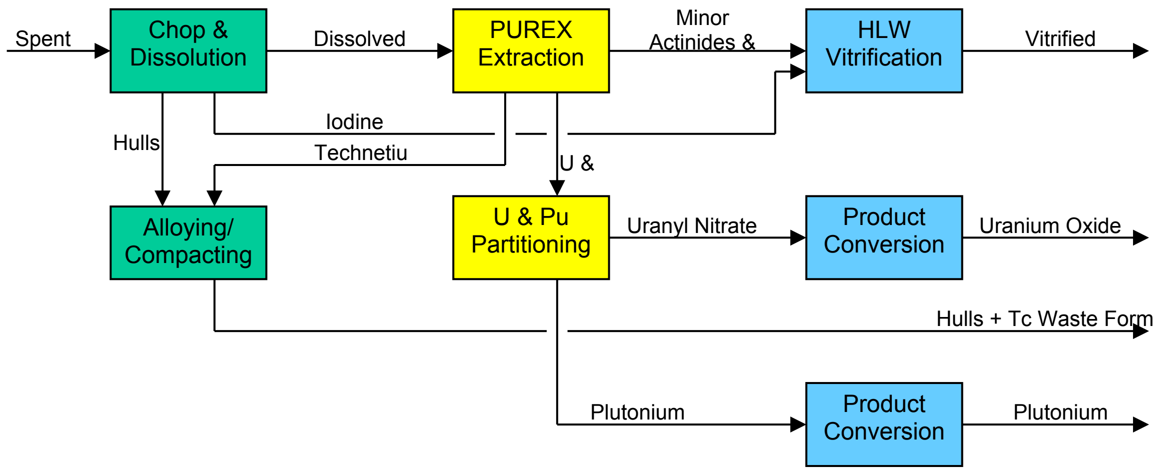

Figure 2: PUREX Reprocessing Plant Concept

The UREX+1a concept was proposed in the original Global Nuclear Energy Partnership (GNEP) plan [3]. UREX+1a focuses on removing the major contributors to heat load and radiotoxicity in spent fuel. Uranium is separated, followed by a cesium/strontium separation step to remove the short-term heat-producers. Lastly, all the TRU species (plutonium, neptunium, americium, and curium) are separated together for use in fabricating fast reactor fuel. Removing all these elements can drastically decrease the heat load and radiotoxicity of the left-over high level waste (HLW). Figure 3 shows the UREX+1a concept.

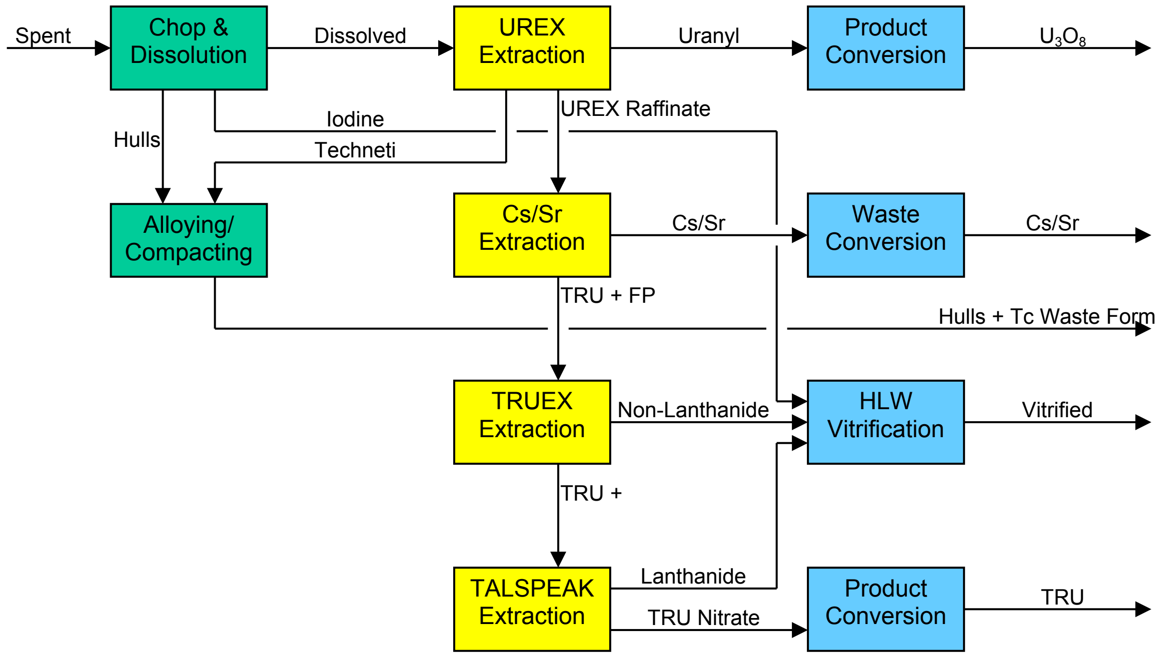

Figure 3: UREX+1a Reprocessing Plant Concept [3]

A heat load reduction factor of 50 or so is possible, meaning that potentially 50 times as much waste could be emplaced in the Yucca Mountain repository. Yet, the other waste streams must also be either stored or burned up in reactors. One of the concerns about a more complicated UREX+ type plant is that the additional waste streams make for many additional regulatory challenges since multiple waste storage facilities would need to be licensed. Also, the TRU product places heat and radioactivity back into the fuel cycle which adds handling complications.

2.3 Transmutation of Waste

The concept of transmutation of waste focuses on burning or fissioning the TRU species. All of the TRU isotopes can undergo fission to help reduce the waste, produce energy, and reduce proliferation concerns. The fissioning of actinides does produce radioactive fission products, but on average the fission products have much shorter half-lives than the actinides. Thus, the goal with transmutation is to turn very long-lived actinides into shorter-lived species that eventually produce much less heat and radioactivity than the actinides.

The term "waste reduction" can be misleading since sometimes it is used to represent removal of species from long-term disposition. This paper focuses on the actual actinide destruction within reactors after being recycled back into the fuel cycle.

Some long-lived fission products can be transmuted into short-lived species as well through neutron capture reactions, but the relatively small contribution of fission products to overall heat and radioactivity in waste makes fission product transmutation somewhat impractical. Also, the two largest contributors, cesium and strontium, cannot be transmuted faster than they naturally decay [4]. Thus, the focus of waste reduction is on actinide burning.

Any neutron source can be used for the burning of actinides, but it is most practical in a nuclear reactor with high neutron fluxes. The fission cross-section depends on the neutron energy, so there are variations in the burnup of actinides in thermal reactors which have low energy neutron fluxes and fast reactors which have high energy neutron fluxes.

2.4 Nuclear Waste Storage

After discharge from existing light water reactors, spent fuel is stored on-site either in cooling pools or dry cask storage. The current plan for sequestering the spent fuel in the Yucca Mountain Repository has been estimated to cost $96 billion for the expanded disposition of 122,100 metric tons [5]. Over the life of the program, this cost is equal to roughly 0.2 ¢/kWh, which is roughly twice 0.1 ¢/kWh that the utilities are paying into the Nuclear Waste Fund. Alternative fuel cycles that can reduce the amount of waste may be able to reduce the cost of disposition on a per kWh basis.

A well-studied alternative option is dry cask storage either at individual reactor sites or at one centralized facility. If the country is not able to decide on a centralized location for waste disposal, dry cask storage at existing sites will likely be the solution for waste in the near future. This may require that new plants be designed with room for storage on site. The cost for interim dry cask storage at existing reactor sites has been estimated to add 0.07 ¢/kWh to the cost of nuclear energy [6]. Transportation to a centralized location would bring the cost up to about 0.09 ¢/kWh, which is in line with the current charge into the Nuclear Waste Fund.

3.0 Recycling of Actinides

In reviewing the literature on the justifications for fast reactors, there is considerable debate among the scientific community as to how well fast reactors can transmute actinides as compared to recycling the actinides into thermal reactors. The following sections compare recycling of actinides in the different reactor types.

3.1 Thermal Reactors

Current light water reactors could be a desirable method for transmutation since the reactors already exist. New designs have taken advantage of improvements in safety and optimized costs. The costs of some minor core changes and increased shielding required for the recycled fuel will be very little compared to the costs of building and fueling an entirely new fleet of fast reactors.

All of the TRU actinides can be recycled into thermal reactors. However, there are practical issues that must be taken into account such as the impact of more radioactivity on fuel handling. In general, recycling of actinides in light water reactors will only make sense if they can either be burned down dramatically or used as a replacement for uranium fuel. The risk of placing actinides in thermal reactors is that some of the isotopes have high neutron capture cross-sections, meaning they will move up the actinide chain as opposed to fissioning.

