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Uncertainty Analysis of Advanced Fuel Cycles to Control Plutonium Inventories

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To the Graduate Council:

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Laurence F. Miller, Major Professor

We have read this thesis and recommend its acceptance:

Lawrence W. Townsend, Martin L. Grossbeck

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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Uncertainty Analysis of the Utilization and Implementation of Advanced Fuel Cycles to Control Plutonium Inventories

A Thesis

Presented for the

Master of Science Degree

The University of Tennessee, Knoxville

Thomas Christopher Anderson
December 2007

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I would also like to thank my family for their support throughout my education. Without them I would not be where I am today.

Abstract

This paper assesses the uncertainty associated with the utilization and implementation of advanced fuel cycles to control plutonium inventories. The specific fuel cycles investigated are a partially closed cycle utilizing MOX reactors and completely closed one-tier fuel cycles utilizing fast reactors. Multiple methods for assessing these uncertainties were utilized. A scenario approach that varied the time and number of the implementation of the advanced reactors was used. It was found that the implementation of 3 FR/yr with a CR of 0.5 could reduce the amount of Pu by over 36% in reference to building 3 LWR/yr. In addition to reducing the inventory with respect to the reference LWR case, the growth rate can be reduced from an initial 22 tons Pu/ year growth to 5 tons Pu / year growth with the 2030 actual initial Pu inventory implementation cases. The MOX cases keep the Pu/ TWhe inventory slightly above 1 ton Pu/TWhe and the extremely low CR FR cases even lower than that value. Thus from this work the extremely low CR FR scenarios show the greatest ability to control the growing Pu inventory. In addition to the scenario approach a Monte Carlo uncertainty model was developed and analyzed. The uncertainty analysis showed the high burn up cases are comparable with the of the low CR FR cases in there ability to control the Pu inventory with the Pu inventories ranging from 2500 tons of Pu to 7500 tons of Pu. However, for the high burn up cases the majority of the Pu is Out-Of-Pile as opposed to the FR cases where a considerable amount of the Pu is In-Pile. From a proliferation stand point, the low CR FR case is better at the controlling the Pu inventory because the total inventories are relatively the same for the majority of the runs, and the FR cases keep most of the Pu In-Pile rather than the high burn up cases which keep most of it Out-Of-Pile. Lastly, a brief economic uncertainty model was developed. The economic results show that the once-through cycle is the cheapest with over 50% of the test cases coming in cheaper than all of the FR and MOX cases. The FR cases come out to be the next cheapest with the MOX cases being the most expensive.

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Chapter 1: Introduction

1.1 Fuel Cycle Descriptions

There are several variations of nuclear fuel cycles; however, in real world applications, there are only a couple of different cycles that are currently used or being considered for use. Listed below is the current fuel cycle used in the U.S. and some of the alternatives that are under consideration.

1.1.1 Current Once-Through Cycle

The once-through cycle is the current fuel cycle practiced by the U.S. nuclear industry. In this cycle fuel is used once in a LWR (light water reactor) and is not reprocessed but sent directly into either interim storage or geological storage. Figure 1.1 shows the steps through this cycle. The once-through cycle however, is not really a cycle since it stops at the spent fuel stage.

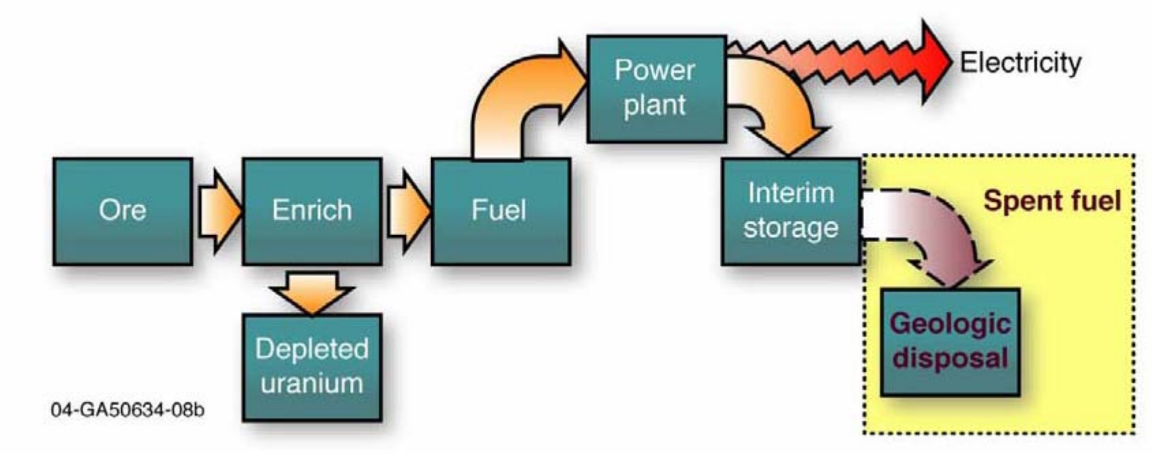


Figure 1.1 Once-Through Fuel Cycle (Taken From Report to Congress: AFCI: Objectives, Approach, and Technology Summary. DOE May 2005)

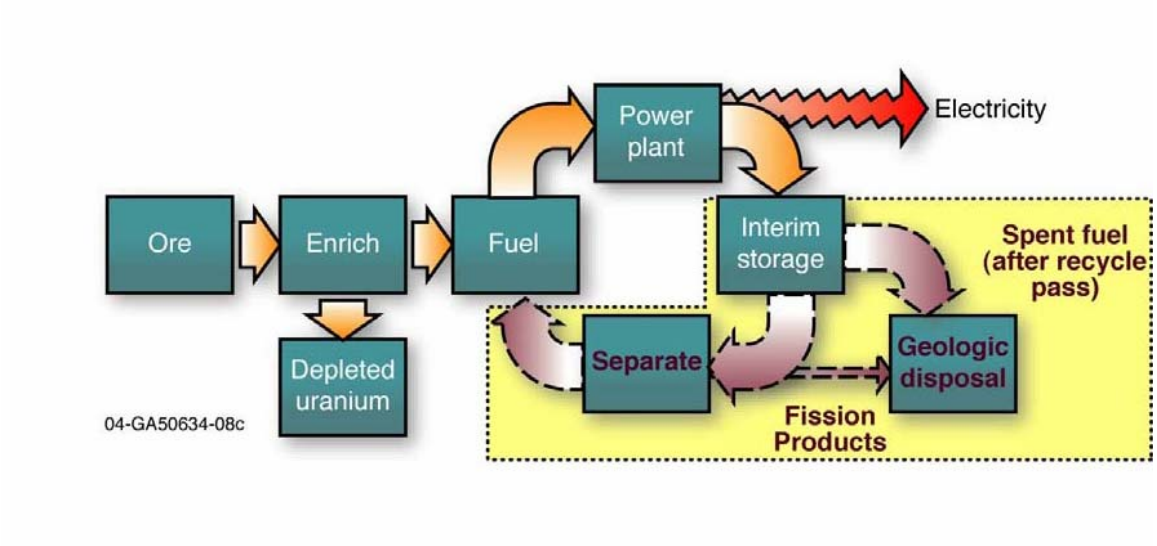


Figure 1.2 Partially Closed Cycle (Taken From Report to Congress: AFCI: Objectives, Approach, and Technology Summary. DOE May 2005)

1.1.2 Partially Closed Cycle

The partially closed fuel cycle is a cycle in which fissile material is recycled from spent fuel and used in thermal reactors as a MOX (mixed oxide) fuel. This cycle is called partially closed because the fuel is only recycled once and then is sent to a repository just as in the open cycle. Figure 1.2 shows the steps involved in a partially closed cycle.

1.1.3 Fully Closed Cycle

The fully closed cycle is a cycle in which spent fuel is recycled continuously and only fission products are disposed in a repository. There are two main types of fully closed fuel cycles; one-tier and two-tier.

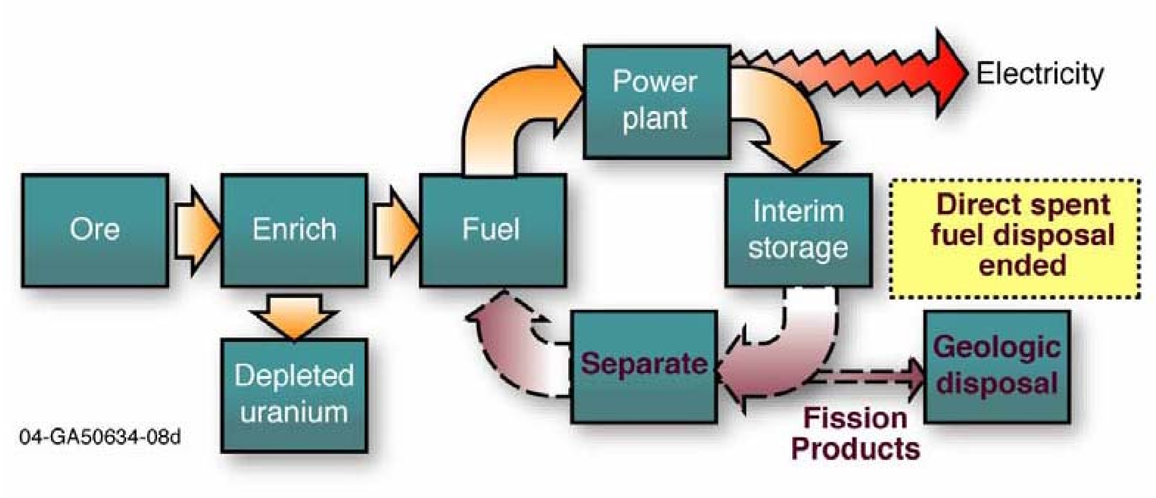


Figure 1.3 Two-Tier Fully Closed Cycle (Taken From Report to Congress: AFCI: Objectives, Approach, and Technology Summary. DOE May 2005)

1.1.3.1 Two-Tier Closed Cycle

In a two-tier closed cycle, LWR fuel is recycled and reused in MOX reactors and more advanced fast reactors. In this instance, this cycle is similar to the partially closed cycle with the addition of a small percentage of fast reactors and is sometimes referred to as a transitional cycle. This transitional cycle is shown in Figure 1.3.

1.1.3.2 One-Tier Closed Cycle

In a one-tier closed cycle approach the same technologies as the two-tier cycle are utilized, but relies on a fleet consisting almost exclusively of fast reactors acting as breeders to create more fissile material than they consume. The fast reactors will burn transuranics as their primary fuel while also transmuting natural or recycled uranium to produce more fuel. In addition to the breeder fast reactors another option exists, to operate the fast reactors as burner reactors in order to destroy actinides such as

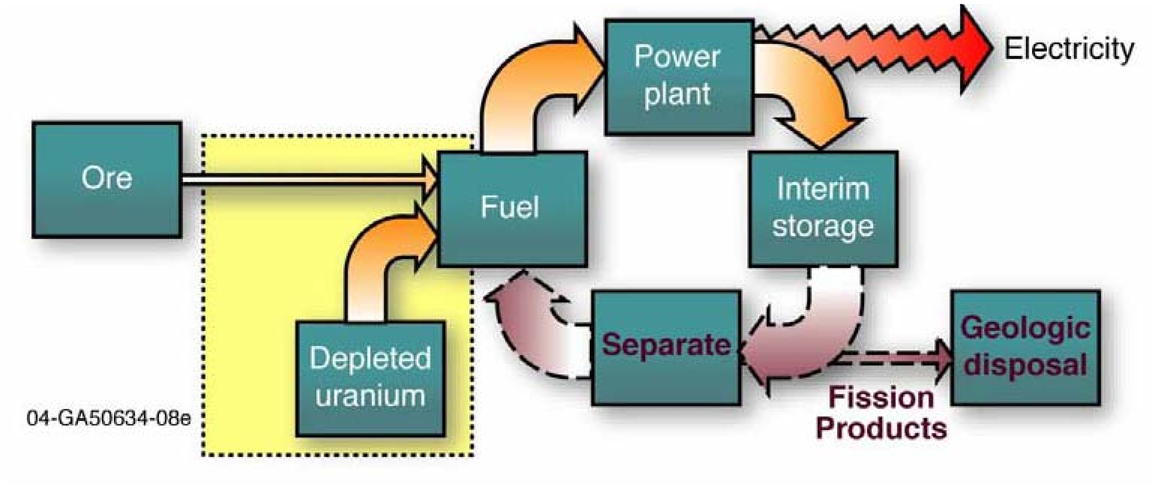


Figure 1.4 One-Tier Fully Closed Cycle (Taken From Report to Congress: AFCI: Objectives, Approach, and Technology Summary. DOE May 2005)

plutonium. This approach is attractive from a nonproliferation stand point. This cycle is shown in Figure 1.4.

1.2 Reactor Replacement

1.2.1 Current Fleet Lifetimes (Licenses)

Nuclear reactors in the United States are licensed and regulated by the NRC (Nuclear Regulatory Commission). The NRC originally licensed all commercial power reactors to an initial 40 years, but also allows for licenses to be renewed and extended. This original 40 years was an arbitrary number that was based on economic and similar industry considerations and was not based on nuclear technology. Some reactors have gone through this renewal process and others are currently going through it. Appendix A contains a list of operating reactors and their license issue and expiration dates. Figure 1.5 shows the current fleet lifetime, i.e. the expiration dates of the current licenses. As can be

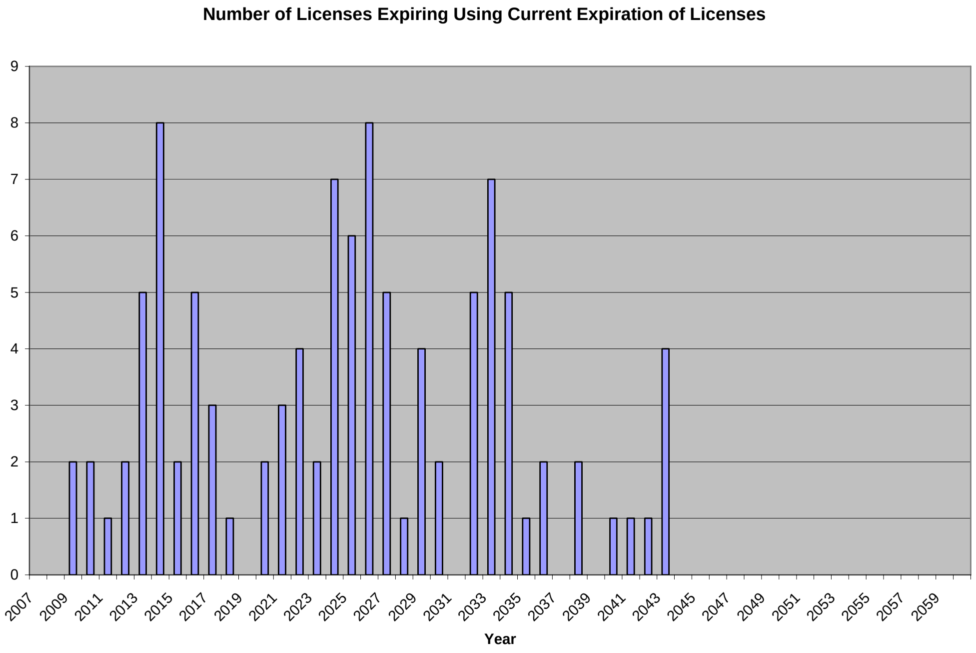


Figure 1.5 Number of Licenses Expiring using the Current Expiration of Licenses

seen in the figure, roughly 10% of the current reactors licenses will expire by the end of 2010 and around 40% by the end of 2015.

1.2.2 Extensions

Currently thirty-nine reactors have already completed the license renewal process and another twelve have applications under review by the NRC. In addition to these reactors, twenty-eight reactors have submitted letters of intent to apply for license renewal. This leaves just twenty-five current reactors that are not currently in the renewal process; however, the NRC believes that the remaining twenty-five will submit letters of intent to extend there licenses sometime in the near future. Figures 1.6 shows the number of licenses expiring per year assuming all that are applying receive extensions and Figure 1.7 shows the number of licenses expiring per year assuming all reactors receive license extensions.

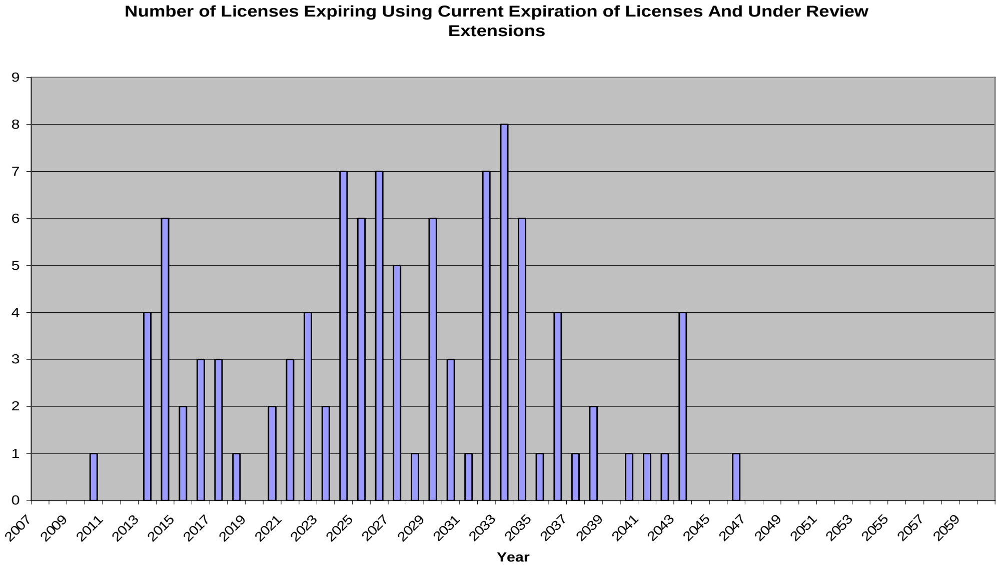


Figure 1.6 Number of Licenses Expiring using the Current Expiration of Licenses and Under Review Extensions

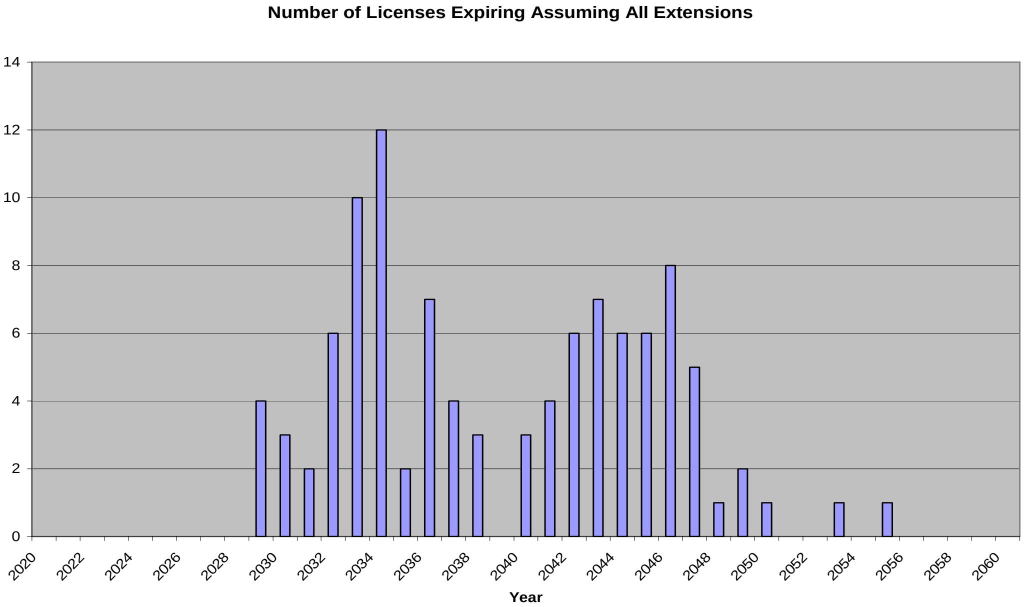


Figure 1.7 Number of Licenses Expiring Assuming all Extensions

1.2.3 Reactor Replacement

Using the data shown in the previous three figures, a scheme for the replacement of these reactors can be produced. Taking a relatively optimistic look at reactor construction and the current political climate, an assumption of a construction time of fours years per reactor is used where the first round of such construction will not start for the next ten years. Using these assumptions the first reactor to be built will not start construction until the year 2016 and will not be complete until 2020. Using the current license expirations, this means that before the first new reactor is under construction twenty-two existing reactors will be shut down.

To develop a strategy for the replacement of these reactors five different linear replacement schemes are examined. They consist of a constant construction tempo using the assumptions of four years per reactor and starting in the year 2016. The different schemes investigated at are for the construction of two, three, four, five, and six reactors per year. Taking into account the shutdown of current reactors and the construction of new reactors using the above schemes, line graphs corresponding to the three license expiration figures can be calculated. These graphs are shown in Figures 1.8, 1.9, and 1.10.

Using the information in the above replacement charts it is easy to see that if maintaining the current level of reactors in the U.S. is a priority an aggressive construction plan for replacing the reactor fleet will be needed. In Figure 1.8, the current shut-down replacement, even with the construction of six reactors per year, will take 15 years to

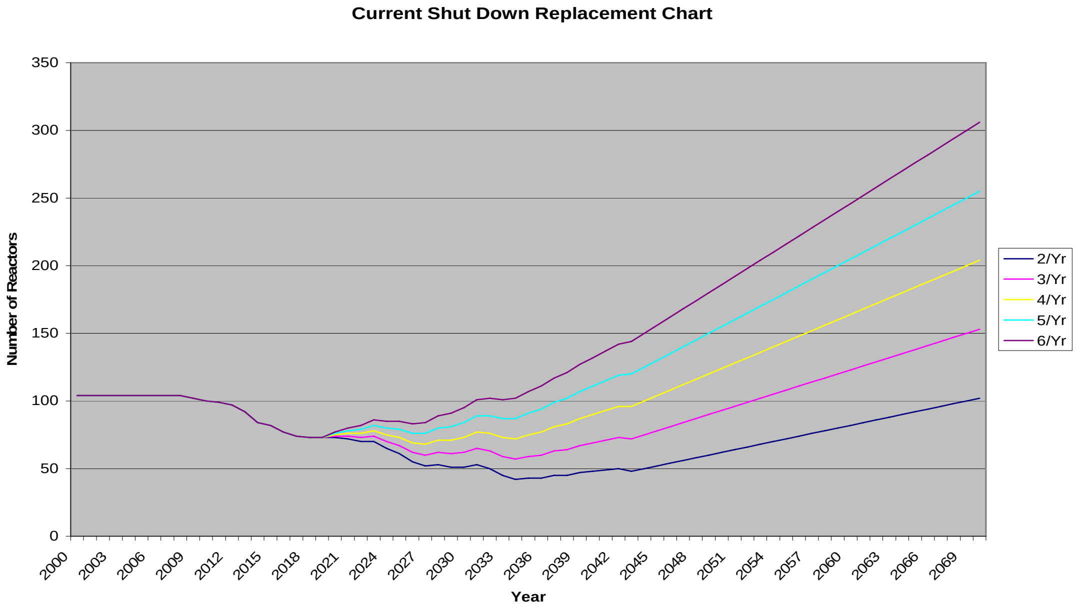


Figure 1.8 Current Shut-down Replacement of Current Reactor Fleet

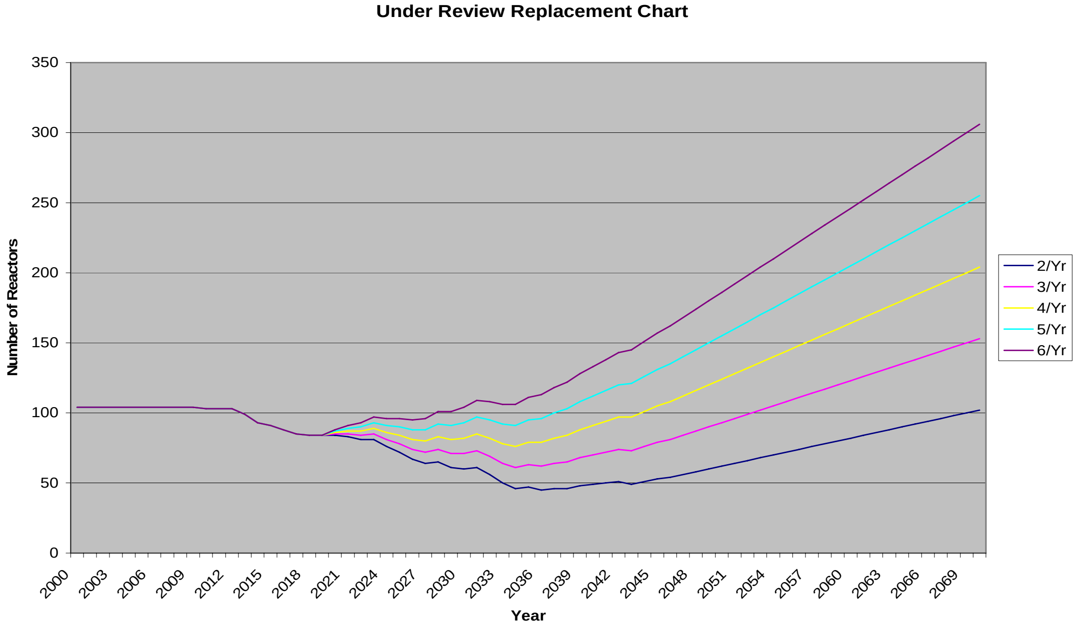


Figure 1.9 Under Review Replacement of Current Reactor Fleet

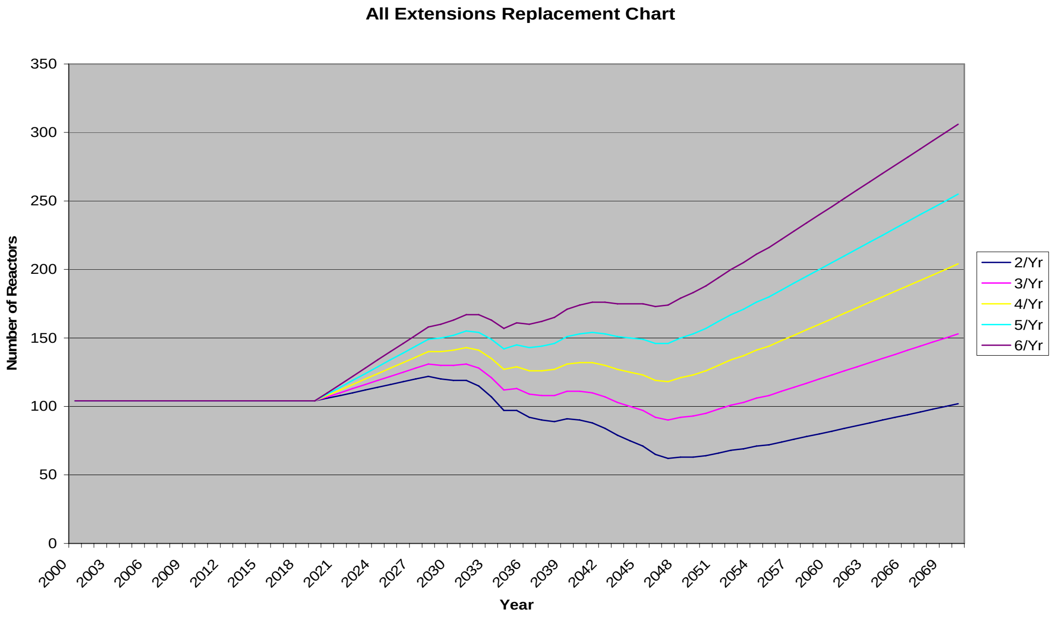


Figure 1.10 All Extensions Replacement of Current Reactor Fleet

bring the number of reactors back to the current level of around 100. In the worst case scenario displayed in Figure 1.8, 30 reactors will need to be replaced in the next 20 years; however, using the more optimistic model, no reactors will be needed for 25 years. In all of the above cases, if one wants to double the number of current reactors to 200 by the year 2100, it will be necessary to average four new reactors per year. Given the number of reactors that were produced between the 1950s and 1990s, this rate of construction should be achievable with enough incentives to build them.

