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Nuclear Fuel Cycle Cost Comparison Between Once-Through and Plutonium Single-Recycling in Pressurized Water Reactors

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REPORT SUMMARY

Within the context of long-term waste management and sustainable nuclear fuel supply, there continue to be discussions regarding whether the United States should consider recycling of light-water reactor (LWR) spent nuclear fuel (SNF) for the current fleet of U.S. LWRs. This report presents a parametric study of equilibrium fuel cycle costs for an open fuel cycle without plutonium recycling (once-through) and with plutonium recycling (single-recycling using mixed-oxide, or MOX, fuel), assuming an all-pressurized water reactor (PWR) fleet. The study examines the impact on fuel cycle costs from changes in the unit costs of uranium, plutonium and uranium recovery by extraction (PUREX) reprocessing, and MOX fuel fabrication. The study also describes the impact associated with changes in the unit costs of UO_2 fuel (natural uranium, conversion, enrichment, and fabrication unit costs), compared to changes in the unit costs associated with MOX fuel (PUREX reprocessing and MOX fuel fabrication).

Background

In technical update report 1015387, *An Economic Analysis of Select Fuel Cycles Using the Steady-State Analysis Model for Advanced Fuel Cycles Schemes (SMAFS)*, published December 2007, EPRI evaluated fuel cycle concepts including the once-through fuel cycle, plutonium recycle with MOX fuel in PWRs, and an advanced fuel cycle that assumed advanced fuel cycle separation technologies and advanced reactors. Since plant capital costs have been depreciated or written off for much of the current fleet of U.S. nuclear power plants, the cost of generating electricity from these plants is comprised of fuel cycle costs and plant operating and maintenance costs. This report examines a range of unit costs for recycling assuming both a private-sector-funded and a government-funded recycling facility, as developed in the analysis contained in EPRI report 1015387.

Objectives

To evaluate fuel cycle costs associated with a once-through fuel cycle compared to a fuel cycle with plutonium recycling using MOX fuel, assuming for both cycles eventual disposal of spent uranium oxide (once-through) or spent mixed-oxide (plutonium recycle) fuel in a geologic repository.

Approach

After adjusting some of the parameters in the SMAFS software, the research team defined key input and output parameters to be used in the parametric cost study. These included nominal costs as well as lower and upper bounding values. The team also generated a summary of the unit costs associated with waste management as well as a summary of the assumptions regarding waste volumes produced for the two fuel cycles evaluated. Finally, they conducted a parametric

study of fuel cycle costs for a once-through fuel cycle and a plutonium-recycle fuel cycle and summarized the results in tabular and graphical forms.

Results

Under the range of fuel cycle unit costs evaluated in this report, unit costs for uranium ore concentrates and PUREX reprocessing have the greatest impact on the overall fuel cycle costs for both fuel cycles. Assuming that other fuel cycle cost components are at the nominal values, the fuel cycle costs for a once-through fuel cycle will be lower than those for a plutonium recycle when the unit costs of uranium are $312/kgU ($120/lb U_3O_8) or lower, and PUREX reprocessing costs are $750/kgHM (kilogram heavy metal) or higher. Variations in the unit cost of uranium have the greatest impact on overall fuel cycle costs. When uranium unit costs increase from $104/kg to $520/kg, the fuel cycle costs increase from 6.54 mills/kWhe to 15.16 mills/kWhe for the once-through fuel cycle, and those for the plutonium recycle increase from 7.86 mills/kWhe to 15.53 mills/kWhe—a 200% or greater increase in overall fuel cycle costs. In scenarios in which the unit cost of uranium is at the top of the range evaluated by EPRI and the unit cost of PUREX reprocessing is at the lower end of the range evaluated, the overall fuel cycle costs for a fuel cycle using plutonium recycle can be lower than those for the once-through fuel cycle. For PUREX reprocessing costs to fall at the lower range of costs, EPRI report 1015387 found that government financing of a reprocessing facility might be necessary.

EPRI Perspective

Based on the analysis presented in EPRI report 1015387 and the analysis in this report, there may not be an economic incentive to recycle SNF in the United States using MOX fuel under current nominal unit costs for front-end nuclear fuel cycle components, PUREX reprocessing, and MOX fuel fabrication. However, other compelling reasons may exist to continue long-term research and development (R&D) associated with eventually closing the fuel cycle in the United States. As a result, EPRI will continue to assess and encourage long-term R&D in this area.

Keywords

Nuclear fuel cycle
Once-through fuel cycle
Plutonium recycle
Fuel cycle cost comparison
Pressurized water reactor (PWR)
Spent nuclear fuel (SNF)
Mixed-oxide fuel (MOX)
Waste management

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1
FRONT-END NUCLEAR FUEL CYCLE COSTS

1.1 Overview

In an EPRI Technical Update published in December 2007, EPRI evaluated alternative fuel cycles to the current U.S. once-through fuel cycle, "*An Economic Analysis of Select Fuel Cycles Using the Steady-State Analysis Model for Advanced Fuel Cycles Schemes (SMAFS).*" (EPRI Report 1015387)[1] The SMAFS Model was developed as part of a 2006 report by the Nuclear Energy Agency entitled *"Advanced Fuel Cycles and Radioactive Waste Management."*[2] EPRI Report 1015387 evaluated fuel cycle concepts including the once-through fuel cycle, plutonium recycle with mixed oxide (MOX) fuel in pressurized water reactors (PWR), and an advanced fuel cycle that assumed advanced fuel cycle separation technologies and advanced reactors. The advanced fuel cycle evaluated was similar to the advanced fuel cycle schemes that were under consideration in the United States (U.S.) by the U.S. Department of Energy (DOE) as part of the Global Nuclear Energy Partnership (GNEP).

EPRI Report 1015387 evaluated fuel cycle costs as part of the total cost of generating electricity using the SMAFS model. In addition, EPRI investigators developed a spreadsheet model to evaluate the potential financing strategies for nuclear fuel recycling facilities that were under consideration as part of the GNEP program. While the GNEP program is no longer pursuing the near-term deployment of an advanced recycling facility in the U.S., long-term research and development efforts regarding advanced fuel cycle schemes continue.

Within the context of long-term waste management and sustainable nuclear fuel supply, there continue to be discussions regarding whether the U.S. should consider recycling of light-water reactor (LWR) spent nuclear fuel (SNF) for the current fleet of U.S. LWRs. Since plant capital costs have been depreciated or written off for much of the current fleet of U.S. nuclear power plants, the cost of generating electricity from these plants is comprised of fuel cycle costs and plant operating and maintenance costs. This report will focus on the evaluation of fuel cycle costs associated with a once-through fuel cycle, described below and shown in Figure 1-1, compared to a fuel cycle with plutonium recycle using mixed oxide (MOX) fuel, as described below and shown in Figure 1-2. A range of unit costs for recycling will be examined assuming both a private-sector funded and a government-funded recycling facility, as developed in the analysis contained in EPRI Report 1015387.

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[1] EPRI, *An Economic Analysis of Select Fuel Cycles Using the Steady-State Analysis Model for Advanced Fuel Cycles Schemes (SMAFS),*" Technical Update 1015387, December 2007 ("*EPRI Report 1015387*").

[2] NEA 2006, Advanced Nuclear Fuel Cycles and Radioactive Waste Management, Nuclear Energy Agency, Organization for Economic Co-Operation and Development, NEA No. 5990, 2006 ("NEA 2006").