For example, plutonium in spent fuel is dominated by ^{239}Pu. The odd isotopes of plutonium (^{239}Pu, ^{241}Pu, and ^{243}Pu) have fission cross-sections that are higher or about the same as the neutron capture cross-sections. The even isotopes of plutonium (^{238}Pu, ^{240}Pu, and ^{242}Pu) have higher capture cross-sections. Therefore, in a thermal spectrum the even isotopes tend to transmute into the next higher odd isotope, and the odd isotopes tend to burn. Yet, a net buildup of undesirable plutonium isotopes still occurs. This pattern is typical for neptunium, americium, and curium as well. The variety of isotopes and cross-sections makes computer codes a requirement when performing these analysis—the modeling results are shown in Section 4.

3.2 Fast Reactors

The advantage of a fast neutron spectrum is that for all TRU isotopes the fission cross-section is higher than the capture cross-section due to the higher neutron energies. On average the fission cross-section is about an order of magnitude higher. Actinides placed into a fast spectrum then tend to burn down and do not build up.

However, as compared to the isotopes with high thermal fission cross-sections, the fast fission cross-section is about an order of magnitude lower. For example, though ^{239}Pu mostly burns and does not capture in a fast spectrum, it can burn down quicker in a thermal spectrum.

The net effectiveness for transmutation of actinides in fast reactors is dependent on the conversion ratio (CR) of the design. Fast reactors can be designed to breed as much or more fissionable material than they burn—a CR=1 means the destruction rate of actinides equals the breeding rate. Burner fast reactors will have a CR<1 if the goal is to destroy actinides. A

CR=0.5 is probably the best burner that could be achieved in the near-term, but lower CR designs are possible with further development.

The proposed use of fast reactors in an advanced nuclear fuel cycle has seen a periodic resurgence in interest over the past four decades. However, fast reactors represent a large jump in technological complexity over current light water reactors. There will be many challenges in the safety and licensing of a liquid metal cooled core. It is expected that fast reactors will cost considerably more than an equivalently-sized light water reactor. Also, it could take as many as 50-150 new fast reactors (depending on the CR) to be able to burn up transuranic actinides as fast as the current light water reactor fleet produces them. Further research is needed to bring down the cost of fast reactors and prove their safety.

3.3 Fast vs. Thermal Recycle Debate

Ultimately, the effectiveness of fast versus thermal recycling for waste reduction will be resolved by economic arguments. Current predictions for fast reactors place the expected capital cost between $2,200 and $2,500 per kWe for an nth of a kind plant [7]. The similar cost prediction for advanced light water reactors is $1,500 to $1,800 per kWe [7]. Light water reactors will be much more competitive unless the government decides to subsidize fast reactors for other reasons.

The difficulty with performing transmutation studies is that there are many assumptions that can be made which can change the results. The spent light water reactor source term, decay time, fast reactor conversion ratio, TRU fueling, spent fast reactor fuel decay time, and number of recycles all can be changed to get different results. For this study, the parameters were kept constant whenever possible to get an accurate comparison between the fast and thermal recycle options.

There are also a number of different ways to interpret the data. The total actinide burnup rate, change in heat load due to the actinides, change in gamma or neutron dose due to the actinides, and individual versus multi-recycle effects can all be examined. All of these variables are important to consider when planning an advanced fuel cycle. While the reduction in waste destined for the repository is important, the amount of actinides, heat load, and radiotoxicity of actinides as a function of electricity produced must also be carefully considered.

4.0 Modeling

Initially this study reviewed the past work on fast versus thermal recycle. Then an independent assessment of fast versus thermal recycling was performed using ORIGEN2.2 in order to assess the relative rates of actinide destruction. Both fast and thermal recycle of TRU actinides were examined for five consecutive recycles.

4.1 Assumptions

The initial spent light water reactor (LWR) fuel used in this calculation was assumed to be pressurized water reactor (PWR) fuel, 4.03% initial enrichment, 60 GWD/MT burnup, and 5 year decay time. For thermal recycle, it was assumed that CORAIL assemblies (A French design) were used which contained all TRU isotopes. The CORAIL fuel and loading parameters were taken from reference [8].

For thermal recycle, the ^{235}U enrichment was assumed to be 5.00%, and the first recycle loading of TRU to heavy metal was 12.4%. The CORAIL assemblies were assumed to use the same residence time as the LWR source term, and a burnup of 57.5 GWD/MT. For multi-recycle, it was assumed that the TRU from the previous spent CORAIL assemblies would be separated and used to fabricate the next recycle after a 5 year decay time. The ^{239}Pu content was assumed to be constant through multi-recycle, so the total TRU enrichment was increased to make up for the changing isotopics. Appendix A shows the charge and discharge data for five recycles. It should be noted that beyond about 2 recycles, multi-recycling of TRU in light water reactors is likely unrealistic due to changing isotopics, but five recycles were assumed for comparison.

For fast recycle, the same source term was used for consistency. The TRU and uranium loadings given in reference [9] were assumed. Conversion ratios (CR) of 1, 0.75, 0.5, 0.25, and 0 were run. The fast reactor fuel was assumed to reach a burnup of 175 GWD/MT, with a 1000 MW_{th} core design, and a fuel residence time of 4.5 years (the same total length as the LWR fuel residence time). Appendix B shows the charge and discharge data for the five recycles.

For fast reactor recycle, a 5 year decay time was assumed between each recycle. The $^{235}U/U$ ratio was kept constant as for the previous runs, but the TRU/HM ratio changed slightly. Reference [10] was used to estimate the change of TRU loading with time based on a conversion ratio 0.25 core (CR0.25). Based on these values, the following increases were assumed on each additional recycle: no change for CR0.0 and CR1.0 cores, +2% change for CR0.75 core, +4% change for CR0.5 core, +5% change for CR0.25 core.

4.2 Modeling Results

The overall purpose of this analysis was to determine the net effectiveness of transmutation of actinides. The best way to show the effectiveness was to track a set amount of TRU as it passed through multiple recycles. Figure 4 shows the change in mass of the dominant species through thermal recycle.

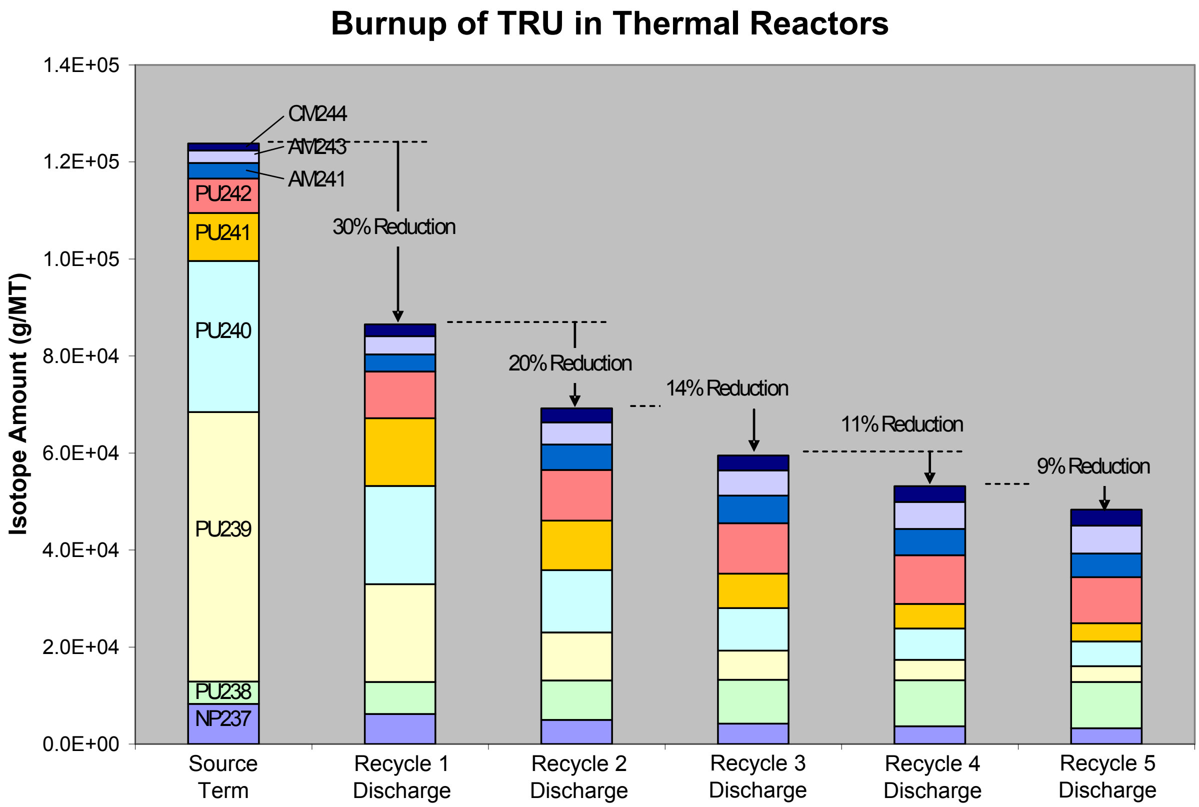

Figure 4: TRU Burnup in Thermal Reactors

The first recycle is able to reduce the total amount of TRU by 30%, but then subsequent recycles see diminishing returns. The modeling results clearly show a net burnup of ^{239}Pu, ^{237}Np, and ^{240}Pu. The isotopes ^{238}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, and ^{244}Cm buildup slightly. In general, this result shows that total plutonium content is decreasing significantly, neptunium decreases slightly, and americium and curium buildup.

