ENVIRONMENTAL ASPECTS OF ADVANCED NUCLEAR FUEL CYCLES: PARAMETRIC MODELING AND PRELIMINARY ANALYSIS

An Honors Fellows Thesis

by

KRISTINA D. YANCEY

Submitted to the Honors Programs Office
Texas A&M University
in partial fulfillment of the requirements for the designation as

HONORS UNDERGRADUATE RESEARCH FELLOW

April 2010

Major: Nuclear Engineering

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Approved by:

Research Advisor: Pavel Tsvetkov
Associate Director of the Honors Programs Office: Dave A. Louis

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ABSTRACT

Environmental Aspects of Advanced Nuclear Fuel Cycles: Parametric Modeling and Preliminary Analysis. (April 2010)

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Nuclear power has the potential to help reduce rising carbon emissions, but to be considered sustainable, it must also demonstrate the availability of an indefinite fuel supply as well as not produce any significant negative environmental effects. The objective of this research was to evaluate the sustainability of nuclear power and to explore the nuclear fuel cycles that best meet this goal. First, the study quantified current and promising nuclear fuel cycles to be further evaluated and developed a set of objective metrics to describe the environmental effects of each cycle. The metrics included such factors as the amount of waste generated and the isotopic composition of the waste. Next, the evaluation used the International Atomic Energy Agency's Nuclear Fuel Cycle Simulation System to compute nuclide compositions at various stages of the fuel cycles. Finally, the study looked at the radioactivity of the waste generated and used this and other characteristics to determine which fuel cycle meets the objectives of sustainability. Results confirm that incorporating recycling into the fuel cycle would help reduce the volume of waste needing to be stored long-term. Also, calculations made with data from the Nuclear Fuel Cycle Simulation System predicted that the waste from fuel cycles using recycling would be slightly more radiotoxic than the open fuel cycle's waste. However, the small increase in radiotoxicity is a manageable issue and would not detract from the benefits of recycling. Therefore, recycling and reprocessing spent fuel must be incorporated into the nuclear fuel cycle to achieve sustainability.

ACKNOWLEDGMENTS

I would like to thank Dr. Pavel Tsvetkov for the mentoring and support he has given me in this research for the past two years. Without his guidance, I would have been lost.

I would also like to thank Ms. Lynn McKay for her insight into environmental litigation involving nuclear power plants.

Finally, I would like to thank my family and friends for encouraging me in this endeavor and pushing me to continue when I felt overwhelmed.

NOMENCLATURE

Becquerel	Unit describing radioactivity such that 1 Becquerel is equal to 1 decay per second, abbreviated Bq
Curie	Unit describing radioactivity such that 1 Curie is equal to 3.7E10 Bq, abbreviated Ci
g	Grams
HEU	High-enriched uranium, or uranium that has an enrichment of more than 20% ^{235}U
HLW	High Level Waste, the highly radioactive materials produced by nuclear reactors
MWe	Megawatt electric, the amount of power entering the electrical grid
LEU	Low-enriched uranium, or uranium that has an enrichment of less than 20% ^{235}U
Sievert	Unit describing biological effects of radiation such that 1 Sievert is equal to 1 Joule/kilogram, abbreviated Sv
tHM	tonne Heavy Metal
tonne	A measurement of mass such that 1 tonne is equal to 1000 kilograms or 10^6 grams
TRU	Transuranic wastes

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CHAPTER I

INTRODUCTION

Global warming and energy challenges are two of the biggest problems of the modern era, threatening to change everyday life for the world's inhabitants. While the public may continue to debate the merits of global warming, the past decade has been the warmest on record.[1] Scientific consensus agrees that climate change promises at least moderate differences in weather patterns, farming economies, and health issues. Compounding this issue, according to Royal Dutch Shell's chief executive Jeroen van der Veer, estimates predict that "after 2015 supplies of easy-to-access oil and gas will no longer keep up with demand."[2] Consequently, sustainable forms of energy must be pursued that are able to meet demand without adding to rising carbon dioxide emissions.

Nuclear power is the most efficient technology that could satisfy both of these requirements. However, the question must be asked if nuclear power can be a long-lasting solution to this problem. To truly be sustainable, it must have enough resources to operate for several generations and must neither contribute to climate change nor

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This thesis follows the style of *Nuclear Technology*.

create environmental problems of its own.

This study seeks to address this question. The following pages describe the literature reviewed to determine what the most important factors are for nuclear power to be considered sustainable and the methodology created to explore these factors. The results of the study are then analyzed, and conclusions are drawn from these results. The evidence suggests the nuclear power must start to incorporate recycling into its fuel cycles to be considered a sustainable source of energy.

CHAPTER II

BACKGROUND

Due to anticipated climate changes and growing world-wide energy consumption, the world faces the challenge of balancing the need for more energy with environmental responsibility. Sustainable forms of energy are the best solution. Nuclear power shows the most promise among technologies that do not emit carbon dioxide, producing nineteen percent of the electricity generated in the United States.[3] However, to be considered sustainable, nuclear power must have enough fuel resources to last for several generations and must neither contribute to climate change nor create environmental problems of its own. The following sections review literature pertaining to one of three issues concerning sustainability: the supply of uranium resources, carbon emissions from nuclear fuel cycles, and radioactive waste management.

Sustainability of uranium resources

According to a report written by the International Atomic Energy Agency and the Nuclear Energy Agency, the world has enough uranium resources to last for at least 100 years. The report's conclusion starts by dividing uranium resources into two categories: Identified and Undiscovered Resources. Based on the agencies' calculations, if nuclear power is significantly expanded, Identified Resources alone could supply the nuclear industry's demand for about 80 years. If nuclear capacity does not increase, Identified Resources could supply the demand for 100 years. Exploitation of the Undiscovered

Resources could extend this supply by about 300 years, albeit through extensive exploration and development.[4]

A definitive supply of 100 years worth of uranium does not qualify as a sustainable resource over the long-term, even if the Undiscovered Resources supplied an extra 300 years. However, current nuclear fuel cycles only use about 3.4% of the total energy in the nuclear fuel before it is transferred into storage as "waste."[5] If policy changed so that the "waste" could be reused and recycled, the supply of uranium could last for thousands of years. Unfortunately, recycling the fuel is considered to be much more expensive than the current system, and many decades would be required to implement such a strategy.[6]

While recycling nuclear fuel is being developed, other strategies could help extend the availability of uranium. For example, researchers from France and Russia have devised a strategy that uses current technology to increase the amount of energy extracted from the uranium by a factor of three. This strategy is composed of three stages:

1. A conventional Pressurized Water Reactor burns standard uranium dioxide fuel.
2. The spent fuel from stage 1 is reprocessed, and the plutonium is used to make a plutonium/thorium mixed oxide fuel. An Advanced Boiling Water Reactor burns this fuel and converts the plutonium to ^{233}U.
3. A heavy or light water reactor with a high breeding ratio burns the $Th/^{233}U$ fuel created during stage 2.

This strategy would increase the energy extracted from the fuel while only slightly increasing the production of plutonium and minor actinides.[7]

While current nuclear fuel cycles do not use uranium resources in a sustainable manner, the long-term availability of uranium seems to be more of a policy issue than a technical one. Recycling nuclear fuel may need decades of research to become economically and politically attractive, but in the meantime, current technology can be used to extend the supply of uranium.