1.3 Previous Work

Prior work focused on the dynamic analyses of several advanced fuel cycles and can be found in "Methodology for Uncertainty Analysis of Advanced Fuel Cycles and Preliminary Results" a thesis by Gary Sweder. Dynamic simulation models were constructed using the DANESS code, which is discussed in more detail in a subsequent chapter. The previous work focused on the modeling of the following advanced fuel cycles:

1. Once-through cycle utilizing high burn up fuels (UOX 60 and UOX 100 GWd/thm)
2. Single MOX recycle
3. Fast Reactors

The study focused on the time of implementation of the above fuel cycles, as well as a general sensitivity and uncertainty analyses of several parameters.

The analysis performed before is primarily a sensitivity analysis; however, it can also be considered a small-scale incremental uncertainty analysis. Mr. Sweder's work presented represents a manual, incremental sampling of a specific input parameter and the resultant distributions of output parameters of interest. The incremental input distribution was placed on the nuclear reactor shutdown profile.

Also several strictly sensitivity analysis were performed in conjunction with this previous work. Sensitivity analysis was performed regarding the input parameters: energy demand and fuel type usage, in conjunction with the incremental input distribution placed on the reactor shutdown profile.

Every fuel cycle scenario modeled in the previous work reduces the total weight of spent fuel and the amount of Pu in the spent fuel when compared to the once through cycle.

Table 1.1 displays the spent fuel total ranges from the simulation models presented in this report. Table 1.2 lists the amount of Pu in the spent fuel. The values in Tables 1.1 and 1.2 have been normalized by the total amount of energy produced by the reactor park in the simulation, i.e. the total electricity produced over the 100-year simulation. Table 1.1 is in units of tons of heavy metal per terawatt-electric. Table 1.2 is in units of tons of Pu in spent fuel per terawatt-electric. The value ranges in the tables are the high and low values at the end of the 100-year simulations. The variance in values is a result of varying the time of implementing the advanced fuels and associated fuel cycle facilities.

In a zero energy growth scenario, the lowest spent fuel totals occur in the reprocessing cases. The "User Defined" MOX scenario has the lowest spent fuel total of the 0% growth cases. Here the spent fuel total is dominated by the fact that there is a reprocessing capacity and some fuel mass is being diverted to the reprocessing plants. However, the high level waste from reprocessing should be considered in order to gain a full understanding of the total amount of waste that would need to go to geological storage.

In the zero energy growth case the advanced fuel cycles utilizing reprocessing show the lowest spent fuel mass values. As energy demand grows there is a change in the trend of spent fuel mass arising. The mass saving of spent fuel is greater in the higher burn up cases than in the MOX fuel cases. This is especially true with UOX100 fuel. From Table 1.1 it can be seen that the UOX100 stands out, especially in scenarios of high-energy demand. The UOX60 and MOX cases are comparable in mass of spent fuel

Table 1.1 Summary Table of Spent Fuel ranges for different fuel cycles in (thm/TWe) From Sweder

Energy Growth	Ref	UOX60	UOX100	MOX, "Automatic"	MOX "User Defined"	FR
0%	3.07	2.56-2.82	1.98-2.62	1.87-1.91	1.37-1.38	1.48-1.54
1.5%	2.87	2.29-2.44	1.61-1.94	2.02-2.04	1.94-1.96	1.73-1.75
3.0%	2.68	2.12-2.19	1.38-1.53	2.16-2.17	2.29-2.30	1.95-1.97

Table 1.2 Summary Table of Pu in spent Fuel ranges for different fuel cycles in (tons Pu /TWe) From Sweder

Energy Growth	Ref	UOX60	UOX100	MOX "Automatic"	MOX "User Defined"	FR
0%	0.036	0.031-0.033	0.027-0.032	0.022-0.023	0.016-0.018	0.019-.020
1.5%	0.033	0.028-0.029	0.023-0.026	0.024-0.025	0.022-0.023	0.022-.023
3.0%	0.031	0.026-0.027	0.021-0.022	0.026-0.026	0.027-0.028	0.023-.024

generated, and the Pu fast burner scenario lies somewhere between the two.

The amount of Pu in the spent fuel, which can be found in Table 1.2, follows similar trends as those seen in Table 1.1. Again in the zero energy growth cases, the lowest values are found in the reprocessing scenarios, with the Pu fast burner being the lowest. As energy demand increases the values in Tables 1.1 and 1.2 for the non-reprocessing cases (UOX60 and UOX100) decrease, while the opposite trend is event in those scenarios that utilize fuel reprocessing.

The values listed in Tables 1.1 and 1.2 provide useful information concerning the amount of heavy metal generated outside the reprocessing loop by the advanced fuel cycles simulated in this thesis. This information is useful when considering the mass of heavy metal being sent to the repository. However, as stated before when comparing scenarios that utilize reprocessing against those that do not, it is important to consider mass flows that are diverted in the reprocessing cycle. Accounting for these considerations yields Tables 1.3 and 1.4. Tables 1.3 and 1.4 have been normalized by the total amount of energy produced by the reactor park in the simulation.

Table 1.3 accounts for the mass of separated uranium found in the reprocessing loop of the fuel cycle. Thus while Table 1.1 accounts only for the heavy metal mass accruing from used fuel destined for the repository, Table 1.3 incorporates the mass of uranium associated with the reprocessing cycle. This yields significantly different values from Table 1.1.

Table 1.3 Summary of Spent Fuel and Separated Uranium ranges for different fuel cycles in (thm/TWe) From Sweder

Energy Growth	Ref	UOX60	UOX100	MOX "Automatic"	MOX "User Defined"	FR
0%	3.07	2.56-2.82	1.98-2.62	2.88-2.90	2.85-2.86	2.80-2.84
1.5%	2.87	2.29-2.44	1.61-1.94	2.71-2.72	2.72-2.73	2.67-2.69
3.0%	2.68	2.12-2.19	1.38-1.53	2.61-2.62	2.63-2.64	2.58-2.60

The same trend, UOX60 and UOX100 values from Table 1.1 to Table 1.3 remain the same due to the fact there is no reprocessing in the cycle. The interesting changes occur in those scenarios that incorporate a reprocessing capacity. The two MOX cases and the fast burner reactor values all increase significantly when the entire amount of heavy metal circulating in the fuel cycle is accounted for; the values between reprocessing and non-reprocessing scenarios in Table 1.3 are not as comparable as those in Table 1.1. In fact, in the 3.0% energy growth case the values of the three reprocessing scenarios are almost double that of the UOX100 value. This can attributed to the importance of high fuel burn up has on spent heavy metal mass.

Comparison of results in Tables 1.2 and 1.4 show similar trends. Table 1.4 accounts for all the Pu out-of-pile, which consists of the Pu in the spent fuel plus the Pu diverted into the reprocessing loop. Table 1.4 now shows that the UOX100 case contains the lowest amount of Pu in the fuel cycle for all energy growths. Also the three reprocessing case

Table 1.4 Summary Table of Pu Out-of-Pile ranges for different fuel cycles in (tons Pu/TWe)

Energy Growth	Ref	UOX60	UOX100	MOX “Automatic"	MOX "User Defined"	FR
0%	0.036	0.031-0.033	0.027-0.032	0.032-0.034	0.032-0.033	0.030-0.032
1.5%	0.033	0.028-0.029	0.023-0.026	0.030-0.031	0.031-0.032	0.028-0.031
3.0%	0.031	0.026-0.027	0.021-0.022	0.028-0.029	0.028-0.029	0.028-0.029

values are now comparable to the UOX60 case, whereas in Table 1.2 they are lower.

It is significant to note that all the advanced fuel scenario values in Tables 1.1-1.4 are less than that of the Same Trend. Thus the mass-flow of heavy metal, which is primarily uranium, and the plutonium specific mass-flow of the advanced fuel cycles is less than that of the projected current industry trends of the once through cycle.

The uncertainty analysis consists of examining the previous figures and the range of spent fuel totals exhibited for each year. Figure 1.11 shows the uncertainty slopes for the individual cases.

What uncertainty slopes means is that beginning in the year 2010 the uncertainty in spent fuel mass follows a linear fit with the slopes in Figure 1.11. This value is obtained by taking the absolute difference between the standard shut down and the standard shut

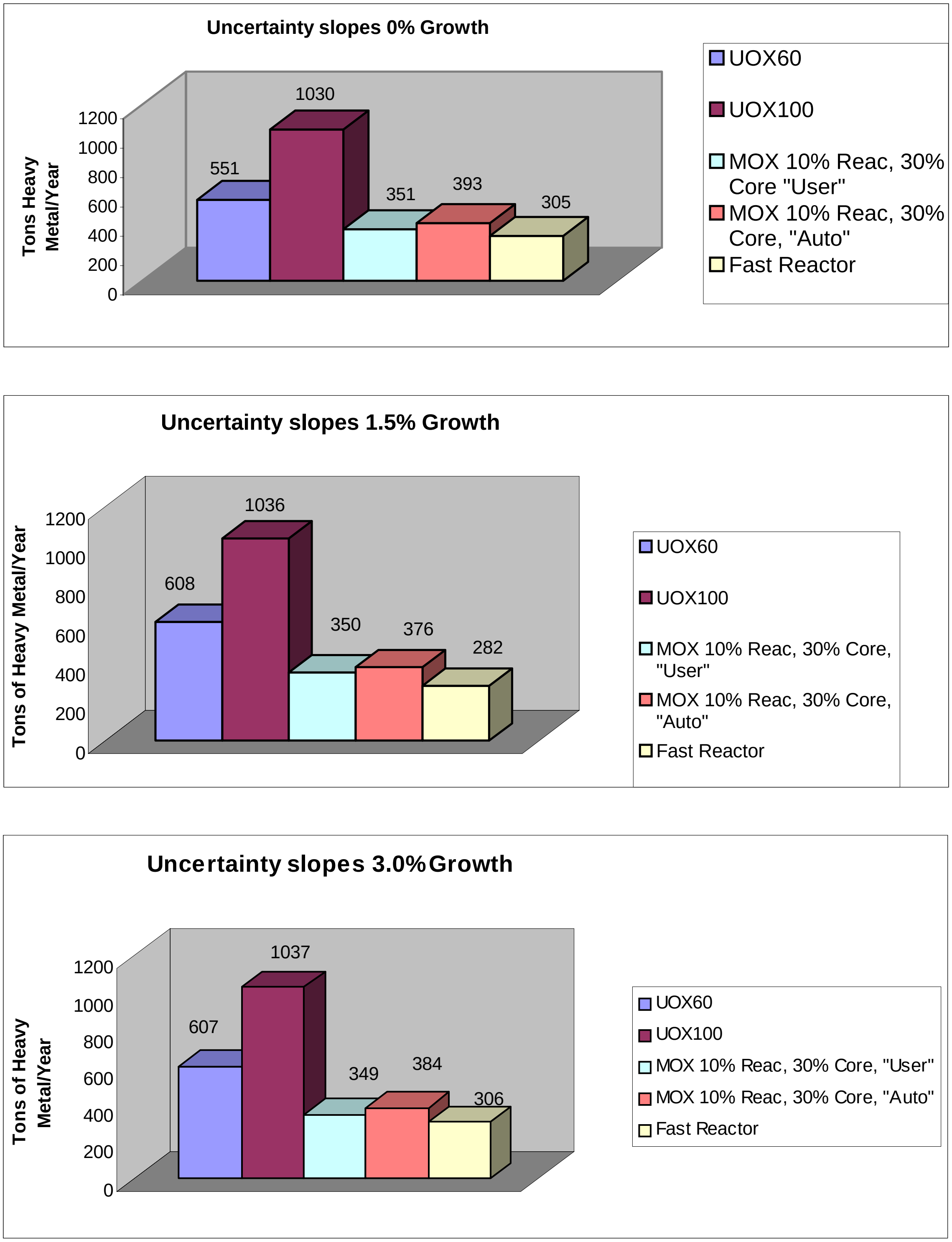


Figure 1.11 Uncertainty Slopes for All Energy Growth Rates in Tons of Heavy Metal per Year

down +50 years, then plotting that difference over time. The slope of that plot is taken as the uncertainty slope. The year 2010 is significant because it is the year energy demand begins.

The slopes are greatest for the burn up cases. This is due to the large discrepancy between the initial and implemented fuel burn-ups. The MOX uncertainty slopes stay relatively consistent, around 350 thm/yr. However, the "Automatic" MOX case has a slightly higher uncertainty slope than "User Defined" due to the changing reprocessing capacity of the model. The fast reactor case has the lowest uncertainty slope value. This may be due to the extremely long in-core time of the fuel. There does not seem to be a correlation between the values in Figure 1.11 and the energy growth rate.

Chapter 2: Methodology

2.1 DANESS- Dynamic Analysis of Nuclear Energy Systems Strategies

Developed by the Nuclear Division of Argonne National Laboratories, DANESS (Dynamic Analysis of Nuclear Energy System Strategies) is an integrated dynamic nuclear process model for analysis of today's and future nuclear energy markets on the fuel batch, reactor, country, and even worldwide scale. Beginning with the current nuclear reactor park and fuel cycle scenario, DANESS will analyze the energy-demand motivated nuclear energy systems over time and accommodates changes in the reactor parks and fuel cycle options as defined by the user. New reactors are introduced based on the energy demand and the economic and technological availability to do so. DANESS is not intended to predict the future of the nuclear market, but instead is intended for projecting and analyzing different nuclear energy paths in a robust and consistent manner. In order to accomplish this task, DANESS encompasses the major aspects of nuclear energy process models, such as:

- Technical Aspects: different reactor types, fuels, and fuel cycle technologies interact in a symbiotic manner
- Economic Aspects: in a competitive energy market, nuclear energy and nuclear technologies must be economically competitive
- Socio-political Aspects: safety, waste management, and non-proliferation are all vital socio-political concerns of nuclear energy and thus are a major aspect of nuclear development

This report focuses heavily on the socio-political aspects of nuclear energy development, especially the concerns of waste management. However all the above aspects receive significant consideration in developing results and conclusions (Van Den Durpel, 2004).

The utility of DANESS is found in nuclear scenario analysis of different possible developmental paths for nuclear energy systems from a governmental, utility, or research and development perspective. Students, professionals, researchers, policy makers can use the program, or anyone interested in situation-based analysis of today's and future nuclear energy systems. The program's intended use is as follows:

- Analysis of exploratory paths for nuclear energy: the impact of new developments in the nuclear reactor park and fuel cycle facilities may be analyzed in an incorporated manner. The impact on the cost, major aspects of the fuel cycle, and the sustainability of a desired industry path may be analyzed.
- Integrated process model: research and design of new nuclear technologies and facilities is a costly endeavor and includes significant amounts of data generated from programs such as DANESS. An integrated process model that includes accurate mathematical modeling of the physics and cost-scaling relationships facilitates the optimization of parameters for the industrial system and the economic feasibility of the system in question.
- Parameter investigation model for new designs: DANESS can assist in examining the influence of key parameters in the complete nuclear system, guide research and development efforts in identifying the major drivers for new technologies, and help analyze the trade-offs between parameters.

- Economic analysis of nuclear energy systems: utilities are continually striving to lower the costs of generating electricity. DANESS can be used to calculate todays as well as future energy cost based on the technical aspects of the plant, the fuel, the fuel cycle, as well as government influence.
- Governmental role: DANESS may be used as a policy advisor for interested governments. Several policy options such as tax rate and price premiums may be examined to analyze the possible policy tools to be used to influence the energy sector.
- Educational Use: the ability to simulate and develop numerous nuclear energy scenarios may facilitate the understanding of nuclear energy systems for students as well as the general public and policy makers (van Durpel, 2004).

This list, of course, may be extended, however it does indicate the major intended uses of the program. This thesis and research work uses the DANESS program primarily for the first three uses bulleted above. Economics and governmental roles were not scrutinized heavily for this thesis.

The DANESS program utilizes the iThink/Stella™ software environment, which is developed by isee™ systems. The iThink/Stella™ software is graphical user interface software that facilitates complex system modeling. It allows the simulation of a system over time and permits the building of sub-models to support hierarchical model structures. The software consists of basic stock and flow diagrams, which support the basic language of systems thinking. Enhanced stock types that allow for discrete or continuous process, action arrows, and decision diamonds allow for complex models such as DANESS to be built. The software easily communicates to the user through input knobs, sliders, switches, and buttons and output graphs and tables. In addition to this graphical user interface there is also a Microsoft Excel user input sheet option that allows a more familiar user of the code more freedom in setting variables.

2.2 Scenario Approach

Fast Reactor Pu Impact

The first set-up examined consisted of inputting the fast reactor data into DANESS, running a contained small reactor fleet of 10 fast burner reactors for 100 years, and examining how much Pu was consumed. The reasoning behind this small exercise is to give a better look at what is happening in the code and to show the effects of just running FRs can have on the Pu inventory and other parameters.

Reference Case

The next set-up was setup for a more realistic viewpoint; however, it still contains some non-realistic in-put parameters. DANESS was set-up with the US LWR fleet of 104 reactors set, with a lifetime of 100 years, in order for them to operate throughout the entire time period. In previous work the LWR fleet has been separated into PWRs and BWRs with varying burn ups; however, for these runs the LWR fleet was lumped into one category using UOX fuel with a 50 GWD/ton burn up. Uranium supply and fuel cycle facility capacities were set to unlimited, in order to eliminate shortages in either of these areas from having any effect on the results. The amount of legacy spent fuel accumulated in the US is around 55,000 tons. This value was used in this set-up. This simple extension of the current US LWR fleet for the next 100 years is set as the reference case for the remainder of runs discussed in this work.

Varied Implementation Year and Number of Reactor Cases

Once this simple reference case was run and data collected, the same set-up was used when adding in fast burner reactors at varying rates and at varying times of implementation. The times of implementation were varied as 2020, 2030, and 2040. The rate of implementation was varied as 1 FR per year, 3 FR per year, and 5 FR per year and reprocessing capacity was set to unlimited, thus assuming enough capacity will be available. For example, in the 2030 implementation year with 3 FR per year rate, the code will run the LWR fleet for the entire time period (present till 2100). Starting in the year 2030 the code will start to build fast reactors at a rate of 3 per year. So, by just varying these two parameters, 9 separate runs are executed. However, these were not the only two parameters varied. The amount of initial spent fuel, i.e. legacy spent fuel, was also varied. This was done in order to vary the amount of Pu available for the start up and continued running of fast burner reactors. Three values were used: the actual amount of spent fuel the US currently has (around 55,000 tons), no initial spent fuel, and infinite initial spent fuel. Hence, varying this parameter as well as the others yields 27 different runs. In addition to these scenarios an additional fast reactor fuel cycle simulation was run. This new run consists of a growing US reactor fleet of mixed LWRs and FRs. This scenario has a mixed growth fleet of LWRs and FRs. The data used for the reactors and there corresponding fuels are the same data used in previous cases shown in Tables 2.1 and 2.2. The DANESS set-up is relatively similar to previous runs with several key differences. The reference case for these runs has reactor growth in it, starting in the year

Table 2.1 LWR Reactor and Fuel Data

Power (Electric)	900 MWe
Thermal Efficiency	34%
Load Factor	90%
Reactor Lifetime	150 Years
Fuel Burn-Up	50 GWd/tHM
Cycle Length	12 Months
Number of Batches	5
Initial Uranium	1 t/tHM
Initial Enrichment	4.7%
Spent Uranium	.93545 t/tHM
Spent Enrichment	.82%
Spent Pu	.012 t/tHM
Spent MA	.00184 t/tHM
Spent Fission Products	.0513 t/tHM

Table 2.2 Fast Reactor with a CR of 0.5 and Fuel Data

Power (Electric)	1500 MWe
Thermal Efficiency	42.425%
Load Factor	76%
Reactor Lifetime	150 Years
Fuel Burn-Up	136 GWd/tHM
Cycle Length	14.6979 Months
Number of Batches	5
Initial Depleted Uranium	.7452 t/tHM
Initial Enrichment	.25%
Initial Pu	.25 t/tHM
Initial MA	.004794 t/tHM
Spent Uranium	.6374 t/tHM
Spent Enrichment	.09844%
Spent Pu	.2148 t/tHM
Spent MA	.009576 t/tHM
Spent Np	.0005577 t/tHM
Spent Am	.007231 t/tHM
Spent Cm	.001788 t/tHM
Spent Fission Products	.1381 t/tHM

2020, the reference case implements 8 new LWRs per year. The subsequent runs also implement 8 new Rx per year, as does the reference except they implement 6 LWRs and 2 FRs per year instead of the 8 LWRs. Again as done in previous cases, the reprocessing capacity is set to unlimited, all of the LWR and FR fuel is reprocessed, the base fleet is set to be the current 100 LWRs, legacy spent fuel is not varied and is set at the current level of 55,000tHM, and time of implementation is varied from 2020 to 2030 to 2040. The following tables give the values used for the LWR and FR reactors in DANESS.

Varied Fast Reactor Conversion Ratio Cases

The scenarios discussed above where then expanded upon in order to yield a better overall assessment of the impact of FRs, specifically focusing on type of FR fuel, metal or oxide, and CR ranging from 0.0, 0.25, 0.5, 0.75, and 1.0. These changes are accomplished by using data from Argonne National Lab and inputting the data into DANESS for the various FR fuel and CR types. The set-up for the DANESS runs done for these more in-depth FR scenarios are as follows: 3000tHM/yr reprocessing capacity online in the year 2010, constant LWR fleet of 105 reactors, a growing fleet of FRs implemented at the year 2030 stated at the rate of 3 Rx/Yr, initial legacy spent fuel is set at the actual amount (55,000 tHM). For the FRs the type of fuel is varied between metal and oxide and for each type there are 5 CRs looked at. The data for these fuel types and CRs is listed below in Table 2.3 and 2.4.

Mixed LWR and FR Growth Case

In addition to the runs performed with solely FR growth, runs were also performed utilizing a mixed growth reactor fleet of both LWR and FRs. The setup was handled in

Table 2.3 Metal Fuels: Reactor and Fuel Data

Metal Fuels					
Rx					
Unit Power(Mwe)	1500	1500	1500	1500	1500
Thermal Eff(%)	42.425	42.425	42.425	42.425	42.425
Average Conversion Factor	90	90	90	90	90
Cycle Length [months]	15	15	15	15	15
Number of Batches [#]	5	5	5	5	5
Fuel					
CR	0	0.25	0.5	0.75	1
BU [GWd/tHM]	294	172	132	100	73
Initial DU [t/tHM]	0.22193	0.542	0.7041	0.793	0.8462
Initial Enrichment 235U [%]	0.21	0.2	0.2	0.2	0.2
Initial Pu [t/tHM]	0.6984	0.4103	0.26463	0.18443	0.13666
Initial MA [t/tHM]	0.00055	0.001204	0.001284	0.001669	0.001659
Initial Np [t/tHM]	0.03672	0.021579	0.013916	0.009702	0.007185
Initial Am [t/t/IHM]	0.03792	0.022282	0.014371	0.010015	0.007419
Initial Cm [t/tHM]	0.00448	0.002635	0.001699	0.001184	0.000877
Spent U [t/tHM]	0.19286	0.4805	0.6221	0.7074	0.77038
Spent Enrichment 235U [%]	0.12	0.1	0.09	0.1	0.11
Spent Pu [t/tHM]	0.43271	0.30025	0.21222	0.1686	0.13836
Spent MA [t/tHM]	0.0323	0.008986	0.005822	0.003567	0.002452
Spent Np [t/tHM]	0.01619	0.011617	0.00731	0.005456	0.00464
Spent Am [t/tHM]	0.03234	0.020151	0.01308	0.009435	0.007334
Spent Cm [t/tHM]	0.00988	0.005167	0.003345	0.002257	0.001517
Spent FP [t/tHM]	0.28372	0.16562	0.13005	0.09867	0.071948

Table 2.4 Oxide Fuels: Reactor and Fuel Data

Oxide Fuels					
Rx					
Unit Power(Mwe)	1500	1500	1500	1500	1500
Thermal Eff(%)	42.425	42.425	42.425	42.425	42.425
Average Conversion Factor	90	90	90	90	90
Cycle Length [months]	15	15	15	15	15
Number of Batches [#]	5	5	5	5	5
Fuel					
CR	0	0.25	0.5	0.75	1
BU [GWd/tHM]	294	229	166	131	103
Initial DU [t/tHM]	0.21948	0.50261	0.6673	0.7629	0.8221
Initial Enrichment 235U [%]	0.21	0.2	0.2	0.2	0.2
Initial Pu [t/tHM]	0.7006	0.4458	0.29776	0.21158	0.15829
Initial MA [t/tHM]	0.00052	0.001073	0.001203	0.001542	0.001667
Initial Np [t/tHM]	0.03686	0.023448	0.01566	0.011129	0.008328
Initial Am [t/t/IHM]	0.03804	0.024206	0.016165	0.01149	0.008599
Initial Cm [t/tHM]	0.0045	0.002863	0.001912	0.001359	0.001017
Spent U [t/tHM]	0.18349	0.41617	0.5655	0.6522	0.71211
Spent Enrichment 235U [%]	0.13	0.08	0.08	0.08	0.08
Spent Pu [t/tHM]	0.44154	0.29878	0.23123	0.18888	0.16279
Spent MA [t/tHM]	0.01924	0.013001	0.007464	0.00483	0.002977
Spent Np [t/tHM]	0.0153	0.008748	0.006481	0.004964	0.004032
Spent Am [t/tHM]	0.03226	0.020732	0.014768	0.010962	0.008526
Spent Cm [t/tHM]	0.01051	0.006907	0.004324	0.002941	0.00214
Spent FP [t/tHM]	0.28446	0.22518	0.16266	0.1292	0.10264

the same manner as before except, starting in 2030 the new reactors constructed consisted of 2 LWRs and 2 FRs. The LWR data was kept the same as before and the FRs used both the metal and oxide fuel with all five CRs.