Figure 5 shows the equivalent result using fast reactors instead. These results are shown for the CR0.5 core, which is probably the lowest conversion ratio that can be realistically achieved for a commercial fast reactor. One of the key differences with using fast reactors is that the percentage reduction stays constant at 23% for each cycle in multi-recycle. Also, every isotope decreases using fast reactor recycle—no isotope builds up.

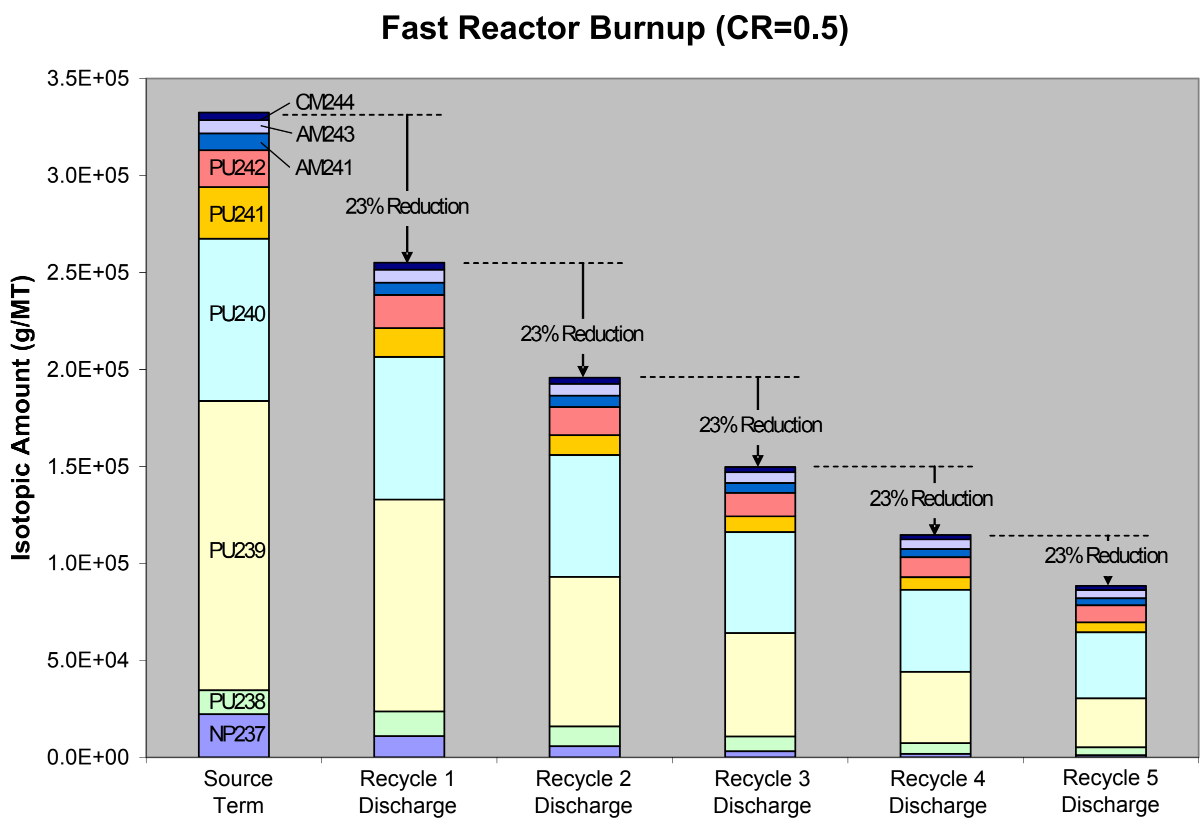

Figure 5: TRU Burnup in Fast Reactors [11]

In comparing the total TRU mass reduction, fast reactors and thermal reactors are not much different. In both cases it takes about 3 recycles to reduce the amount of TRU by a factor of 2. However, fast reactors can be used indefinitely for actinide reduction whereas light water reactors are limited by neutron capture cross-sections.

The mass change alone does not tell the full story, as heat load is also a concern for the repository and fuel cycle. Normalizing the results from the previous two figures, Figure 6 was generated to compare the change in heat load with multi-recycle. The left side shows the effects of thermal recycle while the right side shows the effects of fast recycle.

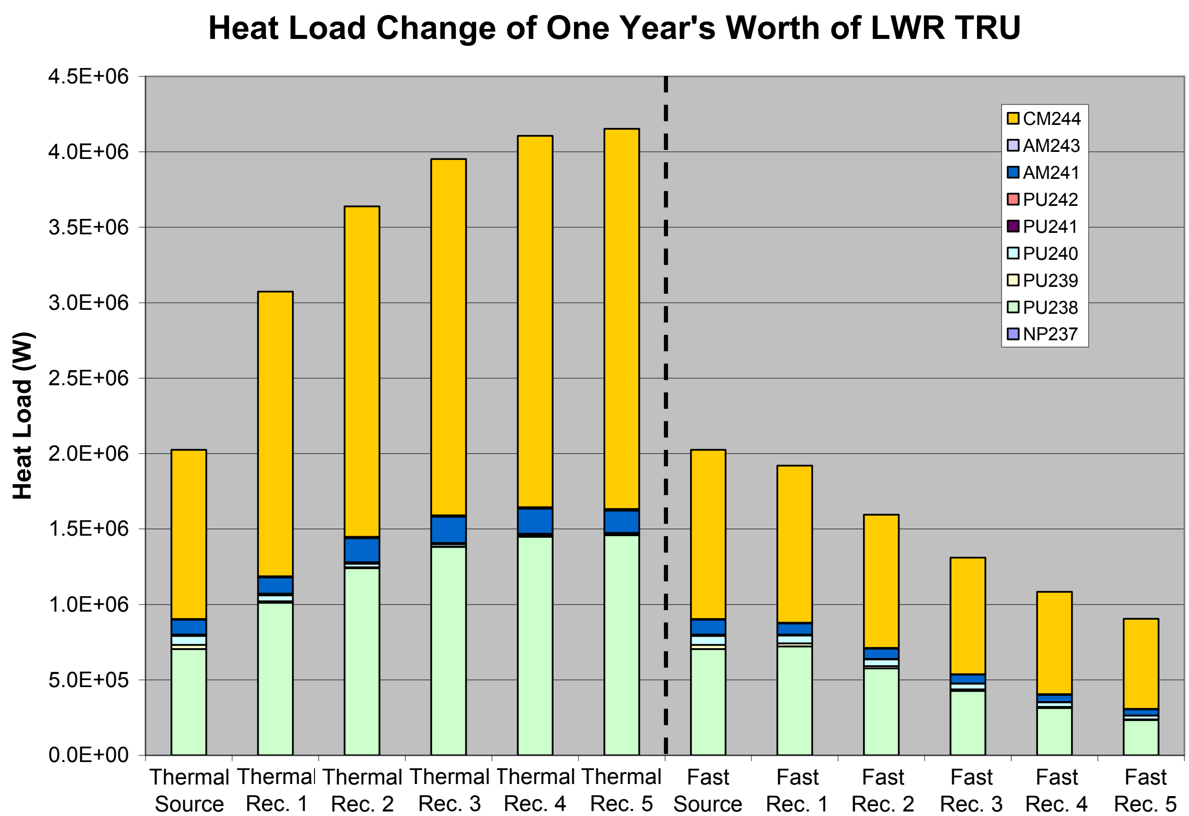

Figure 6: Heat Load Comparison of Thermal and Fast Recycle

Even though thermal recycle is able to decrease the net amount of TRU, the buildup of ^{238}Pu and ^{244}Cm leads to a buildup of heat load. After a few recycles, the net heat load will be a factor of 2 higher. On the other hand, the use of fast reactors lead to a net decrease in heat load of close to a factor of 2 after 3 recycles.