Carbon emissions from the nuclear fuel cycle

Nuclear energy has the potential to help reduce humanity's contribution to climate change. The rise in carbon dioxide emissions is directly related to climate change, and nuclear energy is the most reliable, carbon-free source of energy available. However, current nuclear electrical production only offsets about 0.5 gigatonnes (Gt) of carbon/year (C/y) compared to global emissions of 7 Gt C/y. For nuclear energy to have a significant impact on the rise of carbon emissions, its electrical capacity needs to increase by a factor of three to ten before 2050.[8]

While nuclear power does not directly produce carbon dioxide emissions, its fuel cycle is still involved in their production. Mining the uranium, enriching it to make fuel, constructing the power plant, and managing the waste—all consume energy. Due to the fact that the majority of the world's energy supply comes from fossil fuels, these activities produce carbon emissions.

Over 100 studies have investigated the life cycle emissions of nuclear power, and their results vary from 1.4 g of carbon dioxide produced per kWh (g C/kWh) to 288 g C/kWh. This variation is a result of different assumptions, either too simple (looking at only one segment of the fuel cycle) or too harsh (relying on outdated data or ignoring the coproduction of minerals). The most reasonable value for the life cycle emissions would be the mean value of this variation, 66 g C/kWh.[9] While this number is significantly smaller than the life cycle emissions from the average coal-fired plant, 984 g C/kWh,[10] it indicates that nuclear power is not as carbon-free as it is assumed to be.

On the other hand, the value for nuclear power's life cycle emissions is misleading. It is mainly a result of the upstream energy mix that provides the power for the stages of the nuclear fuel cycle. For example, Sweden uses an energy mix of 51% hydroelectric and 43% nuclear; the life cycle emissions from Vattenfall, one of its utilities, were estimated to be less than 5 g C/kWh.[11] Therefore, the emissions associated with nuclear power are more a result of how clean a country's energy portfolio is rather than with nuclear itself.

Environmental effects of radioactive waste

The best long-term solution to manage radioactive waste is deep geological disposal. As early as the 1950's, the United States recognized the need to safely manage the waste, and in 1956, the National Academy of Sciences recommended deep geological disposal. Specifically, the Academy suggested further investigations into salt formations, the most promising geology, and other types of rock.[12] Disposal in these formations would provide a "unique level and duration of protection,…[taking] advantage of the capabilities of both the local geology and the engineered materials to fulfill specific safety functions in complementary fashion, providing multiple and diverse barrier roles."[13]

Unfortunately, politics make deep geological disposal difficult to implement. Many people do not understand the basics of radiation, and the technical community's confidence in the strategy is not sufficient to gain the public's acceptance.[13] Problems such as these plagued the United States' Yucca Mountain repository program and helped cause its eventual failure. It will take decades for the country to find and develop another repository site.

Fortunately, the failure of the Yucca Mountain repository program does not put the country in an immediate crisis. Traditionally, nuclear power plants have stored used nuclear fuel in pools of water that were supposed to serve as temporary cooling areas for the fuel. Because a permanent waste repository had not been built, the storage capacity in the pools began to reach capacity by the early 1980's. This situation prompted nuclear power plants to develop alternative solutions for their waste: primarily, dry cask storage. With this solution, the plants could move the cooled fuel from the pool into the casks, making more room for fuel recently removed from the reactor.[14] This arrangement has given the United States and the nuclear industry at least 100 years to develop a more permanent solution.[15] However, the nuclear industry is not happy about storing all their waste on-site.

Incorporating recycling into the nuclear fuel cycle would help the country develop and implement a long-term waste management strategy. First, recycling would decrease the amount of waste needed to be stored on-site, allowing more time for policy makers to work out the details of a new repository. Moreover, recycling would reduce the radiotoxicity of the spent fuel, one of the major objections with Yucca Mountain. The plutonium and the long-lived elements in the fuel are considered "useful material" and can be recycled. By reusing these elements, which take tens of thousands of years to decay, recycling would divide the radiotoxicity of spent fuel by 10 and dramatically decrease the spent fuel's highly radioactive lifetime.[16]

CHAPTER III

METHODS

Two conclusions can be made based on the literature reviewed for this research. The first is that the dependence of the nuclear fuel cycle's carbon emissions on a country's energy profile emphasizes the need for nuclear and renewable energy to replace fossil fuel technology. The second is that recycling nuclear fuel is important for both the sustainability of uranium resources and radioactive waste management. These two conclusions suggest that to understand the sustainability of nuclear power, it would be useful to focus on different ways of incorporating recycling into the nuclear fuel cycle.

Given this focus, the first step was to identify promising nuclear fuel cycles and then to quantify a set of objective metrics by which to evaluate their environmental effects. Next, the fuel cycles were analyzed using the International Atomic Energy Agency's Nuclear Fuel Cycle Simulation System. Finally, the results from the simulations were compared to determine the most sustainable nuclear fuel cycle. The following sections describe these steps in more detail.

Description of chosen nuclear fuel cycles

Three nuclear fuel cycles were considered during this study. Each uses varying degrees of recycling in their waste management programs that range from traditional approaches to more innovative techniques. Moreover, generic reactor types rather than unique designs were specified for the fuel cycles to accommodate for changes in technology. The three cycles are:

1. The once-through open fuel cycle
2. The plutonium-burning fuel cycle
3. The actinide-burning fuel cycle

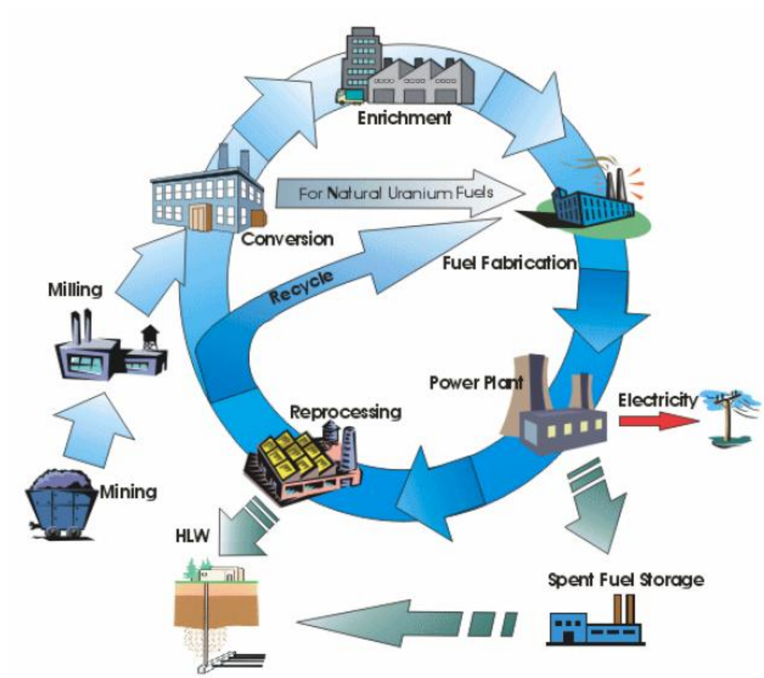

Fig. 1. Diagram of the average nuclear fuel cycle.[17]

Before describing each of these cycles, it is important to understand how the average nuclear fuel cycle works. Figure 1 shows how material flows through this cycle. Material enters the cycle through the process of mining and milling. Here, uranium ore (the primary fuel for nuclear reactors) is taken out of the ground, and the uranium is extracted from the ore before it can be used.[17]

After milling, the uranium is sent to a conversion plant where it is purified and converted to a chemical form, such as uranium oxide (UO_2). The chemical form of the uranium can then be sent to an enrichment facility. Natural uranium is comprised of about 0.7% ^{235}U, the main source of energy in reactors, and 99.3% ^{238}U. The enrichment facility will increase the amount of ^{235}U in the fuel based on its desired use.[17] However, some reactors are optimized to use natural uranium as their fuel, so not all fuel is sent to the enrichment facility.