2.3 Uncertainty Analysis for Dynamic Fuel Cycle Scenarios

In addition to the scenario approach described above a true uncertainty analysis is needed. For this the uncertainty capabilities inside DANESS are utilized to model various fuel cycle options and obtain monte carlo uncertainties. DANESS offers a multitude of input parameter options. Through literature and expert solicitation a sample of eight of these parameters were selected to be monte carlo sampled. These eight parameters were chosen because of there importance to the overall fuel cycle scheme. The parameters selected were given triangular distributions according to the following tables below (2.5, 2.6 and 2.7) for each scenario analyzed.

The range of values for the uncertainty input variables were not chosen randomly. Each variable was researched in order to give as realistic a distribution as possible. The growth rate for the LWRs is set from zero to seven with the nominal value at three reactors per year. This is based on historical data taken during the booming construction of the late sixties and all throughout the seventies it is not unthinkable to believe that this accelerated rate could be again obtained if the need is there.

The growth rate for the FRs is a little more subjective and required a more in depth search since historical data for these types of reactors does not exist. Taking into account

Table 2.5 Input Variables, Ranges, and Nominal Values: FR Implementation

Input Variable	Range	Nominal Value
Growth rate of reactors LWRs	0 to 7	3
Growth rate of reactors FRs	0 to 3	2
SF At-Rx Cooling Time	1 to 10	3
SF Interim Cooling Time	1 to 10	3
Year of Implementation of New LWR Construction	2015 to 2050	2030
Year of Implementation Reprocessing	2015 to 2030	2020
Year of Implementation of New FR Construction	2030 to 2060	2040
LWR Burn up	40 to 70	50
FR Burn up	80 to 200	120

Table 2.6 Input Variables, Ranges, and Nominal Values: MOX Rx Implementation

Input Variable	Range	Nominal Value
Growth rate of reactors LWRs	0 to 7	3
Growth rate of reactors MOX	0 to 3	2
SF At-Rx Cooling Time	1 to 10	3
SF Interim Cooling Time	1 to 10	3
Year of Implementation of New LWR Construction	2015 to 2050	2030
Year of Implementation Reprocessing	2015 to 2030	2020
Year of Implementation of New MOX Construction	2030 to 2060	2040
LWR Burn up	40 to 70	50
MOX Burn up	40 to 70	50

Table 2.7 Input Variables, Ranges, and Nominal Values: High Burn up LWR Implementation

Input Variable	Range	Nominal Value
Growth rate of reactors LWRs	0 to 7	3
Growth rate of reactors High Burn up LWRs	0 to 3	2
SF At-Rx Cooling Time	1 to 10	3
SF Interim Cooling Time	1 to 10	3
Year of Implementation of New LWR Construction	2015 to 2050	2030
Year of Implementation of New High Burn up LWR Construction	2030 to 2060	2040
LWR Burn up	40 to 70	50
LWR High Burn up	75 to 100	87.5

the increased initial cost and the unfamiliarity with this type of reactor construction, a considerable reduction in the building capacity of FRs, zero to three, is seen as compared to that of the LWRs, zero to seven. However, the nominal value for the FRs is only one lower at two per year than that of the LWRs at three per year. This is due to the assumed need for an aggressive construction strategy not only to keep up with current power production levels but to expand power production to meet ever increasing needs. The rate for the implementation of the MOX reactors and high burn up reactors is set as the same value as the one used for the FRs. This is due to similar concerns as the FRs and also so that the results can be easily compared.

The ranges for the two cooling time variables should be a simple matter of looking up how long spent fuel is kept at a reactor and cooled, and how long it is kept in interim storage; however, since there is currently no open repository or a operating reprocessing facility in the U.S. these become more problematic variables. Originally the idea was that spent fuel would be stored on-site at reactors in wet storage for a minimum of two years and a maximum of five years and then would be sent to a reprocessing facility or taken control of by the government and stored. This all changed when the U.S. decided not to reprocess spent fuel, instead opting for storage in a repository. This decision changed the amount of time that spent fuel would be stored at a reactor and introduced the need for interim storage. This provides for the reasoning behind the ranges of the cooling times to be between one and ten years. The nominal values were chosen as three years each for a total of six years of cooling as an attempt to stay true to the original thinking of five years of storage and adding an additional year due to the increased burn up of LWR fuel needing a little additional time to cool.

The variable Year of Implementation of New LWR Construction takes a very conservative look at new LWR reactor construction. The lower bound is set at the year 2015, which would have the construction of new reactors starting in the year 2010 assuming a five year construction time, and the upper bound set at the year 2050 with a very conservative nominal value set at the year 2030. The lower bound allows for the expansion of the LWR fleet in an attempt to keep up with current growths in energy demand. The upper bound would symbolize a reduction in the need for nuclear power and most likely would not even be able to account for current energy demand. And the nominal value represents an attempt to keep the fleet at current energy production and just replace old shutting down reactors with new ones.

The driving force of this research is to look into advanced fuel cycles; therefore, it becomes necessary to implement the use of a reprocessing facility in order to use LWR spent fuel again in the FRs or MOX reactors. This is the main influence on the range of Year of Implementation of Reprocessing variable. The lower bound is set to a very optimistic year of 2015, this representing the absolute earliest that a reprocessing plant could realistically be built in the US. The upper bound is perhaps to some another optimistic year of 2030, this year was chosen in order to allow for FRs and MOX reactors to start to be built in that same year. The nominal value is set at the year 2020, this value coincides with the thought that the US will need to have a better long term view for the control of spent fuel and before any utilities would likely build a FR or MOX reactor they would need to be certain that there will be fuel for them.

The construction of new advanced reactors: FR, MOX, and high burn up LWRs; distribution is set in a way as to assume that as some of the older LWRs begin to shut down they will be replaced with the advanced reactors. Thus the lower bound is set to the year 2030 accounting for the beginning of the decade of considerable LWRs end of life time frame. The upper bound is set to the year 2060, roughly after all of the old LWRs will be shut down. And the nominal value is set at the year 2040 to allow for some LWRs to be shut down and replaced with new LWRs, before advanced reactor construction begins.

The burn up variables are given distributions given the best data available. The LWR burn up ranges coincide with relatively standard values in the 40-50 GWd/ton to more advanced burn ups in the 70 GWd/ton range. Some research suggest that burn ups ranging all the way up to 100 GWd/ton could be possible; however, most literature suggests that this high value is impractical and thus is considered to be the extreme end of high burn up distribution. The FR burn up range is taken from the GE research into the Super Prism. Most of there research puts the burn up between the 80-200 GWd/ton range seen here with the most likely conversion ratio burner reactor having a burn up close to 120 GWd/ton. The distribution of the MOX reactor burn ups is set to the same as that of the LWR burn up. This is due to the fact that MOX fuel will most likely follow the same burn up trends that the UOX LWR fuel will follow. The distribution of the high burn up LWR fuel is set as an extremely high value burn up for an LWR ranging between 75 and 100 GWd/ton. This distribution is stretching the extreme limits of what is considered to be feasible for LWR burn ups; however, research in this range is ongoing, thus it is included in this work.

In an attempt to define distributions for various values in the fuel cycle for the dynamic uncertainty study and the economic one, literature studies were conducted and an expert elicitation survey was drawn up to survey experts in the nuclear field. The survey consisted of 27 multiple choice questions designed to aid in our research that ranged from expected times of implementation of advanced reactors to economics of those advanced fuel cycles. The survey was distributed to top experts in the nuclear field around the country and 17 such surveys were completed. The questions and there corresponding percentage of responses are included in Appendix B.

The respondents answers seem to correspond relatively well with our literature research and those that have been used thus far while conducting the work. The vast majority of respondents seem to agree on the time of implementation of new reactors needs to be soon, 94% say by the year 2010, and 76% say that this will happen. When asked about how many reactors will be constructed per year the range is closely correlated to the values used in this work; 44% say 1 Rx/yr, 38% say 3 Rx/yr, and 13% say 7 Rx/yr. This is almost exactly the distribution assigned to new LWR growth for the uncertainty analysis. As for the burn up of the LWR fuel, 100% of respondents say that within the next 20yrs we will see burn ups of between 50-75 GWd/ton. Again this is spot on for the distribution of burn ups used. And 38% say we could see 90 GWd/ton burn ups. This is slightly lower than the high burn up value used. Such consensus seems to break down when we get to the economic questions. This is most likely because the economics of advanced fuel cycles is not widely known or studied and thus may not be uniformly considered through out the nuclear community.

Triangular distributions were chosen for these distributions because of its simplicity and data correlation. The distributions were implemented by the use of a simple MatLab script. This method was used for each variable in the above tables and a list of one hundred input values for each variable were calculated for each scenario.

2.4 Economic Uncertainty

In order to truly consider implementing any advanced fuel cycle, the cost of doing so will inevitably become a concern. Therefore, included in this work is a preliminary economic overview of the fuel cycles considered and some uncertainty economic results. The initial economic data are found using the GNEP Excel code G4ECONS, developed by Kent Williams at ORNL, which evaluates equilibrium scenarios from an economic point of view. This code is supplemented by the coupling of the @RISK code, which allows us to extract uncertainties from the G4ECONS code.

The @RISK software allows the use of the same monte carlo sampling done in DANESS by assigning distributions to cell values rather than constant numbers and then simulating the entire spreadsheet 100 times. This yields data that can be plotted in CDFs as with the fuel cycle uncertainty work to compare uncertainties between different scenarios. An example flow diagram from the G4ECONS code for a totally closed fuel cycle is shown below in Figure 2.1.

As with DANESS, G4ECONS has numerous input parameters that can be monte carlo sampled. In this instance the input parameters of interest are more concrete and distributions are readily available in the “Advanced Fuel Cycle Cost Basis” report from Idaho National Labs, prepared for the Department of Energy. Using this document and the distribution functionality in @RISK, distributions are defined for several parameters inside the G4ECONS code. Table 2.8 shows an example of these parameters and there distributions for the open fuel cycle scenario. Appendix C contains distribution tables used in the G4ECONS code.

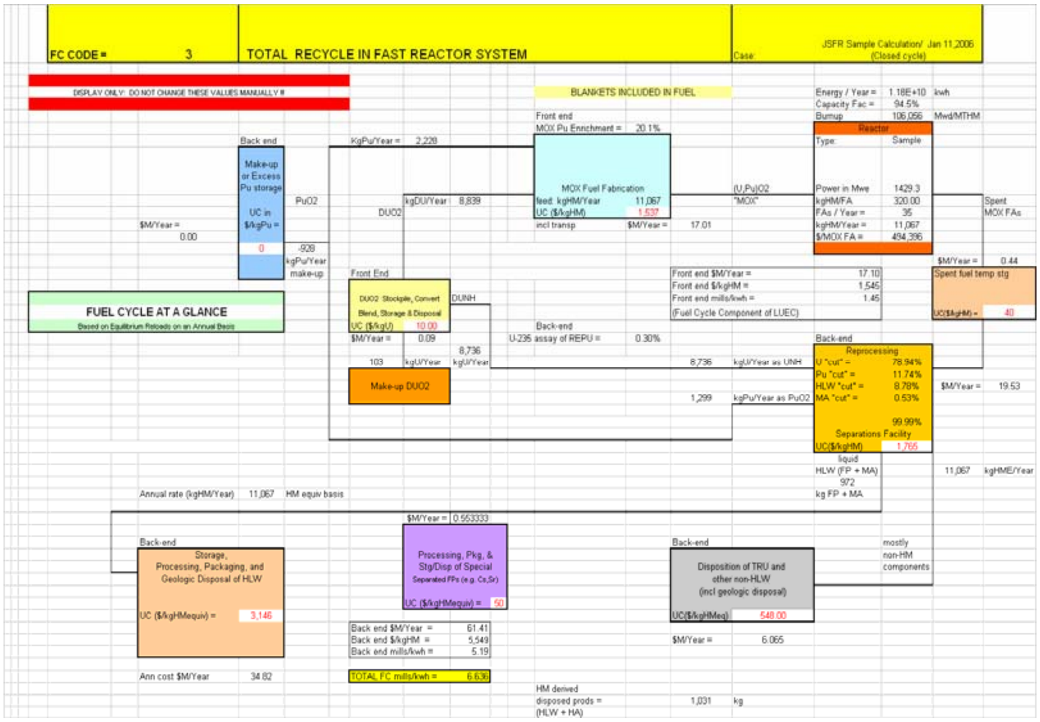


Figure 2.1 Example Flow Diagram from G4ECONS code for Totally Closed Fuel Cycle

Table 2.8 Parameter Distributions for LWR Open Cycle

Input	Minimum	Maximum	Nominal
Reactor Average Capacity Factor over Life	0.74	0.97	0.87
Thermal Efficiency	0.31	0.34	0.33
Plant Economic and Operational Life	36.02	70.19	47.80
Years to Construct (up to 10 years allowed)	3.69	8.06	5.17
Real discount rate for Interest during Construction & Amortization	0.03	0.09	0.05
Estimated D&D cost for Reactor at end-of-life	274.96	939.33	533.14
Capital replacements as a % of direct capital	0.01	0.02	0.01
Contingency on non-fuel O&M cost	12.23	94.17	48.32
Required U-enrichment level for virgin EU reactor fuel (initial [first] core average)	0.03	0.03	0.03
Required U-enrichment level for virgin EU reactor fuel (reload average)	0.04	0.04	0.04
Uranium Ore (Mining and Milling U3O8)	12.49	75.89	42.66
Oxide to UF6 conversion (natural or virgin EU)	5.21	14.39	10.00

Chapter 3: Results

3.1 Reference Cases

The first data inspected were the out-put from the 10 FR case. This case was run using 10 fast reactors with a CR of 0.5 running for the duration of the time period, i.e. until the year 2100. The main area of focus for this run was to examine the impact that the 10 FRs had on the overall Pu inventory. As stated before the initial amount of Pu was set by inputting the actual amount of legacy spent fuel (55,000 tHM) in the U.S. at present and allowing it to be reprocessed. The results are shown below in Figure 3.1. Figure 3.1 shows a decrease in total Pu inventory of 253 tHM. This illustrates that just 10 FRs, with conversion ratios of 0.5, can burn up 253 tons of Pu in 100 years. This is very important if one is looking for ways to control the Pu inventory inside the US for political or proliferation reasons.

Next, data from the reference case were taken and examined. The Pu inventory obviously continues to grow at a constant rate from the initial amount of 720 tHM to 2920 tHM and is used as an excellent benchmark for the remainder of cases examined. Figure 3.2 below shows the Pu inventory for the reference case.

3.2 Time of Implementation Scenarios

<u>2020 Implementation Case</u>

After the reference case the 2020 implementation data were examined. These runs yield more interesting data and are more complicated to observe and analyze. With the

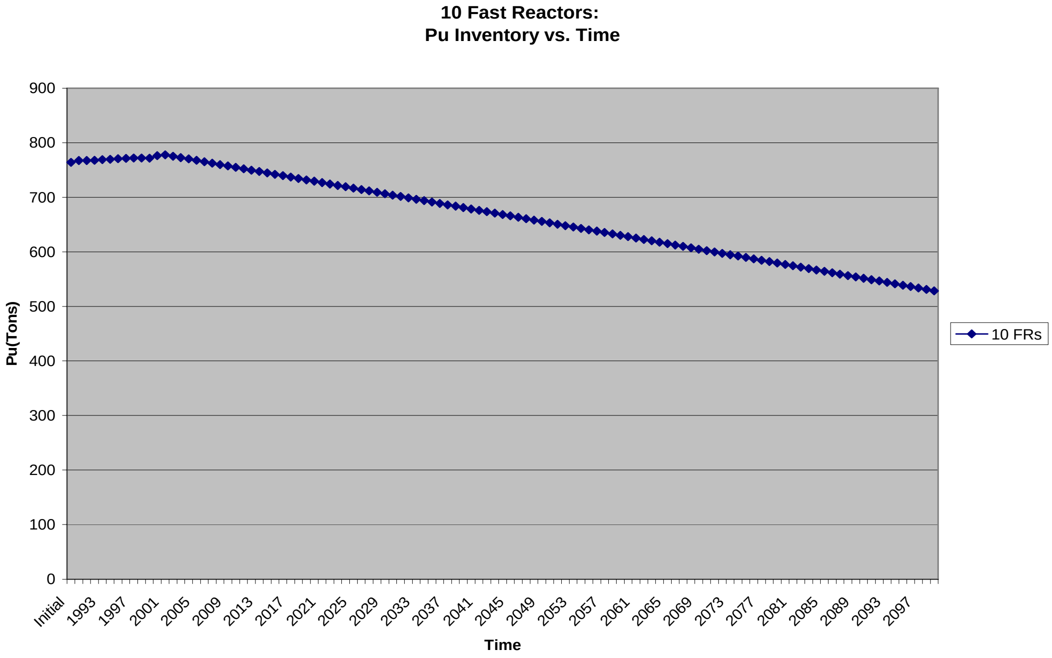


Figure 3.1 10 FR: Total Amount of Pu vs. Time: Run to see Effect of FRs on Pu Inventory

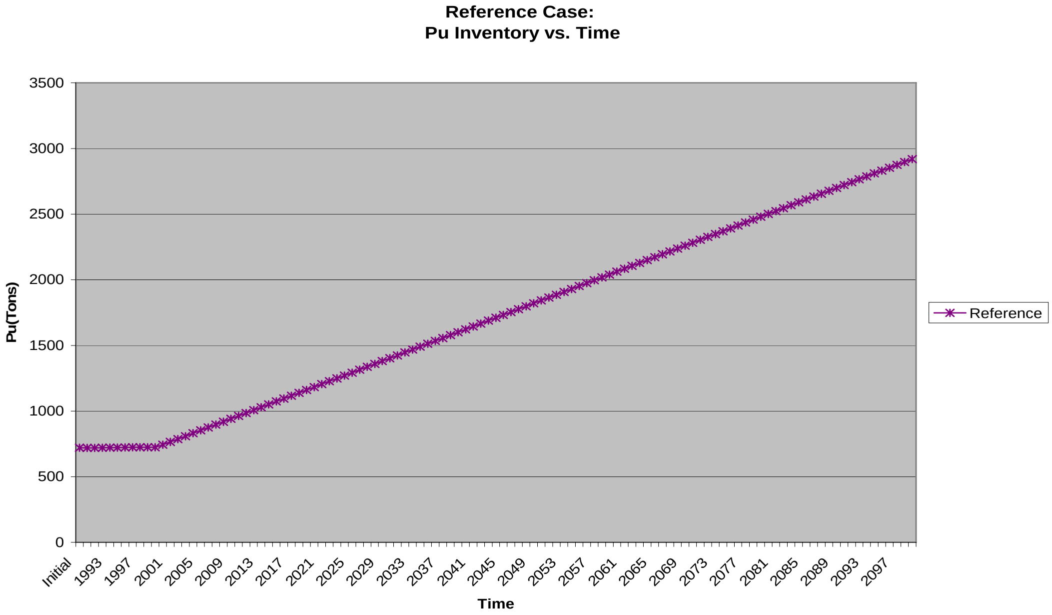


Figure 3.2 Reference: Total Amount of Pu vs. Time

implementation scheme presented before, 9 separate runs are carried out for the 2020 implementation separated into 3 subsets consisting of 3 runs apiece. These subsets are characterized by the initial amount of spent fuel (i.e. initial Pu) used in the code. First the no initial Pu data will be examined, followed by the actual initial Pu data, then the infinite initial Pu, ending with a discussion comparing all three subsets. This analysis of results will be repeated for the other two implementation schemes as well.

Figure 3.3 below characterizes the Pu inventory for the 2020 implementation with no initial Pu inventory and Figure 3.4 is a corresponding figure showing the number of FRs built.

In Figure 3.3 a dip in the Pu inventory is observed around the year 2025. This dip characterizes the initial fuel loading of the FRs that are coming online in the fleet and correlates with the FR production in Figure 3.4. The dip is more pronounced for the 5FR/yr case than for the 1FR/yr case since more FRs are being loaded in the 5FR/yr case. This dip is then followed by a steady climb in the Pu inventory for the 5FR and 3FR cases. This climb corresponds to the steep rise in FRs in Figure 3.4. The reason this steep climb in Pu is not observed for the 1FR case is because of the slow and steady production rate in Figure 3.4. Now as seen in Figure 3.4, there is a point where FRs cease to be built. This point corresponds to the decreased slope section in Figure 3.3. The reason for the halt in construction of new FRs has to deal with a parameter inside of the DANESS code that requires a type of fuel reserve. The code saves fuel for each reactor built for the next 15 years unless that reactor is going to be shut down and since for these scenarios all

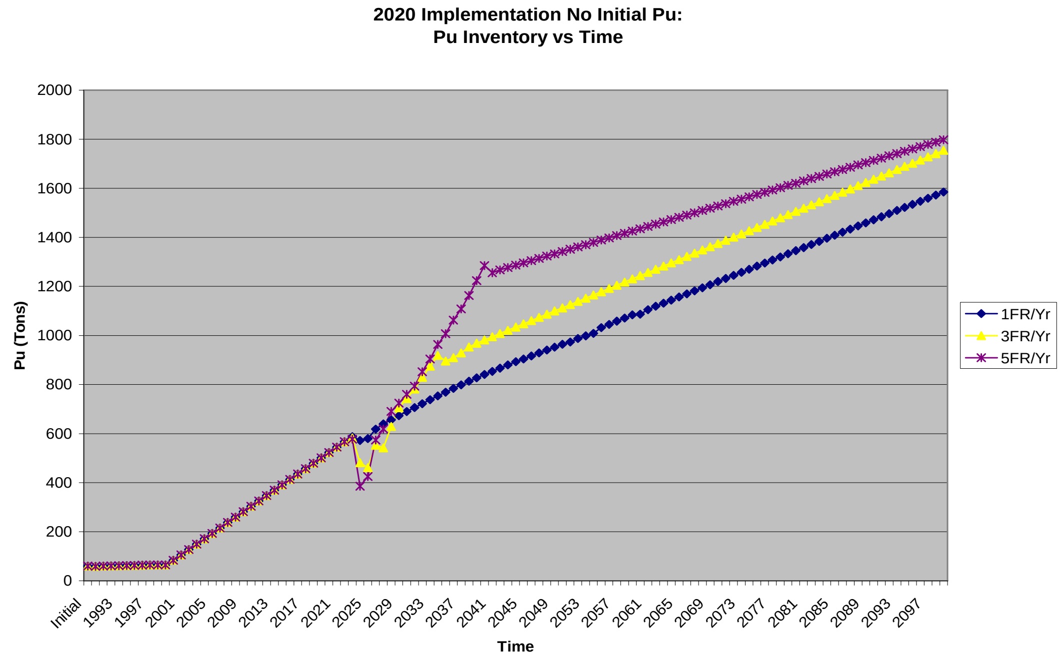


Figure 3.3 2020 Implementation No Initial Pu: Total Amount of Pu vs. Time

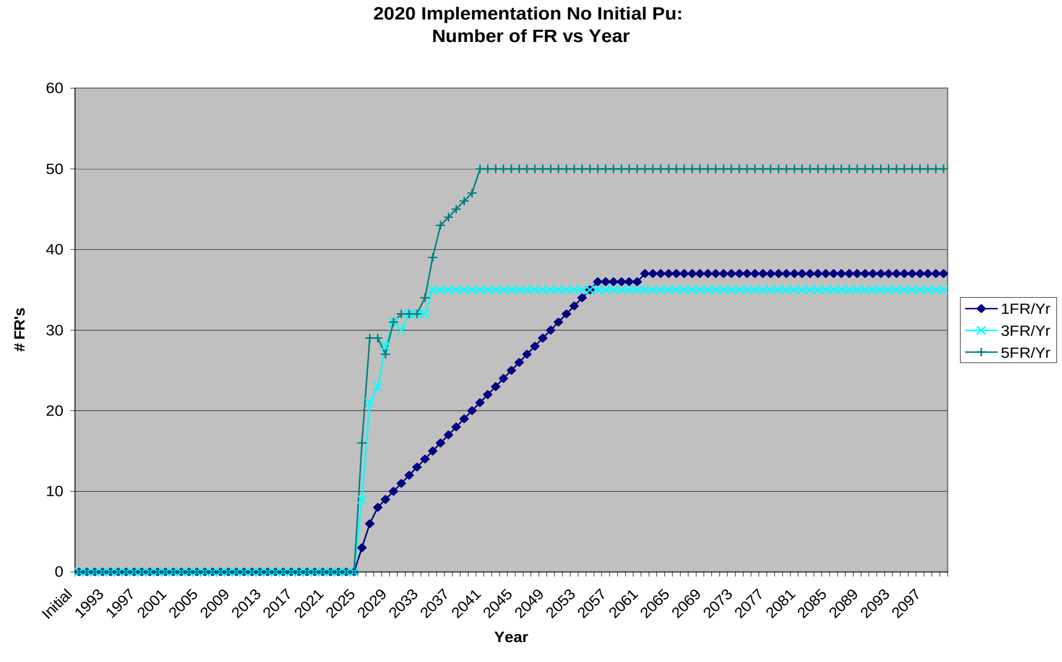


Figure 3.4 2020 Implementation No Initial Pu: Number of FRs vs. Time

of the reactors are to operate for the entire time period no reactors are shut down and a fuel saving issue arises. This issue continues to be prevalent in the discussion of the results and will be referred to again. The way that the FRs are reducing the total Pu inventory can be easily shown using a little algebra by comparing the slopes of the Pu growth before the implementation of the FRs and then after the volatile construction period is over. Table 3.1 below compares these slopes.