Another useful comparison between thermal and fast reactors is the net burnup/buildup rates for the various elements. Figure 7 shows the elemental burnup/buildup rates for thermal recycle and three different fast reactor cores: CR0.75, CR0.5, CR0.25. Thermal recycle tends to be equivalent or better for burnup of neptunium, plutonium, and americium. However, thermal recycle results in a large buildup rate of curium. As expected, the low conversion ratio fast reactor cores achieve higher burnup rates since the fuel contains less depleted uranium for breeding.

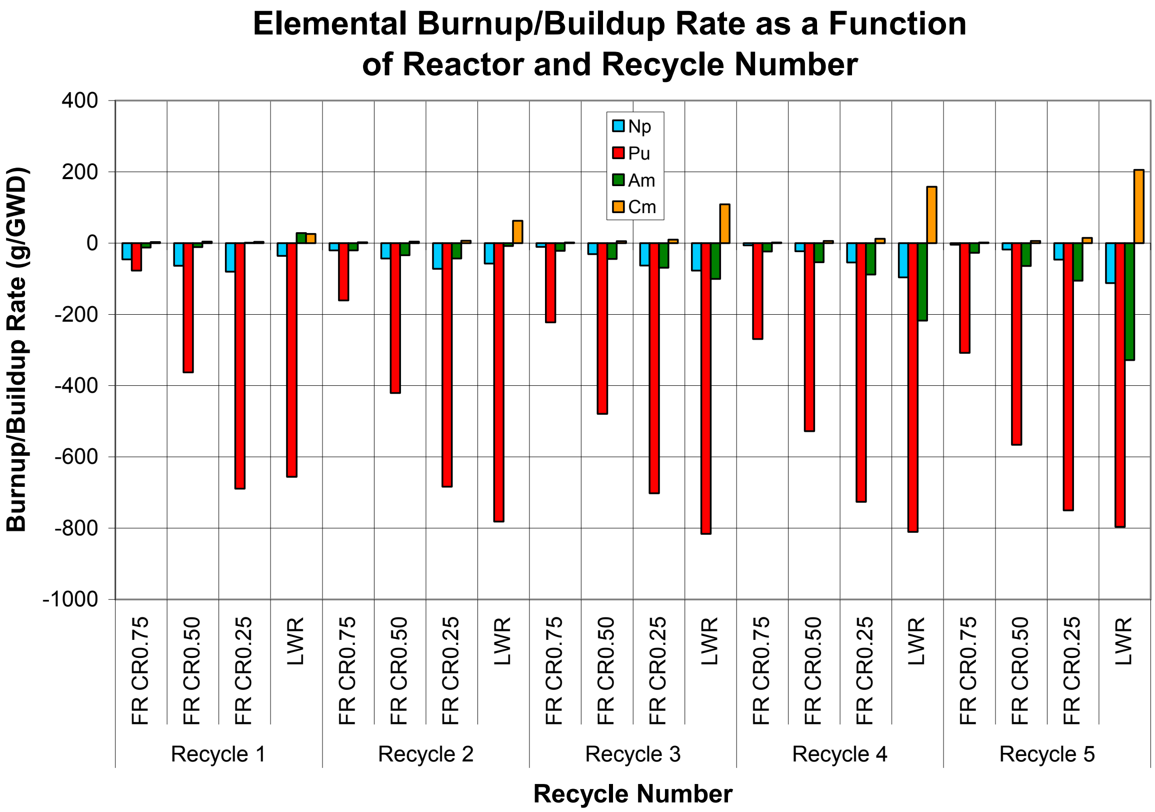

Figure 7: Rates of Actinide Destruction/Creation

4.3 Discussion

Due to the buildup of heat load, recycling actinides in thermal reactors does not seem to provide an actinide reduction benefit. Fast recycling can reduce to both the amount and heat load of actinides. However, in the end these results may not justify the building of a reprocessing plant and fast reactors unless the costs are comparable to the once-through cycle using light water reactors.

The main benefit to waste reduction in either case is in separating out the actinides from the high level waste destined for disposal. A cost benefit to the repository may be seen by this, but only at the expense of adding cost to the fuel cycle to be able to handle the added radioactivity and heat load. This added radioactivity will require more remote fuel handling and higher risk to workers and facilities.

4.4 Comparison to Past Studies

The Advanced Fuel Cycle Initiative (AFCI) and GNEP programs have produced a number of references on the topic of thermal and fast recycle.

Reference [10] provides charge and discharge data on a fast reactor CR=0.25 core recycling TRU over 5 recycles. The actinide percent reduction varies from 27% on the first recycle to 22% on the fifth recycle, similar to the results of this study. Similarly reference [9] provides charge and discharge data for one recycle in various conversion ratio fast reactor cores. The isotopic change is similar to the results of this study.

Reference [12] provides a comparison of thermal recycle and fast recycle and ends with a conclusion that favors fast recycle for plutonium and thermal recycle of americium and curium. The reference study shows a 73% reduction in ^{239}Pu content from one thermal recycle, which is a much larger drop than the results presented here. However, this is due to the fact that the assemblies in the core were assumed to be a mix of uranium oxide (UOX) assemblies, U-Pu-Np MOX assemblies, and U-Am-Cm target rods. The 73% drop only includes the MOX assemblies and target rods, so the study did not account for the increase of ^{239}Pu content in the UOX rods. The study presented in this paper accounts for the plutonium change in the entire core, which is a more representative result. After accounting for this difference, the results are similar to this paper.

In general the data presented in this report matches well with that used for past analyses. Subtle differences can occur depending on assumptions for the burnup and age of the spent fuel source term and various recycling strategies, but these subtle differences will not make an impact on the overall conclusions of this report.

5.0 Uranium Resource Utilization

In the much longer-term, breeding of plutonium followed by reprocessing and recycling can dramatically extend uranium resources. If uranium resources are expected to become scarce in the future (and in turn if the price of uranium gets high enough), reprocessing may be able to produce mixed-oxide fuel competitively. This justification depends on known and estimated uranium resources, the price of uranium as compared to the price of reprocessed plutonium, and the expected growth of nuclear energy.

5.1 Uranium Resources

The availability of any resource is usually broken down into economically recoverable reserves and total estimated reserves. Economically recoverable reserves refer to known resources that are economic to extract at current prices. Total estimated reserves are all reserves that may be recoverable at higher prices. Uranium reserves are further complicated by the fact that until recently, there has not been much exploration for new sources in the United States. Additional resources are likely to be found which are not included in the estimates.

The most recent study on uranium resources [13] has found that the amount of conventional uranium resources in the world that can be mined for less than $130/kg is equal to about 5.5 million metric tons—enough to power the existing 435 commercial reactors in the world for about 100 years. Undiscovered resources were estimated at 10.5 million metric tons. These estimates have recently changed due to additional exploration.

It is important to note that $130/kg (or $60/lb) is economic in today's market. If the price of uranium goes up, the amount of economically recoverable uranium will also increase to beyond 100 year's worth of fuel.

5.2 Alternative Sources

A few alternative sources of uranium exist that may have value if the price of uranium increases. These include depleted uranium from enrichment, uranium in spent fuel, and more exotic ideas like uranium extraction from sea water.

The enrichment process produces about 1 kg of enriched fuel for every 8 kg of mined uranium. Thus, enrichment produces 8 times as much depleted uranium as useful fuel, and this resource is simply being stored. Depleted uranium contains about 0.15-0.55% ^{235}U [7], and this material could go through enrichment again to make additional fuel. However, the costs of enriching depleted uranium will be higher, so uranium prices would likely need to rise for this to make economic sense.

Uranium in spent fuel could also be re-enriched. After it is pulled out of the reactor, the uranium in typical spent fuel may have an enrichment of about 0.5-1%. Re-enriching uranium from spent fuel requires reprocessing, so the cost will be significant. Also, the production of undesirable uranium isotopes may limit the number of times uranium can be recycled like this. Altogether, reprocessed uranium is another source of fuel that may be important in the future.

Uranium also exists in sea water in very low quantities (along with many other metals). It could be possible to extract uranium from sea water if resources become scarce, but it would be expensive. Initial estimates have placed the cost near $300 per kg [7].