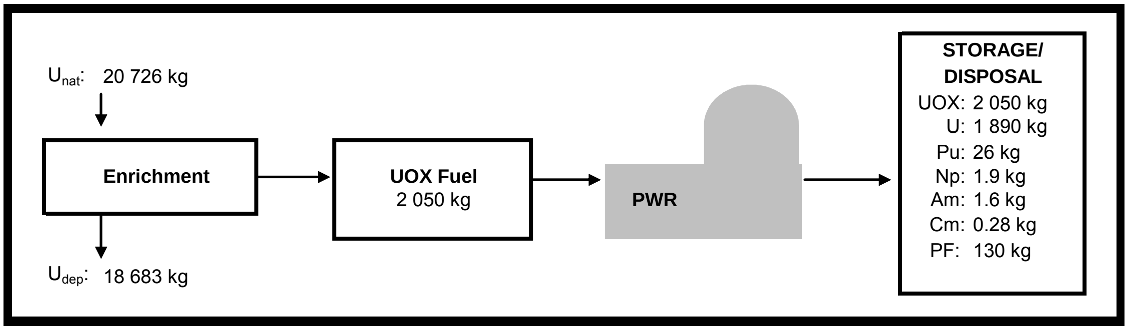

Figure 1-1
Fuel Cycle 1: Once Through Fuel Cycle – Mass Flow Assumptions per Terawatt-hour-electric (TWhe) [Note: PF stands for Fission Products] *(Source: NEA 2006)*

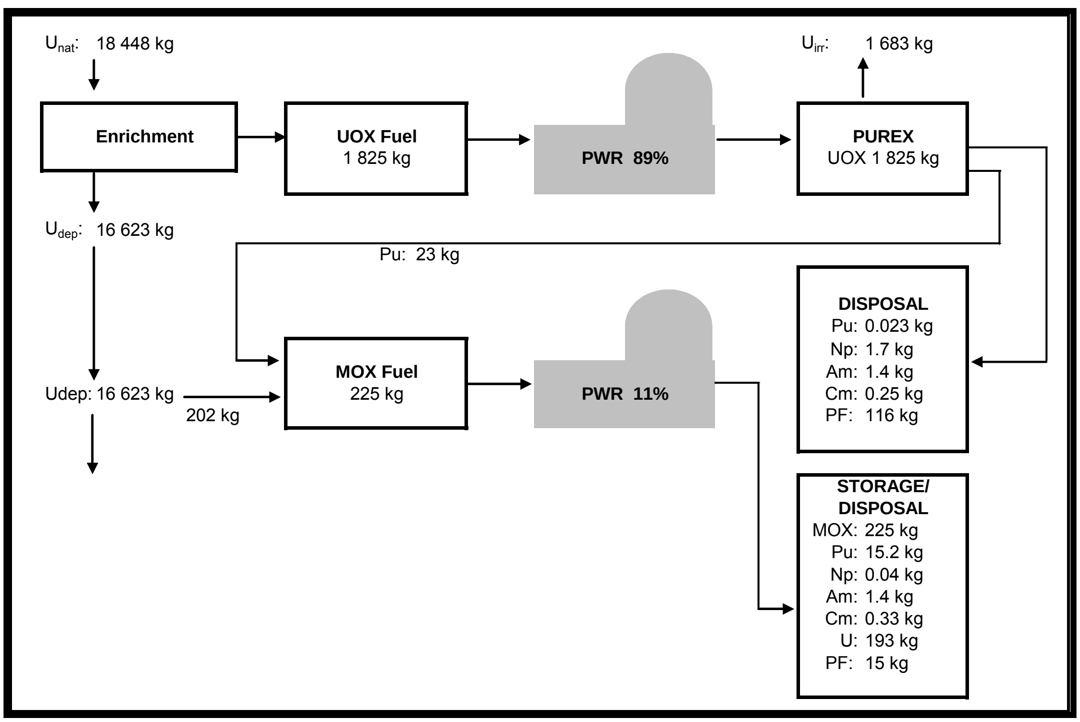

Figure 1-2
Fuel Cycle 2: Plutonium Single Recycling Using MOX Fuel – Mass Flow Assumptions per Terawatt-hour-electric (TWhe) [Note: PF stands for Fission Products]. "PWR 89%" and "PWR 11%" refer to the fraction of total energy supplied by PWRs using only fresh UO_2 and PWRs using MOX fuel, respectively. *(Source: NEA 2006)*

1.2 Fuel Cycles Evaluated

The two fuel cycles evaluated in this report include:

- **Once-Through Fuel Cycle in PWR:** This fuel cycle assumes the use of thermal LWRs and is the current fuel cycle scheme being used in the U.S. For simplicity and consistency with previous analyses (NEA 2006), the once-through fuel cycle assumed in this study relies on the use of 4,250 megawatt-thermal (MWth)/1,450 megawatt-electric (MWe) Pressurized Water Reactors (PWRs) operating on a 12-month cycle at a 90% capacity factor, conventional uranium dioxide (UO_2) fuel, and direct disposal of spent nuclear fuel (SNF) in a geologic repository. This fuel cycle scheme is shown in Figure 1-1. This will be referred to as "Fuel Cycle 1" throughout this report. Fuel Cycle 1 will be used as the reference fuel cycle for comparison with a fuel cycle that utilizes MOX recycle as represented by Fuel Cycle 2, shown in Figure 1-2.

  The SMAFS model assumes that UO_2 fuel will have an average enrichment of 4.90 weight percent (w/o) Uranium-235 (U^{235}) with a burnup of 60 gigawatt-days per metric ton of uranium (GWd/MTU). SNF is assumed to be cooled in the spent fuel storage pool for five years prior to dry storage. The SNF is assumed to remain in dry storage for a period of 50 years prior to disposal.

- **Plutonium Recycle with MOX Fuel in PWR (Pu Recycle)**: In this study, the fuel cycle assumes conventional reprocessing of LWR fuel, similar to current fuel cycle schemes being used in some European and Asian countries. This Pu recycle scheme assumes the use of 1,450 MWe PWRs using UO_2 fuel. The spent UO_2 fuel is subjected to conventional PUREX processing and the separated plutonium (Pu) is recycled in the form of uranium-plutonium MOX fuel in PWRs. Equilibrium fuel cycle costs assume that 89% of the energy for this fuel cycle comes from PWRs utilizing UO_2 fuel and 11% of the energy comes from PWRs utilizing MOX fuel, as shown in Figure 1-2.[3] This fuel cycle assumes disposal of the resulting high-level radioactive waste (HLW) from the PUREX reprocessing step as well as direct disposal of MOX SNF in a geologic repository. This will be referred to as "Fuel Cycle 2" throughout this report.

  The SMAFS model assumes that UO_2 fuel will have an average enrichment of 4.90 weight percent (w/o) U^{235} with a burnup of 60 GWd/MTU. MOX fuel is also assumed to have a burnup of 60 GWd/MTU. UO_2 SNF is assumed to be cooled in the spent fuel storage pool for five years prior to being transported for reprocessing. MOX SNF is assumed to cool for a period of five years prior to dry storage. The resulting HLW from reprocessing UO_2 SNF and the MOX SNF are assumed to remain in dry storage for a period of 50 years prior to disposal.

[3] This results from recycling the plutonium contents from eight spent UO_2 fuel into one fresh MOX fuel assembly. For the latter, depleted uranium (and not reprocessed uranium) provides the make-up uranium. The plutonium content in the MOX assembly is ~10.2 wt%.

In utilizing the SMAFS model, EPRI compared the equilibrium fuel cycle costs for the current U.S. once-through fuel cycle to Pu recycle using MOX fuel. As noted in EPRI Report 1015387, nuclear fuel cycle costs for these two fuel cycles are most sensitive to the unit cost of uranium and the unit cost of reprocessing. The results of a parametric study that examines the impact on fuel cycle costs from changes in the unit costs of uranium, PUREX reprocessing, and MOX fuel fabrication are presented. The parametric study also examines the impact on fuel cycle costs associated with changes in the unit costs for UO_2 fuel (natural uranium, conversion, enrichment and fabrication unit costs) in a range of cost estimates (lower bound, nominal and upper bound) compared to changes in the unit costs associated with MOX fuel (PUREX reprocessing and MOX fuel fabrication).

Chapter 2 provides an overview of the SMAFS model including the input parameters used in this study and key output parameters. Chapter 3 provides a summary of the unit costs for front-end nuclear fuel cycle costs utilized by EPRI in this report, including nominal costs and lower and upper bounding values for each front-end fuel cycle cost component. Also presented is a summary of the unit costs associated with waste management as well as a summary of the assumptions regarding waste volumes produced for the two fuel cycles evaluated. The results of the parametric study of fuel cycle costs for a once-through fuel cycle and a Pu recycle fuel cycle are summarized in Chapter 4 of this report. Conclusions are provided in Chapter 5.