Next, the fuel is transferred to a fabrication facility where it is manufactured into pellets or other geometries before it can be placed inside a reactor. Once inside the reactor, the fuel produces energy that can be converted into electricity. After a certain amount of time, the fuel is removed from the core and is considered to be spent nuclear fuel.[18] The spent fuel can be transferred to a reprocessing facility that will extract useful material to be reused, or it can be transferred to storage to await final disposal.

The once-through open fuel cycle

The once-through open fuel cycle refers to the current system used by the United States. In this cycle, fresh fuel is manufactured and used to power light water reactors. After it is removed from the reactor, the fuel is put in storage, as shown in Fig. 2. This cycle does not include recycling, so it will be used for comparison purposes.

Fig. 2. Simplified schematic of the once-through open fuel cycle.

The open fuel cycle shown in Fig. 2 uses a pressurized water reactor (PWR) to represent light water reactors. This decision was made based on the fact that the majority of light water reactors operating in the United States are PWRs (69 out of 104).[19] Table 1 shows more assumptions made about the once-through open fuel cycle.

TABLE 1

Assumptions about Open Fuel Cycle

Parameter	**Description**
Reactor Power	1000 MWe
Reactor Efficiency	33%
Reactor Load Factor	95%
Reactor Tails Assay	0.3%
Reactor Residence Time	4 years
Reactor Fuel Type	Uranium Oxide (UOX) • Enrichment=4% • Discharge Burnup = 45 GWD/t

The plutonium-burning fuel cycle

The plutonium-burning fuel cycle refers to a system currently used in some other countries where fresh fuel enters a light water reactor, produces energy, and then is transferred to a reprocessing facility. The reprocessing facility separates the plutonium

(Pu) from the rest of the spent fuel and sends the Pu to a fabrication facility that will use it to make new fuel. The rest of the material is put in storage. The fuel made from the separated Pu then is put back into the light water reactor to produce more energy, as shown in Fig. 3.

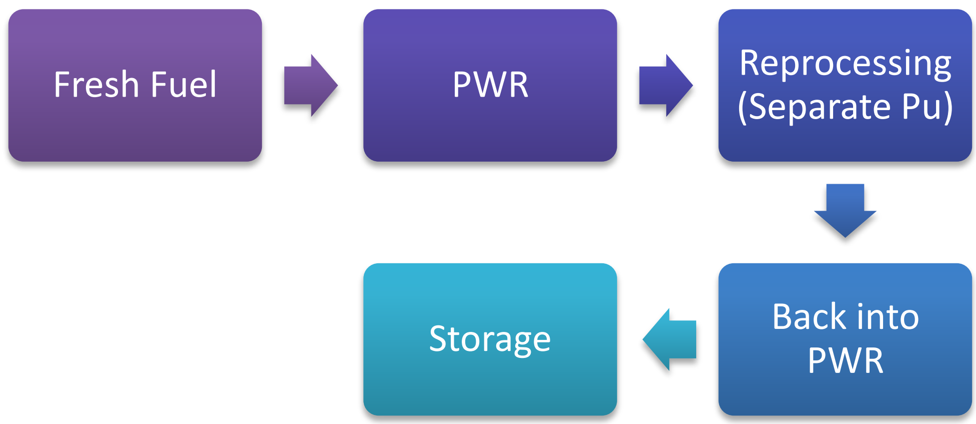

Fig. 3. Simplified schematic of the plutonium-burning fuel cycle.

Again, the fuel cycle shown in Fig. 3 uses a PWR to represent light water reactors. Because reprocessing is more of a policy challenge in the United States than a technical challenge, the plutonium-burning fuel cycle could feasibly be deployed within several years. Therefore, the reasoning used to justify the PWR's representation of light water reactors still applies. Table 2 shows more assumptions made about the plutonium-burning fuel cycle.

TABLE 2

Assumptions about Plutonium-Burning Fuel Cycle

Parameter	Description
Reactor Power	1000 MWe
Reactor Efficiency	33%
Reactor Load Factor	95%
Reactor Tails Assay	0.3%
Reactor Residence Time	4 years
Reactor Fuel Type	Uranium Oxide (UOX) • Enrichment = 4% ^{235}U • Discharge Burnup = 45 GWD/t • Reprocessing Ratio = 1 Mixed Oxide (MOX)[20] • Enrichment = 7.4% Pu • Discharge Burnup = 44 GWD/t • Reprocessing Ratio = 0 Ratio of type in fuel: • UOX = 75% of fuel • MOX = 25% of fuel

The actinide-burning fuel cycle

The actinide-burning fuel cycle is similar to the plutonium-burning fuel cycle in that it separates useful material from the spent fuel and uses the separated material to produce more energy. However, it goes beyond the plutonium-burning fuel cycle by separating not only plutonium but also minor actinides from the spent fuel. **Actinides** are the elements on the periodic table from actinium to lawrencium.[21] Uranium and plutonium are considered the major actinides since they produce the most energy in reactors, and the rest are considered to be minor actinides.

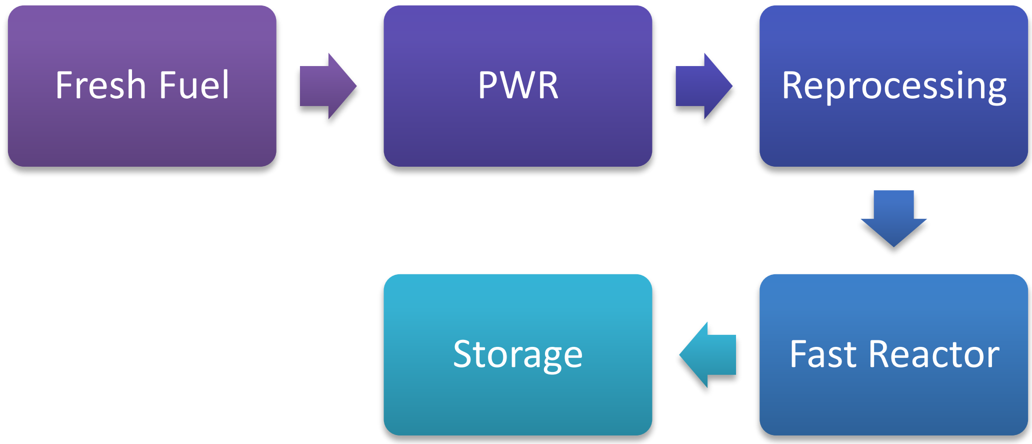

Fig. 4. Simplified schematic of actinide-burning fuel cycle.