5.3 Plutonium from Reprocessing

In order for reprocessing to have an economic justification, the fissionable material liberated from spent fuel would need to compete with the price of uranium. Reprocessing plants are expensive facilities. An optimistic estimate of capital cost for a 2,000 MT/yr plant is $10 billion [7], while the recent 800 MT/yr Rokkosho Plant in Japan cost $18 billion [14]. Economic assessments of the cost of reprocessing typically present the cost in terms of $ per kg of spent fuel. Estimates have been as low as $500 per kg [7], though existing plants around the world reprocess spent fuel for $1,500 to $4,000 per kg [14]. $1,000 per kg is probably an optimistic estimate assuming a large plant and government financing.

At this cost, reprocessing will have an economic justification if the price of uranium is near $360 per kg [14]. Note, though, that this assumes the plutonium product alone would support the cost of the reprocessing plant. If an advanced reprocessing and recycling strategy could make a serious impact on the amount of high level waste produced, there may be additional justifications for the government to help subsidize the plant.

The use of Pu MOX in thermal recycle will have limited effect on displacing uranium, ranging from 10-20% displacement [15,16]. For multi-recycling, ^{235}U must be added to make up for the loss of ^{239}Pu, meaning that multi-recycling will not significantly change uranium requirements. Therefore, from a sustainability standpoint, multi-thermal recycle does not make sense. However, fast reactors can drastically extend uranium resources through breeding and multi-recycle.

Since the amount of neptunium, americium, and curium in spent fuel is so small compared to plutonium, these minor actinides will make little difference on displacing uranium fuel if recycled. If reprocessing is established solely to generate another source of fuel, it would be better to leave these minor actinides in with the waste and prevent increasing the heat and radioactivity of the fuel.

Based on sections 5.1 and 5.2, traditional and alternative uranium sources will likely be much less expensive than reprocessed plutonium for a number of decades. Even in an expanding nuclear future, traditional sources of uranium should stay reasonably priced for the next 40-50 years. Beyond that time frame, at higher uranium prices, low-quality ores and re-enrichment of depleted uranium will become useful sources. It will only be after these sources are exhausted that reprocessed plutonium will be competitive.

6.0 Conclusion

This study investigated two of the justifications for reprocessing and recycling of actinides. The effectiveness of actinides destruction in thermal and fast reactors was assessed along with the availability of uranium supplies.

Both thermal and fast recycle will require three or four passes to reduce the actinide content by a factor of 2. Fast recycle will also decrease the heat load by a factor of 2, but thermal recycle will increase the heat load by a factor of 2. Thus, fast recycle will be the only long-term solution for stabilizing actinides without creating additional heat load.

Fuel utilization is not a good justification for reprocessing at the current time, but this could change depending on how quickly new reactors are built. Uranium resources are still plentiful—it could be many decades before uranium price increases will make reprocessed fuel competitive. Even alternative sources of uranium from low quality ores and re-enrichment of depleted uranium will be economic well-before reprocessed plutonium.

Longer term research and development should focus on evolutionary and revolutionary changes to reprocessing and transmutation concepts that will make more dramatic improvements on long-lived isotope destruction. Fast reactors may be needed at some point in the future for breeding of fissionable material, and at that point it would also make sense to burn up the higher order actinides. Fast reactor research should continue to develop less risky and more economic designs.

7.0 References

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Appendix A: Thermal Recycle Data

	Recycle 1		Recycle 2		Recycle 3		Recycle 4		Recycle 5	
	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS
U-235/U	5.00%		5.00%		5.00%		5.00%		5.00%	
TRU/HM	12.40%		24.00%		39.06%		55.63%		71.04%	
U232	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.03	0.00	0.03
U233	0.00	0.01	0.00	0.02	0.00	0.03	0.00	0.05	0.00	0.06
U234	0.00	185.30	0.00	704.50	0.00	1682.00	0.00	3009.00	0.00	4420.00
U235	43800.00	26880.00	38000.00	26920.00	30470.00	23120.00	22185.00	17480.00	14480.00	11700.00
U236	0.00	3109.00	0.00	2086.00	0.00	1421.00	0.00	947.40	0.00	602.40
U237	0.00	2.97	0.00	1.37	0.00	0.74	0.00	0.43	0.00	0.25
U238	832200.00	823900.00	722000.00	716900.00	578930.00	575600.00	421515.00	419400.00	275120.00	273800.00
U239	0.00	0.17	0.00	0.10	0.00	0.06	0.00	0.04	0.00	0.02
NP236	0.01	0.01	0.02	0.02	0.04	0.03	0.06	0.05	0.07	0.06
NP237	8282.81	6187.00	17172.80	13850.00	28196.58	23730.00	39578.14	34040.00	49268.98	42810.00
NP238	0.00	5.85	0.00	8.62	0.00	11.41	0.00	13.99	0.00	16.07
NP239	0.00	24.53	0.01	14.04	0.02	8.72	0.04	5.46	0.06	3.30
PU236	0.01	0.01	0.01	0.02	0.01	0.03	0.01	0.04	0.01	0.04
PU237	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.03
PU238	4610.37	6623.00	18570.55	22560.00	45759.03	50800.00	83407.39	87860.00	124129.83	126400.00
PU239	55527.42	20130.00	55551.76	27550.00	55527.13	33670.00	55528.03	38820.00	55527.63	43070.00
PU240	31167.96	20250.00	56957.79	35560.00	74338.28	49250.00	86027.26	60070.00	93108.09	67650.00
PU241	9905.29	13990.00	30326.02	28420.00	44993.69	39920.00	51705.33	46740.00	52498.33	49550.00
PU242	7091.51	9634.00	26562.84	28970.00	58346.79	58430.00	96292.53	92910.00	132789.05	125600.00
PU243	0.00	0.84	0.00	1.65	0.00	2.58	0.00	3.50	0.00	4.32
PU244	1.38	2.06	5.68	7.39	14.89	18.10	29.82	34.88	49.84	56.90
AM241	3210.89	3502.00	17795.86	14560.00	41287.86	31970.00	66271.14	50350.00	85606.29	64330.00
AM242	0.00	171.90	0.01	731.30	0.02	1632.00	0.03	2609.00	0.04	3376.00
AM242M	24.75	2.02	463.44	5.53	1439.64	9.39	2628.11	12.64	3643.73	14.77
AM243	2561.89	3743.00	10316.36	12800.00	25759.59	29110.00	47948.54	51390.00	73403.35	76080.00
AM244M	0.00	0.05	0.00	0.10	0.00	0.18	0.00	0.28	0.00	0.37
AM244	0.00	0.06	0.00	0.13	0.00	0.22	0.00	0.34	0.00	0.46
CM242	0.15	378.60	1.57	1065.00	4.41	1827.00	7.66	2475.00	10.35	2906.00
CM243	10.22	14.77	36.06	44.40	79.19	84.61	123.45	124.00	156.89	153.40
CM244	1472.09	2478.00	5640.64	7990.00	13290.66	17420.00	23710.63	29920.00	35308.49	43760.00
CM245	108.31	163.50	450.75	552.60	1112.56	1253.00	2064.59	2224.00	3176.48	3332.00
CM246	24.42	52.22	143.86	216.40	435.64	573.00	943.48	1161.00	1657.54	1963.00
CM247	0.47	1.25	3.45	5.89	11.87	17.07	28.13	37.18	53.13	66.94
CM248	0.05	0.18	0.50	1.01	2.04	3.32	5.48	8.02	11.47	15.81
BK249	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.06	0.00	0.11
CF249	0.00	0.00	0.01	0.01	0.04	0.05	0.12	0.13	0.27	0.28
SUM NP	8282.82	6217.39	17172.83	13872.68	28196.64	23750.17	39578.24	34059.50	49269.12	42829.43
SUM PU	108303.94	70629.92	187974.66	143069.07	278979.83	232090.72	372990.37	326438.44	458102.79	412331.30
SUM AM	5797.53	7419.02	28575.67	28097.06	68487.11	62721.80	116847.82	104362.25	162653.42	143801.60
SUM CM	1615.71	3088.52	6276.83	9875.31	14936.37	21178.00	26883.42	35949.20	40374.34	52197.15
SUM TRU	124000.00	87354.86	239999.99	194914.15	390599.98	339740.76	556299.97	500809.58	710399.94	651159.86

Appendix B: Fast Recycle Data

Recycle 1 Charge & Discharge Data (values given as g/MT):