2
OVERVIEW OF THE SMAFS MODEL

The SMAFS model was developed as a part of the Nuclear Energy Agency's (NEA) 2006 study, "*Advanced Fuel Cycles and Radioactive Waste Management*," which focused on the impact that advanced fuel cycles might have on waste management policies. The fuel cycles evaluated in NEA 2006 included current fuel cycles utilized in the U.S., Europe and Asia (once-through and Pu recycle), as well as advanced fuel cycles that involve fast reactors and advanced fuel processing facilities. This chapter provides an overview of the SMAFS model as well as the SMAFS fuel cycle unit cost parameters that were utilized in the parametric analysis of fuel cycle costs associated with a once-through fuel cycle compared to a Pu recycle fuel cycle.

2.1 Key Fuel Cycle and Waste Management Indicators

The SMAFS model was designed to conduct fuel cycle economic analyses and to provide a means of comparing not only costs, but also other key fuel cycle and waste management indicators. The key fuel cycle and waste management indicators, utilized in the SMAFS model for comparison of the various fuel cycle schemes evaluated, include the following indicators as described in NEA 2006:[4]

- Fuel cycle cost – this indicator includes front-end costs as well as waste management costs.
- Total generation cost – this indicator includes the fuel cycle and waste management costs as well as the capital, investment and operating costs of the nuclear reactors considered.
- Uranium consumption – this is driven, in part, by the number of fast reactors in the fuel cycle scheme considered.
- Reduction of transuranics (TRU) in waste (referred to as TRU Loss) – this indicator is dependent upon the amount of multi-recycling in the fuel cycle scheme.
- Activity of the HLW after 1,000 years – this indicator describes the radioactive source term after the decay of heat generating isotopes in HLW.
- Decay heat of the HLW after 50 years, 200 years – this indicator is important in the handling, conditioning and final disposal of SNF and HLW in underground repositories; and also has consequences for fuel reprocessing and transportation.
- HLW and SNF volume to be disposed – this indicator is of some importance in the capacity needed for HLW and SNF disposal facilities.

[4] NEA 2006, p. 13.

As noted in the NEA study, the use of the above indicators in carrying out an economic analysis of a range of fuel cycle schemes is meant to illustrate "through parametric sensitivity cases the impacts of different cost elements, and moreover of the uncertainties on those elements, on the total fuel cycle costs of the various schemes considered."[5] While the SMAFS model examined the broad range of parameters important to a comparison of alternative fuel cycles under evaluation, this analysis by EPRI only examines those parameters associated with fuel cycle costs. Thus, indicators described above regarding total generation costs and waste disposal indicators such as reduction in transuranics, activity and decay heat of HLW and SNF and disposal volumes, will not be discussed further in this report.

2.2 SMAFS Input Parameters

In order to calculate fuel cycle costs for a once-through fuel cycle (Fuel Cycle 1) and Pu Recycle (Fuel Cycle 2), the SMAFS model utilizes the following data input parameters:

- Unit cost parameters associated with fuel cycle costs include:
  - Front-end fuel cycle (natural uranium, conversion, enrichment, fuel fabrication).
  - SNF transport and storage for all fuel types to be transported and stored.
  - Reprocessing (PUREX).
  - Dry storage, packaging and long-term storage for all fuel types considered. Long-term storage costs are for materials such as depleted uranium (DU), and reprocessed uranium (REPU).
  - Waste disposal, including short-lived (SL) and long-lived (LL), low and intermediate level waste [LILW], and SNF and HLW.
- Waste generation parameters associated with:
  - Front-end of the fuel cycle (enrichment and fuel fabrication).
  - Reactor operation: LILW-SL, LILW-LL, and SNF.
  - PUREX reprocessing: LILW-SL, LILW-LL, and HLW.

The SMAFS model includes the waste generation and unit cost parameters that were used in NEA 2006.[6] Unit costs are input as a nominal value (NV), lower bound (LB) and upper bound UB). In addition to the waste generation and cost data, the model also includes mass flows for each fuel cycle considered, and data regarding waste activity, decay heat and neutron sources for SNF and HLW requiring long-term storage and disposal. All of these parameters can be changed by the user.

Chapter 3 of this report will describe the data input parameters used by EPRI in this study for the two fuel cycles modeled, as well as the rationale for the unit costs assumptions made by EPRI in this report. While the model includes the input of cost associated with nuclear waste

[5] NEA 2006, p. 14.

[6] NEA 2006, Appendix L.

management, the results of EPRI Report 1015387 indicated that changes in the waste management unit costs associated with management of fuel cycle waste and the storage, transport and disposal of SNF and high-level radioactive waste (HLW) do not have a significant impact on overall fuel cycle costs. Thus, this report only examines the unit cost components associated with the front-end of the nuclear fuel cycle, including the unit costs for PUREX recycle and MOX fuel fabrication. The nominal unit costs assumed for waste management are summarized in Chapter 3, but these unit costs remain constant throughout this study.

2.3 SMAFS Output

The SMAFS model was designed to calculate equilibrium fuel cycle costs assuming that all reactors in a given fuel cycle scheme operate at constant power and that all mass flows have reached equilibrium.[7] It should be noted that establishing equilibrium conditions may require decades. Regarding fuel cycle costs, the SMAFS model calculates fuel cycle costs, including a detailed breakout of costs for front-end fuel cycle materials; reprocessing, and waste management. Costs are calculated on a mill per kWhe (mill/kWhe) basis as well as on a comparative basis among the fuel cycles analyzed.

Sensitivity analyses are built into the SMAFS model to allow cost sensitivity studies to be performed and to model the comparative costs of the fuel cycles evaluated. However, the detailed comparison of fuel cycle costs in the SMAFS model is calculated only for the nominal unit costs. The sensitivity analysis calculates costs as relative to the costs for Fuel Cycle 1. In this report, EPRI researchers changed the unit costs manually for the fuel cycle cost components being examined in order to have a breakout of fuel cycle costs for the range of unit costs examined. This allowed a more detailed graphic comparison of results as presented in the figures in Chapter 4 of this report.

[7] NEA 2006, p. 21.

3
FRONT-END NUCLEAR FUEL CYCLE UNIT COSTS

The chapter describes projected unit costs assumed by EPRI for the front-end nuclear fuel cycle components examined in this report: natural uranium ore concentrates; conversion of U_3O_8 to UF_6, enrichment of natural UF_6 to enriched UF_6, fabrication of UO_2 fuel assemblies; reprocessing of LWR SNF using the PUREX process; and fabrication of MOX fuel assemblies. The nominal unit costs for the various fuel cycle cost components are based on current nuclear fuel cost indicators, if available, or on other publicly available sources of this information. This chapter also describes the range of unit costs for each front-end fuel cycle component that EPRI assumed in its parametric analysis of overall fuel cycle costs associated with Fuel Cycle 1 and Fuel Cycle 2. The results of EPRI's parametric analysis of overall fuel cycle costs are summarized in Chapter 4.

3.1 Uranium Ore Concentrates

The spot market price for U_3O_8 rose from approximately $14 per pound U_3O_8 in December 2003 to approximately $135/lb U_3O_8 in June 2007.[8] In July 2008, the spot market price for U_3O_8 was approximately $65/lb U_3O_8.[9] EPRI assumes a nominal value of $65/lb U_3O_8 ($169/kgU) for the purposes of calculating nominal fuel cycle costs for Fuel Cycle 1 and Fuel Cycle 2.

In performing its parametric analysis of fuel cycle costs, EPRI assumes that U_3O_8 unit costs will range from a low of $40/lb U_3O_8 ($104/kgU) up to a high of $200/lb U_3O_8 ($520/kgU). As was shown by the results of EPRI Report 1015387, as uranium prices rise, the fuel cycle costs associated with a Pu recycle become more competitive with those for a once-through fuel cycle. Therefore, EPRI utilized a higher upper bound unit cost in this report than was utilized in EPRI Report 1015387 in order to provide a greater range of comparison between Fuel Cycle 1 and Fuel Cycle 2.

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[8] Platts, NuclearFuel, Volume 28, Number 25, December 8, 2003, p. 2; Platts, Nuclear Fuel , Uranium Pricing Supplement, July 6, 2007.

[9] Platts, NuclearFuel, Volume 33, Number 15, July 28, 2008, p. 2.