These slopes show the long term value of implementing FRs to curtail Pu buildup over a long period of time. As can be seen in the table, the initial slope is 21.98, which corresponds to roughly a growth of 22 tons of Pu per year, and with the 5FR/yr scenario this is reduced by more than half to around 9 tons of Pu per year.

Figures 3.5 and 3.6 are plots of the Pu inventory and number of FRs respectively corresponding to the 2020 implementation with actual amount of initial Pu.

For these sets of data the initial amount of Pu used was the actual value available here in the US. As can be seen in Figure 3.6 a smoother production line can be observed; however, the same limitations arise as before with the fuel saving causing a cap in the

Table 3.1 2020 Implementation No Initial Pu: Slopes of Pu Inventory Curves

	Initial Slope	End Slope
	Tons Pu / Year	
1FR/Yr	21.98	12.59
3FR/Yr	21.98	13.10
5FR/Yr	21.98	9.29

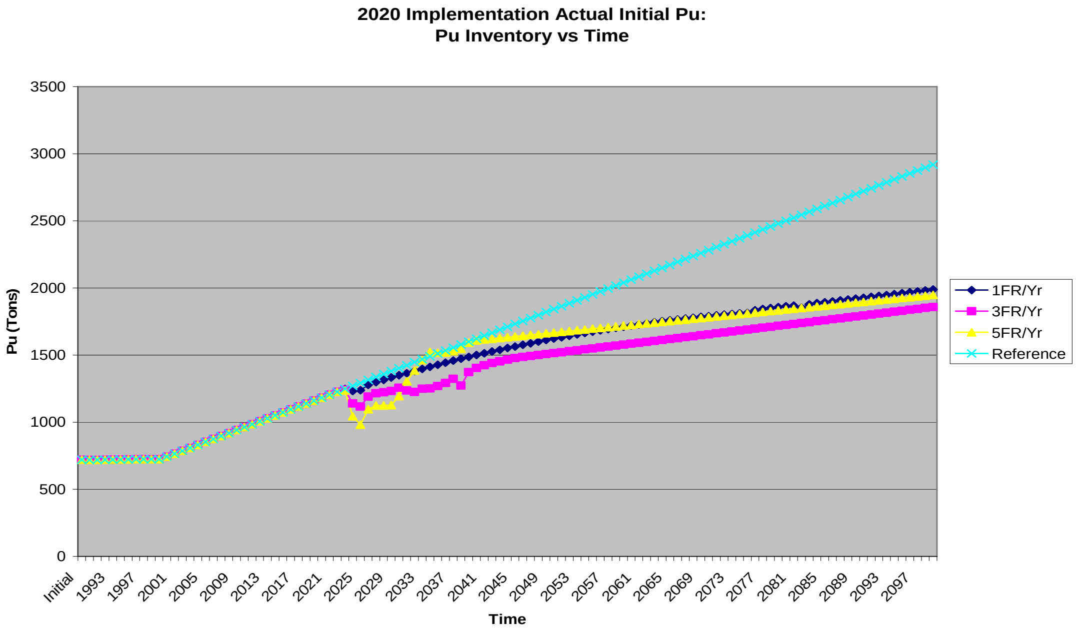


Figure 3.5 2020 Implementation Actual Initial Pu: Pu Inventory vs. Time

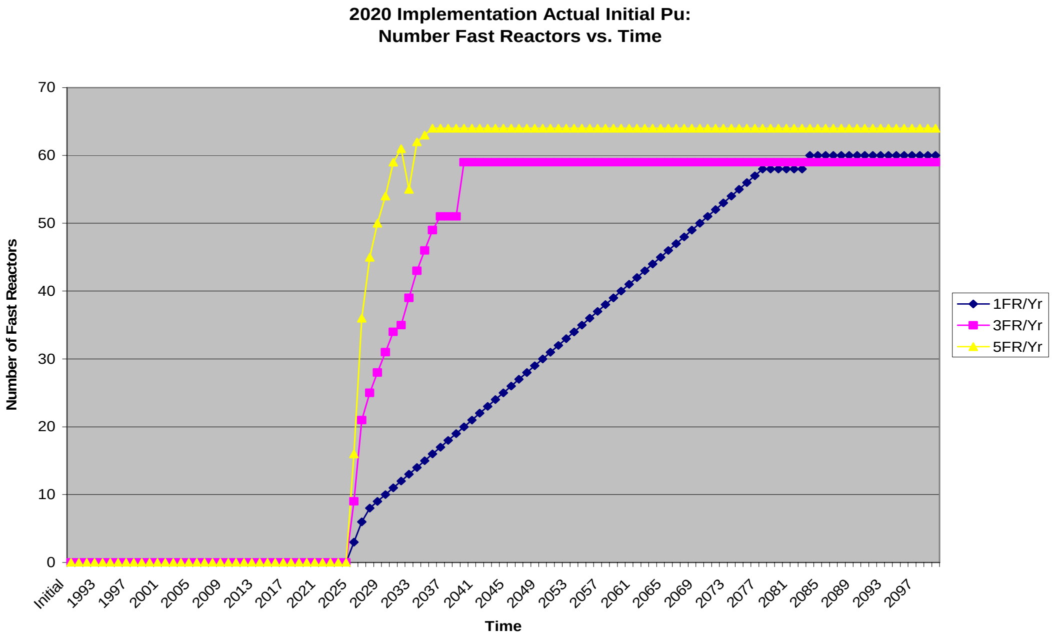


Figure 3.6 2020 Implementation Actual Initial Pu: Number of FRs vs. Time

number of FRs that can be constructed. As in the previous runs a small dip in Pu inventory is seen when the FRs first start coming online and as before this is due to the initial fuel loading of the reactors. The Pu slopes are again a key in observing the long term Pu savings ability of FRs and are shown in Table 3.2 below.

Since this case correlates exactly with the reference case in set-up save for the implementation of FRs a comparison can be made. This comparison is done in the form of percentage of savings in total Pu inventory and is shown in Table 3.3 below.

As shown in Table 3.3 the implementation of FRs into the US reactor fleet yields a minimum savings of 30% in total Pu inventory.

The last subset looked at in the 2020 implementation case is the infinite initial Pu case. This is used to remove the effects of actinide limitations and to theoretically look at the effect of actually building the FRs at the rates specified until the end of 2100. Figures 3.7 and 3.8 show the Pu inventory and the number of FRs respectively corresponding to the 2020 implementation with infinite amount of initial Pu.

Table 3.2 2020 Implementation Actual Initial Pu: Slopes of Pu Inventory Curves

	Initial Slope	End Slope
	Tons Pu / Year	
1FR/Yr	21.98	7.22
3FR/Yr	21.98	7.01
5FR/Yr	21.98	5.74

Table 3.3 2020 Implementation Actual Initial Pu: Percentage Savings in Pu

	Percentage Savings in Pu
1FR/Yr	31.89%
3FR/Yr	36.36%
5FR/Yr	33.25%

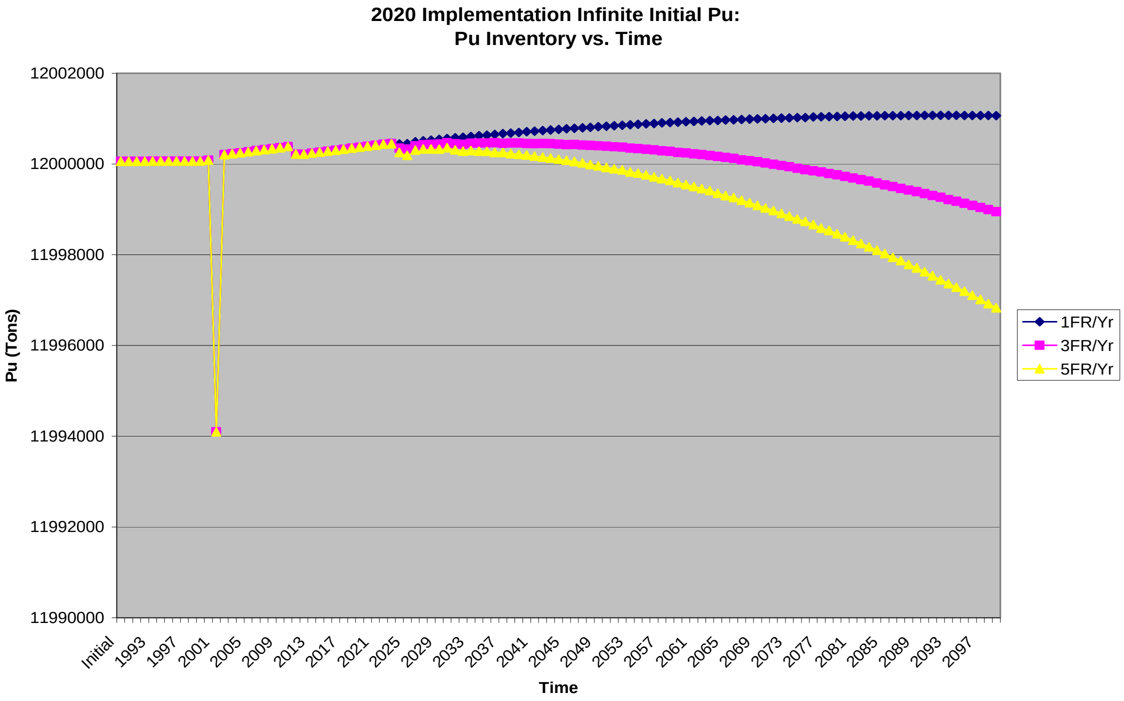


Figure 3.7 2020 Implementation Infinite Initial Pu: Pu Inventory vs. Time

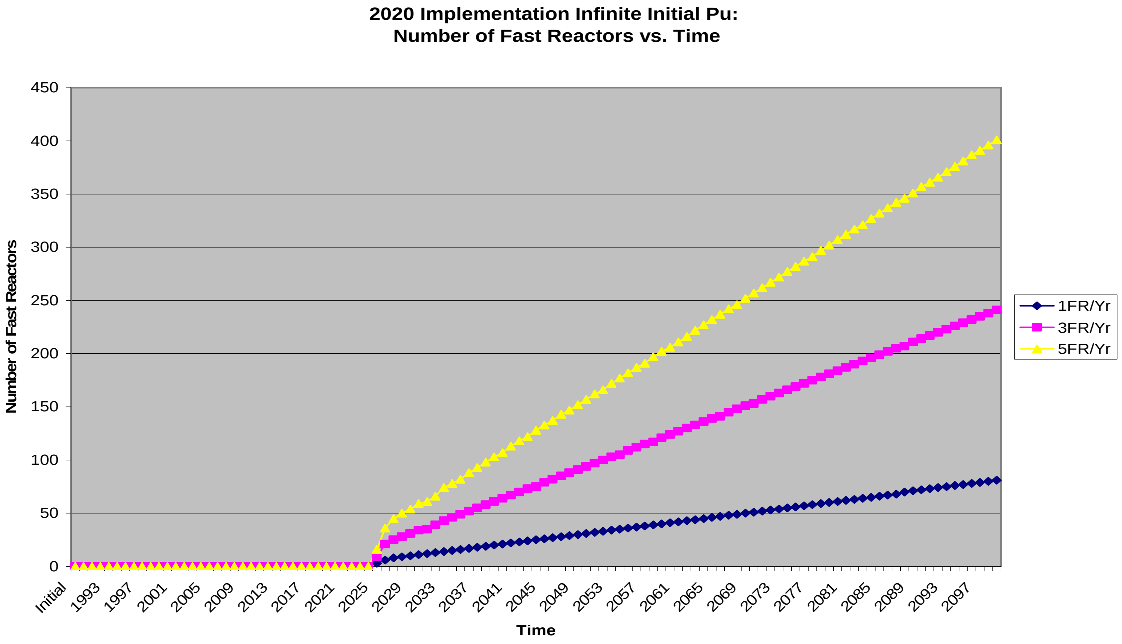


Figure 3.8 2020 Implementation Infinite Initial Pu: Number of FRs vs. Time

As seen in Figure 3.8, with the initial Pu value being set to infinite, there is no actinide limitation and each scheme builds its amount of reactors at the rate intended for the duration of the time period. This results in the change in the Pu inventory seen in Figure 3.7. The numerical change is shown above in Table 3.4. Table 3.4 shows that the construction of 1 FR/Yr does not result in enough Pu burning capacity to hold steady or lower the Pu inventory; however, it does decrease its rate of increase. On the other hand the implementation of 3 or 5 FR/Yr can potentially lower the initial Pu inventory; however, as shown in Figure 3.8 requires an enormous number of FRs to do so.

Table 3.4 2020 Implementation Infinite Initial Pu: Change in Pu Inventory

	Change in Pu
	Tons Pu
1FR/Yr	1006.81
3FR/Yr	-1112.24
5FR/Yr	-3230.01

2030 Implementation Case

Now that the results for the 2020 implementation have been presented and explained the 2030 implementation results will be presented and examined. For the most part the structure and reasoning for the look of the data graphs correspond to the same reasoning given for the 2020 implementation; however, there are a few areas of difference and these areas will be the main focus of discussion for this and the 2040 implementation results.

Figures 3.9 and 3.10 correspond to the 2030 implementation with no initial Pu: Pu Inventory vs. Time and Number of FRs vs. Time respectively.

These data in these figures correspond relatively with that from the 2020 Implementation with no Initial Pu (Figures 3.3 and 3.4) except for the time implementation shift to the right and more FRs are built in this case than before. This increase in the number of FRs can be attributed to the delayed time of implementation which allowed the LWR fleet to run for an additional 10 years producing Pu that could be used to startup more FRs and in turn aid in off setting the Pu saving issue encountered in the 2020 Implementation. The Pu saving issue; however, is not totally removed just compensated for a little more in this case. As seen in Figure 3.10 there is still a point where FR construction is halted and this

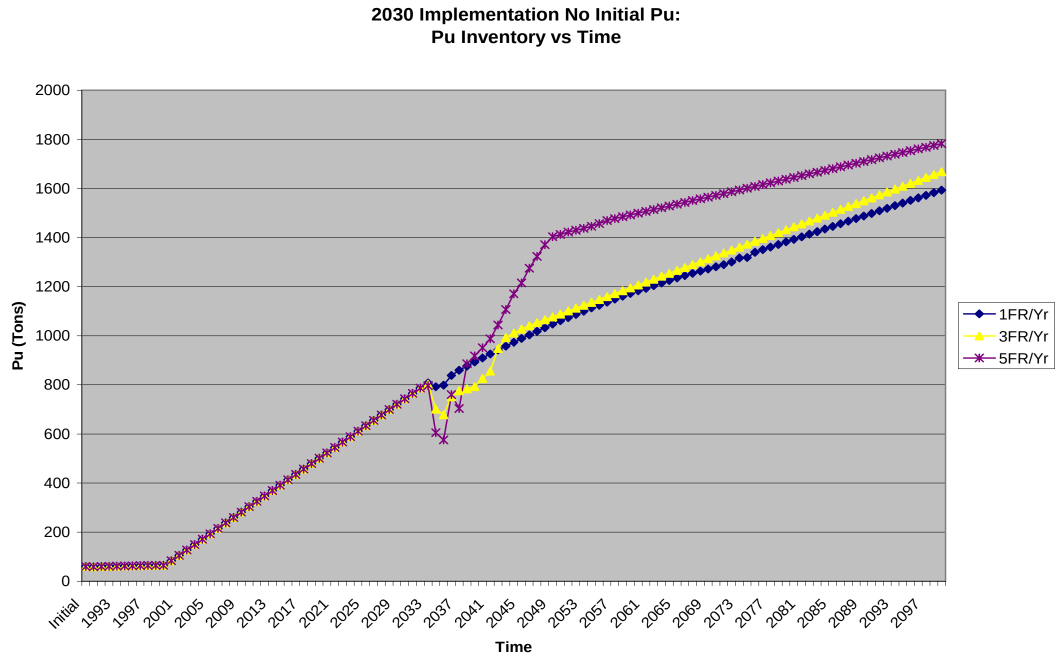


Figure 3.92030 Implementation No Initial Pu: Pu Inventory vs. Time

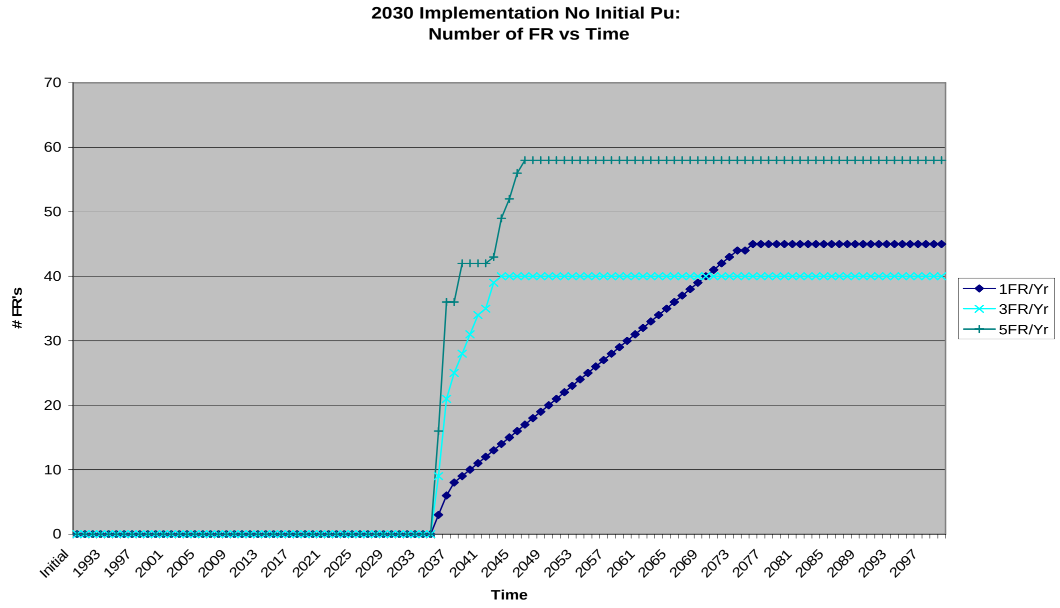


Figure 3.10 2030 Implementation No Initial Pu: Number of FRs vs. Time

Table 3.5 2030 Implementation No Initial Pu: Slopes of Pu Inventory Curves

	Initial Slope	End Slope
1FR/Yr	21.98	10.55
3FR/Yr	21.98	11.83
5FR/Yr	21.98	7.26

is due to the Pu saving issue discussed earlier. Table 3.5 shows the rate decrease in Pu inventory growth.

As seen before the growth rate is significantly slowed, even more so than the 2020 implementation with no initial Pu.

Figures 3.11 and 3.12 show the 2030 implementation with actual initial Pu: Pu inventory and number of FRs respectively.

As with the 2030 no initial Pu cases, these show a slight increase in the number of FRs built over the 2020 Implementation case. Again this is because of the additional 10 years of operation time of the LWR fleet. As shown in Figure 3.11, the Pu growth rate is slowed even further in this case and is shown more clearly in Table 3.6 below.

These slopes show that with these cases the FRs are almost able to control the growth of the Pu inventory. Table 3.7 shows the percentage savings of Pu in regard to the reference case.

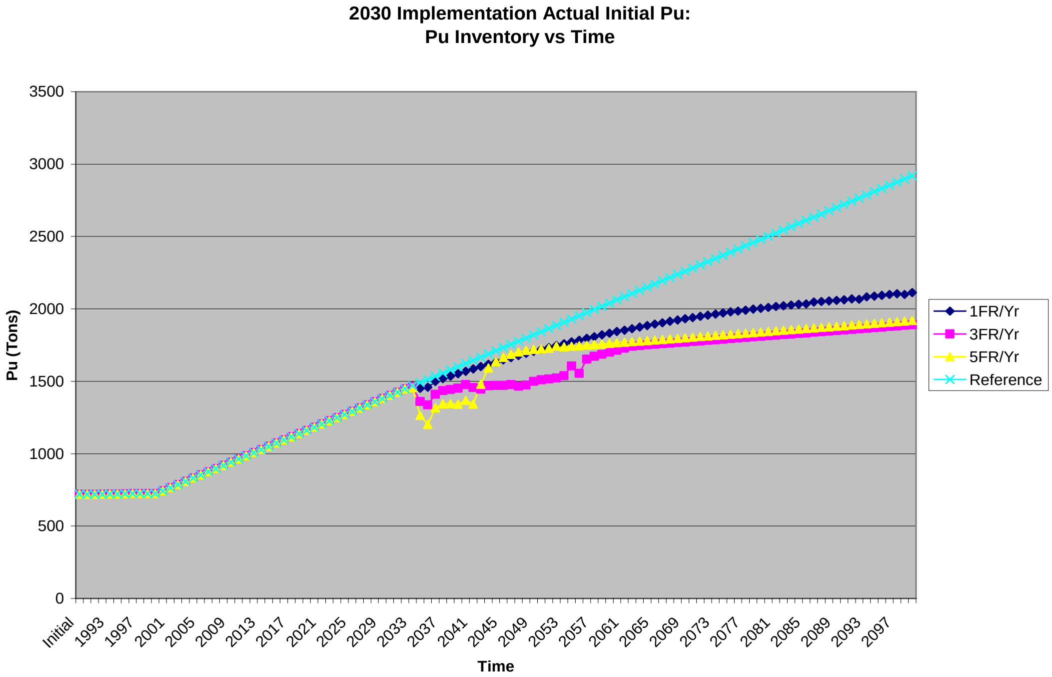


Figure 3.11 2030 Implementation Actual Initial Pu: Pu Inventory vs. Time

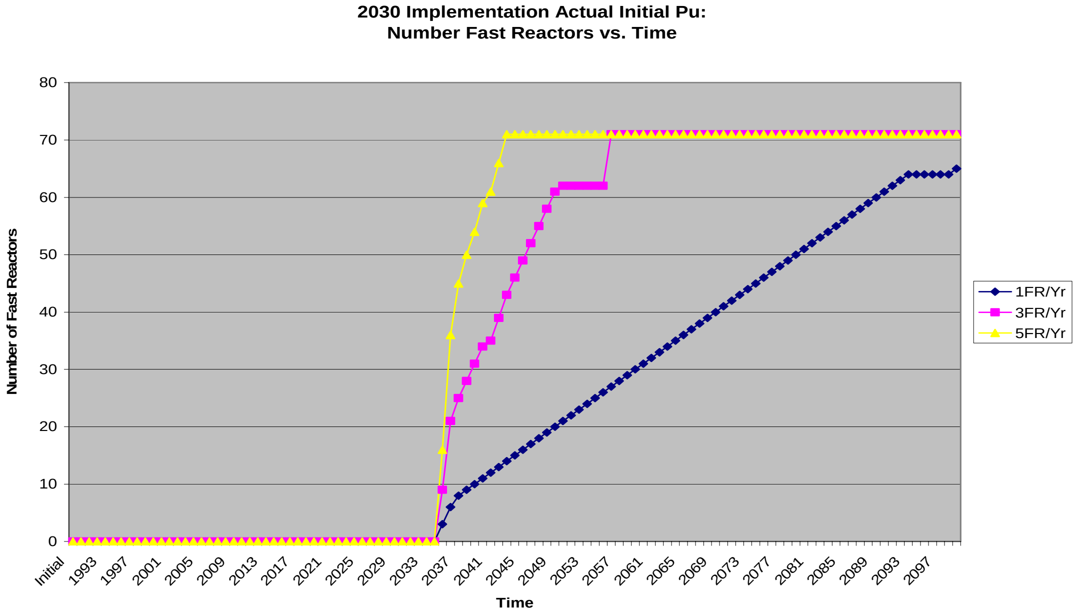


Figure 3.12 2030 Implementation Actual Initial Pu: Number of FRs vs. Time

Table 3.6 2030 Implementation Actual Initial Pu: Slopes of Pu Inventory Curves

	Initial Slope	End Slope
	Tons Pu / Year	
1FR/Yr	21.98	5.54
3FR/Yr	21.98	3.96
5FR/Yr	21.98	3.96

Table 3.7 2030 Implementation Actual Initial Pu: Percentage Savings in Pu

	Percentage Savings in Pu
1FR/Yr	27.64%
3FR/Yr	35.27%
5FR/Yr	34.24%

In this case the percentage savings is not as high as the 2020 implementation, but it is quite impressive since the lowest savings is 27%.

Figures 3.13 and 3.14 show the 2030 implementation infinite with initial Pu: Pu inventory and number of FRs respectively.

As seen before in the previous infinite initial Pu case, Figure 3.14 shows the constant construction rate expected. Also as before, the 3 and 5 FR/Yr cases actually lower the total Pu inventory over the time period, shown above in Table 3.8.