	CR1.0		CR0.75		CR0.50		CR0.25		CR0.0	
	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS
U-235/U	0.04%		0.05%		0.08%		0.15%		0.61%	
TRU/HM	13.90%		21.20%		33.30%		56.00%		98.60%	
U232	0.00	0.15	0.00	0.23	0.00	0.35	0.00	0.53	0.00	0.71
U233	0.00	0.03	0.00	0.05	0.00	0.06	0.00	0.09	0.00	0.12
U234	0.00	143.30	0.00	229.80	0.00	388.00	0.00	704.30	0.00	1301.00
U235	355.00	97.54	427.00	146.50	509.00	232.50	645.00	402.50	841.00	674.60
U236	0.00	72.60	0.00	86.33	0.00	102.80	0.00	128.30	0.00	172.20
U237	0.00	7.28	0.00	6.34	0.00	4.65	0.00	2.21	0.00	0.11
U238	860600.00	663700.00	787500.00	632500.00	666200.00	563900.00	438500.00	393800.00	7870.00	7404.00
U239	0.00	1.89	0.00	1.63	0.00	1.19	0.00	0.55	0.00	0.01
NP236	0.01	0.35	0.02	0.51	0.02	0.76	0.04	1.08	0.07	1.36
NP237	9285.00	3707.00	14160.00	5965.00	22240.00	10980.00	37410.00	23260.00	65860.00	50020.00
NP238	0.00	5.52	0.00	8.07	0.00	12.13	0.00	17.06	0.00	20.28
NP239	0.00	271.60	0.00	235.30	0.01	171.40	0.01	79.53	0.02	0.84
PU236	0.01	0.31	0.01	0.46	0.02	0.68	0.04	0.96	0.07	1.18
PU237	0.00	0.11	0.00	0.15	0.00	0.21	0.00	0.25	0.00	0.24
PU238	5168.00	4781.00	7882.00	7604.00	12380.00	12700.00	20820.00	22330.00	36660.00	39180.00
PU239	62240.00	93430.00	94930.00	96130.00	149100.00	109200.00	250800.00	160700.00	441500.00	308600.00
PU240	34940.00	36080.00	53290.00	48570.00	83700.00	73620.00	140800.00	128100.00	247800.00	236200.00
PU241	11100.00	6014.00	16930.00	8961.00	26600.00	14770.00	44730.00	27460.00	78760.00	53380.00
PU242	7949.00	6574.00	12120.00	10360.00	19040.00	17030.00	32030.00	30050.00	56390.00	54640.00
PU243	0.00	0.30	0.00	0.43	0.00	0.58	0.00	0.68	0.00	0.68
PU244	1.54	1.71	2.36	2.58	3.70	3.96	6.22	6.50	10.96	11.23
AM241	3599.00	1885.00	5490.00	3345.00	8623.00	6550.00	14500.00	14330.00	25530.00	31210.00
AM242M	27.75	161.00	42.32	271.90	66.47	469.70	111.80	789.00	196.80	1151.00
AM242	0.00	0.84	0.00	1.36	0.00	2.18	0.00	3.17	0.00	3.81
AM243	2872.00	2635.00	4380.00	4092.00	6880.00	6566.00	11570.00	11260.00	20370.00	20070.00
AM244M	0.00	0.02	0.00	0.03	0.00	0.04	0.00	0.05	0.00	0.05
AM244	0.00	0.03	0.00	0.04	0.00	0.05	0.00	0.06	0.00	0.06
CM242	0.17	175.70	0.25	280.70	0.40	438.30	0.67	619.20	1.18	734.40
CM243	11.45	17.33	17.47	24.80	27.44	33.70	46.14	44.37	81.24	65.15
CM244	1650.00	1567.00	2517.00	2373.00	3953.00	3670.00	6648.00	6003.00	11710.00	10260.00
CM245	121.40	366.80	185.20	533.60	290.90	767.10	489.20	1098.00	861.30	1562.00
CM246	27.37	63.41	41.75	85.85	65.58	113.50	110.30	154.20	194.20	229.30
CM247	0.53	3.36	0.80	4.35	1.26	5.37	2.12	6.50	3.74	8.18
CM248	0.06	0.34	0.09	0.40	0.15	0.46	0.24	0.51	0.43	0.64
BK249	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
CF249	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.02
SUM NP	9285.01	3984.46	14160.02	6208.88	22240.03	11164.29	37410.05	23357.67	65860.09	50042.49
SUM PU	121398.55	146881.43	185154.37	171628.62	290823.72	227325.43	489186.26	368648.38	861121.03	692013.33
SUM AM	6498.75	4681.89	9912.32	7710.33	15569.47	13587.97	26181.80	26382.27	46096.80	52434.91
SUM CM	1810.98	2193.93	2762.56	3302.70	4338.73	5028.43	7296.67	7925.78	12852.09	12859.66
SUM TRU	138993.29	157741.73	211989.27	188850.55	332971.95	257106.13	560074.78	426314.11	985930.02	807350.41

Recycle 2 Charge & Discharge Data (values given as g/MT):

	CR1.0		CR0.75		CR0.50		CR0.25		CR0.0	
	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS
U-235/U	0.04%		0.05%		0.08%		0.15%		0.61%	
TRU/HM	13.90%		23.30%		37.30%		61.00%		98.60%	
U232	0.00	0.08	0.00	0.16	0.00	0.33	0.00	0.62	0.00	0.90
U233	0.00	0.02	0.00	0.04	0.00	0.07	0.00	0.11	0.00	0.14
U234	0.00	93.09	0.00	224.90	0.00	498.40	0.00	986.20	0.00	1706.00
U235	355.00	94.88	427.00	156.10	509.00	252.90	645.00	419.70	841.00	668.30
U236	0.00	71.12	0.00	87.82	0.00	110.60	0.00	146.20	0.00	197.10
U237	0.00	7.29	0.00	6.02	0.00	4.20	0.00	1.97	0.00	0.15
U238	860700.00	667700.00	766600.00	623400.00	626500.00	534600.00	389400.00	349400.00	13910.00	13000.00
U239	0.00	1.89	0.00	1.55	0.00	1.07	0.00	0.49	0.00	0.01
NP236	0.31	0.24	0.63	0.50	1.10	1.04	1.55	1.86	2.50	2.95
NP237	3296.00	1895.00	7423.00	3611.00	16070.00	8352.00	33550.00	20860.00	54230.00	40110.00
NP238	0.00	2.81	0.00	4.70	0.00	8.75	0.00	15.16	0.00	17.90
NP239	0.00	272.00	0.00	223.40	0.01	154.20	0.01	69.92	0.02	1.62
PU236	0.08	0.15	0.17	0.29	0.29	0.55	0.41	0.96	0.66	1.21
PU237	0.00	0.06	0.00	0.13	0.00	0.23	0.00	0.32	0.00	0.34
PU238	4210.00	2859.00	9382.00	6621.00	18380.00	14690.00	31670.00	29440.00	51200.00	49390.00
PU239	82680.00	97460.00	119100.00	101700.00	159000.00	111900.00	230700.00	147900.00	372800.00	252700.00
PU240	32060.00	36350.00	60500.00	55120.00	107900.00	91050.00	185000.00	160000.00	299100.00	273800.00
PU241	4172.00	5147.00	8707.00	8512.00	16890.00	14680.00	30960.00	25620.00	50040.00	41410.00
PU242	5802.00	4668.00	12810.00	10400.00	24770.00	21030.00	43110.00	38810.00	69680.00	65300.00
PU243	0.00	0.21	0.00	0.42	0.00	0.68	0.00	0.87	0.00	0.89
PU244	1.51	1.55	3.19	3.29	5.76	5.96	9.32	9.62	15.07	15.36
AM241	2781.00	1389.00	6461.00	3469.00	14030.00	8666.00	28780.00	21360.00	46510.00	41470.00
AM242M	138.90	124.40	328.50	316.30	667.70	749.80	1106.00	1574.00	1788.00	2523.00
AM242	0.00	0.62	0.00	1.36	0.01	2.74	0.01	4.68	0.02	5.59
AM243	2324.00	2001.00	5057.00	4499.00	9545.00	8842.00	16140.00	15510.00	26080.00	25490.00
AM244M	0.00	0.02	0.00	0.03	0.00	0.05	0.00	0.06	0.00	0.06
AM244	0.00	0.02	0.00	0.04	0.00	0.06	0.00	0.08	0.00	0.08
CM242	0.40	127.20	0.94	281.30	1.89	559.40	3.06	940.90	4.95	1108.00
CM243	13.55	13.08	27.14	26.82	43.40	46.76	56.36	65.28	91.10	83.05
CM244	1142.00	1168.00	2423.00	2489.00	4408.00	4515.00	7111.00	7117.00	11490.00	10880.00
CM245	323.60	302.20	659.30	636.40	1115.00	1131.00	1575.00	1701.00	2546.00	2655.00
CM246	55.92	84.35	106.00	158.80	164.90	242.50	221.10	305.10	357.30	442.40
CM247	2.96	5.64	5.37	10.02	7.80	14.12	9.32	15.86	15.07	21.60
CM248	0.30	0.84	0.50	1.32	0.67	1.61	0.73	1.50	1.18	1.89
BK249	0.00	0.02	0.00	0.03	0.00	0.03	0.00	0.02	0.00	0.02
CF249	0.01	0.03	0.02	0.04	0.03	0.05	0.02	0.04	0.04	0.06
SUM NP	3296.31	2170.04	7423.63	3839.61	16071.11	8515.99	33551.56	20946.94	54232.52	40132.47
SUM PU	128925.59	146485.98	210502.36	182357.12	326946.05	253357.42	521449.73	401781.76	842835.73	682617.80
SUM AM	5243.90	3515.06	11846.50	8285.73	24242.71	18260.65	46026.01	38448.82	74378.02	69488.73
SUM CM	1538.73	1701.31	3222.25	3603.66	5741.66	6510.39	8976.57	10146.64	14505.60	15191.94
SUM TRU	139004.54	153872.44	232994.76	198086.20	373001.56	286644.53	610003.89	471324.22	985951.91	807431.01