3.2 Conversion Services

The current spot market price for conversion services is approximately $10/kgU as UF_6.[10] EPRI uses this as its nominal unit cost for conversion services. In performing its parametric study of fuel cycle costs, EPRI assumes UF_6 conversion unit costs will range from $5/kgU to $20/kgU.

3.3 Enrichment Services

The current market price for enrichment services is approximately $150/SWU.[11] EPRI uses this value as its nominal unit cost for enrichment services. In performing its parametric analysis of fuel cycle costs, EPRI assumes that unit costs for enrichment services will range from $90/SWU to $210/SWU.

3.4 Uranium Oxide Fuel Fabrication

Unlike prices for uranium, conversion services, and enrichment services, fuel fabrication unit costs are not contained in regularly published price indicators. The NEA 2006 study assumed UO_2 fuel fabrication unit costs with a nominal value of $250 per kgU. Based on EPRI's knowledge of the nuclear fuel market, a reasonable nominal value for PWR fuel fabrication services is $200/kgU. The unit costs for UO_2 fuel fabrication include the cost to transport fuel from the fabrication facility to nuclear reactor sites. In performing its parametric study of fuel cycle costs, EPRI assumes that unit costs for PWR fuel fabrication services will range from $150/kgU to $250/kgU.

3.5 PUREX Reprocessing

In EPRI Report 1015387, EPRI assumed that the unit costs for reprocessing uranium oxide SNF using the PUREX process had a lower bound value of $700/kgHM, a nominal value of $1,000/kgHM, and an upper bound unit cost of $1,250/kgHM. Based on the analysis in EPRI Report 1015387, EPRI investigators found that depending upon the type of financing strategy utilized to develop a nuclear fuel recycling facility in the U.S., the unit costs would vary as a function of variables such as: whether the facility had government or private-sector financing, the system throughput, operations and maintenance costs, and various financing factors. In this study, EPRI assumed the same nominal unit cost of $1,000/kgHM but expanded the lower and upper bounding unit costs to capture the range of reprocessing unit costs examined in EPRI Report 1015387. The lower bound value used in this report is $500/kgHM and the upper bound value assumed is $1,500/kgHM.

[10] Ibid.

[11] Ibid.

3.6 MOX Fuel Fabrication

In EPRI Report 1015397, EPRI utilized the unit costs for MOX fuel fabrication that were assumed in NEA 2006. In this report, EPRI utilizes the same nominal unit cost for MOX fuel fabrication of $1,250/kgHM. The unit costs for MOX fuel fabrication include the cost for land transport of MOX fuel from the fuel fabrication facility to nuclear reactor sites. In addition, EPRI assumed a lower bounding unit cost of $750/kgHM and an upper bounding unit cost of $1,750/kgHM.

3.7 Waste Management Costs and Parameters

As discussed in EPRI Report 1015387, changes in the unit costs associated with waste management do not have a significant effect on overall fuel cycle costs. Thus, this report uses the nominal waste management costs assumed in EPRI Report 1015387. These unit costs are described below as well EPRI's assumptions regarding volumes of SNF, HLW and low and intermediate level (LILW) radioactive wastes requiring disposal for both fuel cycles. A breakout of the waste management costs is provided to clearly summarize the waste management costs comparison between Fuel Cycle 1 and Fuel Cycle 2.

3.7.1 Waste Management Unit Costs

As noted in Chapter 2, this report only examines the impact of changes to the unit cost components associated with the front-end of the nuclear fuel cycle, PUREX recycle, and MOX fuel fabrication. The nominal unit costs for waste-management-related components are described below. The bases for these nominal unit costs are discussed in more detail in EPRI Report 1015387. These unit costs remain constant throughout this study.

- Uranium oxide SNF storage: fixed cost of $50/kgHM plus $5/kgHM per year of wet interim storage
- MOX SNF: a fixed cost of $90/kgHM plus $7.5/kgHM per year of wet interim storage
- Dry storage of uranium oxide SNF: $150/kgHM
- Dry storage of MOX SNF: $300/kgHM
- Dry storage of PUREX HLW: $120,000/$m^3$
- UO_2 SNF transport: $100/kgHM
- MOX SNF transport: $188/kgHM
- Disposal packaging for uranium oxide SNF: $200/kgHM
- Disposal packaging for MOX SNF: $400/kgHM
- Disposal packaging for PUREX HLW: $200,000/$m^3$
- Short-lived LILW (LILW-SL) disposal: $2,000/$m^3$
- Long-lived LILW (LILW-LL) disposal: $6,000/$m^3$

- Unit volume of disposal galleries/drifts to be excavated for heat generating waste: 41 m^3/kW
- Unit cost for disposal galleries/drifts for SNF & HLW: \$2,500/m^3

3.7.2 Waste Management Volumes

The SMAFS model includes assumptions regarding volumes of LILW, HLW, and SNF produced during the front end of the nuclear fuel cycle, during reactor operations, and as a result of reprocessing operations. According to NEA 2006, the volume of HLW for the once-through fuel cycle "corresponds to the volume of the fuel element."[12] Regarding Fuel Cycle 1, EPRI found that the volume for PWR SNF contained in the SMAFS model, 4.1 m^3 per terawatt hour electric (TWhe), representing 3.981 fuel assemblies is incorrect. A typical PWR fuel assembly has a volume of approximately 0.188 m^3. This would result in a volume of 0.75 m^3 for the 3.981 fuel assemblies assumed in the SMAFS model. In Fuel Cycle 2, the volume of MOX fuel assemblies would also be changed to 0.08 m^3 (assuming that MOX recycle represents 11% of Fuel Cycle 2 energy as noted in Section 1.2). These values are shown in Table 3-1, in terms of volume of waste per TWhe).

EPRI also made changes to the assumptions for the volumes of waste resulting from reprocessing in Fuel Cycle 2. The SMAFS model assumed that 1,825 kgU of UO_2 fuel is reprocessed, resulting in 119.37 kg of HLW, requiring 2.592 HLW canisters per TWhe of energy produced. According to a 2005 report by the French waste management authority, ANDRA, the volume of a "standard canister of vitrified waste" is 0.175 m^3. Thus, 2.592 HLW canisters would have a volume of 0.45 m^3/TWhe, as shown in Table 3-1.[13] The SMAFS model assumed a HLW volume of 0.234 m^3/TWhe. EPRI's analysis of fuel cycle costs for Fuel Cycle 2 relies on the values from ANDRA.

In addition, the SMAFS model assumed that the volume of LIWL-LL would be 0.8 m^3/MTHM. Based on the 2005 ANDRA report, the volumetric ratio between HLW and LILW-LL produced during reprocessing operations is 1.55 for low heat loading glass formulation and 2.0 for high heat loading glass formulation. Given the assumption that spent fuel will have burnups of 60 GWd/MTU, the high-heat-loading parameter is appropriate. Therefore, if the volume of HLW produced by recycling 1,825 kgU of UO_2 fuel in Fuel Cycle 2 is 0.45 m^3/TWhe, then the volume of LILW-LL produced will be 0.9 m^3/TWhe. This is equivalent to 0.493 m^3/MTHM, compared to 0.8 m^3/MTHM assumed in the SMAFS model. Regarding the amount of LILW-SL produced during reprocessing, EPRI consulted an October 2005 study from the U.K. waste management agency, NIREX, and the Department of Environment, Food and Rural Affairs (DEFRA).[14] This study assumed that a volume of 1.67 m^3/MTHM of LILW-SL, or

[12] NEA 2006, p. 68.

[13] ANDRA, "Référentiel de connaissance et modèle d'inventaire des colis de déchets à haute activité et à vie longue" June 2005, (ANDRA 2005), p. 86

[14] U.K. DEFRA and NIREX, "The 2004 UK Radioactive Waste Inventory Main Report," DEFRA/RAS/05.002, NIREX Report N/090, October 2005.

3.05 m^3/TWhe, would be produced from reprocessing of UO_2 SNF, as shown in Table 3-1. The SMAFS model used a value of 1.21 m^3/MTHM.