2040 Implementation Case

Figures 3.15 and 3.16 correspond to the 2040 implementation no initial Pu: Pu Inventory vs. Time and Number of FRs vs. Time respectively. The figures shown below correspond

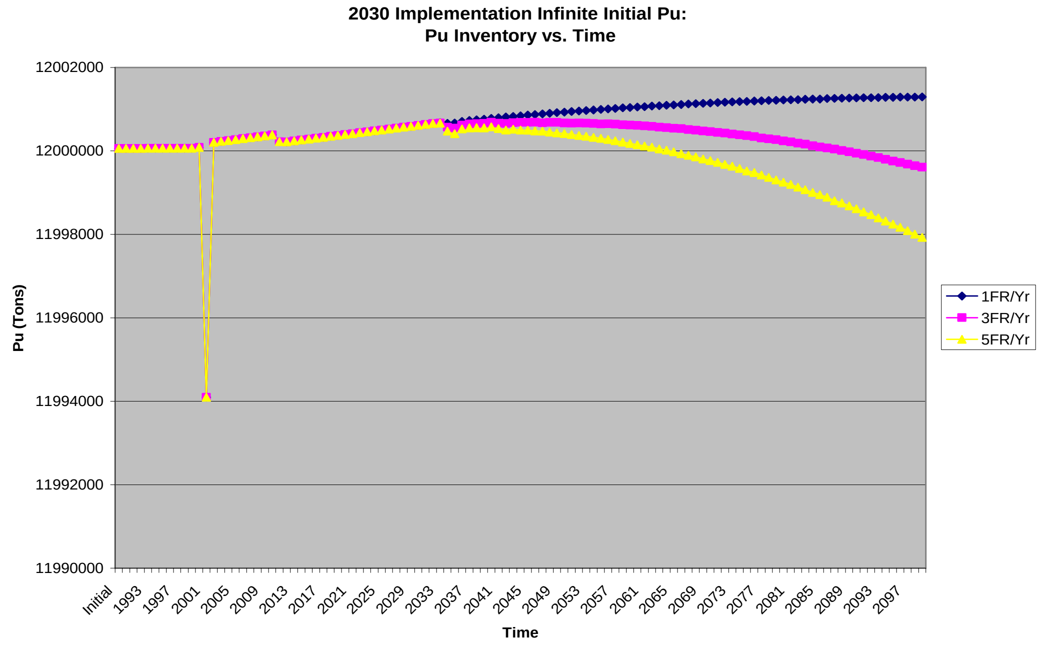


Figure 3.13 2030 Implementation Infinite Initial Pu: Pu Inventory vs. Time

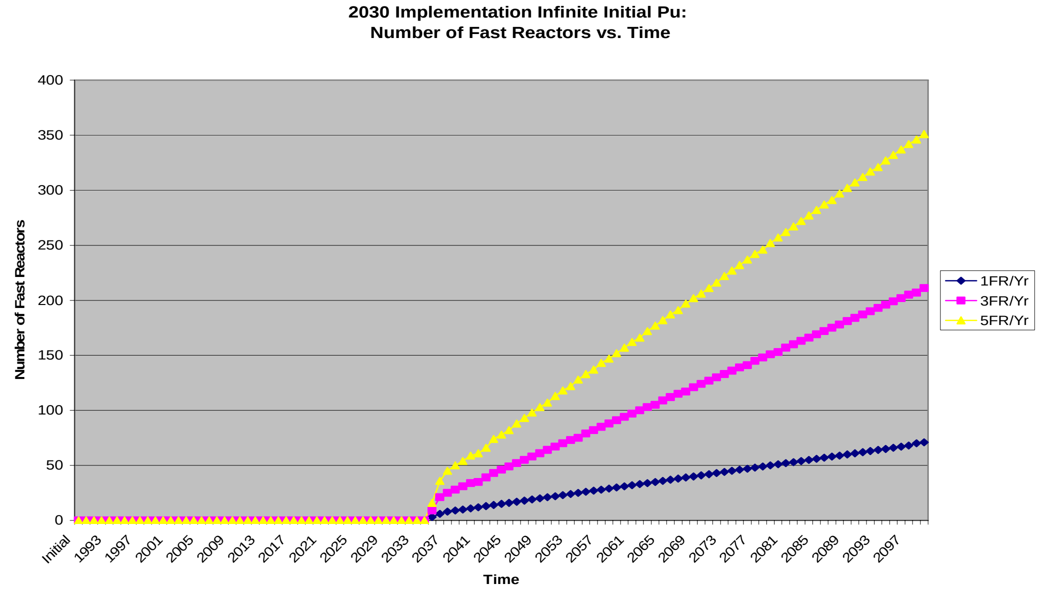


Figure 3.14 2030 Implementation Infinite Initial Pu: Number of FRs vs. Time

Table 3.8 2030 Implementation Infinite Initial Pu: Change in Pu Inventory

	Change in Pu
	Tons
1FR/Yr	1230.69
3FR/Yr	-451.93
5FR/Yr	-2132.14

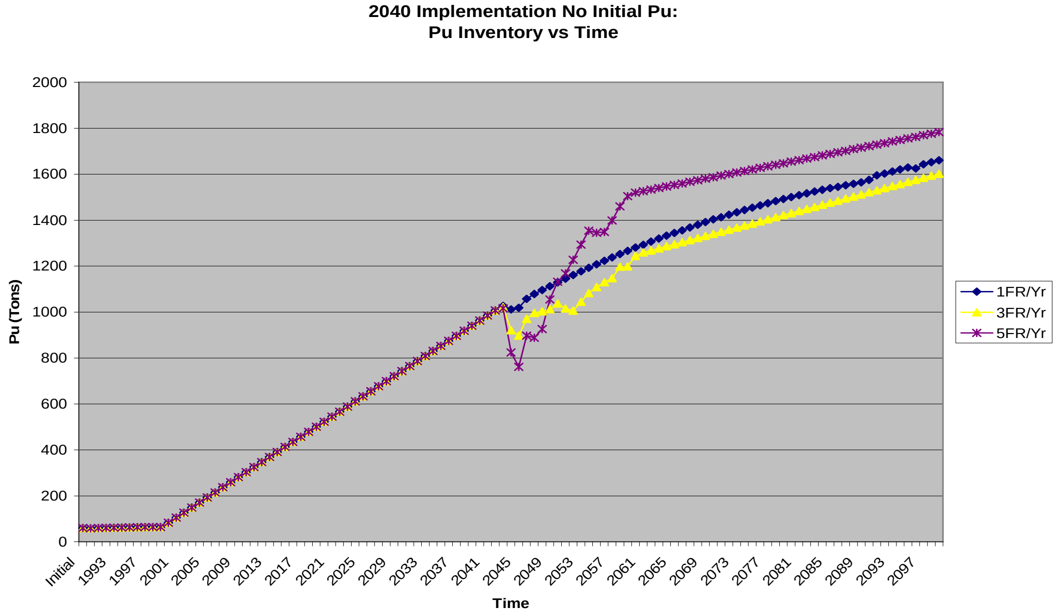


Figure 3.15 2040 Implementation No Initial Pu: Pu Inventory vs. Time

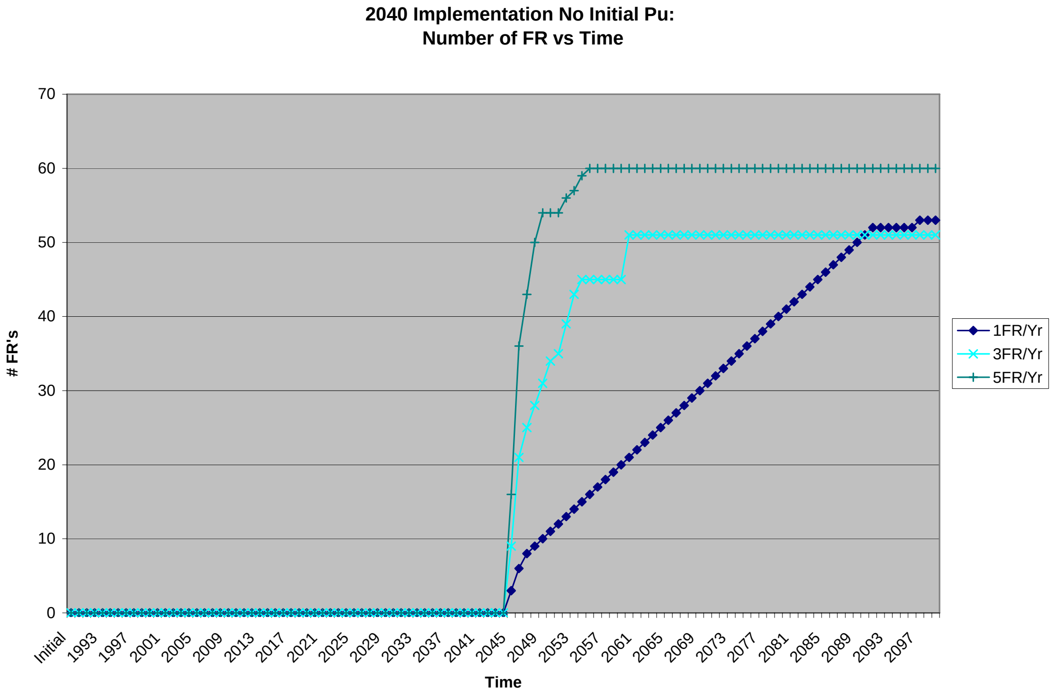


Figure 3.16 2040 Implementation No Initial Pu: Number of FRs vs. Time

relatively closely with those from the 2020 and 2030 Implementations with no initial Pu. As with the 2030 over the 2020, the 2040 has an increased number of FRs that are built. This increase in the number of FRs can be attributed to the delayed time of implementation which allowed the LWR fleet to run for an additional 10 years producing Pu that could be used to startup more FRs and in turn aid in offsetting the Pu saving issue encountered in the 2030 Implementation. The Pu saving issue is not totally removed just compensated for a little more in this case. As seen in Figure 3.16 there is still a point where FR construction is halted and this is due to the Pu saving issue discussed earlier. Table 3.9 shows the rate of decrease in Pu inventory growth.

Table 3.9 2040 Implementation No Initial Pu: Slopes of Pu Inventory Curves

	Initial Slope	End Slope
	Tons Pu / Year	
1FR/Yr	21.98	8.59
3FR/Yr	21.98	9.04
5FR/Yr	21.98	6.75

As seen before the growth rate is significantly slowed, even more so then the 2030 implementation with no initial Pu.

Figures 3.17 and 3.18 show the 2040 Implementation Actual Initial Pu: Pu inventory and number of FRs respectively. As with the 2040 no initial Pu cases, these show a slight increase in the number of FRs built over the 2030 Implementation case. Again this is because of the additional 10 years of operation time of the LWR fleet. As shown in Figure 3.17, the Pu growth rate is slowed even further in this case shown more clearly in Table 3.10 below.

These slopes show that with these cases the FRs are almost able to control the growth of the Pu inventory and the 5FR/Yr case is almost there allowing only a slight increase in Pu inventory. Table 3.11 shows the percentage savings of Pu in regard to the reference case.

In this case the percentage savings is not as high as the 2020 or 2030 implementations; however, as was the case in the 2030 implementation it is still significant seeing as the lowest percentage savings is still over 20%.

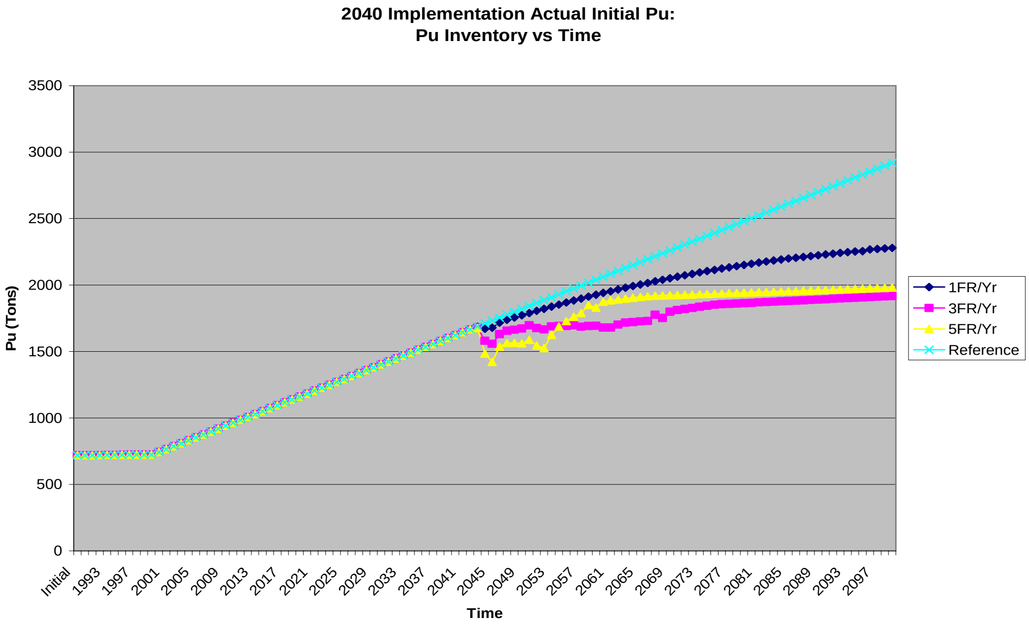


Figure 3.17 2040 Implementation Actual Initial Pu: Pu Inventory vs. Time

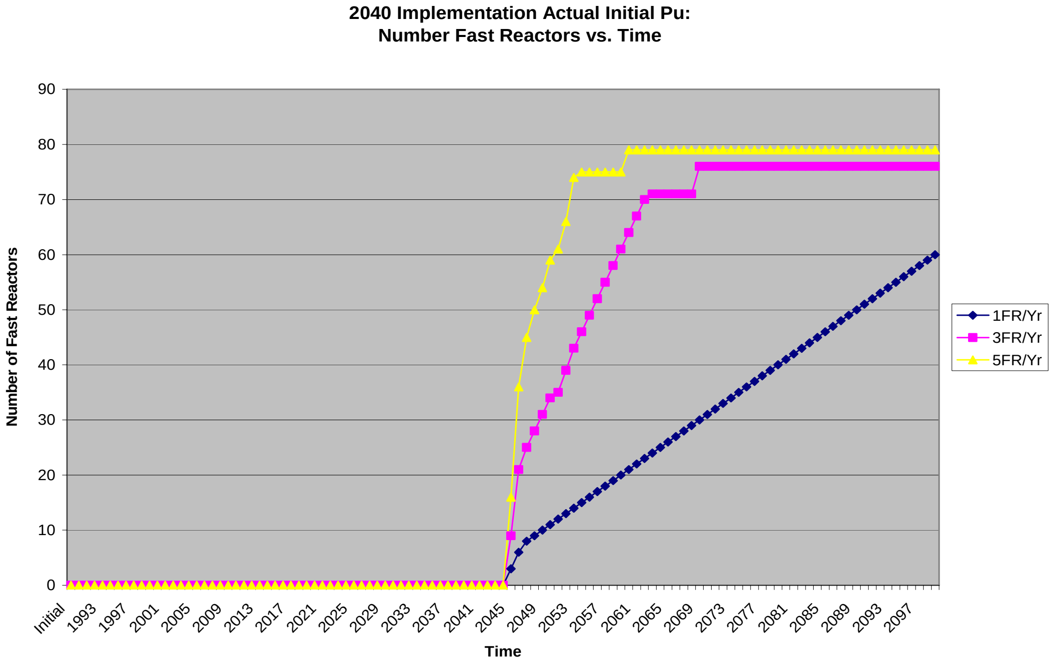


Figure 3.18 2040 Implementation Actual Initial Pu: Number of FRs vs. Time

Table 3.10 2040 Implementation Actual Initial Pu: Slopes of Pu Inventory Curves

	Initial Slope	End Slope
	Tons Pu / Year	
1FR/Yr	21.98	6.86
3FR/Yr	21.98	2.74
5FR/Yr	21.98	1.93

Table 3.11 2040 Implementation Actual Initial Pu: Percentage Savings in Pu

	Percentage Savings in Pu
1FR/Yr	21.94%
3FR/Yr	34.32%
5FR/Yr	32.15%

Figures 3.19 and 3.20 show the 2040 implementation with infinite initial Pu: Pu inventory and number of FRs respectively. As noted in the previous infinite initial Pu cases, Figure 3.20 shows the constant construction rate expected. However, unlike before, only the 5 FR/Yr case actually lowers the total Pu inventory over the time period. The 3FR/Yr case keeps the Pu inventory relatively steady but does not decrease it. This is shown below in Table 3.12.

The reasoning for this difference in reduction capability from the other cases is due to the short time that the FRs are operating for and the longer period of time the LWRs have to build up Pu.

The results displayed previously in this chapter in graphical form have been duplicated below in tabular form below giving absolute inventories of Pu and Ma concentrations and

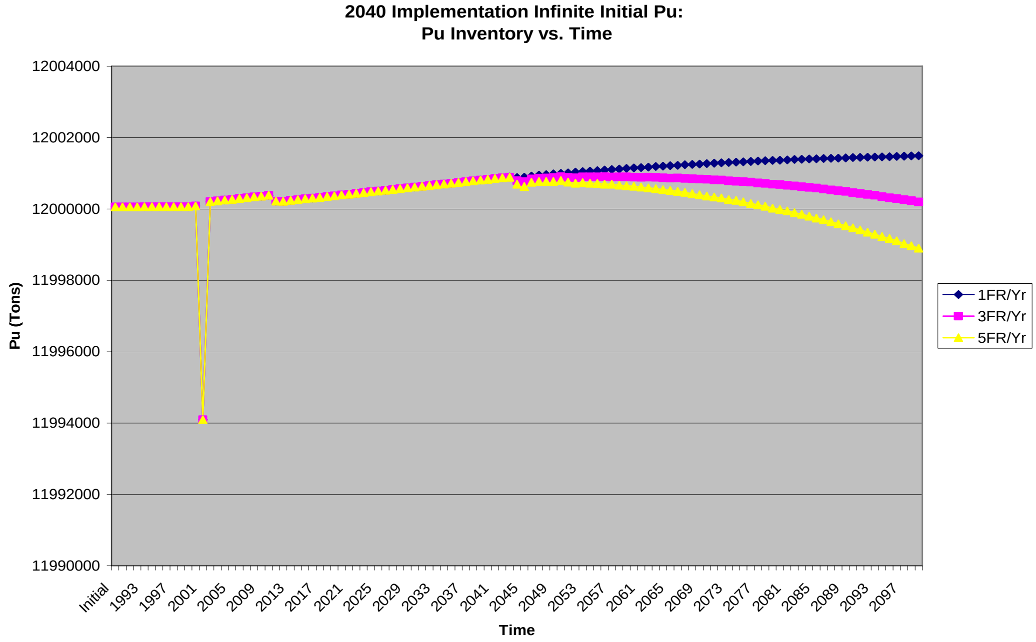


Figure 3.19 2040 Implementation Infinite Initial Pu: Pu Inventory vs. Time

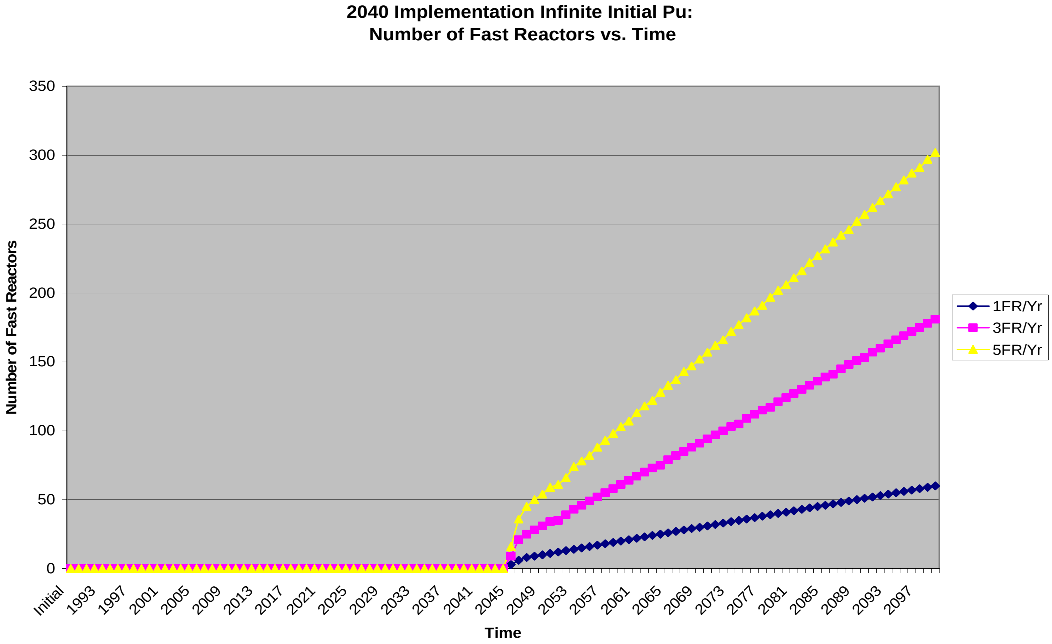


Figure 3.20 2040 Implementation Infinite Initial Pu: Number of FRs vs. Time

Table 3.12 2040 Implementation Infinite Initial Pu: Change in Pu Inventory

	Change in Pu
	Tons
1FR/Yr	1428.27
3FR/Yr	138.36
5FR/Yr	-1158.44

relative inventories as ratios compared to there reference case. The time delayed runs for all of the cases do not construct FR for the entire time period. Due to constraints placed on fuel inventories by DANESS the FR construction usually stops around 60 FRs; however, it does vary therefore the ending number of FRs is included in parentheses after the run title. The tables showing the relative inventories (3.13-3.18) clearly illustrates the advantages of implementing FRs into the reactor fleet; however, it does not illustrate that the non-reference runs also produce considerably more energy while still reducing the Pu inventory. In each of the non-reference runs there are a minimum of 35 additional reactors and in some of the cases 70 or more. That equates to a considerable amount of additional energy and still results in a significant reduction in the overall Pu inventory. Also, the total Pu inventory that is left is located in different areas. Considerably more Pu is located in-pile, in a reactor, rather than out-of-pile, elsewhere such as spent fuel storage or reprocessing plant, thus giving a further proliferation security for the stockpile of Pu. The MA inventory for the runs does increase; however, the FRs do not burn MA but they produce them at a slower rate compared to the LWRs.

Table 3.13 Absolute Inventories of Pu and MA at 2100 1FR/Yr

	Pu Inventories			MA Inventories		
FR Growth Act Initial Pu	In-Pile	Out-Of-Pile	Total	In-Pile	Out-Of-Pile	Total
Reference(No Growth)	55	2865	2920	8	438	446
2020 (60)	680	1309	1988	29	532	561
2030 (65)	733	1379	2113	31	511	542
2040 (60)	687	1592	2279	29	491	520
FR Growth No Initial Pu						
Reference(No Growth)	55	2203	2258	8	337	346
2020 (37)	436	1149	1585	20	414	434
2030 (45)	521	1072	1593	23	407	430
2040 (53)	605	1055	1661	26	392	418

Table 3.14 Relative Inventories as Ratios 1FR/Yr

	Pu Inventories			MA Inventories		
FR Growth Act Initial Pu	In-Pile	Out-Of-Pile	Total	In-Pile	Out-Of-Pile	Total
Reference	1.00	1.00	1.00	1.00	1.00	1.00
2020	12.34	0.46	0.68	3.41	1.22	1.26
2030	13.31	0.48	0.72	3.64	1.17	1.21
2040	12.48	0.56	0.78	3.43	1.12	1.17
FR Growth No Initial Pu						
Reference(No Growth)	1.00	1.00	1.00	1.00	1.00	1.00
2020	7.91	0.52	0.70	2.41	1.23	1.26
2030	9.45	0.49	0.71	2.76	1.21	1.24
2040	10.99	0.48	0.74	3.10	1.16	1.21

Table 3.15 Absolute Inventories of Pu and MA at 2100 3FR/Yr

	Pu Inventories			MA Inventories		
FR Growth Act Initial Pu	In-Pile	Out-Of-Pile	Total	In-Pile	Out-Of-Pile	Total
Reference(No Growth)	55	2865	2920	8	438	446
2020 (59)	662	1196	1858	27	585	613
2030 (71)	786	1104	1890	31	582	613
2040 (76)	839	1079	1917	33	564	597
FR Growth No Initial Pu						
Reference(No Growth)	55	2203	2258	8	337	346
2020 (35)	428	1327	1754	20	429	449
2030 (40)	475	1193	1668	21	430	451
2040 (51)	579	1023	1602	25	432	597

Table 3.16 Relative Inventories as Ratios 3FR/Yr

	Pu Inventories			MA Inventories		
FR Growth Act Initial Pu	In-Pile	Out-Of-Pile	Total	In-Pile	Out-Of-Pile	Total
Reference	1.00	1.00	1.00	1.00	1.00	1.00
2020	12.01	0.42	0.64	3.23	1.34	1.37
2030	14.27	0.39	0.65	3.70	1.33	1.38
2040	15.22	0.38	0.66	3.91	1.29	1.34
FR Growth No Initial Pu						
Reference(No Growth)	1.00	1.00	1.00	1.00	1.00	1.00
2020	7.76	0.60	0.78	2.37	1.27	1.30
2030	8.63	0.54	0.74	2.54	1.27	1.30
2040	10.51	0.46	0.71	2.92	1.28	1.73

Table 3.17 Absolute Inventories of Pu and MA at 2100 5FR/Yr

	Pu Inventories			MA Inventories		
FR Growth Act Initial Pu	In-Pile	Out-Of-Pile	Total	In-Pile	Out-Of-Pile	Total
Reference(No Growth)	55	2865	2920	8	438	446
2020 (64)	734	1215	1949	30	606	635
2030 (71)	802	1379	2181	32	599	631
2040 (79)	869	1592	2460	34	589	623
FR Growth No Initial Pu						
Reference(No Growth)	55	2203	2258	8	337	346
2020 (50)	581	1149	1729	25	461	486
2030 (58)	664	1072	1736	27	462	489
2040 (60)	691	1055	1746	28	449	478

Table 3.18 Relative Inventories as Ratios 5 FR/Yr

	Pu Inventories			MA Inventories		
FR Growth Act Initial Pu	In-Pile	Out-Of-Pile	Total	In-Pile	Out-Of-Pile	Total
Reference	1.00	1.00	1.00	1.00	1.00	1.00
2020	13.32	0.46	0.67	3.51	1.38	1.42
2030	14.55	0.48	0.75	3.76	1.37	1.42
2040	15.77	0.56	0.84	4.01	1.35	1.40
FR Growth No Initial Pu						
Reference(No Growth)	1.00	1.00	1.00	1.00	1.00	1.00
2020	10.54	0.52	0.77	2.92	1.37	1.40
2030	12.05	0.49	0.77	3.23	1.37	1.41
2040	12.53	0.48	0.77	3.34	1.33	1.38

Mixed LWR and FR Implementation Case

The next scenario analyzed was a mixed growth fleet of LWRs and FRs. The data used for the reactors and their corresponding fuels are the same data used in previous cases. The DANESS set-up is similar to previous runs with several key differences. The reference case for these runs has reactor growth starting in the year 2020, and implements 8 LWRs per year. The subsequent runs also implement 8 Rx per year, as does the reference case, except they implement 6 LWRs and 2 FRs per year instead of the 8 LWRs. Again as done in previous cases, the reprocessing capacity is set to unlimited, all of the LWR and FR fuel is reprocessed, the base fleet is set to be the current 105 LWRs, legacy spent fuel is not varied and is set at the current level of 55,000tHM, and time of implementation is varied from 2020 to 2030 to 2040. The results for Pu and MA concentrations from this case are shown below in Figures 3.21 and 3.22. Following those is a more in depth tabular listing of these results in Tables 3.19 and 3.20.