Recycle 3 Charge & Discharge Data (values given as g/MT):

	CR1.0		CR0.75		CR0.50		CR0.25		CR0.0	
	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS
U-235/U	0.04%		0.05%		0.08%		0.15%		0.61%	
TRU/HM	13.90%		25.30%		41.30%		66.00%		98.60%	
U232	0.00	0.05	0.00	0.11	0.00	0.27	0.00	0.57	0.00	0.79
U233	0.00	0.01	0.00	0.03	0.00	0.06	0.00	0.11	0.00	0.14
U234	0.00	59.92	0.00	200.30	0.00	554.70	0.00	1222.00	0.00	1932.00
U235	355.00	91.52	427.00	160.20	509.00	266.30	645.00	435.90	841.00	659.20
U236	0.00	70.85	0.00	90.15	0.00	118.30	0.00	162.20	0.00	215.30
U237	0.00	7.29	0.00	5.74	0.00	3.79	0.00	1.72	0.00	0.17
U238	860700.00	669000.00	746600.00	612700.00	586500.00	504300.00	339500.00	304800.00	13910.00	12930.00
U239	0.00	1.89	0.00	1.48	0.00	0.96	0.00	0.42	0.00	0.01
NP236	0.21	0.16	0.64	0.42	1.50	1.12	2.61	2.37	3.61	3.63
NP237	1734.00	1406.00	4672.00	2587.00	12190.00	6647.00	29560.00	18490.00	49560.00	35770.00
NP238	0.00	2.08	0.00	3.27	0.00	6.64	0.00	13.21	0.00	17.27
NP239	0.00	272.20	0.00	212.80	0.01	138.60	0.02	59.98	0.03	1.75
PU236	0.04	0.10	0.11	0.20	0.24	0.44	0.40	0.88	0.44	1.15
PU237	0.00	0.04	0.00	0.11	0.00	0.24	0.00	0.38	0.00	0.41
PU238	2600.00	1950.00	8498.00	5797.00	21190.00	15720.00	41060.00	35100.00	59500.00	55490.00
PU239	88360.00	98510.00	130400.00	104000.00	161800.00	111900.00	207800.00	134200.00	309400.00	204500.00
PU240	33030.00	37300.00	71020.00	62590.00	132600.00	108800.00	226200.00	189800.00	337300.00	299200.00
PU241	3658.00	5215.00	8561.00	9486.00	16670.00	16710.00	28280.00	27560.00	39860.00	38820.00
PU242	4222.00	3672.00	13310.00	10960.00	30380.00	25660.00	54510.00	48380.00	79970.00	73810.00
PU243	0.00	0.17	0.00	0.42	0.00	0.79	0.00	1.06	0.00	1.09
PU244	1.40	1.37	4.21	4.17	8.62	8.69	13.50	13.76	18.81	19.11
AM241	2238.00	1238.00	6723.00	3791.00	16930.00	10510.00	37420.00	26450.00	61180.00	49310.00
AM242M	109.90	106.10	395.50	345.40	1059.00	954.40	2161.00	2219.00	3020.00	3536.00
AM242	0.00	0.55	0.00	1.44	0.01	3.16	0.03	5.70	0.04	7.19
AM243	1809.00	1540.00	5755.00	4977.00	12770.00	11530.00	21770.00	20570.00	31200.00	30200.00
AM244M	0.00	0.01	0.00	0.03	0.00	0.06	0.00	0.08	0.00	0.08
AM244	0.00	0.02	0.00	0.04	0.00	0.08	0.00	0.10	0.00	0.10
CM242	0.32	111.30	1.11	295.50	2.91	645.70	5.80	1154.00	7.90	1442.00
CM243	10.47	10.82	30.39	27.95	59.82	56.48	81.16	85.99	90.05	94.97
CM244	872.50	896.40	2629.00	2733.00	5387.00	5700.00	8253.00	8784.00	11000.00	11340.00
CM245	273.20	235.40	814.00	718.10	1632.00	1489.00	2389.00	2269.00	3250.00	3072.00
CM246	76.21	88.69	203.00	241.30	350.10	426.00	428.10	527.10	541.30	640.40
CM247	5.10	6.75	12.82	17.40	20.40	28.41	22.27	31.43	26.45	35.26
CM248	0.76	1.38	1.69	3.04	2.32	4.13	2.10	3.64	2.31	3.56
BK249	0.00	0.04	0.00	0.07	0.00	0.08	0.00	0.05	0.00	0.04
CF249	0.05	0.06	0.09	0.12	0.11	0.15	0.08	0.12	0.09	0.12
SUM NP	1734.21	1680.44	4672.64	2803.49	12191.51	6793.35	29562.63	18565.56	49563.64	35792.64
SUM PU	131871.44	146648.68	231793.32	192837.90	362648.86	278800.15	557863.90	435056.08	826049.25	671841.76
SUM AM	4156.90	2884.68	12873.50	9114.92	30759.01	22997.70	61351.03	49244.88	95400.04	83053.37
SUM CM	1238.56	1350.74	3692.01	4036.29	7454.55	8349.72	11181.43	12855.16	14918.01	16628.19
SUM TRU	139001.16	152564.63	253031.56	208792.79	413054.04	316941.15	659959.07	515721.85	985931.03	807316.12

Recycle 4 Charge & Discharge Data (values given as g/MT):