As shown in Table 3-1, the values of LILW-SL produced during the front end of the fuel cycle were 1.86 m^3/TWhe for Fuel Cycle 1 and 1.80 m^3/TWhe for Fuel Cycle 2 (this includes waste from front-end fuel cycle plus that from MOX fabrication). No LILW-LL was assumed to be produced during the front-end of the fuel cycle for Fuel Cycle 1; however, 0.14 m^3/TWhe of LILW-LL was assumed to be produced during MOX fabrication in Fuel Cycle 2. During reactor operations, both Fuel Cycle 1 and Fuel Cycle 2 were assumed to produce 12.8 m^3/TWhe of LILW-SL and 0.30 m^3/TWhe of LILW-LL.

Table 3-1
Comparison of Waste Volumes Produced (m^3/TWhe)

Waste Parameter	Fuel Cycle 1			Fuel Cycle 2		
	LILW-SL	LILW-LL	SNF	LILW-SL	LILW-LL	SNF/HLW
Front-End Fuel Cycle	1.86	--	--	1.66	--	--
Reactor Operations	12.80	0.30	--	12.80	0.30	--
Reprocessing	--	--	--	3.05	0.90	--
MOX Fabrication	--	--	--	0.14	0.14	--
SNF (UO_2 and MOX)	--	--	0.75	--	--	0.08
HLW	--	--	--	--	--	0.45
Total Volumes:	**14.66**	**0.30**	**0.75**	**17.65**	**1.34**	**0.53**

3.7.3 Waste Management Cost Summary

Using the waste management unit costs and waste volumes discussed above, EPRI calculated total waste management costs of 1.39 mills/kWhe for Fuel Cycle 1 and 1.17 mills/kWhe for Fuel Cycle 2. As shown in Table 3-2, waste management costs for Fuel Cycle 1 include the costs of interim wet storage of SNF at reactor sites prior to dry storage (0.15 mills/kWhe), SNF dry storage for a 50-year period (0.31 mills/kWhe), and the costs to transport SNF after dry storage to the permanent repository where disposal packaging is performed in surface facilities and permanent disposal in the underlying geologic formation (0.21 mills/kWhe). Waste management costs also include costs for packaging (0.41 mills/kWhe) and disposal (0.22 mills/kWhe) costs. SNF dry storage and SNF packaging costs are based on the weight of SNF stored. The cost of disposal is associated with the volume of excavated disposal galleries and is based on the thermal load of the SNF being disposed, as summarized in Section 3.7.1. Waste management costs also include costs for LILW-SL and LILW-LL disposal (0.03 mills/kWhe) and depleted uranium (DepU) storage (0.07 mills/kWhe). EPRI assumed that the cost for LILW disposal costs includes the cost to transport waste to disposal facilities.

Table 3-2
Comparison of Waste Management Cost Components for Fuel Cycle 1 and Fuel Cycle 2

Cost Component	Fuel Cycle 1 (mills/kWhe)	Fuel Cycle 2 (mills/kWhe)
SNF Wet Storage	0.15	0.17
SNF Dry Storage	0.31	0.07
SNF Transport	0.21	0.22
SNF Packaging	0.41	0.09
SNF Disposal	0.22	0.09
HLW Transport		0.16
HLW Dry Storage		0.05
HLW Packaging		0.09
HLW Disposal		0.12
LILW-SL, LILW-LL Disposal	0.03 0.04	
Storage of DepU, RepU	0.07	0.07
Total Waste Management	1.39 1.17	
Numbers may not add exactly due to rounding.		

In Fuel Cycle 2, the cost of 0.17 mills/kWhe for SNF wet storage includes PWR SNF interim wet storage prior to reprocessing (0.14 mills/kWhe), MOX SNF interim wet storage prior (0.03 mills/kWhe) and MOX dry storage (0.07 mills/kWhe) prior to transport for permanent disposal (0.03 mills/kWhe). As shown in Table 3-2, SNF transport cost of 0.22 mills/kWhe includes transporting PWR SNF to the reprocessing facility (0.18 mills/kWhe) as well as the cost of transporting MOX SNF to the permanent repository (0.04 mills/kWhe).

Other cost components included in Fuel Cycle 2 waste management costs are MOX packaging (0.09 mills/kWhe) and disposal (0.09 mills/kWhe); HLW dry storage (0.05 mills/kWhe), packaging (0.09 mills/kWhe) and disposal (0.12 mills/kWhe). HLW dry storage and packaging costs are based on the volume of HLW stored (0.45 m^3/TWhe). HLW disposal costs are based on the volume of the excavated disposal galleries per kilowatt of HLW disposed. Waste management costs also included the cost for LILW- SL and LILW-LL disposal (0.04 mills/kWhe); and storage of DepU and reprocessed uranium (RepU) (0.07 mills/kWhe). EPRI assumed that the cost for LILW disposal costs includes the cost to transport waste to disposal facilities.

The SMAFS model omitted the transportation costs associated for transport of canistered HLW from the reprocessing facility to a permanent repository. As noted in Section 3.7.2, Fuel Cycle 1 utilizes 2,050 kgU/TWhe of PWR SNF, with a volume of 0.75 m^3 and the recycle of 1,825 kgU of PWR SNF in Fuel Cycle 2 produces a volume of 0.45 m^3 of canistered HLW. The cost to transport the PWR SNF was calculated to be 0.21 mills/kWhe. If it is assumed that the cost to transport 0.45 m^3 of canistered HLW is proportional to the cost to transport 0.75 m^3 of PWR SNF, the HLW transport cost would be 60% of the PWR SNF transport cost, or 0.13 mills/kWhe. As noted below, canistered HLW will have a similar heat content to the PWR SNF from which it originated. If it is assumed that the cost of transporting HLW would be the same as the cost to transport the PWR SNF from which it originated (assuming $100/kgHM from Section 3.7.1), the cost of transporting the canistered HLW that result from reprocessing 1,825 kgHM of SNF is estimated to be 0.18 mills/kWhe. Thus, EPRI estimates that the cost to transport canistered HLW will fall within this range of 0.13 to 0.18 mills/kWhe. For the purposes of this study, EPRI assumes an average cost of 0.16 mills/kWhe, as shown in Table 3-2. Including the cost to transport canistered HLW to a repository with the waste management costs discussed above, total waste management costs for Fuel Cycle 2 are 1.17 mills/kWhe.

Examining the costs to dispose of SNF and HLW, the disposal costs for Fuel Cycle 1 are 0.22 mills/kWhe and for Fuel Cycle 2 are 0.21 mills/kWhe (0.09 + 0.12 mills/kWhe). Since the disposal costs are related to the volume of excavated material per kW of waste disposed, these costs appear to be reasonable since the HLW will have a similar heat content to SNF with a similar cooling time. The greatest difference in overall waste management costs between Fuel Cycle 1 and Fuel Cycle 2 are associated with dry storage and packaging of SNF and HLW prior to disposal. The costs for dry storage and packaging of 2,050 kgU of UO_2 SNF in Fuel Cycle 1 are 0.72 mills/kWhe. The costs for dry storage and packaging of 225 kgU of MOX SNF are 0.16 mills/kWhe and the costs for dry storage and packaging of 0.45 m^3 of HLW are 0.14 mills/kWhe. The total dry storage and packaging costs for SNF and HLW in Fuel Cycle 2 are 0.30 mills/kWhe – 42% of the costs for dry storage and packaging under Fuel Cycle 1.

3.8 Nominal Fuel Cycle Costs for Fuel Cycle 1 and Fuel Cycle 2

Using the nominal unit costs for the fuel cycle parameters discussed above, EPRI calculated nominal fuel cycle costs for a Fuel Cycle 1, a once-through fuel cycle, and Fuel Cycle 2, Pu recycle. The nominal equilibrium fuel cycle costs for these two fuel cycles are presented in Table 3-3. The SMAFS model calculates fuel cycle costs proportionally to the mass flows of nuclear fuel cycle materials in the various fuel cycle scenarios. Since the mass flows in the SMAFS model are normalized to the amount needed to produce one TWhe, the fuel cycle costs are also normalized.