Figure 4 shows how fuel would move in the actinide-burning fuel cycle. It would start as fresh fuel that is burned in a light water reactor, again represented by a PWR. The spent fuel from the PWR would be sent to a reprocessing facility that would separate the actinides from the rest of the spent fuel, which would be put in storage. The fuel made with the actinides would then be placed in a fast reactor. In this type of reactor, the actinides would not only produce energy but also be **transmuted**, or transformed into nonradioactive elements via nuclear reactions. Therefore, the waste coming out of the fast reactor would be significantly less radioactive, and the remaining radioactivity could decay within several centuries.[18]

Realistically, the actinide-burning fuel cycle could not be deployed for at least a decade. Reprocessing technology needs to improve, and candidates for the fast reactor most likely would come from the concepts being pursued by the Gen-IV International Forum:

the Gas-cooled Fast Reactor, the Lead-cooled Fast Reactor, and the Sodium-cooled Fast Reactor.[22] However, it is still important to consider how a generic fast reactor could improve the sustainability of nuclear fuel cycles. Table 3 shows the assumptions made to do this.

Table 3

Assumptions about Actinide-Burning Fuel Cycle

Parameter	Description
Reactor Power	PWR = 1000 MWe Fast Reactor = 1000 MWe
Reactor Efficiency	PWR = 33% Fast Reactor = 36%[23]
Reactor Load Factor	PWR = 95% Fast Reactor = 95%
Reactor Tails Assay	PWR = 0.3% Fast Reactor = 0.3%
Reactor Residence Time	PWR = 4 years Fast Reactor = 25 years[24]
Reactor Fuel Type	PWR = Uranium Oxide (UOX) • Enrichment=4% • Discharge Burnup = 45 GWD/t • Reprocessing Ratio = 1 Fast Reactor = • Enrichment = 40%[23] • Discharge Burnup = 78 GWD/t[24] • Reprocessing Ratio = 0

Metrics to evaluate environmental effects

As mentioned previously, the supply of uranium resources and radioactive waste management are two of the biggest issues that determine the sustainability of nuclear power. Consequently, any metrics that describe a fuel cycle's sustainability should also describe these two factors. In relation to the supply of uranium resources, the metrics should evaluate how a fuel cycle utilizes its fissile material. For radioactive waste management, the metrics should evaluate the manageability of the waste, including how long the waste would stay radioactive.

Two metrics best quantify these issues:

1. The amount of waste put into storage,
2. The radiotoxicity of the waste.

The first metric is a simple calculation based on how material flows through a given fuel cycle. The second is slightly more complicated. *Radiotoxicity* refers to the weighted sum of toxic isotopes found in spent fuel.[25] It is often a more meaningful way of interpreting the activity in material because it also considers the level of harm that would result if someone ingested or inhaled certain isotopes. The radiotoxicity of a certain isotope is defined by equation (1).

$$R_i(Sv) = F_{d,i}\left(\frac{Sv}{Bq}\right) * A_i(Bq) \qquad (1)$$

In equation (1), R_i represents the radiotoxicity of isotope i in Sievert per mass unit, $F_{d,i}$ represents the dose factor of isotope i in Sievert per Bequerel activity, and A_i represents the activity of isotope i in Bequerel.[26] The overall radiotoxicity of a sample is the sum of the radiotoxicities for all the isotopes present. The International Commission on Radiation Protection has determined the values of various dose factors; Table 4 lists the ones used in this research.

Table 4

Dose Factors for Important Nuclides in Spent Fuel[27]

Isotope	Dose Factor [Sv/Bq]
^{235}U	0.46×10^{-7}
^{236}U	0.46×10^{-7}
^{238}U	0.44×10^{-7}
^{237}Np	0.11×10^{-6}
^{238}Pu	0.23×10^{-6}
^{239}Pu	0.25×10^{-6}
^{240}Pu	0.25×10^{-6}
^{241}Pu	0.47×10^{-8}
^{242}Pu	0.24×10^{-6}
^{241}Am	0.20×10^{-6}
^{242m}Am	0.19×10^{-6}
^{243}Am	0.20×10^{-6}
^{242}Cm	0.12×10^{-7}
^{244}Cm	0.12×10^{-6}

The amount of waste generated and its radiotoxicity sufficiently describe the sustainability of nuclear fuel cycles. Adequate utilization of the fuel would burn away most of the fissile material and would result in smaller volumes of waste. Radioactive waste management would also seek to decrease the volume of the waste and its radiotoxicity. Both of these metrics can be solved for using the Nuclear Fuel Cycle Simulation System.

The Nuclear Fuel Cycle Simulation System

The Nuclear Fuel Cycle Simulation System (NFCSS) is a tool that was developed by the International Atomic Energy Agency to estimate long-term front-end and back-end material requirements for nuclear fuel cycles. It is a web-based computer application that allows users "to use existing fuel types and data files for reactor types to generate a new scenario or…[to] define new fuel types and data sets for a reactor or group of reactors to use in new scenarios."[17] To simulate a realistic nuclear fuel cycle, the NFCSS makes a number of assumptions:

- All calculations are performed annually, meaning that every reactor is loaded at the beginning of the year and discharged at the end.
- All mass loss in heavy metal is considered to be a fission product accumulation.
- For scenarios using more than one reactor, it is possible to group together reactors based on neutronic characteristics, rather than evaluate every individual reactor.
- The user can provide an isotopic composition table.
- The NFCSS can operate in two modes: Requirement Driven Mode and Capacity Driven Mode. In the former, the facilities work without limitations and all tasks are completed immediately. In the latter, the facilities are limited by their capacities.
- Multiple recycling of material is only possible when using the same fuel composition as the second fuel type.

- Material flow calculations are based on heavy metal masses, using tonne Heavy Metal (tHM) as the unit.[17]

These assumptions help the NFCSS make simplified calculations to estimate material requirements and arisings. For more detailed information, refer to the NFCSS User Manual.[17]

CHAPTER IV

RESULTS

The nuclear fuel cycles described in Chapter III were simulated using the Nuclear Fuel Cycle Simulation System (NFCSS) and the parameters given in Tables 1 through 3. All of the simulations started calculations in 2010 and ended in 2050. Moreover, the assumption was made that the power levels, enrichments, and other reactor parameters did not change over the timeframe. Given these conditions, the NFCSS calculated the material requirements for each fuel cycle and generated material flow charts for each year of operation. This section compares the results given in the flow charts and seeks to understand them, not only through the volume of the waste generated but also through the level of radioactivity present in the waste.