	CR1.0		CR0.75		CR0.50		CR0.25		CR0.0	
	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS
U-235/U	0.04%		0.05%		0.08%		0.15%		0.61%	
TRU/HM	13.90%		27.30%		45.30%		71.00%		98.60%	
U232	0.00	0.04	0.00	0.08	0.00	0.22	0.00	0.52	0.00	0.75
U233	0.00	0.01	0.00	0.02	0.00	0.06	0.00	0.11	0.00	0.14
U234	0.00	46.02	0.00	185.40	0.00	589.70	0.00	1402.00	0.00	2121.00
U235	355.00	89.96	427.00	164.10	509.00	275.80	645.00	448.60	841.00	652.30
U236	0.00	70.92	0.00	93.05	0.00	126.10	0.00	176.60	0.00	229.90
U237	0.00	7.29	0.00	5.47	0.00	3.43	0.00	1.48	0.00	0.20
U238	860700.00	669500.00	726600.00	600700.00	546600.00	472900.00	289600.00	260300.00	13910.00	12860.00
U239	0.00	1.89	0.00	1.41	0.00	0.86	0.00	0.35	0.00	0.01
NP236	0.14	0.12	0.55	0.35	1.60	1.10	3.27	2.66	4.44	4.05
NP237	1302.00	1269.00	3443.00	2110.00	9670.00	5499.00	25850.00	16310.00	44330.00	31300.00
NP238	0.00	1.88	0.00	2.59	0.00	5.26	0.00	11.43	0.00	16.15
NP239	0.00	272.20	0.01	202.60	0.01	124.50	0.02	50.27	0.03	1.86
PU236	0.03	0.08	0.08	0.16	0.19	0.36	0.36	0.79	0.42	1.10
PU237	0.00	0.04	0.00	0.10	0.00	0.24	0.00	0.42	0.00	0.47
PU238	1809.00	1616.00	7673.00	5450.00	22570.00	16530.00	48180.00	39420.00	67120.00	60220.00
PU239	90060.00	98800.00	136500.00	105000.00	160500.00	110000.00	185400.00	120700.00	250500.00	162500.00
PU240	34130.00	37980.00	82490.00	70380.00	157200.00	126600.00	264000.00	217400.00	368700.00	318400.00
PU241	3737.00	5332.00	9759.00	10750.00	18810.00	19290.00	29910.00	30770.00	37390.00	39770.00
PU242	3348.00	3166.00	14340.00	12020.00	36770.00	31100.00	66820.00	58930.00	90440.00	82550.00
PU243	0.00	0.14	0.00	0.45	0.00	0.91	0.00	1.27	0.00	1.31
PU244	1.25	1.18	5.46	5.25	12.45	12.29	19.00	19.13	23.41	23.67
AM241	2133.00	1227.00	7566.00	4408.00	20030.00	12680.00	44340.00	31080.00	70050.00	53900.00
AM242M	94.55	102.90	441.80	397.40	1337.00	1161.00	2995.00	2754.00	4234.00	4334.00
AM242	0.00	0.55	0.01	1.63	0.02	3.66	0.04	6.58	0.05	8.40
AM243	1403.00	1237.00	6511.00	5577.00	16520.00	14690.00	28390.00	26440.00	36980.00	35400.00
AM244M	0.00	0.01	0.00	0.04	0.00	0.08	0.00	0.10	0.00	0.10
AM244	0.00	0.01	0.00	0.05	0.00	0.10	0.00	0.13	0.00	0.12
CM242	0.27	109.60	1.24	332.60	3.64	745.40	7.94	1334.00	11.02	1694.00
CM243	8.73	10.25	32.39	30.65	71.66	65.68	105.10	104.50	103.00	112.40
CM244	675.00	702.50	2954.00	3056.00	6745.00	7174.00	10020.00	10960.00	11470.00	12580.00
CM245	214.50	183.60	939.40	812.40	2132.00	1902.00	3132.00	2885.00	3761.00	3449.00
CM246	80.81	83.67	315.70	336.60	610.00	672.50	727.30	826.60	783.90	884.70
CM247	6.16	6.86	22.77	26.36	40.71	49.15	43.40	54.56	43.19	54.05
CM248	1.26	1.78	3.98	5.75	5.92	8.76	5.02	7.60	4.36	6.38
BK249	0.00	0.05	0.00	0.14	0.00	0.17	0.00	0.11	0.00	0.07
CF249	0.09	0.09	0.25	0.26	0.32	0.37	0.23	0.29	0.18	0.23
SUM NP	1302.14	1543.20	3443.56	2315.54	9671.61	5629.86	25853.29	16374.36	44334.47	31322.06
SUM PU	133085.28	146895.45	250767.54	203605.96	395862.64	303533.80	594329.36	467241.61	814173.83	663466.55
SUM AM	3630.55	2567.47	14518.81	10384.11	37887.02	28534.83	75725.04	60280.81	111264.05	93642.63
SUM CM	986.73	1098.26	4269.48	4600.36	9608.93	10617.49	14040.76	16172.26	16176.47	18780.53
SUM TRU	139004.79	152104.51	272999.64	220906.38	453030.52	348316.52	709948.68	560069.43	985949.00	807212.06

Recycle 5 Charge & Discharge Data (values given as g/MT):

	CR1.0		CR0.75		CR0.50		CR0.25		CR0.0	
	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS	FUEL CHG	FUEL DIS
U-235/U	0.04%		0.05%		0.08%		0.15%		0.61%	
TRU/HM	13.90%		29.30%		49.30%		76.00%		98.60%	
U232	0.00	0.03	0.00	0.07	0.00	0.19	0.00	0.47	0.00	0.70
U233	0.00	0.01	0.00	0.02	0.00	0.05	0.00	0.11	0.00	0.14
U234	0.00	41.32	0.00	184.20	0.00	621.80	0.00	1538.00	0.00	2251.00
U235	355.00	89.43	427.00	168.60	509.00	283.40	645.00	458.00	841.00	645.60
U236	0.00	71.03	0.00	96.26	0.00	134.00	0.00	189.60	0.00	240.90
U237	0.00	7.29	0.00	5.22	0.00	3.09	0.00	1.24	0.00	0.21
U238	860700.00	669700.00	706600.00	587700.00	506600.00	440600.00	239600.00	215700.00	13910.00	12790.00
U239	0.00	1.89	0.00	1.34	0.00	0.78	0.00	0.28	0.00	0.01
NP236	0.11	0.11	0.47	0.31	1.56	1.04	3.62	2.78	4.96	4.23
NP237	1180.00	1231.00	2869.00	1881.00	7971.00	4698.00	22570.00	14380.00	38920.00	26940.00
NP238	0.00	1.82	0.00	2.24	0.00	4.33	0.00	9.89	0.00	14.71
NP239	0.00	272.20	0.01	192.90	0.02	111.70	0.03	40.88	0.04	1.96
PU236	0.02	0.08	0.06	0.13	0.15	0.31	0.32	0.72	0.40	1.04
PU237	0.00	0.04	0.00	0.10	0.00	0.24	0.00	0.44	0.00	0.52
PU238	1519.00	1513.00	7390.00	5518.00	23580.00	17440.00	53380.00	42780.00	73030.00	63280.00
PU239	90590.00	98900.00	139700.00	105200.00	156200.00	106700.00	164400.00	107700.00	199100.00	127800.00
PU240	34820.00	38370.00	94120.00	78200.00	181300.00	144200.00	298400.00	242900.00	392700.00	331500.00
PU241	3832.00	5407.00	11220.00	12060.00	21500.00	21960.00	32920.00	34230.00	38310.00	41870.00
PU242	2896.00	2914.00	15960.00	13510.00	44130.00	37380.00	80220.00	70480.00	101200.00	91460.00
PU243	0.00	0.13	0.00	0.49	0.00	1.06	0.00	1.49	0.00	1.53
PU244	1.08	1.02	6.98	6.59	17.43	16.93	26.04	25.92	29.01	29.16
AM241	2152.00	1244.00	8847.00	5225.00	23680.00	15190.00	50880.00	35670.00	75910.00	56760.00
AM242M	91.99	104.00	515.90	470.10	1610.00	1392.00	3664.00	3235.00	5191.00	4895.00
AM242	0.00	0.55	0.01	1.88	0.02	4.22	0.04	7.41	0.06	9.37
AM243	1130.00	1053.00	7404.00	6335.00	20820.00	18330.00	35970.00	33110.00	43360.00	41000.00
AM244M	0.00	0.01	0.00	0.04	0.00	0.09	0.00	0.13	0.00	0.12
AM244	0.00	0.01	0.00	0.05	0.00	0.12	0.00	0.16	0.00	0.15
CM242	0.27	111.10	1.44	383.60	4.35	860.00	9.66	1504.00	13.47	1895.00
CM243	8.30	10.26	36.04	34.79	82.50	75.55	125.90	121.10	122.00	131.20
CM244	530.50	573.30	3351.00	3454.00	8405.00	8912.00	12320.00	13590.00	12730.00	14460.00
CM245	167.90	147.10	1078.00	924.90	2698.00	2388.00	3925.00	3595.00	4226.00	3877.00
CM246	76.45	74.66	446.70	448.80	953.20	993.70	1124.00	1214.00	1083.00	1178.00
CM247	6.27	6.38	35.01	37.12	69.72	77.41	74.26	86.46	66.24	78.48
CM248	1.63	1.99	7.64	9.68	12.43	16.35	10.34	14.18	7.82	10.83
BK249	0.00	0.06	0.00	0.23	0.00	0.31	0.00	0.20	0.00	0.12
CF249	0.13	0.11	0.53	0.49	0.75	0.77	0.53	0.60	0.36	0.42
SUM NP	1180.11	1505.13	2869.48	2076.45	7972.58	4815.07	22573.65	14433.55	38925.00	26960.90
SUM PU	133658.10	147105.26	268397.04	214495.32	426727.58	327698.54	629346.36	498118.57	804369.41	655942.25
SUM AM	3373.99	2401.57	16766.91	12032.07	46110.02	34916.43	90514.04	72022.69	124461.06	102664.64
SUM CM	791.32	924.79	4955.83	5292.89	12225.20	13323.01	17589.16	20124.74	18248.53	21630.51
SUM TRU	139003.65	151936.91	292989.79	233897.44	493036.13	380754.12	760023.74	604700.35	986004.36	807198.85

Distribution

1	MS	0736	John Kelly, 6770
1		0747	JD Smith, 6772
5		0747	Ben Cipiti, 6774
1		0747	Ken Sorenson, 6774
1		0123	Donna Chavez, 1011
1		0899	Technical Library, 9536 (1 electronic copy)