Table 3-3
Comparison of Fuel Cycle Costs for Fuel Cycle 1 and Fuel Cycle 2 Using Nominal Front-End Unit Costs

Cost Component	Nominal Unit Cost	Fuel Cycle 1 (mills/kWhe)	Fuel Cycle 2 (mills/kWhe)
Uraniu	$65/lb U_3O_8 3.50		3.12
Conversio	$10/kgU 0.21		0.18
Enrichme	$150/SWU 2.37		2.11
UO_2 Fuel Fabricatio	$200/kgU 0.41		0.37
PUREX Recycle	$1,000/kgHM		1.83
MOX Fuel Fabrication	$1,250/kgHM		0.28
Waste Management	1.39		1.17
Total		7.88 9.06	

As noted in Section 1.2, Fuel Cycle 1 is based on a 1,450 MWe PWR operating on a 12-month cycle at a 90% capacity factor. The SMAFS model assumes the PWR fuel has an initial enrichment of 4.9 w/o U-235 and a burnup of 60 GWd/MTU. Review of the SMAFS model indicates there are no assumed material losses during nuclear fuel processing. The total calculated fuel cycle costs for Fuel Cycle 1 of 7.88 mills/kWhe (6.49 mills/kWhe for front-end costs) are somewhat lower than calculated by EPRI in a recent parametric analysis of front-end fuel cycle costs.[15] This difference is due in part to the assumed uranium requirements, burnup and enrichment in the SMAFS model.

Fuel Cycle 2 assumes the use of a 1,450 MWe PWR using UO_2 fuel. The spent UO_2 fuel is processed with conventional PUREX reprocessing and the separated plutonium is recycled in the form of MOX fuel to be utilized in a second PWR. Equilibrium fuel cycle costs assume that 89% of the energy for this fuel cycle comes from the PWR utilizing UO_2 fuel and 11% of the energy comes from the PWR utilizing MOX fuel. Overall fuel cycle cost for Fuel Cycle 2 is 9.06 mills/kWhe, assuming the nominal unit costs discussed above. The overall fuel cycle costs for Fuel Cycle 2 are 15% higher than the nominal fuel cycle costs for Fuel Cycle 1. If one only compares the front-end fuel cycle costs plus the cost of recycling without waste management costs, the fuel cycle costs for Fuel Cycle 2 are 7.89 mills/kWhe compared to 6.49 mills/kWhe for Fuel Cycle 1 – a 22% increase in front-end costs.

[15] *Parametric Study of Front-End Fuel Cycle Costs.* EPRI, Palo Alto, CA: 2009. 1018574

4
IMPACT OF CHANGES IN FUEL CYCLE COST COMPONENTS ON OVERALL FUEL CYCLE COST

This chapter summarizes EPRI's parametric analysis of fuel cycle costs for a once-through fuel cycle compared to Pu recycle. As determined in EPRI Report 1015387, the fuel cycle costs for these two fuel cycles are most sensitive to changes in the unit costs of uranium concentrates and PUREX reprocessing. Since overall fuel cycle costs are not particularly sensitive to changes in the unit costs for conversion services or UO_2 fuel fabrication, this analysis does not include any sensitivity studies that vary these two parameters individually. EPRI also examined the impact of changing multiple fuel cycle parameters, such as the price of uranium and the unit cost of PUREX reprocessing, on the overall fuel cycle costs for the two fuel cycles evaluated.

4.1 Impact of Change in Unit Cost of U_3O_8

Assuming that the unit costs for other fuel cycle components remain at the nominal values described in Chapter 2, EPRI varied the unit costs for U_3O_8 from \$104/kgU (\$40/lb U_3O_8) to \$520/kgU (\$200/lb U_3O_8). Over this range of unit costs for U_3O_8, the overall fuel cycle costs for Fuel Cycle 1 range from 6.54 mills/kWhe at \$104/kgU up to 15.16 mills/kWhe at \$520/kgU. Overall fuel cycle cost for Fuel Cycle 2 range from 7.86 mills/kWhe when the unit cost of U_3O_8 is \$104/kgU and rises to \$15.53 mills/kWhe when the unit cost is \$520/kgU. Overall fuel cycle costs for Fuel Cycle 2 are approximately 20% higher than those for Fuel Cycle 1 at the lower range of uranium unit costs and are less than 3% higher than those for Fuel Cycle 1 at the highest range of uranium unit costs evaluated (\$520/kgU), as presented in Figure 4-1. Thus, assuming that all other unit costs are at the nominal values, Pu recycle may be cost effective if uranium prices exceed approximately \$520/kgU.

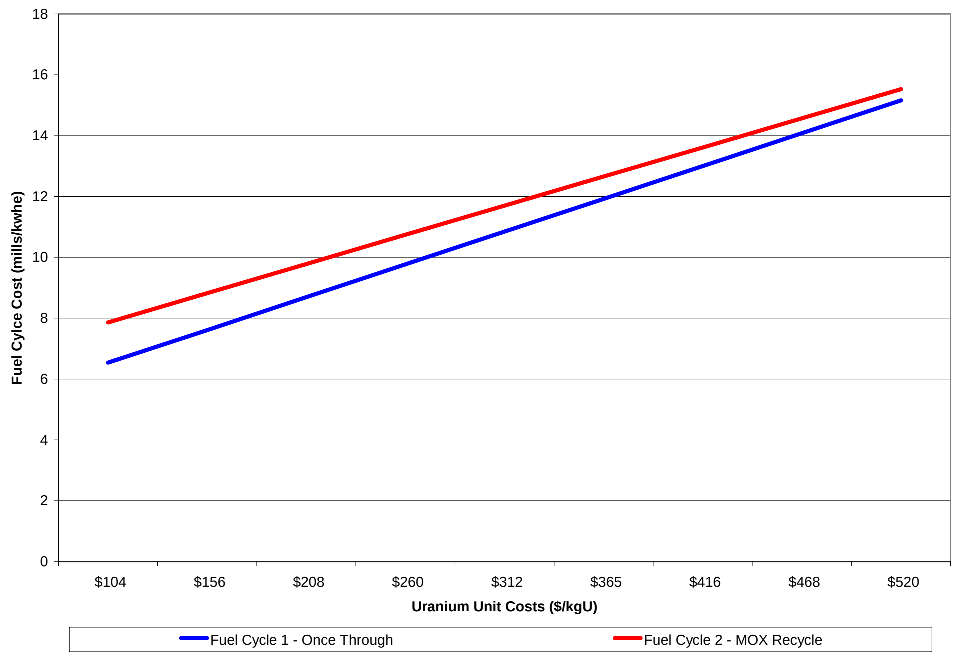

Figure 4-1
Comparison of Fuel Cycle Costs for Once-Through and Pu Recycle Fuel Cycles as a Function of U_3O_8 Unit Costs

4.2 Impact of Change in Unit Cost of Enrichment Services

Assuming that the unit costs for other fuel cycle components remain at the nominal values, EPRI varied the unit costs for enrichment services from $90/SWU to $210/SWU. Over this range of unit costs for enrichment services, the overall fuel cycle costs for Fuel Cycle 1 range from 6.93 mills/kWhe at $90/SWU to 8.83 mills/kWhe at $210/SWU. Overall fuel cycle cost for Fuel Cycle 2 range from 8.21 mills/kWhe at $90/SWU to 9.90 mills/kWhe at $210/SWU. Overall fuel cycle costs for Fuel Cycle 2 are 18% higher than those for Fuel Cycle 1 at the lower range of uranium enrichment unit costs and are approximately 12% higher when enrichment unit costs are $210/SWU. As shown in Figure 4-2, overall fuel cycle costs for Fuel Cycle 1 and Fuel Cycle 2 are not as sensitive to changes in the unit cost of uranium enrichment as they are to changes in the unit cost of U_3O_8 over the range of unit costs evaluated.