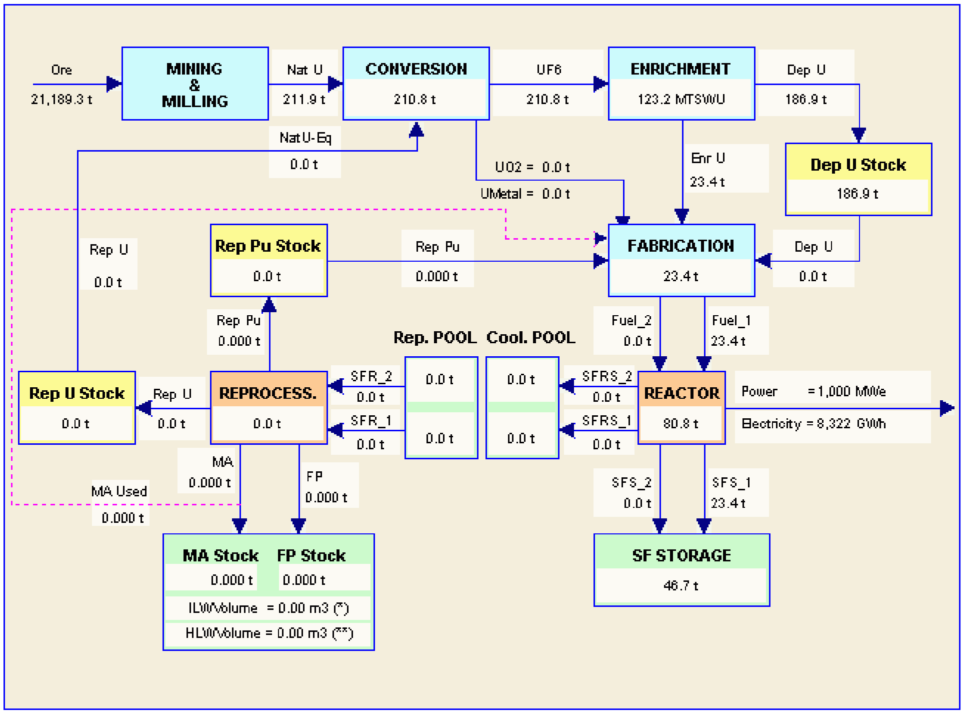

Fig. 5. Material flow for the open fuel cycle, year 0.

Figure 5 shows a material flow diagram created using the NFCSS that describes the once-through open fuel cycle in its first year of operation, assuming it begins in 2010. Noteworthy aspects of this diagram are that none of the material is being recycled and that 46.7 tonnes of spent fuel is put into storage within the first year.

The material flow chart for the cycle at the end of the timeframe is shown in Fig. 6. The material requirements are the same in this diagram as those in Fig. 5, but the amount of spent fuel in storage has increased to 980.7 tonnes. This scenario considered only one PWR as a representation of light water reactors, so in a country with more than 100 light water reactors and without a long-term nuclear waste disposal strategy, that is a lot of waste to be stored. As stated before, this fuel cycle is considered for comparison purposes with the two fuel cycles that use recycling.

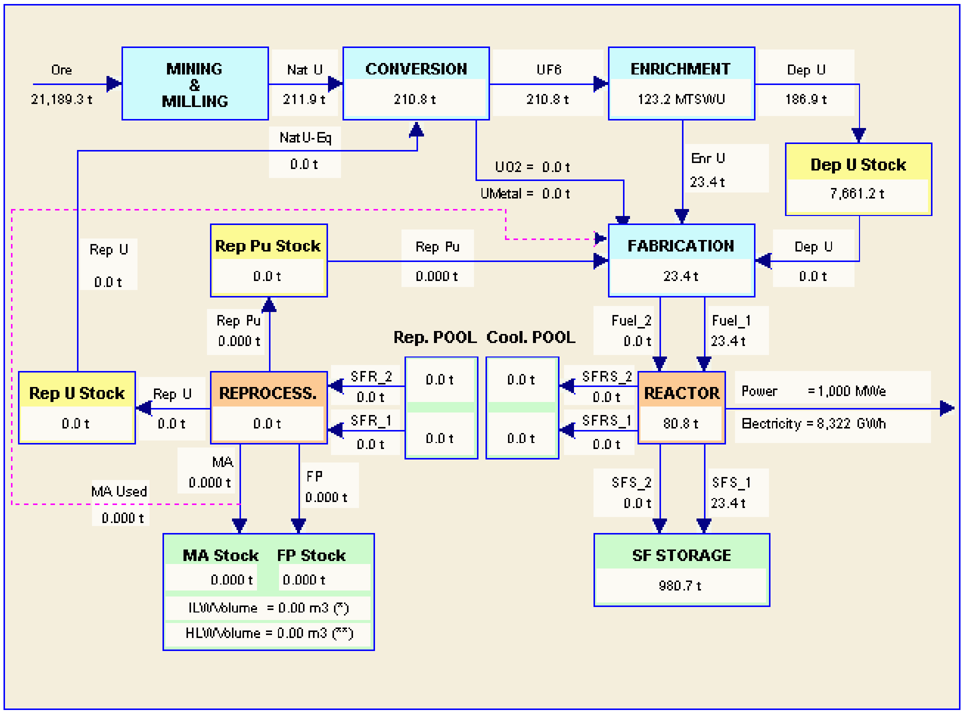

Fig. 6. Material flow for the open fuel cycle, year 40.

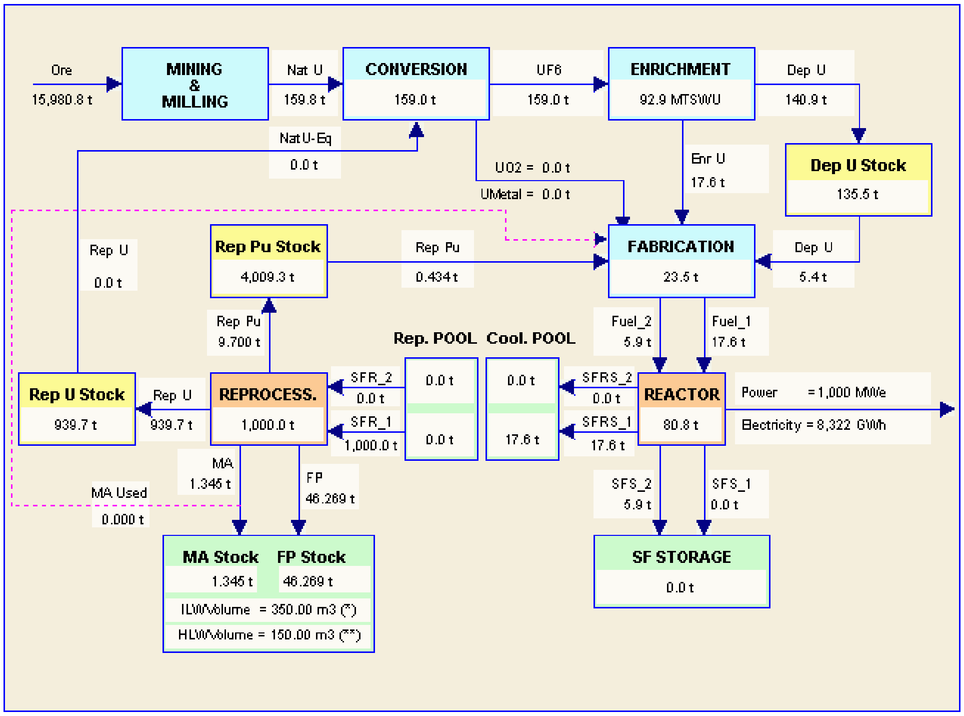

Fig. 7. Material flow for the plutonium-burning fuel cycle, year 0.