It can be seen that the introduction of the FRs, as opposed to a complete LWR only reactor fleet yields significant savings in Pu inventory. However, it appears from the figure and table that the best savings can be obtained by waiting till 2040 to implement them. This is misleading. The reason for the much lower values for this case is because of the number of total reactors. This difference can be easily illustrated as shown below in Figure 3.23.

As can easily been observed in Figure 3.23, the 2040 implementation run yields

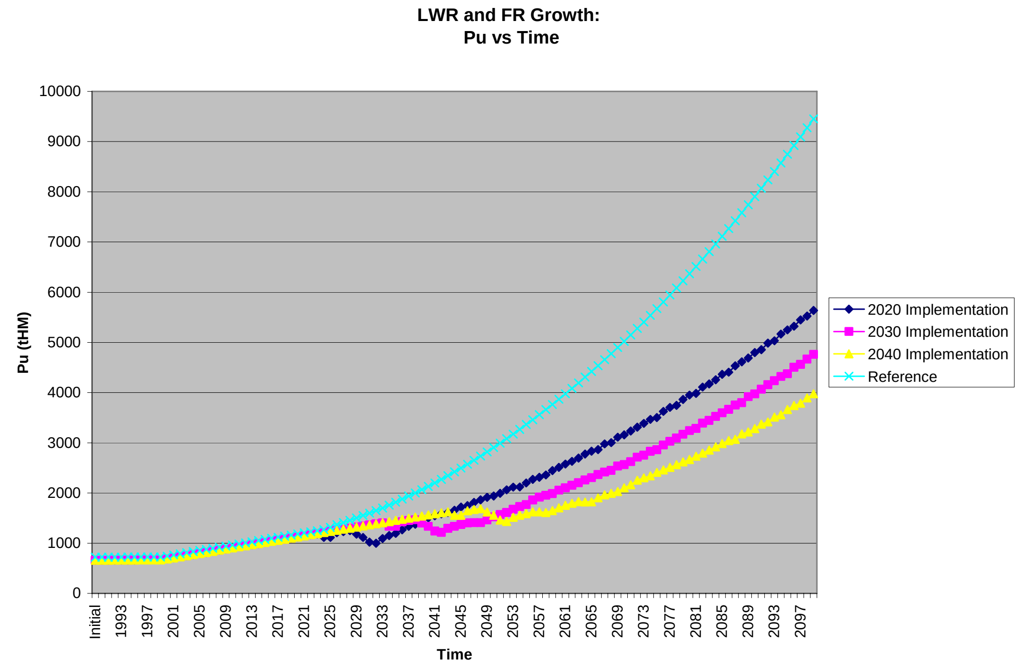


Figure 3.21 Total Amount of Pu vs. Time: LWR and FR Growth Case: 8Rx/Yr (The Reference run grows 8 LWRs per Year and the other runs build 6 LWRs and 2 FRs per Year)

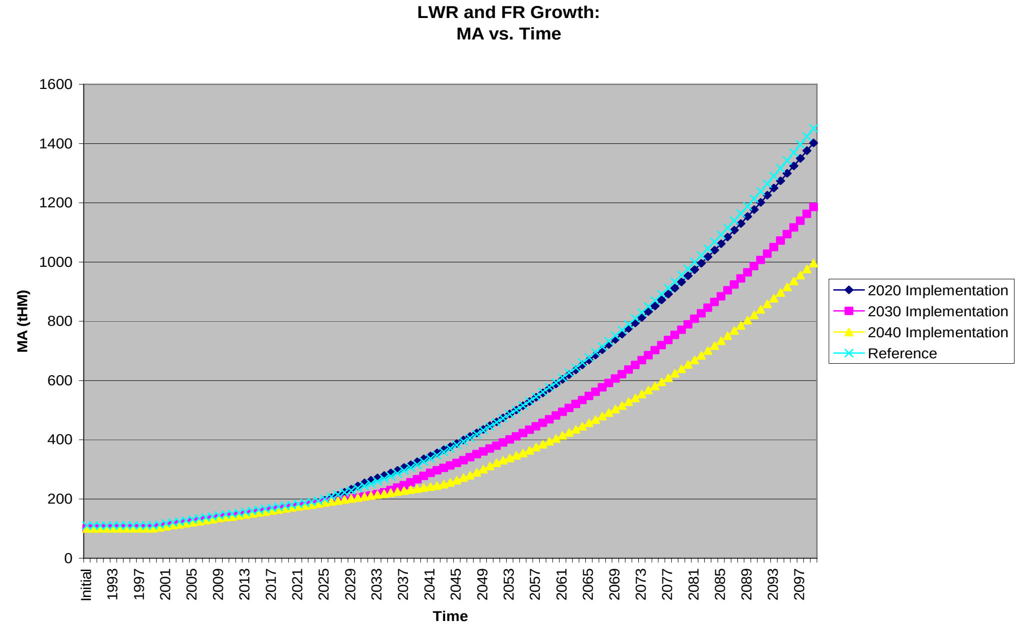


Figure 3.22 Total Amount of MA vs. Time: LWR and FR Growth Case: 8Rx/Yr (The Reference run grows 8 LWRs per Year and the other runs build 6 LWRs and 2 FRs per Year)

Table 3.19 Absolute Inventories of Pu and MA at 2100: 8Rx/Yr (The Reference run grows 8 LWRs per Year and the other runs build 6 LWRs and 2 FRs per Year)

	Pu Inventories			MA Inventories		
LWR & FR Growth Actual Initial Pu	In-Pile	Out-Of-Pile	Total	In-Pile	Out-Of-Pile	Total
Reference	442	9012	9454	68	1384	1451
2020 Implementation	1776	3861	5636	97	1306	1402
2030 Implementation	1546	3216	4762	85	1101	1186
2040 Implementation	1365	2613	3977	75	922	996

Table 3.20 Relative Inventories as Ratios: 8Rx/Yr (Ref 8 LWRs: others 6 LWRs and 2 FRs)

	Pu Inventories			MA Inventories		
LWR & FR Growth Actual Initial Pu	In-Pile	Out-Of-Pile	Total	In-Pile	Out-Of-Pile	Total
Reference	1.00	1.00	1.00	1.00	1.00	1.00
2020 Implementation	4.02	0.43	0.60	1.42	0.94	0.97
2030 Implementation	3.50	0.36	0.50	1.26	0.80	0.82
2040 Implementation	3.09	0.29	0.42	1.11	0.67	0.69

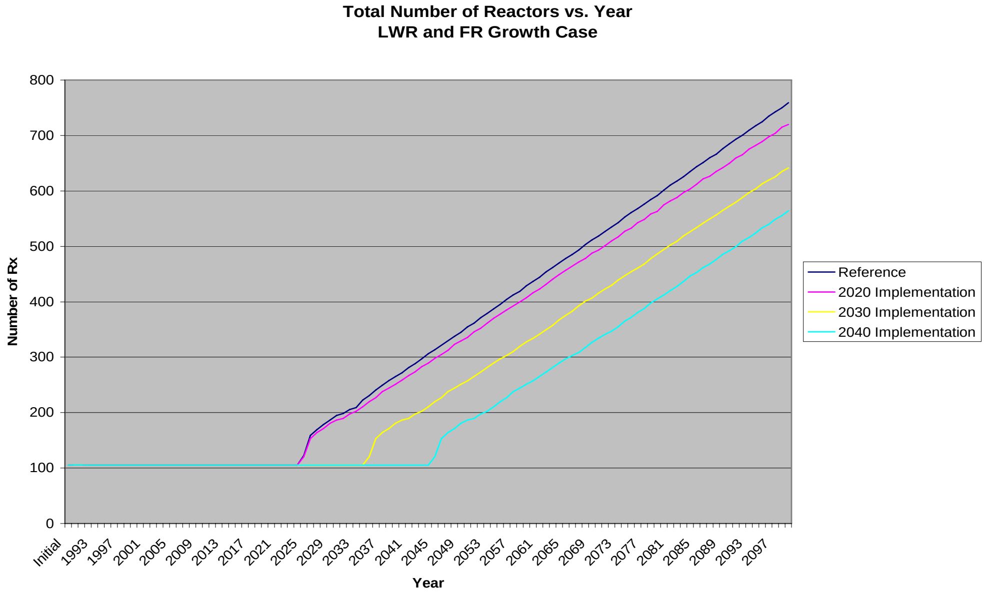


Figure 3.23 Total Number of Reactors vs. Year: LWR and FR Growth Case: 8Rx/Yr (The Reference run grows 8 LWRs per Year and the other runs build 6 LWRs and 2 FRs per Year)

significantly fewer total reactors than do the reference or the 2020 implementation runs.

Thus the best runs to compare are the reference and the 2020 implementation. Keeping this in mind and comparing those 2 runs with the implementation of the 2 FRs per year instead of an additional 2 LWRs yields a savings of 40% in total Pu inventory. The majority of that inventory is in-pile rather than out-of-pile. In addition to the Pu savings, the total amount of MA has actually decreased for the 2020 implementation case as compared to the reference. As has been stated in earlier reports the FR used for these cases does not actually burn MA; however, the apparent savings is due to the lower amount produced by the FR as opposed to a regular LWR. Thus this case is very important in showing the usefulness at controlling Pu and MA inventories with a combined fleet of FRs and LWRs.

3.3 Fast Reactor Conversion Ratios

The results obtained by using the various conversion ratio metal and oxide fueled fast reactors are shown below in graphical format for the Oxide Fuel only. The results for all the other runs and the Oxide are shown later in table format. The metal and oxide results are relatively similar in structure due to the similarities in the data of the different fuels; however, the oxide fuel shows an advantage at higher CRs for Pu inventory control. This is due to the higher burn-up of the oxide fuel when compared to the metal fuel. It is shown at lower CRs, that the oxide and metal fuels yield almost identical results when the burn-ups are roughly the same.

The following figures show the FR construction for the oxide fuel with varied CRs. Figure 3.24, the total Pu per TWhe Figure 3.25, the total Pu Figure 3.26, the total MA per TWhe Figure 3.27, and the total MA Figure 3.28. Following these graphs are tables listing the results of the other runs (3.21-3.24).

As in previous work, the tables showing the relative inventories easily illustrates the obvious advantages of implementing the FRs into the reactor fleet; however, it does not illustrate that the non-reference runs produce considerably more energy while still reducing the Pu inventory. In each of the non-reference runs there are a minimum of 39 additional reactors and, in some of the cases, 180 or more. That equates to a considerable amount of additional energy with little to no appreciable Pu inventory growth, and in some of the lower CR cases, a reduction in the inventory. Figure 3.25 shows the Pu/TWhe gain yielded from the implementation of FRs. It is easily seen the advantage even with the 1.0 CR reactor case of the savings potential the FRs yield. However, the MA inventory for the runs does increase. This is because of the fact that the FRs do not burn MA but they produce them at a slower rate compared to the LWRs.

3.1. Uncertainty Analyses for Dynamic Fuel Cycle Scenarios

The list of Monte Carlo sampled input variables were loaded in an Excel sheet and imported into DANESS via the MC Sampling function. The code was then run one hundred times utilizing the batch run capacity in DANESS. The output from these runs is extensive and it was decided to limit the output to areas of interest. Pu inventory was determined to be the most important output; and thus, for this paper Pu inventory will be

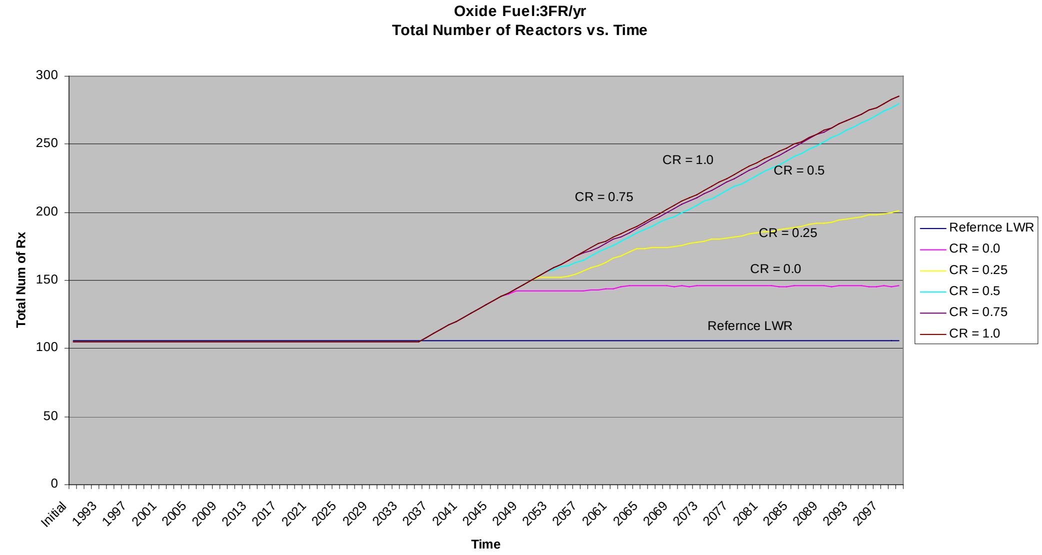


Figure 3.24 Total Number of Reactors Constructed (Oxide Fuel: 3 FR/yr)

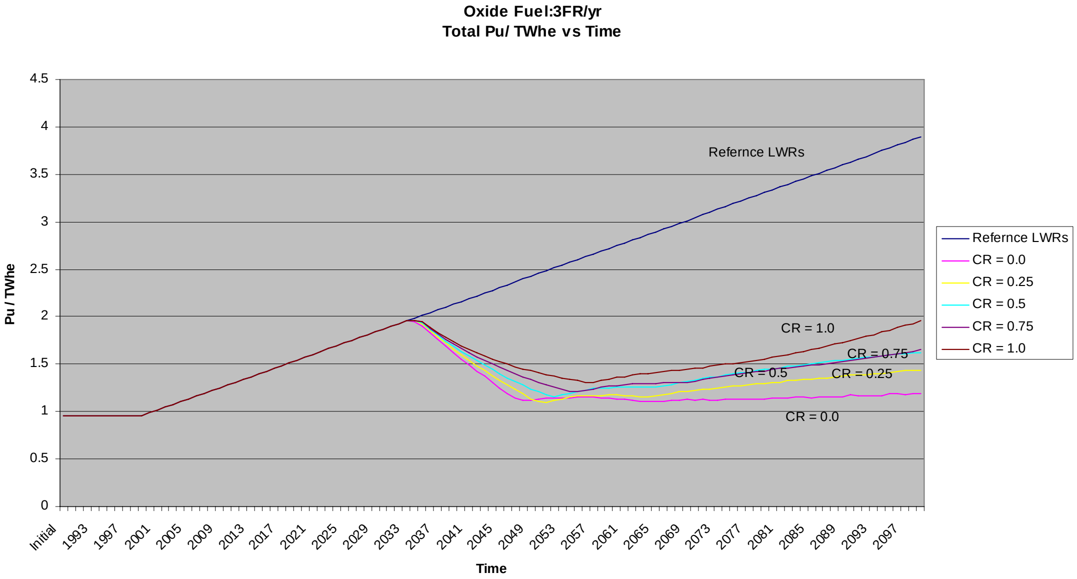


Figure 3.25 Total Pu/TWhe (Oxide Fuel: 3 FR/yr)

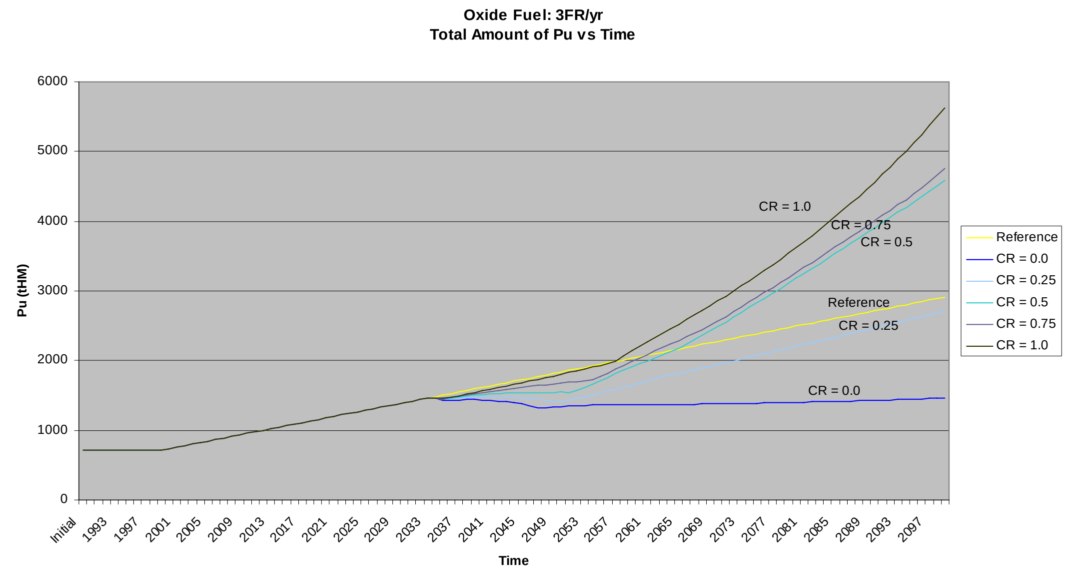


Figure 3.26 Total Amount of Pu (Oxide Fuel: 3 FR/yr)

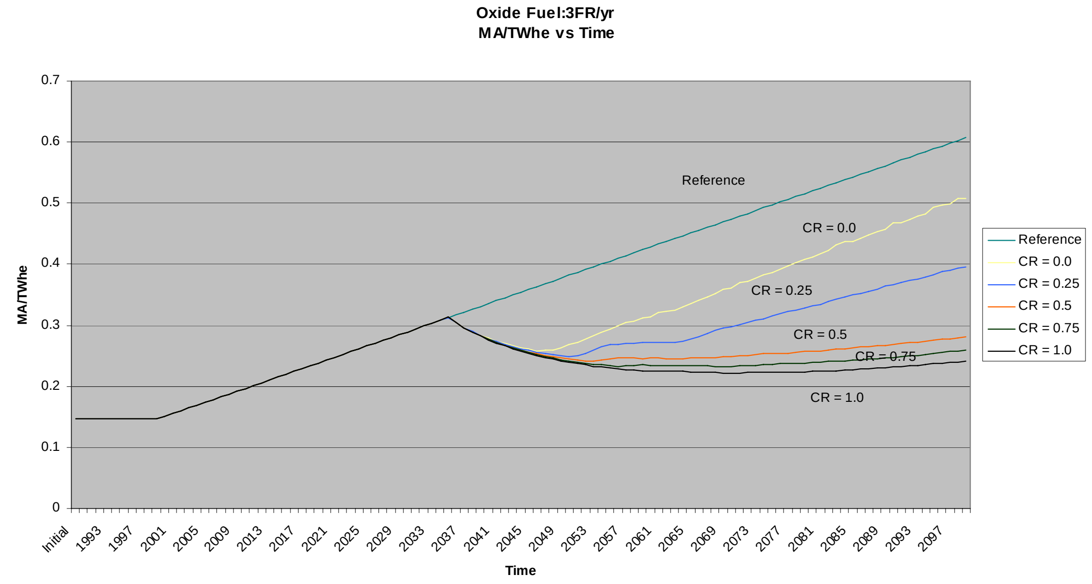


Figure 3.27 Total MA/TWhe (Oxide Fuel: 3 FR/yr)

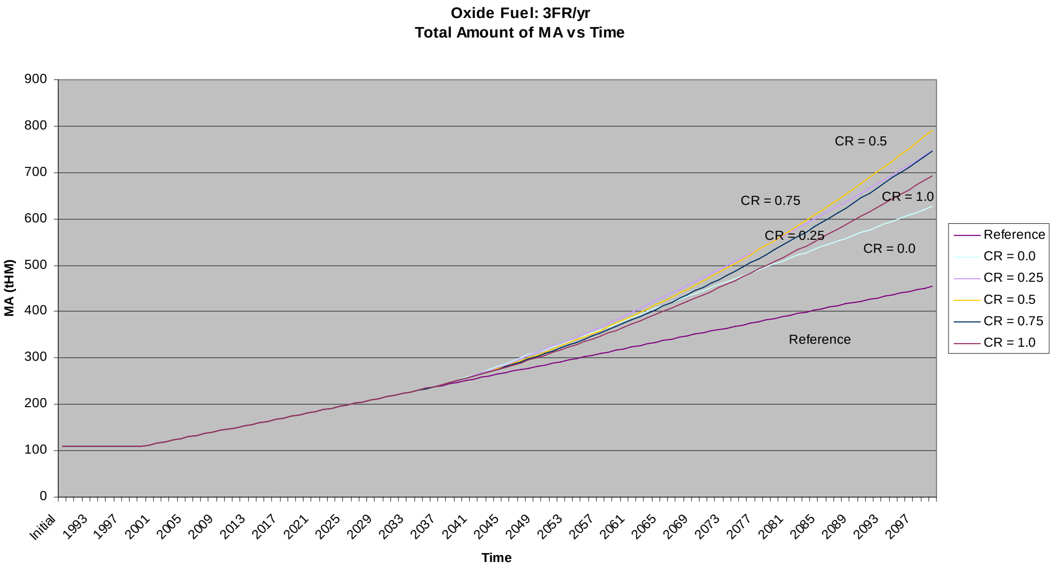


Figure 3.28 Total Amount of MA (Oxide Fuel: 3 FR/yr)

Table 3.21 Oxide Results

Data Taken at the Year 2100	Pu (tHM)			MA (tHM)			# RX		
Run	In-Pile	Out-Pile	Total	In-Pile	Out-Pile	Total	LWR	FR	Total
Oxide Fuel : 3 FR/yr									
CR = 0.0	635	826	1462	18	608	626	105	41	146
CR = 0.25	1195	1517	2712	30	716	746	105	96	201
CR = 0.5	2083	2495	4578	42	750	791	105	175	280
CR = 0.75	2064	2690	4754	40	707	747	105	180	285
CR = 1.0	2101	3529	5630	38	656	694	105	180	285

Table 3.22 Metal Results

Data Taken at the Year 2100	Pu (tHM)			MA (tHM)			# RX		
Run	In-Pile	Out-Pile	Total	In-Pile	Out-Pile	Total	LWR	FR	Total
Metal Fuel : 3 FR/yr									
CR = 0.0	623	762	1384	25	712	737	105	39	144
CR = 0.25	1739	2162	3901	33	700	732	105	112	217
CR = 0.5	2383	2948	5331	43	747	790	105	177	282
CR = 0.75	2372	3859	6231	43	699	742	105	180	285
CR = 1.0	2531	5762	8293	45	688	733	105	180	285

Table 3.23 LWR and Oxide Results

Data Taken at the Year 2100	Pu (tHM)			MA (tHM)			# RX		
Run	In-Pile	Out-Pile	Total	In-Pile	Out-Pile	Total	LWR	FR	Total
Oxide Fuel : 2 FR/yr & 2 LWR/yr									
CR = 0.0	686	1600	2285	28	741	769	233	40	273
CR = 0.25	975	2322	3297	35	791	826	233	72	305
CR = 0.5	1341	3159	4499	39	775	814	233	104	337
CR = 0.75	1292	3404	4696	37	746	783	233	104	337
CR = 1.0	1367	4037	5403	36	724	760	233	108	341

Table 3.24 LWR and Metal Results

Data Taken at the Year 2100	Pu (tHM)			MA (tHM)			# RX		
Run	In-Pile	Out-Pile	Total	In-Pile	Out-Pile	Total	LWR	FR	Total
Metal Fuel : 2 FR/yr & 2 LWR/yr									
CR = 0.0	670	1536	2206	35	847	881	233	39	272
CR = 0.25	1204	2998	4202	34	770	804	233	72	305
CR = 0.5	1470	3686	5156	39	770	809	233	102	335
CR = 0.75	1470	4096	5566	39	742	780	233	104	337
CR = 1.0	1628	5075	6703	41	743	784	233	108	341

the only output value discussed. The Pu inventory is reported for in-pile, actually physically in a reactor, and out-of-pile, in reprocessing, spent fuel storage, HLW, etc. Even with the reduction of the output down to only two parameters, a total of one hundred years for one hundred runs yields an enormous amount of data for each scenario. For the purpose of this paper a sample comparison CDF plot taken at the year 2100 for the Pu in-pile and out-of-pile will be representative of the results obtained. These plots are shown below in Figures 3.29 and 3.30. The complete out put plots for all runs can be found in Appendix D.