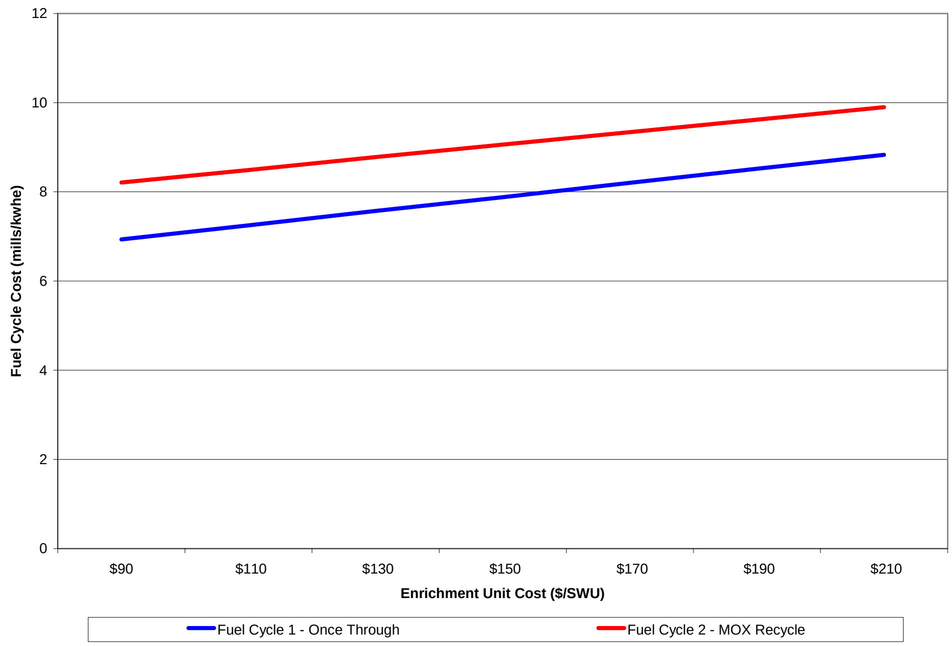

Figure 4-2
Comparison of Fuel Cycle Costs for Once-Through and Pu Recycle Fuel Cycles as a Function of Uranium Enrichment Unit Costs

4.3 Impact of Change in Unit Cost of MOX Fuel Fabrication

Assuming that the unit costs for other fuel cycle components remain at the nominal values, EPRI varied the unit costs for MOX fuel fabrication from $750/kgHM to $1,750/kgHM. Over this range of unit costs for MOX fuel fabrication, the overall fuel cycle costs for Fuel Cycle 1 are 7.88 mills/kWhe and do not change. The overall fuel cycle costs for Fuel Cycle 2 range from 8.95 mills/kWhe when MOX fabrication unit costs are $750/kgHM and rise to 9.17 mills/kWhe when unit costs are $1750/kgHM. This corresponds to an increase in fuel cycle costs of less than 3% associated with an increase in MOX fuel fabrication unit costs of more than 200%, as presented in Figure 4-3. Thus, overall fuel cycle costs are not sensitive to changes in the unit cost of MOX fuel fabrication.

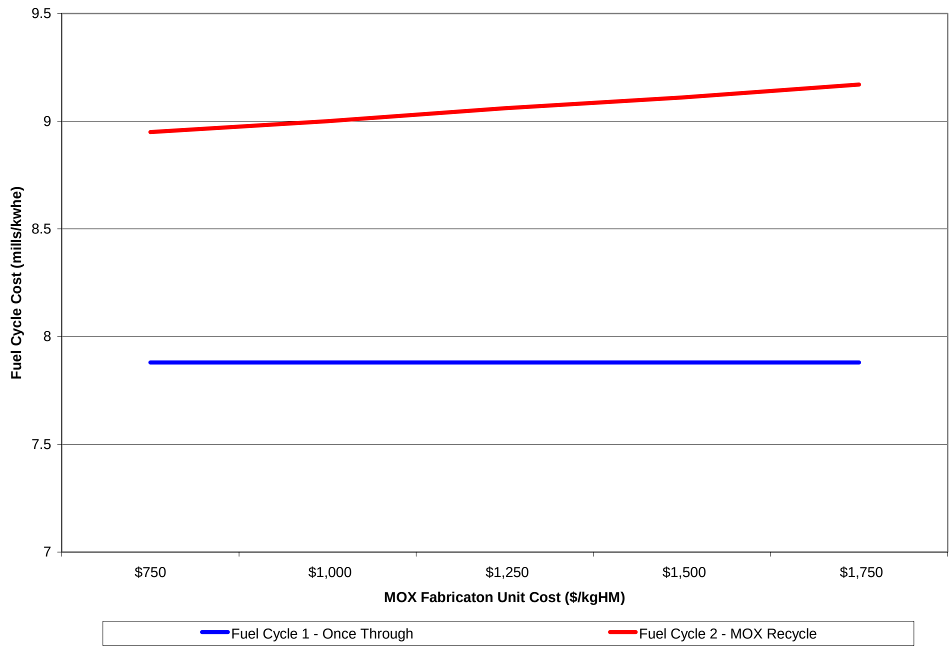

Figure 4-3
Comparison of Fuel Cycle Costs for Once-Through and Pu Recycle Fuel Cycles as a Function of MOX Fuel Fabrication Unit Costs

4.4 Impact of Change in Unit Cost of PUREX Reprocessing

Assuming that the unit costs for other fuel cycle components remain at the nominal value, EPRI varied the unit costs for PUREX reprocessing of UO_2 SNF from $500/kgHM to $1,500/kgHM. Over this range of unit costs for PUREX reprocessing, the overall fuel cycle costs for Fuel Cycle 1 are 7.88 mills/kWhe and do not change. The overall fuel cycle costs for Fuel Cycle 2 range from 8.15 mills/kWhe when PUREX unit costs are $500/kgHM to 9.97 mills/kWhe when PUREX unit costs are $1,500/kgHM, an increase in fuel cycle costs of approximately 22%. As presented in Figure 4-4, there is less than a 4% difference in the overall fuel cycle costs for Fuel Cycle 1 and Fuel Cycle 2 when PUREX reprocessing unit costs are $500/kgHM, the lower bounding range of the unit costs evaluated. Referring to the analysis of potential financing alternatives for a recycling facility in EPRI Report 1015387, a unit cost for PUREX reprocessing that is this low would require government financing and very efficient operations. When PUREX reprocessing unit costs are at the upper bounding range of unit costs evaluated, $1,500/kgHM, fuel cycle costs for Fuel Cycle 2 are approximately 27% higher than those for Fuel Cycle 1. As shown in Chapter 3, at nominal values for all fuel cycle components, fuel cycle costs for Fuel Cycle 2 are 15% higher than those for Fuel Cycle 1.

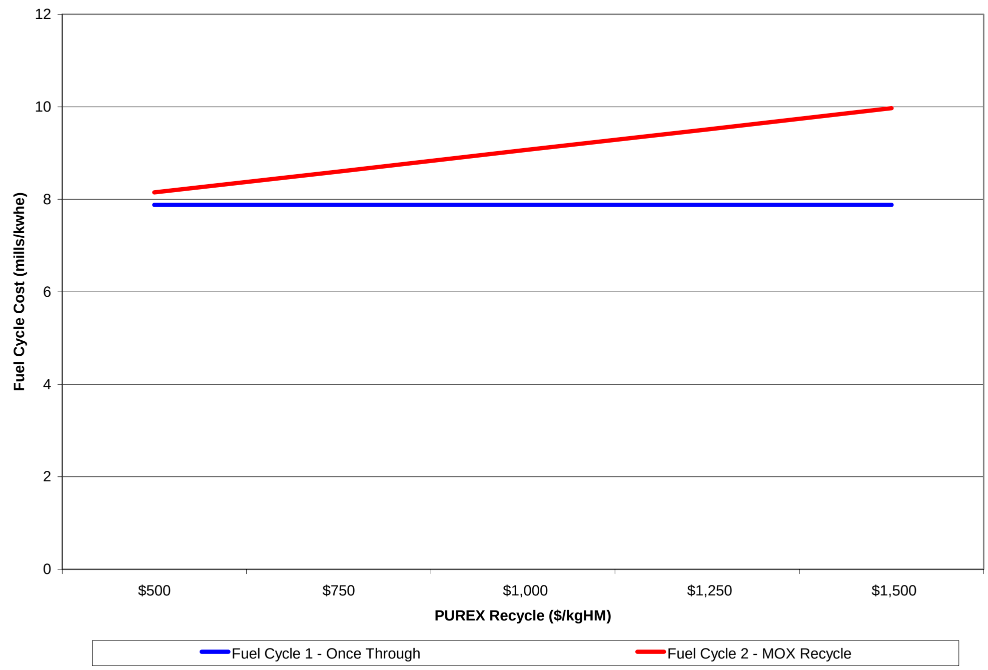

Figure 4-4
Comparison of Fuel Cycle Costs for Once-Through and MOX Recycle as a Function of PUREX Reprocessing Unit Costs