Figure 7 shows the material flow diagram for the plutonium-burning fuel cycle in its first year of operation. This scenario also used only one PWR to represent the reactor fleet, and the assumption was made that 100% of the fuel in the PWR could be recycled. Unlike the open fuel cycle, none of the material is put into storage during the first year.

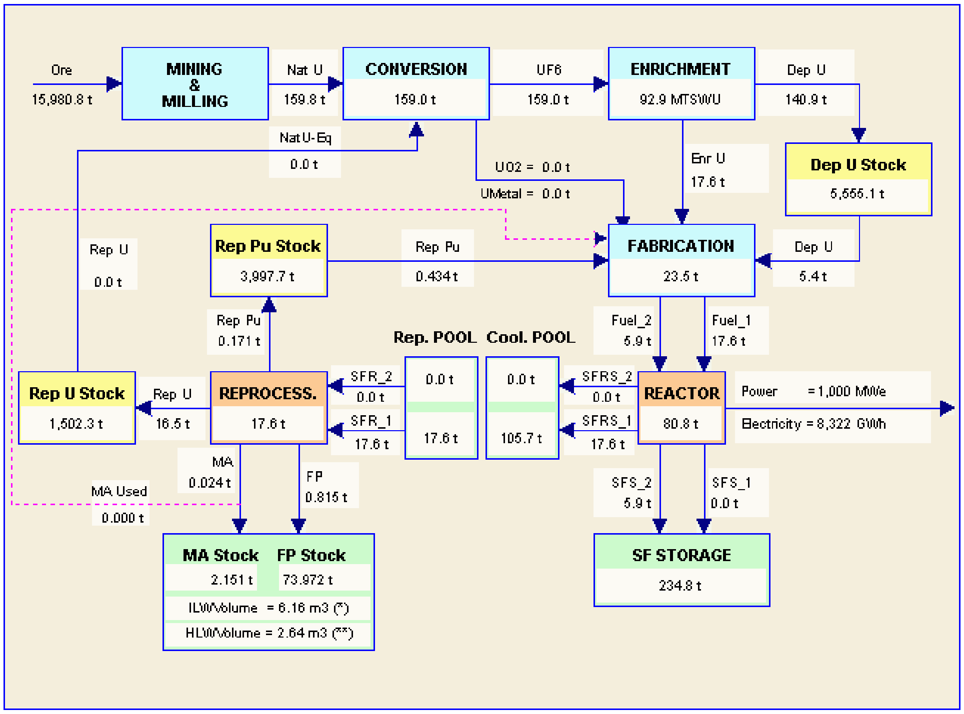

Fig. 8. Material flow for the plutonium-burning fuel cycle, year 40.

The material flow diagram for this cycle at the end of the timeframe is shown in Fig. 8. Again, the material requirements have remained the same, but the amount of spent fuel put into storage has only increased to 234.8 tonnes. The total amount of spent fuel in storage for the entire reactor fleet would still be significant. However, the plutonium-burning fuel cycle produces less than one-fourth the amount of waste created by the open fuel cycle. This is a dramatic reduction and would give the industry more time and space to develop a more permanent solution for the waste.

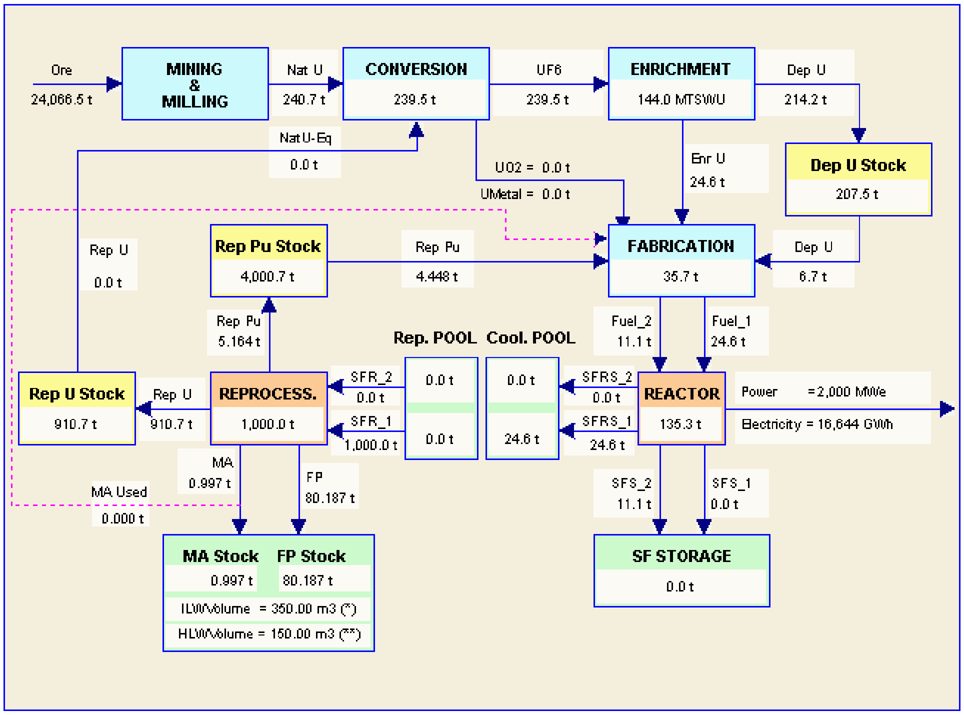

Fig. 9. Material flow for the actinide-burning fuel cycle, year 0.

Figure 9 shows the material flow diagram for the actinide-burning fuel cycle in its first year of operation. This scenario considered one PWR to represent all light water reactors and one fast reactor to represent all fast reactors (refer to Fig. 4 in Chapter III). While in reality the fast reactor's design would fall under a specific category, such as a sodium-cooled fast reactor or a lead-cooled fast reactor, a non-descript fast reactor was used for the sake of generality and flexibility. Also, the assumption was made that 100% of the PWR's fuel could be recycled, but only the fresh fuel put in the fast reactor could be recycled. Again, like the plutonium-burning fuel cycle, none of the waste is put into storage within the first year of operation.