In Figure 3.29, it appears that the high burn up LWR scenario has the lowest amount of Pu never exceeding 200 tons of Pu as opposed to the 1000 to 1500 tons that the MOX and FR cases reach. However, this is misleading due to the higher content of Pu in the MOX and FR fuel. Figure 3.30 appears to show very little savings going to the MOX and FR reactors over the high burn up LWR scenario. At the 50% mark on the CDF the FR case is only saving about 200 tons of Pu over the high burn up case and about 600 tons of Pu over the MOX case which when added together with the in-pile results yields roughly identical values for Pu inventory. This plot appears to show that the MOX case is the worst in the Pu savings aspect and the FR is marginally the best. In order to better understand these results additional plots were made normalizing the data over energy produced and are shown below in Figures 3.31 and 3.32. These energy normalized plot yields the same conclusions as the previous results in a much easier to view manner. The FR energy normalized Pu out-of-pile inventory for 50% of the runs is lower than all of the MOX and high Burn up runs and when adjusted for the in-pile inventories the FR

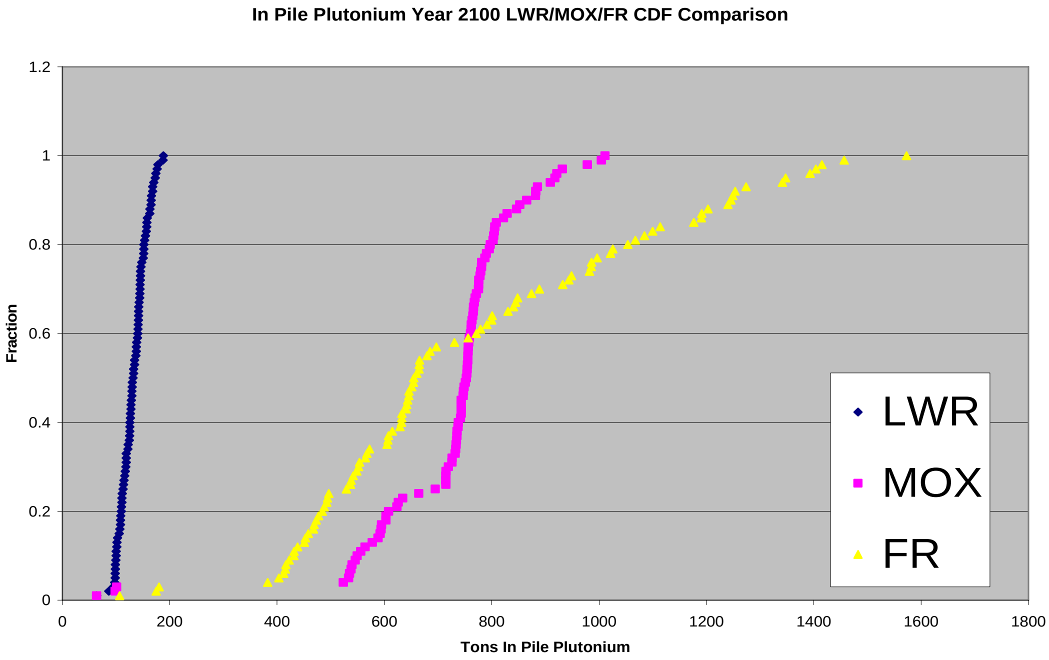


Figure 3.29 Sample Comparison CDF of Results. Pu In-Pile year 2100

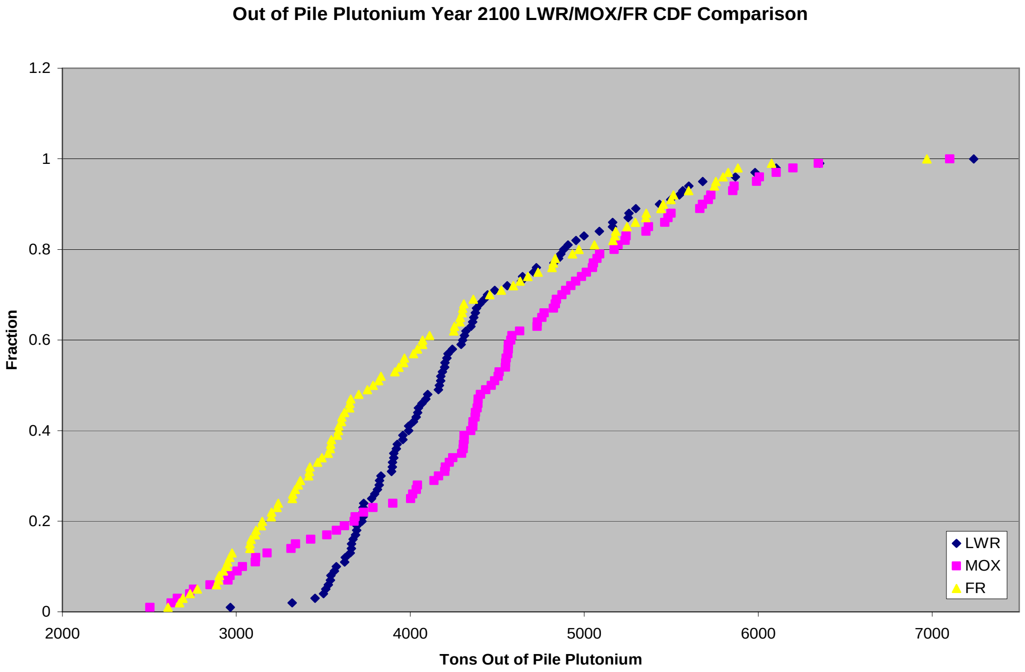


Figure 3.30 Sample Comparison CDF of Results. Pu Out-of-Pile year 2100

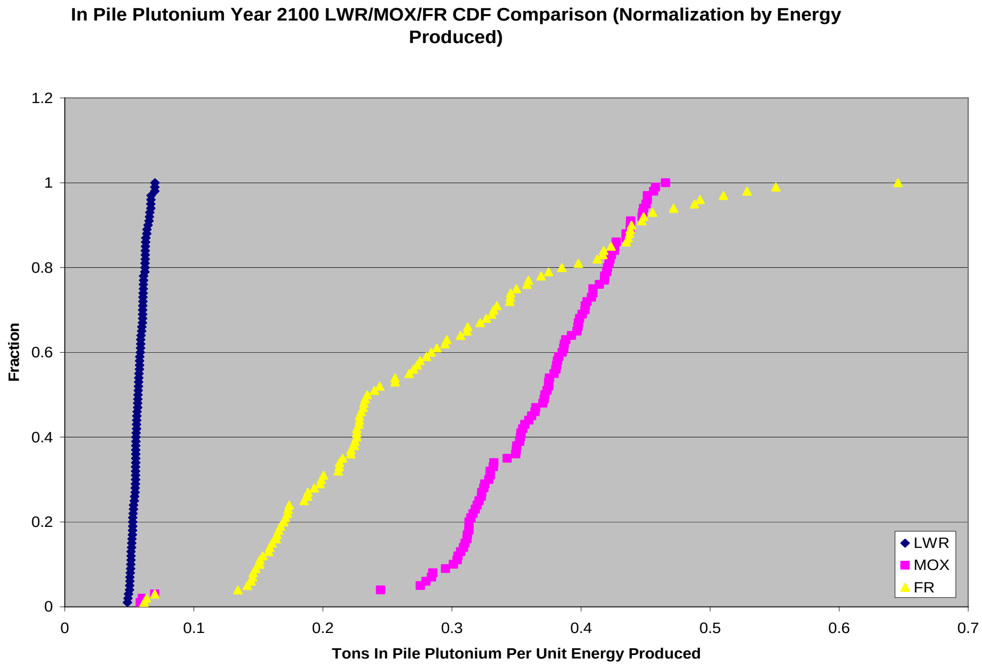


Figure 3.31 Sample Comparison CDF of Results Normalized Over Energy Produced. Pu In-Pile year 2100

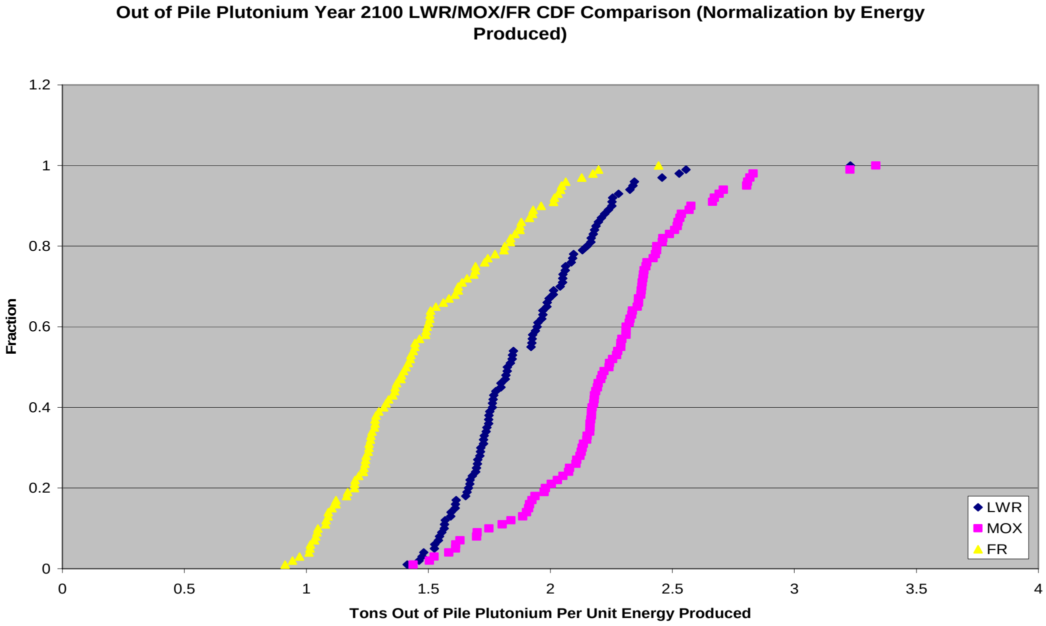


Figure 3.32 Sample Comparison CDF of Results Normalized Over Energy Produced. Pu Out-of-Pile year 2100

scenario comes out slightly ahead of the high burn up scenario. This small Pu savings is further significant when coupled with the fact that a significantly more Pu in the FR scenario is located in-pile and thus in a reactor rather than that of the high burn up scenario where it is out-of-pile. Also as before the MOX case turns out to be the least favorable in terms of Pu inventory for in-pile and out-of-pile inventories.

3.4 Economic Uncertainty

The G4ECONS code run coupled with @RISK coupled to it produced CDFs for the fuel cycle total cost for all three scenarios. These results are shown below in Figure 3.33. As can be seen in the CDF plot, the LWR open cycle is by far the lowest in cost with 80% of the runs coming in cheaper than both of the recycle cases. The FR full recycle comes in second and the MOX partial recycle cycle turns out to be the most expensive. The range of values for the CDF were for the LWR case 5 to 8 mills/kWh, for the FR case 7 to 10 mills/ kWh, and for the MOX cases 7 to 14 mills/kWh This is a very limited uncertainty analysis and is only a preliminary study of the economics of the advanced fuel cycles. Further work needs to be done and should include varying additional parameters varied and a more in-depth break down of the cost structure; however, this initial work added to the Pu inventory uncertainty study would seem to suggest that the MOX cycle is not only the most expensive but the worst at controlling the Pu supply.

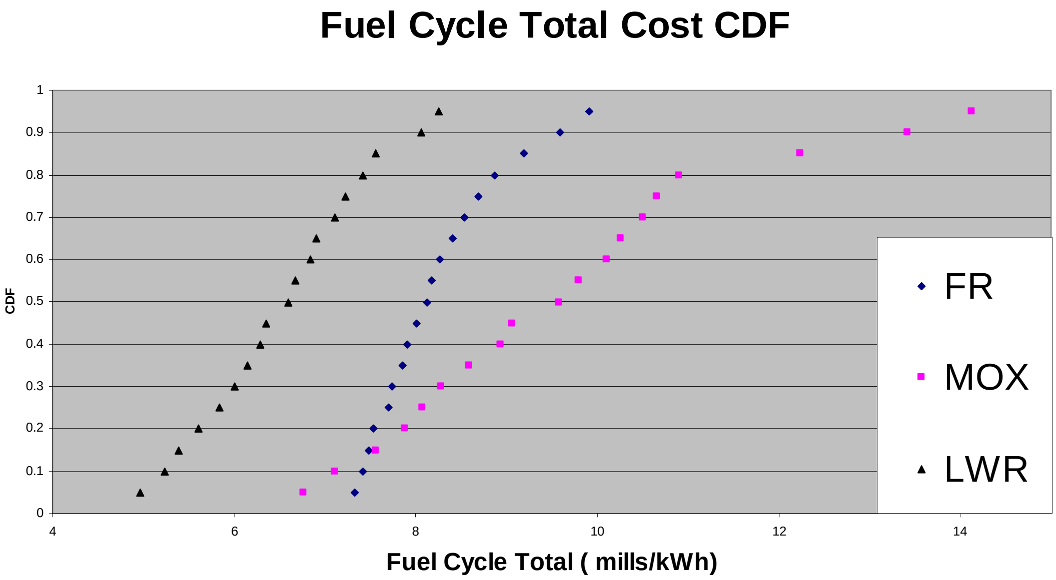


Figure 3.33 CDF of Fuel Cycle Total Cost in mills/kWh

Chapter 4: Conclusions

4.1 *Pu Growth Rate Reduction*

As is shown in all of the scenarios, each of the advanced fuel cycles looked at in this work and previous work can reduce the Pu inventory over that of the current once-through cycle by reducing the growth rate of the Pu inventory. The implementation of a 3 FR/yr with a CR of 0.5 can reduce the amount of Pu by over 36% as compared to building 3 LWR/yr. In addition to reducing the inventory with respect to the reference LWR case, the growth rate can be reduced from an initial 22 tons Pu/ year growth to 5 tons Pu / year growth with the 2030 actual initial Pu inventory implementation cases. The MOX cases keep the Pu/ TWhe inventory slightly above 1 ton Pu/TWhe and the extremely low CR FR cases lower that value even more. However, for these runs the fuel saving issue inside the DANESS code only allows for a small number of low CR FR to be constructed. If additional low CR FR are constructed this value would be lowered by a sizeable amount. Thus from this work the extremely low CR FR scenarios show the greatest ability to control the growing Pu inventory.

4.2 *Uncertainty Analysis*

The uncertainty analysis showed the high burn up cases are comparable with the of the low CR FR cases in there ability to control the Pu inventory with the Pu inventories ranging from 2500 tons of Pu to 7500 tons of Pu. However, for the high burn up cases the majority of the Pu is Out-Of-Pile as opposed to the FR cases where a considerable amount of the Pu is In-Pile. From a proliferation stand point, the low CR FR case is better at the controlling the Pu inventory because the total inventories are relatively the same for the majority of the runs, and the FR cases keep most of the Pu In-Pile rather than the high burn up cases which keep most of it Out-Of-Pile.

4.3 Economics

The economic results show that the once-through cycle is the cheapest with over 50% of the runs coming in cheaper than all of the FR and MOX cases. The range of values for the CDF were for the LWR case 5 to 8 mills/kWh, for the FR case 7 to 10 mills/ kWh, and for the MOX cases 7 to 14 mills/kWh. The FR cases come out to be the next cheapest with the MOX cases being the most expensive.

Chapter 5: Recommendations

Given the results and conclusions shown in this paper, it is the author's recommendation that the best fuel cycle to control the Pu inventory would be to go to a one-tier completely closed fuel cycle utilizing low conversion ratio fast burner reactors of at least CR= 0.5. A significant amount of fast reactors would be needed to reduce the overall Pu inventory; however, with the implementation of just a small number of low CR FR the Pu growth rate can be reduced significantly.

Chapter 6: Future Work

Additional work to be done in the future includes performing simulations utilizing FRs with conversion ratios with a range of burn ups as opposed to the single burn up used for each conversion ratio in this paper, additional realistic models that evaluate the fuel cycle using shut-down and replacement scenarios, the implementation of Two-Tier fuel cycles using MOX and FR. Also the evaluation of the implementation of more advanced technologies such as HTGRs and inert matrix fuels, additional parameters should be varied for the uncertainty analysis, and a more in-depth economic model should to be constructed and evaluated.

References

“Annual Energy Outlook 2006 with Projections to 2030”. Energy Information Administration. February 2006. www.eia.doe.gov/oiaf/aeo/

“Nuclear Waste Disposal for the Future: The Potential of Reprocessing and Recycling”. Nuclear Energy Institute. March 2006

A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00, USDOE, December 2002.

Boardman, C.E., Dubberley, A.E., Yoshida, K., Wu, T. “SuperPRISM Oxide and Metal Core Design”. Proceedings of ICONE 8. April 2000

Cochran, R. G. and Tsoulfanidis. The Nuclear Fuel Cycle: Analysis and Management. American Nuclear Society. 1990

Duderstadt, J. J. and Hamilton L. J. Nuclear Reactor Analysis. John Wiley and Sons, Inc. 1976

Generation IV Nuclear Energy Systems Ten-Year Program Plan,” Volume II: Appendices, DOE Office of Nuclear Energy, Science and Technology, March 2005.

Hill, R. N. and Taiwo, T. A. “Transmutation Impacts of Generation IV Nuclear Energy Systems”. Argonne National Laboratory.

Hill, Robert and Smith, Micheal. “Development and Analysis of a Compact Low-Conversion Ratio Fast Burner Reactor”. Argonne National Laboratory. June 2003

IThink-software by high Performance Systems Inc., http://www.hps-inc.com

Luc Van Den Durpel and Abdellatif Yacout, *Dynamic Analysis of Nuclear Energy System Strategies*, *DANESS*, Argonne National Laboratory (June 2004)

OECD/NEA “Comparative Study of ADS and FR in Advanced Nuclear Fuel Cycles”. 2002

Report to Congress Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary, Prepared by U.S. Department of Energy Office of Nuclear Energy, Science, and Technology, May 2005.

Stacey, W. M. Nuclear Reactor Physics. John Wiley and Sons, Inc. 2001

Sweder, Gary. “Methodology for Uncertainty Analysis of Advanced Fuel Cycles and Preliminary Results.” May 2006

Appendices

Appendix A

Plant Name Docket Number	Reactor Type	Operating License Issued	License Expiration
Arkansas Nuclear 1 5000313	PWR	5/21/1974	5/20/2034
Arkansas Nuclear 2 5000368	PWR	9/1/1978	7/17/2038
Beaver Valley 1 5000334	PWR	7/2/1976	1/29/2016
Beaver Valley 2 5000412	PWR	8/14/1987	6/27/2027
Braidwood 1 5000456	PWR	7/2/1987	10/17/2026
Braidwood 2 5000457	PWR	5/20/1988	12/18/2027
Browns Ferry 1 5000259	BWR	12/20/1973	12/20/2013
Browns Ferry 2 5000260	BWR	8/2/1974	6/28/2014
Browns Ferry 3 5000296	BWR	8/18/1976	7/2/2016
Brunswick 1 5000325	BWR	11/12/1976	9/8/2016
Brunswick 2 5000324	BWR	12/27/1974	12/27/2014
Byron 1 5000454	PWR	2/14/1985	10/31/2024
Byron 2 5000455	PWR	1/20/1987	11/6/2026
Callaway 5000483	PWR	10/18/1984	10/18/2024
Calvert Cliffs 1 5000317	PWR	7/31/1974	7/31/2034
Calvert Cliffs 2 5000318	PWR	11/30/1976	8/13/2036
Catawba 1 5000413	PWR	1/17/1985	12/5/2043
Catawba 2 5000414	PWR	5/15/1986	12/5/2043
Clinton 5000461	BWR	4/17/1987	9/29/2026
Columbia Generating Station 5000397	BWR	4/13/1984	12/20/2023

Plant Name Docket Number	Reactor Type	Operating License Issued	License Expiration
Comanche Peak 1 5000445	PWR	4/17/1990	2/8/2030
Comanche Peak 2 5000446	PWR	4/6/1993	2/2/2033
Cooper 5000298	BWR	1/18/1974	1/18/2014
Crystal River 3 5000302	PWR	1/28/1977	12/3/2016
D.C. Cook 1 5000315	PWR	10/25/1974	10/25/2034
D.C. Cook 2 5000316	PWR	12/23/1977	12/23/2037
Davis-Besse 5000346	PWR	4/22/1977	4/22/2017
Diablo Canyon 1 5000275	PWR	11/2/1984	9/22/2021
Diablo Canyon 2 5000323	PWR	8/26/1985	4/26/2025
Dresden 2 5000237	BWR	2/20/1991	12/22/2029
Dresden 3 5000249	BWR	1/12/1971	1/12/2031
Duane Arnold 5000331	BWR	2/22/1974	2/21/2014
Farley 1 5000348	PWR	6/25/1977	6/25/2037
Farley 2 5000364	PWR	3/31/1981	3/31/2041
Fermi 2 5000341	BWR	7/15/1985	3/20/2025
FitzPatrick 5000333	BWR	10/17/1974	10/17/2014
Fort Calhoun 5000285	PWR	8/9/1973	8/9/2033
Ginna 5000244	PWR	9/19/1969	9/18/2029
Grand Gulf 1 5000416	BWR	11/1/1984	6/16/2022
Harris 1 5000400	PWR	1/12/1987	10/24/2026
Hatch 1 5000321	BWR	10/13/1974	8/6/2034
Hatch 2 5000366	BWR	6/13/1978	6/13/2038

Plant Name **Docket Number**	**Reactor Type**	**Operating License Issued**	**License Expiration**
Hope Creek 1 5000354	BWR	7/25/1986	4/11/2026
Indian Point 2 5000247	PWR	9/28/1973	9/28/2013
Indian Point 3 5000286	PWR	4/5/1976	12/15/2015
Kewaunee 5000305	PWR	12/21/1973	12/21/2013
La Salle 1 5000373	BWR	4/17/1982	4/17/2022
La Salle 2 5000374	BWR	2/16/1983	12/16/2023
Limerick 1 5000352	BWR	8/8/1985	10/26/2024
Limerick 2 5000353	BWR	8/25/1989	6/22/2029
McGuire 1 5000369	PWR	7/8/1981	6/12/2041
McGuire 2 5000370	PWR	5/27/1983	3/3/2043
Millstone 2 5000336	PWR	9/26/1975	7/31/2035
Millstone 3 5000423	PWR	1/31/1986	11/25/2045
Monticello 5000263	BWR	1/9/1981	9/8/2010
Nine Mile Point 1 5000220	BWR	12/26/1974	8/22/2009
Nine Mile Point 2 5000410	BWR	7/2/1987	10/31/2026
North Anna 1 5000338	PWR	4/1/1978	4/1/2038
North Anna 2 5000339	PWR	8/21/1980	8/21/2040
Oconee 1 5000269	PWR	2/6/1973	2/6/2033
Oconee 2 5000270	PWR	10/6/1973	10/6/2033
Oconee 3 5000287	PWR	7/19/1974	7/19/2034
Oyster Creek 5000219	BWR	7/2/1991	4/9/2009
Palisades 5000255	PWR	2/21/1991	3/24/2011

Plant Name Docket Number	Reactor Type	Operating License Issued	License Expiration
Palo Verde 1 5000528	PWR	6/1/1985	12/31/2024
Palo Verde 2 5000529	PWR	4/24/1986	12/9/2025
Palo Verde 3 5000530	PWR	11/25/1987	3/25/2027
Peach Bottom 2 5000277	BWR	10/25/1973	8/8/2033
Peach Bottom 3 5000278	BWR	7/2/1974	7/2/2034
Perry 1 5000440	BWR	11/13/1986	3/18/2026
Pilgrim 1 5000293	BWR	9/15/1972	6/8/2012
Point Beach 1 5000266	PWR	10/5/1970	10/5/2030
Point Beach 2 5000301	PWR	3/8/1973	3/8/2033
Prairie Island 1 5000282	PWR	4/5/1974	8/9/2013
Prairie Island 2 5000306	PWR	10/29/1974	10/29/2014
Quad Cities 1 5000254	BWR	12/14/1972	12/14/2032
Quad Cities 2 5000265	BWR	12/14/1972	12/14/2032
River Bend 1 5000458	BWR	11/20/1985	8/29/2025
Robinson 2 5000261	PWR	9/23/1970	7/31/2030
Saint Lucie 1 5000335	PWR	3/1/1976	3/1/2036
Saint Lucie 2 5000389	PWR	6/10/1983	4/6/2043
Salem 1 5000272	PWR	8/13/1976	8/13/2016
Salem 2 5000311	PWR	5/20/1981	4/18/2020
San Onofre 2 5000361	PWR	9/7/1982	2/16/2022
San Onofre 3 5000362	PWR	9/16/1983	11/15/2022
Seabrook 1 5000443	PWR	3/15/1990	10/17/2026

Plant Name **Docket Number**	**Reactor Type**	**Operating License Issued**	**License Expiration**
Sequoyah 1 5000327	PWR	9/17/1980	9/17/2020
Sequoyah 2 5000328	PWR	9/15/1981	9/15/2021
South Texas 1 5000498	PWR	3/22/1988	8/20/2027
South Texas 2 5000499	PWR	3/28/1989	12/15/2028
Summer 5000395	PWR	11/12/1982	8/6/2042
Surry 1 5000280	PWR	5/25/1972	5/25/2032
Surry 2 5000281	PWR	1/29/1973	1/29/2033
Susquehanna 1 5000387	BWR	11/12/1982	7/17/2022
Susquehanna 2 5000388	BWR	6/27/1984	3/23/2024
Three Mile Island 1 5000289	PWR	4/14/1974	4/19/2014
Turkey Point 3 5000250	PWR	7/19/1972	7/19/2032
Turkey Point 4 5000251	PWR	4/10/1973	4/10/2033
Vermont Yankee 5000271	BWR	2/28/1973	3/21/2012
Vogtle 1 5000424	PWR	3/16/1987	1/16/2027
Vogtle 2 5000425	PWR	3/31/1989	2/9/2029
Waterford 3 5000382	PWR	3/16/1985	12/18/2024
Watts Bar 1 5000390	PWR	2/7/1996	11/9/2035
Wolf Creek 1 5000482	PWR	6/4/1985	3/11/2025

Appendix B

Questionnaire for Uncertainty Analyses of Advanced Fuel Cycle

This expert elicitation is distributed to facilitate uncertainty analyses for a NERI grant on “Uncertainty Analysis of Advanced Fuel Cycles.” Results from this survey will be used to define distributions for parameters used to model fuel cycle scenarios with two codes. One is the DANESS code developed by Argonne National Laboratory and the other is a Matlab code written by a graduate student at The University of Tennessee. The uncertainty analyses will be performed by a Monte Carlo sampling method. Results will be ranked and will be evaluated using non-parametric statistical methods.