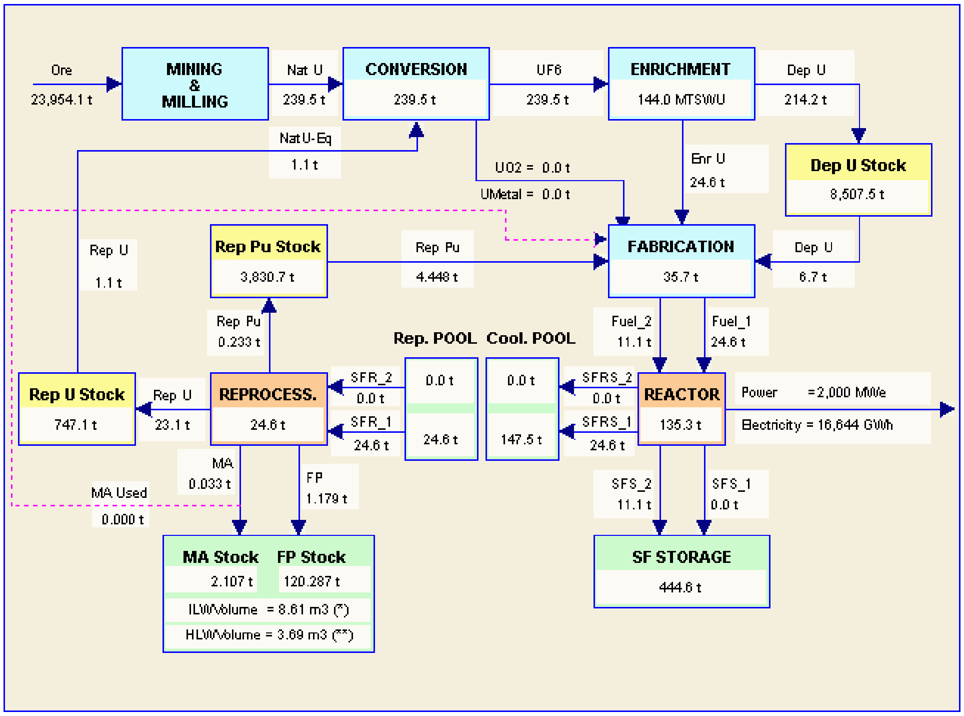

Fig. 10. Material flow for the actinide-burning fuel cycle, year 40.

Figure 10 shows the material flow diagram for the actinide-burning fuel cycle at the end of the timeframe. Here, the amount of spent fuel put into storage has increased to 444.6 tonnes. While this is less than half the amount of waste generated by the once-through fuel cycle, it is almost twice the amount generated by the plutonium-burning fuel cycle. Because the actinide-burning fuel cycle reuses more of the fuel than the plutonium-burning fuel cycle, this increase in the amount of waste is an unexpected result. The simplified nature of the NFCSS could be one of the contributors to this increase.

The data from the material flow calculations was then used to calculate the radiotoxicity of the waste. The radioactivity of the waste was calculated using basic nuclear data[28] and tables generated by the NFCSS that quantified the isotopic distribution of the waste coming out of the reactor. The results of these calculations are shown in Fig. 11, with Activity in Curies/tonne Heavy Metal (Ci/tHM) on the logarithmic vertical axis and time in years on the horizontal axis.

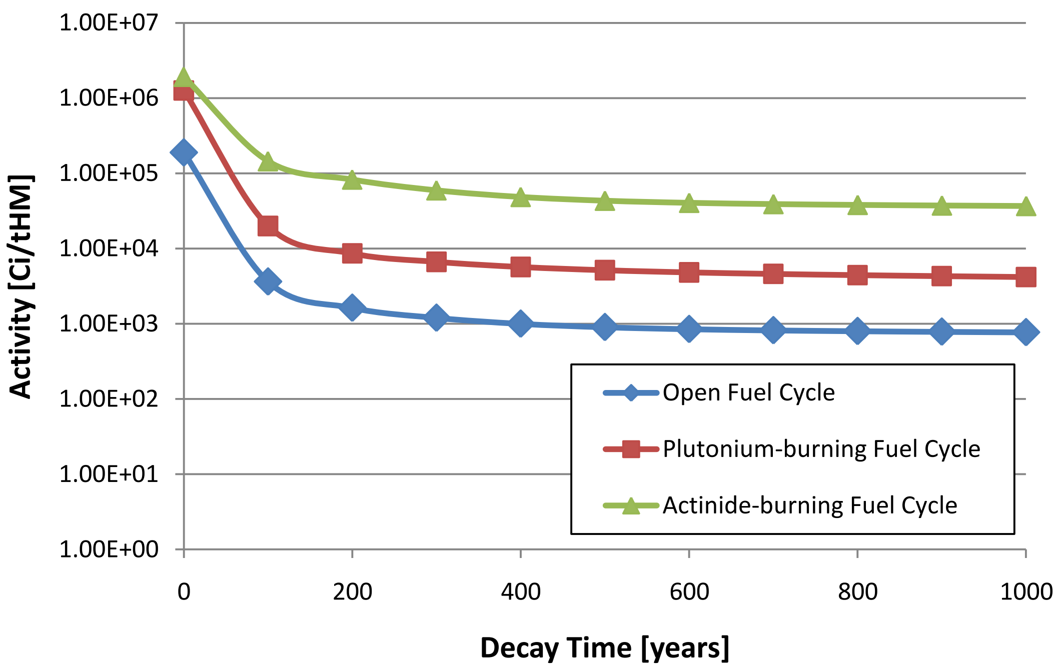

Fig. 11. Radioactivity of each nuclear fuel cycle's waste.

Figure 11 shows that the activities of the plutonium-burning and actinide-burning fuel cycles are initially greater than the activity of the once-through open fuel cycle. This is expected because one of the benefits of reusing plutonium and other actinides is that they can be transmuted into shorter-lived isotopes, as discussed in Chapter III. The shorter-lived isotopes will be more radioactive due to their smaller half-life. However, these “smaller” half-lives can still be on the order of thousands to hundreds of thousands of years. Therefore, the waste from the fuel cycles incorporating recycling will continue to be more radioactive than waste from the open fuel cycle for a very long time.

Closer inspection reveals that the increased radioactivity is not much of a problem. Figure 12 shows the change in radiotoxicity over time for each nuclear fuel cycle’s waste, calculated using equation (1). While the radioactivity of the waste for the plutonium-burning fuel cycle may be greater than the radioactivity of the open fuel cycle, its radiotoxicity is only slightly higher. Also, the difference between the radiotoxicities of the actinide-burning fuel cycle and the open fuel cycle is much smaller than the difference in radioactivity shown in Fig. 11. Because recycling dramatically reduces the volume of waste, the small increase in the level of radiotoxicity seems to be a fair trade-off.

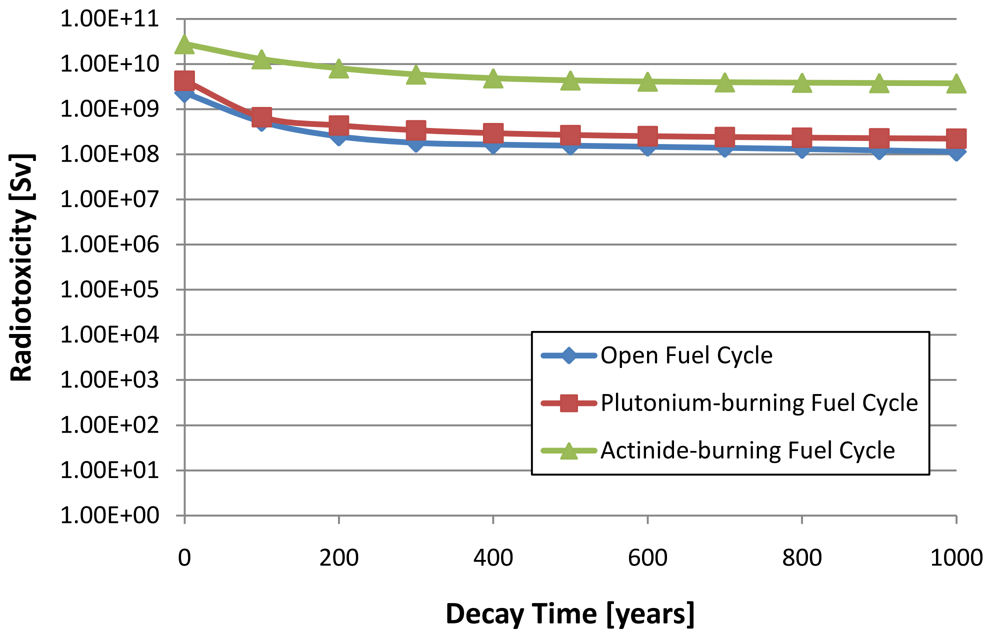

Fig. 12. Radiotoxicity of each nuclear fuel cycle's waste.

Figure 13, on the next page, splits the activity of the actinide-burning fuel cycle into the activities of the separate isotopes in its waste. If the longer-lived isotopes shown in Fig. 13 were reused instead of put in storage, the radiotoxicity of the actinide-burning fuel cycle's waste would decrease. Moreover, telling the NFCSS to reuse the spent fuel until all the isotopes are transmuted into shorter-lived isotopes produces an encouraging result: none of the spent fuel is put into storage over the entire timeframe. While this may not be realistic within the next decade, reusing nuclear material until all of its energy has been utilized is the most sustainable route for nuclear power.

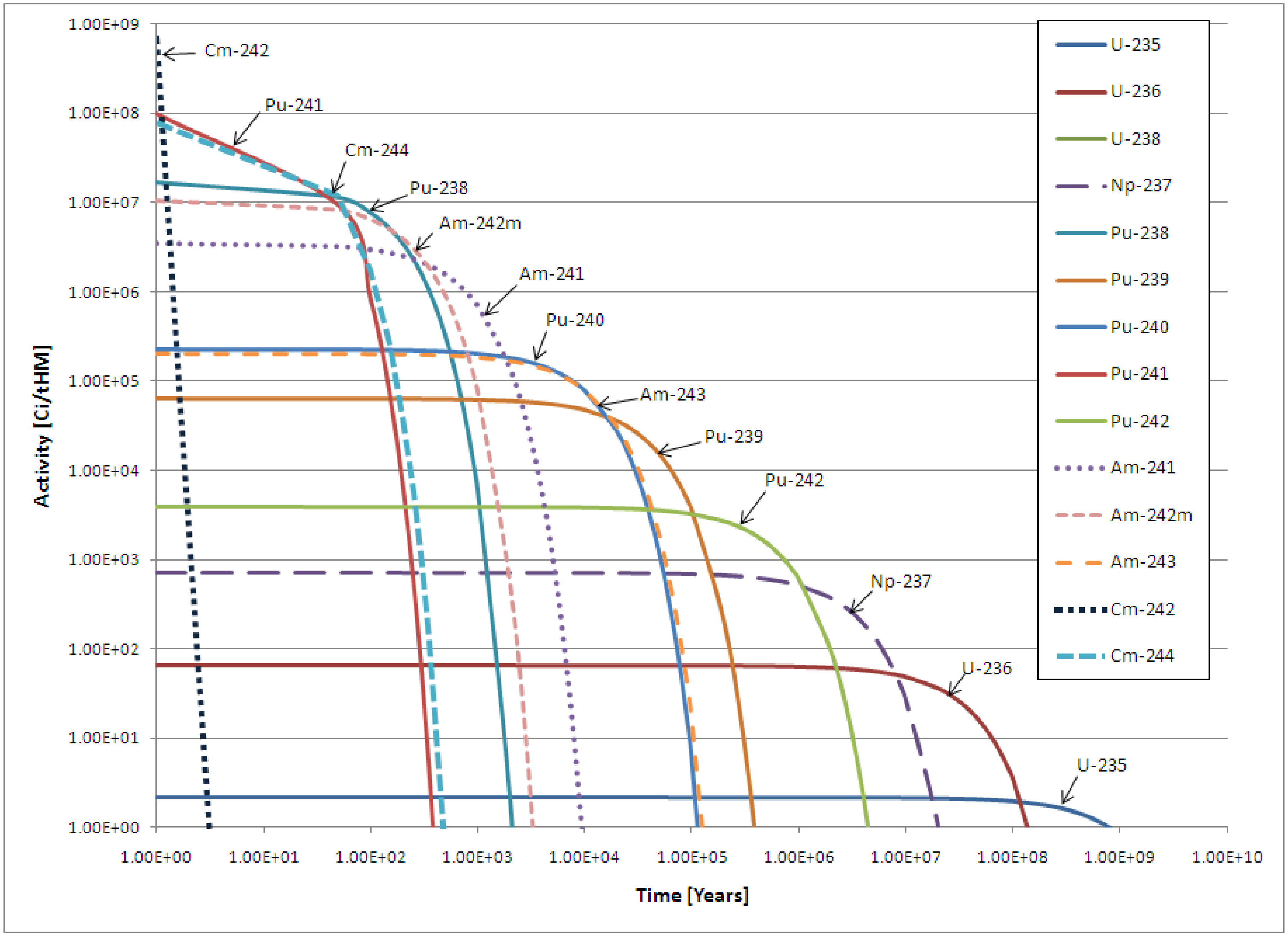

Fig. 13. Activities of important isotopes in actinide-burning fuel cycle over time.

CHAPTER V

SUMMARY AND CONCLUSIONS

Nuclear power should play a major role in the effort to reduce rising carbon emissions; but to be one of the long-term solutions to climate change, it must also be produced in a sustainable manner. Two of the biggest issues facing nuclear power in this regard are the under-utilization of current fuel resources, such as uranium, and the radiotoxicity of the spent fuel waiting for disposal. The former issue could contribute to an exhaustion of resources, and the latter issue would make nuclear waste difficult to manage over the timeframe it is radioactive—millions of years. However, reusing and reprocessing spent fuel can help solve both of these issues, making nuclear power more sustainable.

The objective of this research was to evaluate the sustainability of two nuclear fuel cycles that incorporated different levels of recycling. These fuel cycles were the plutonium-burning fuel cycle and the actinide-burning fuel cycle. The evaluation used the International Atomic Energy Agency's Nuclear Fuel Cycle Simulation System (NFCSS) to compute nuclide compositions and material requirements at various stages of the cycles. Calculations were also made for the once-through open fuel cycle for comparison purposes.

The NFCSS helped confirm that nuclear power must incorporate some form of recycling to be more sustainable. While the open fuel cycle produced about 980 tonnes of waste per reactor over forty years, the actinide-burning fuel cycle only produced about 440 tonnes, and the plutonium-burning fuel cycle only produced 230 tonnes of waste. This means that recycling would help reduce the volume of waste significantly, allowing more time to develop a sophisticated long-term disposal strategy. This also indicates that recycling would lead to better utilization of the fuel, which would help conserve resources.

Data from the NFCSS also showed that the radiotoxicity of spent fuel increased only slightly for fuel cycles that incorporate recycling. Because of the dramatic reduction in the volume of waste, this small increase in radiotoxicity remains manageable and is an acceptable tradeoff. Moreover, the radiotoxicity can be decreased by targeting specific, longer-lived isotopes to be reused indefinitely.

In conclusion, this research shows that recycling spent fuel must be incorporated for nuclear power to be sustainable.

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