If you would like to receive a report on this study please provide your email address. If you feel that you are not qualified to answer a particular question you may leave it blank.

1. If the US production of nuclear power is to remain constant, in what decade will (should) construction of new reactors need to begin?

Will:	2010	2020	2030	2040	2050
	76%	18%	6%	0%	0%
Should:	2010	2020	2030	2040	2050
	94%	6%	0%	0%	0%

2. If the international production of nuclear power is to remain constant, in what decade will (should) construction of new reactors need to begin?

Will:	2010	2020	2030	2040	2050
	100%	0%	0%	0%	0%
Should:	2010	2020	2030	2040	2050
	94%	6%	0%	0%	0%

3. Given the current, and expected, infrastructure for construction of nuclear plants, how many LWRs (on average) will (should) be constructed per year during the next 20 years in the US?

Will:	1	3	7	11	>11
	44%	38%	13%	0%	6%

Should:	1	3	7	11	> 11
	0%	44%	25%	19%	13%

4. Given the current, and expected, infrastructure for construction nuclear plants, how many LWRs (on average) will (should) be constructed per year during the next 20 years in all countries excluding the US?

Will:	5	10	20	30	> 30
	31%	25%	31%	6%	6%
Should:	5	10	20	30	> 30
	0%	38%	31%	19%	13%

5. Given the trend for increased burn up fuels, how high of a burn up will (could) be achieved by PWRs (GWd/ton) during the next 20 years?

Will:	50	60	75	90	>100
	6%	50%	44%	0%	0%
Could:	50	60	75	90	>100
	6%	0%	56%	38%	0%

6. How long will (should) spent LWR fuel need to be cooled before being reprocessed? (years)

Will:	1	5	10	50	100 or more
	0%	7%	33%	60%	0%
Should:	1	5	10	50	100 or more
	0%	56%	25%	13%	6%

7. When do you expect a commercial-sized (~2000 t/yr) reprocessing plant in the US will (should) be completed?

Will:	2020	2030	2040	2050	2060 or later
	6%	35%	41%	6%	12%
Should:	2020	2030	2040	2050	2060 or later
	65%	18%	6%	6%	6%

8. When will (should) a fast reactor be placed in operation relative to the operation of a commercial-sized reprocessing plant?

Will:	10 years before	same year	10 years after	20 years after
	13%	25%	25%	38%
Should:	10 years before	same year	10 years after	20 years after
	24%	29%	29%	18%

9. How many fast reactors (FRs) will (should) be constructed per year on average during a 20 year period following implementation of reprocessing?

Will:	1	2	3	4	>5
	71%	29%	0%	0%	0%
Should:	1	2	3	4	>5
	38%	6%	19%	25%	13%

10. How large of reprocessing plant will need to be constructed to support the operation of 100 LWRs and 50 FRs? (tHM / yr)

1,500	2,000	3,000	5,000	>5,000
0%	25%	56%	19%	0%

11. What FR transuranic conversion ratio should, could or will be designed and operated?

Should:	0.25	0.5	0.75	1.0	>1.0
	24%	18%	12%	18%	29%
Could:	0.25	0.5	0.75	1.0	>1.0
	29%	12%	18%	6%	35%
Will:	0.25	0.5	0.75	1.0	>1.0
	0%	13%	63%	13%	13%

12. What is the expected burn up (GWd/tHM) of FRs with conversion ratios listed below for oxide fuel, including your insight into economic and technology issues?

CR<0.25	80	110	150	180	>180
	18%	9%	18%	27%	27%
CR~0.75	80	110	150	180	>180
	8%	33%	58%	0%	0%
CR~1.0	80	110	150	180	>180
	33%	42%	17%	8%	0%

13. What is the expected burn up (GWd/tHM) of FRs with conversion ratios listed below for metal fuel, including your insight into economic and technology issues?

CR<0.25	80	110	150	180	>180
	18%	9%	9%	36%	27%
CR~0.75	80	110	150	180	>180
	0%	33%	67%	0%	0%
CR~1.0	80	110	150	180	>180
	25%	33%	33%	8%	0%

14. Should MOX fuel be used in thermal reactors?

Yes	No
75%	25%

15. What burn up do you expect for MOX fuel relative to UOX fuel in LWRs?

The same	15 % higher	15 % lower	30 % higher	50 % higher
56%	19%	25%	0%	0%

16. If a reactor is licensed to burn MOX fuel, about what fraction of MOX fuel do you expect will be used relative to UOX fuel if the reactor is designed for a full load of MOX fuel?

10 %	30 %	50%	75%	100%
7%	50%	36%	0%	7%

17. What do you expect a 2000 tHM/year PUREX liquid extraction type reprocessing plant would cost (the reference case)?

$\$10x10^9$	$\$20x10^9$	$\$30x10^9$	$\$40x10^9$	$\$50x10^9$
20%	47%	7%	13%	13%

18. What do you expect a 2000 tHM/yr liquid extraction type reprocessing plant will cost relative to the base case if special effort is made to isolate actinides to achieve a factor of 30 reduction of decay heat in the product sent to the repository?

The same	30 % more	50 % more	100 % more	200 % more
27%	47%	13%	7%	7%

19. When do you expect Yucca Mountain to start accepting waste if it is tied to the current once-through fuel cycle?

2010	2020	2030	2040	>2040
0%	56%	38%	0%	6%

20. Would the adoption of recycling in the US delay or accelerate opening of Yucca Mountain?

Accelerate	Delay	No Impact
12%	35%	53%

21. The 1 mil/kW-hr fee for the waste management fund yields about $400/kg for the amount of spent fuel generated. What do you expect the final cost to be for disposing 70,000 tons of spent fuel (or spent fuel equivalent) in Yucca Mountain relative to funds provided by this fee (please ignore time value of money and cost to the waste management fund ($800/kg) issues)?

0.5	0.75	1.0	1.5	>=2
13%	6%	6%	13%	63%

22. How many tons of spent fuel (or spent fuel equivalent) do you believe will be disposed of in Yucca Mountain?

0	70,000	120,000	200,000	>200,000
0%	19%	19%	38%	25%

23. What do you expect the cost of dry cask storage of spent fuel for 100 years to be per kg of heavy metal relative to the 1 mil/kW-hr fee?

0.2	0.5	1.0	1.5	>2
38%	31%	15%	8%	8%

24. What do you expect the cost of dry cask storage of spent fuel for 200 years to be per kg of heavy metal relative to the 1 mil/kW-hr fee?

0.2	0.5	1.0	1.5	>2
15%	31%	31%	8%	15%

25. If a second U.S. geologic repository is built, how do you think will be the fractional cost relative to Yucca Mountain?

<=0.5	0.7	1.0	1.3	>1.3
19%	25%	13%	6%	38%

26. What would you expect the cost of interim storage of high level waste (or whatever you would like to call it) from a liquid extraction type reprocessing plant for 100 years per metric ton of heavy metal relative to the funds generated by the waste management fee?

<=0.1	0.3	0.5	1	>1
8%	38%	23%	8%	23%

27. What would you expect the cost of interim storage of high level waste (or whatever you would like to call it) from a liquid extraction type reprocessing plant for 200 years per metric ton of heavy metal relative to the funds generated by the waste management fee?

<=0.1	0.3	0.5	1	>1
8%	15%	23%	15%	38%

Appendix C

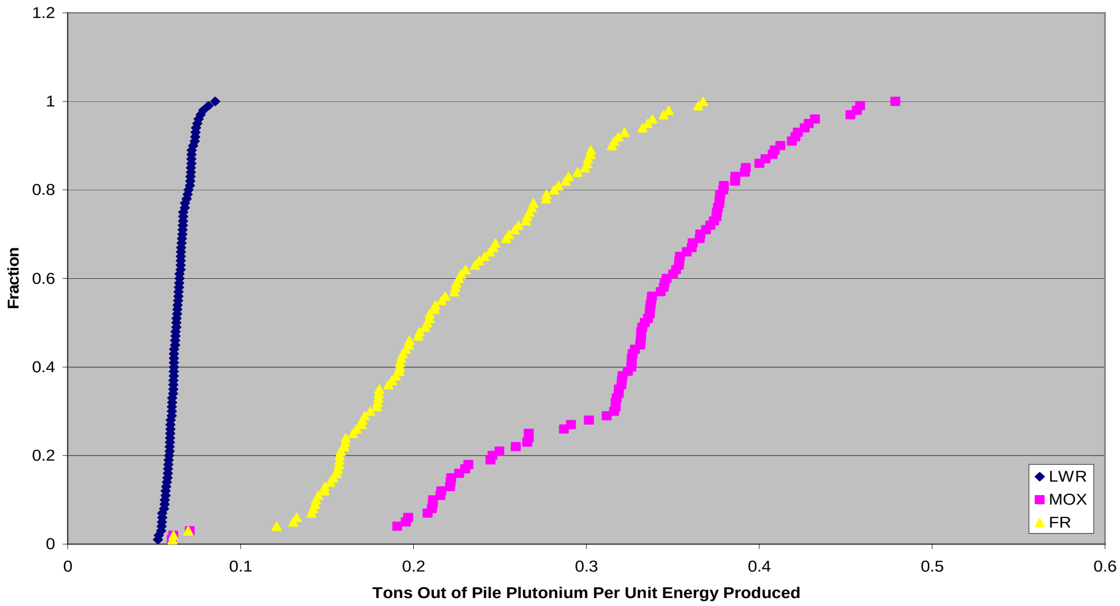
List of @RISK Probability Distributions in G4 ECONS Input

Input	**Open Cycle LWR**	**Partially Closed Cycle MOX**	**Closed Cycle FR**
Capacity factor [%]	min: 50% m likely: 80% max: 100%	min: 50% m likely: 80% max: 100%	min: 50% m likely: 94% max: 100%
Thermal efficiency [%]	5% prob: 32% 95% prob: 34%	5% prob: 32% 95% prob: 34%	5% prob: 41% 95% prob: 43%
Plant life [yr]	95% prob: 60 loc: 35	95% prob: 60 loc: 35	95% prob: 80 loc: 55
Construction time [yr]	5% prob: 4 loc: 3.6	5% prob: 4 loc: 3.6	5% prob: 3.83 loc: 3.45
Discount rate [%]	min: 3% m likely: 5% max: 10%	min: 3% m likely: 5% max: 10%	min: 3% m likely: 3% max: 10%
Decommissioning costs [$M]	5% prob: 250 95% prob: 500	5% prob: 250 95% prob: 500	50% prob: 468 loc: 420
Capital replacement costs [%]	min: 0% m likely: 1% max: 3%	min: 0% m likely: 1% max: 3%	0%
Non-fuel O&M costs [$M/yr]	95% prob: 10 loc: 0	95% prob: 10 loc: 0	0
Refueling period [yr]	5% prob: 1 95% prob: 2	5% prob: 1 95% prob: 2	2.34
U-235 enrichment (virgin) [%]	min: 2.5% m likely: 2.64% max: 2.8%	min: 2.5% m likely: 2.64% max: 2.8%	n/a
U-235 enrichment (reloads) [%]	min: 3.5% m likely: 3.78% max: 4%	min: 3.5% m likely: 3.78% max: 4%	n/a
Uranium ore cost [$/lb]	min: 10 m likely: 12 max: 40	min: 10 m likely: 12 max: 40	n/a
UO2 to UF6 conversion cost (virgin) [$/kgU]	min: 5 m likely: 6 max: 12	min: 5 m likely: 6 max: 12	n/a
REPU to UF6 conversion cost [$/kgU]	n/a	min: 8 m likely: 10 max: 20	n/a

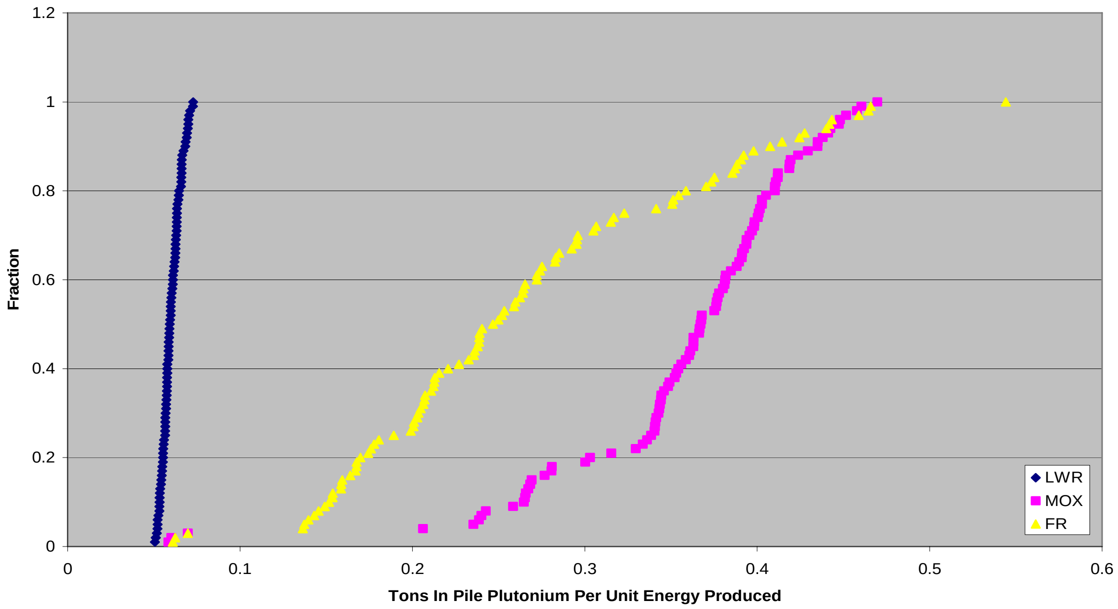
Input	**Open Cycle LWR**	**Partially Closed Cycle MOX**	**Closed Cycle FR**
UF6 enrichment cost (virgin) [$/SWU]	min: 85 m likely: 100 max: 125	min: 85 m likely: 100 max: 125	n/a
UF6 enrichment cost (REPU) [$/SWU]	n/a	min: 100 m likely: 120 max: 150	n/a
Fabrication cost (virgin) [$/kgHM]	min: 170 m likely: 180 max: 275	min: 170 m likely: 180 max: 275	n/a
Fabrication cost (REPU) [$/kgHM]	n/a	min: 200 m likely: 300 max: 300	n/a
DU to DUO2 conversion cost [$/kgU]	n/a	min: 2 m likely: 10 max: 20	n/a
MA fuel fabrication cost [$/kgHM]	0	min: 1500 m likely: 3200 max: 4000	1537
Spent fuel storage cost [$/kgHM]	min: 0 m likely: 0 max: 200	min: 0 m likely: 90 max: 200	40
Spent fuel reprocessing cost [$/kgHM]	n/a	min: 400 m likely: 770 max: 1000	1765
DUF6 tails storage cost [$/kgDU]	99% prob: 8 loc: 0	99% prob: 8 loc: 0	n/a
REPU disposal cost [$/kgU]	n/a	50% prob: 120 loc: 100	n/a
HLW treatment cost [$/kgHM]	n/a	min: 100 m likely: 200 max: 400	3146
TRU treatment cost [$/kgHM]	n/a	min: 2 m likely: 5 max: 10	548
Repository fee [mill/kWh]	min: 100 m likely: 307.5 max: 1920	0	0
Total contingency cost [%]	5% prob: 15% 95% prob: 35%	5% prob: 15% 95% prob: 35%	n/a

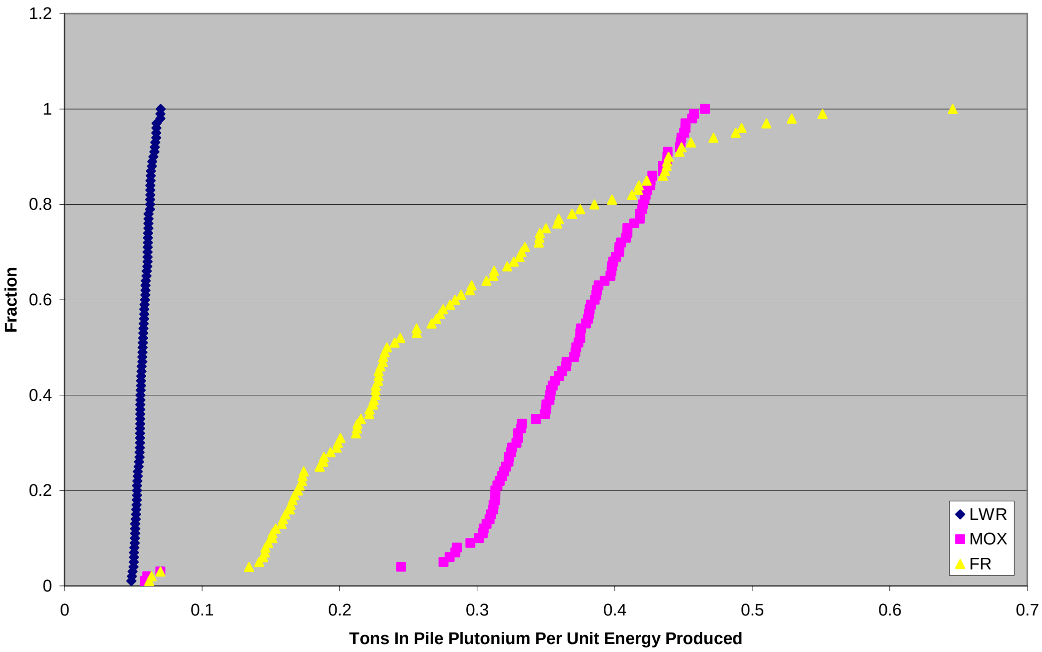
Appendix D

In Pile Plutonium Year 2050 LWR/MOX/FR CDF Comparison (Normalization by Energy Produced)

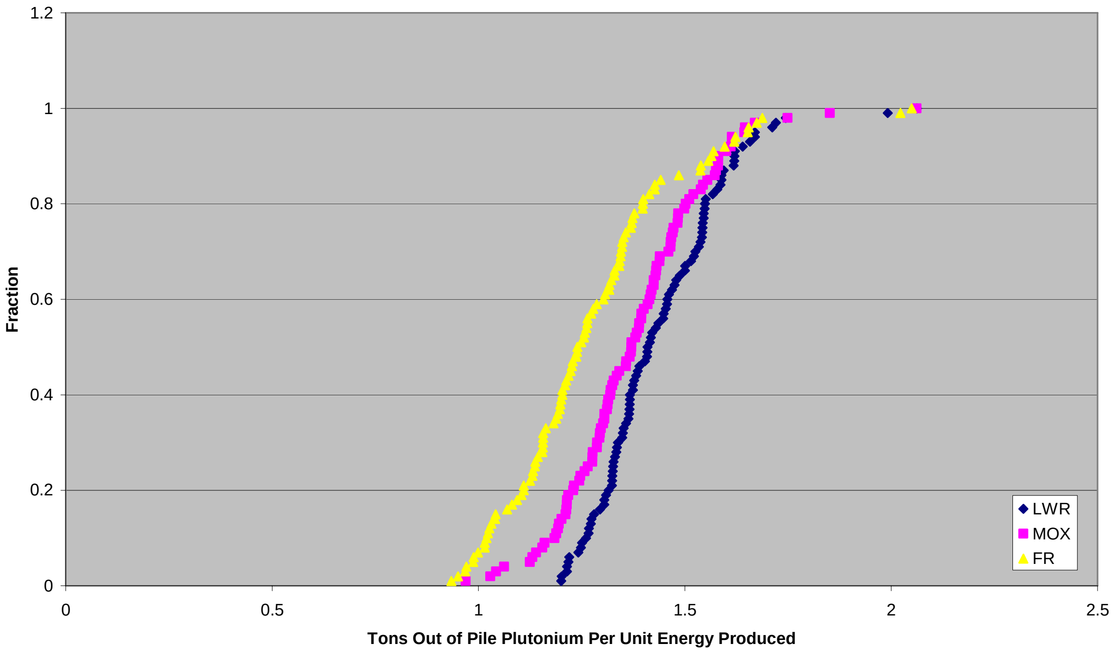


In Pile Plutonium Year 2075 LWR/MOX/FR CDF Comparison (Normalization by Energy Produced)

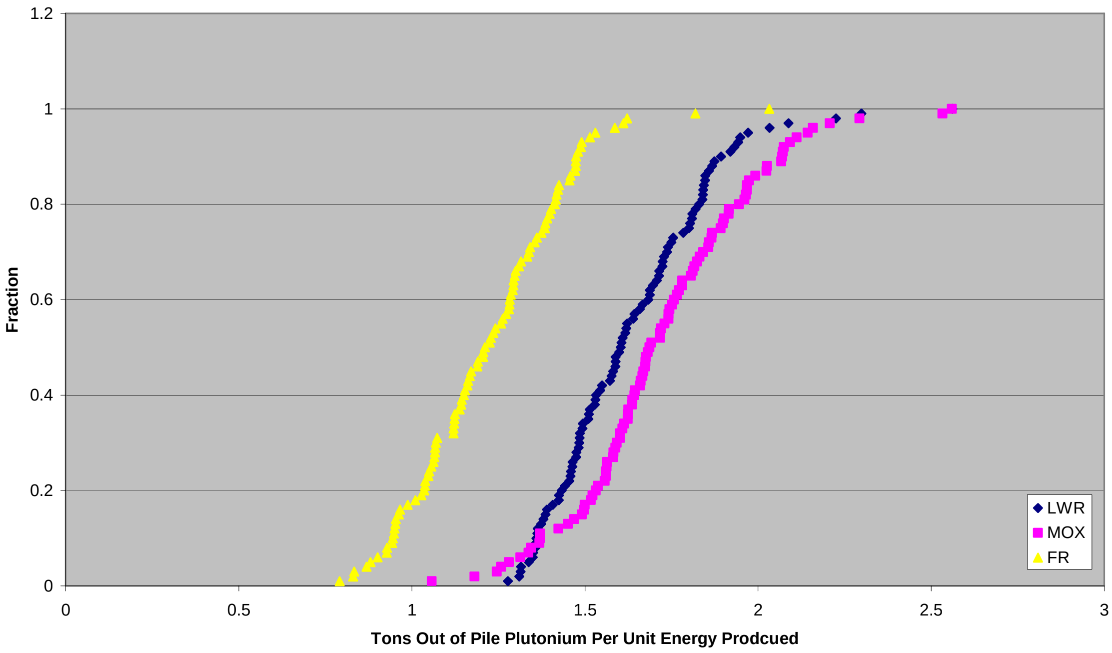


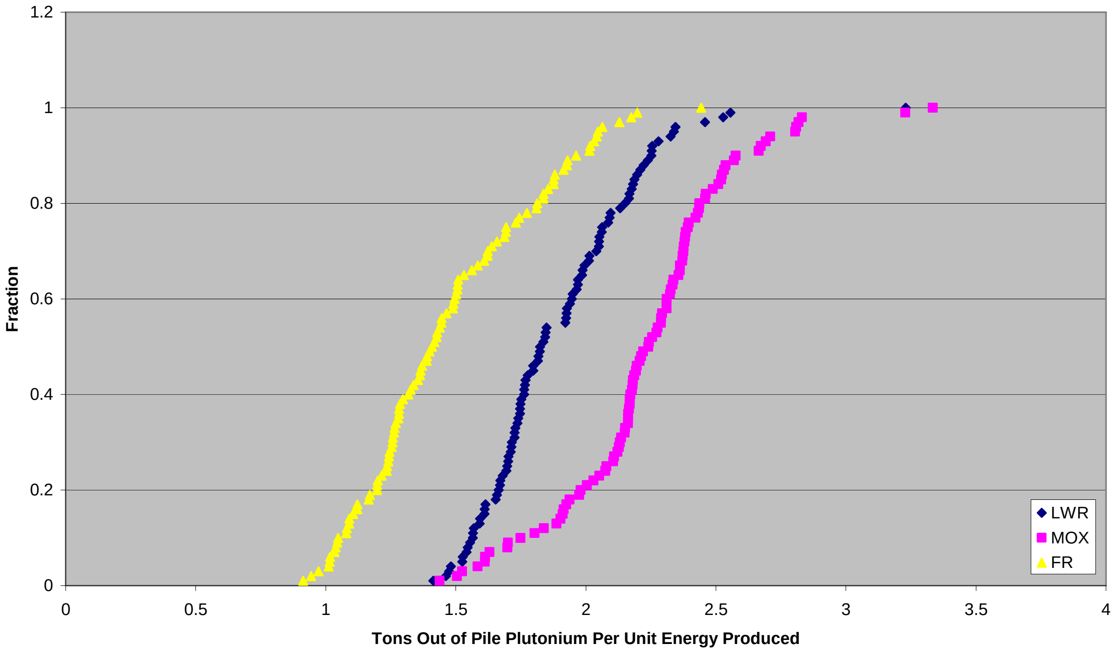


In Pile Plutonium Year 2100 LWR/MOX/FR CDF Comparison (Normalization by Energy Produced)



Out of Pile Plutonium Year 2050 LWR/MOX/FR CDF Comparison (Normalization by Energy Produced)


Out of Pile Plutonium Year 2075 LWR/MOX/FR CDF Comparison (Normalization by Energy Produced)


Out of Pile Plutonium Year 2100 LWR/MOX/FR CDF Comparison (Normalization by Energy Produced)

Vita

Thomas Anderson received his Bachelor of Science in Nuclear Engineering from the University of Tennessee in May, 2006. He continued at the university to complete his Master of Science in Nuclear Engineering in December, 2007.