4.5 Impact of Change in Unit Costs of Uranium and PUREX Reprocessing

Assuming that the unit costs for other front-end fuel cycle components remain at the nominal values, EPRI varied the unit costs for U_3O_8 from $104/kgU ($40/lb U_3O_8) to $520/kgU ($200/lb U_3O_8) and the unit costs for PUREX reprocessing from $500/kgHM to $1,500/kgHM. As seen in the preceding analyses, the unit cost of U_3O_8 and the unit cost of PUREX reprocessing have the greatest impact on the comparison of fuel cycle costs between Fuel Cycle 1 and Fuel Cycle 2 over the range of fuel cycle unit costs evaluated. As shown in Table 4-1, increasing the cost of uranium from the nominal value of $104/kgU (column a) to $520/ kgU (column e), results in increasing the overall fuel cycle cost for Fuel Cycle 1 from 6.54 mills/kWhe to 15.16 mills/kWhe. Fuel cycle costs for Fuel Cycle 2 are shown in the bottom of Table 4-1, varying both the unit cost of U_3O_8 and the unit cost of PUREX reprocessing. Assuming a U_3O_8 unit cost of $104/kgU and varying the unit cost of PUREX reprocessing from $500/kgHM to $1,500/kgHM (column a), the fuel cycle costs for Fuel Cycle 2 increase from 6.95 mills/kWhe to $8.77 mills/kWhe, an increase of 26%. Even at the lowest unit costs for PUREX reprocessing, the overall fuel cycle costs for Fuel Cycle 2 are higher than those for Fuel Cycle 1 when uranium costs are $104/kgU. As the unit cost of uranium increases, the overall fuel cycle costs for Fuel Cycle 2 may be lower than those for Fuel Cycle 1 when PUREX reprocessing unit costs are between $500 and $750/kgHM. However, when PUREX reprocessing unit costs are $1,000/kgU (the nominal value) or higher, the Fuel Cycle 1 will have lower fuel cycle costs than Fuel Cycle 2, as shown in Table 4-1 and Figure 4-5 below.

Table 4-1
Impact of Changing U_3O_8 and PUREX Reprocessing Costs on Overall Fuel Cycle Costs

U_3O_8 Unit Cost ($/kgU) ►	(a) 104	(b) 208	(c) 312	(d) 416	(e) 520
Fuel Cycle 1 (mills/kWhe)	6.54	8.69	10.85	13.0	15.16
PUREX Reprocessing Costs ($/kgHM) ▼	Fuel Cycle Costs for Fuel Cycle 2 (mills/kWhe)				
500	6.95	8.86	10.78	12.70	14.62
750	7.40	9.32	11.24	13.16	15.08
1,000	7.86	9.78	11.70	13.61	15.53
1,250	8.31	10.23	12.15	14.07	15.99
1,500	8.77	10.69	12.61	14.53	16.45

Figure 4-5 shows a graphical representation of the data presented in Table 4-1. Fuel cycle costs are plotted as a function of changes to the unit cost of U_3O_8 and the unit cost of PUREX reprocessing.

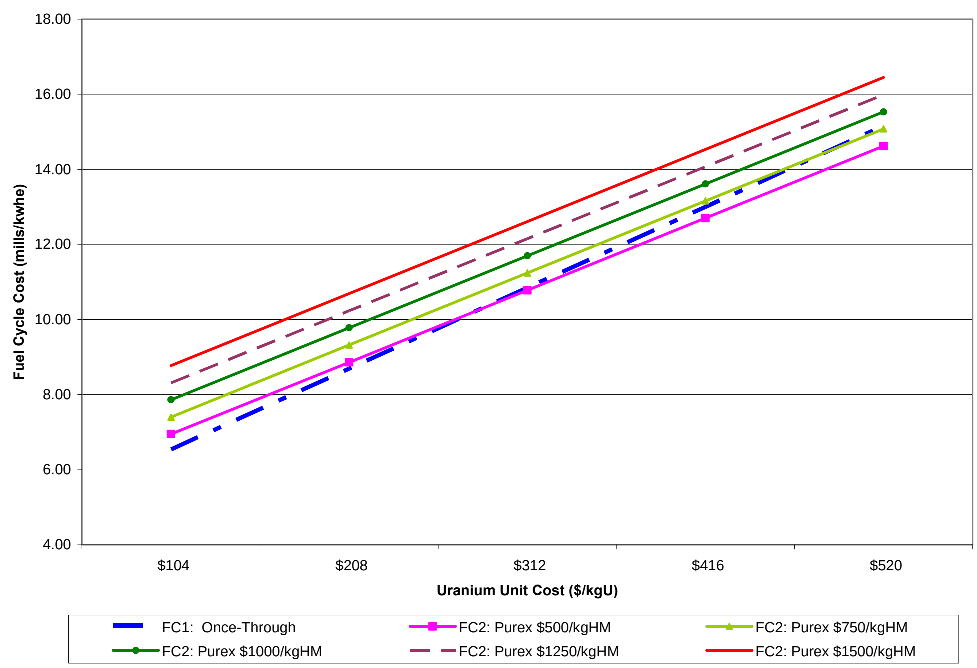

Figure 4-5
Comparison of Fuel Cycle Costs as a Function of Uranium and PUREX Reprocessing Unit Costs

4.6 Impact of Change in Unit Costs of Uranium and MOX Fabrication

Assuming that the unit costs for other front-end fuel cycle components remain at the nominal values, EPRI varied the unit costs for U_3O_8 from $104/kgU ($40/lb U_3O_8) to $520/kgU ($200/lb U_3O_8) and the unit costs for MOX fuel fabrication from $750/kgHM to $1,750/kgHM. As shown in Table 4-2, increasing the cost of uranium from the nominal value of $104/kgU (column a) to $520/kgU (column e), results in increasing the overall fuel cycle cost for Fuel Cycle 1 from 6.54 mills/kWhe to 15.16 mills/kWhe, an increase of more than 200%. Fuel cycle costs for Fuel Cycle 2 are shown in the bottom of Table 4-2, varying both the unit cost of U_3O_8 and the unit cost of MOX fuel fabrication. Assuming a U_3O_8 unit cost of $104/kgU and varying the unit cost of MOX fuel fabrication from $750/kgHM to $1,750/kgHM, the fuel cycle costs for Fuel Cycle 2 increase from 7.75 mills/kWhe to $7.97 mills/kWhe, less than a 3% change in fuel cycle costs. Clearly, increases in the unit price of U_3O_8 have a much more significant impact on fuel cycle costs than the unit cost of MOX fuel fabrication. Even assuming the lowest unit costs for MOX fuel fabrication ($750/kgHM) and the highest unit costs for U_3O_8, the overall fuel cycle costs for Fuel Cycle 2 are approximately 2% higher than those for Fuel Cycle 1.

Table 4-2
Impact of Changing U_3O_8 and MOX Fuel Fabrication Unit Costs on Overall Fuel Cycle Costs

U_3O_8 Unit Cost ($/kgU) ►	(a) **104**	(b) **208**	(c) **312**	(d) **416**	(e) **520**
Fuel Cycle 1 (mills/kWhe)	6.54	8.69	10.85	13.0	15.16
MOX Fabrication Costs ($/kgHM) ▼	Fuel Cycle Costs for Fuel Cycle 2 (mills/kWhe)				
750	7.75	9.66	11.58	13.50	15.42
1,000	7.80	9.72	11.64	13.56	15.48
1,250	7.86	9.78	11.70	13.61	15.53
1,500	7.91	9.83	11.75	13.67	15.59
1,750	7.97	9.89	11.81	13.73	15.65

Figure 4-6 shows a graphical representation of the data presented in Table 4-2. Fuel cycle costs are plotted as a function of changes to the unit cost of U_3O_8 and the unit cost of MOX fuel fabrication. It is evident that the unit cost of MOX fuel fabrication does not have a significant effect on overall fuel cycle costs for Fuel Cycle 2. Thus, the unit cost for MOX fuel fabrication would not be expected to be a driver in decisions associated with whether to pursue plutonium recycle rather than a once-through fuel cycle.

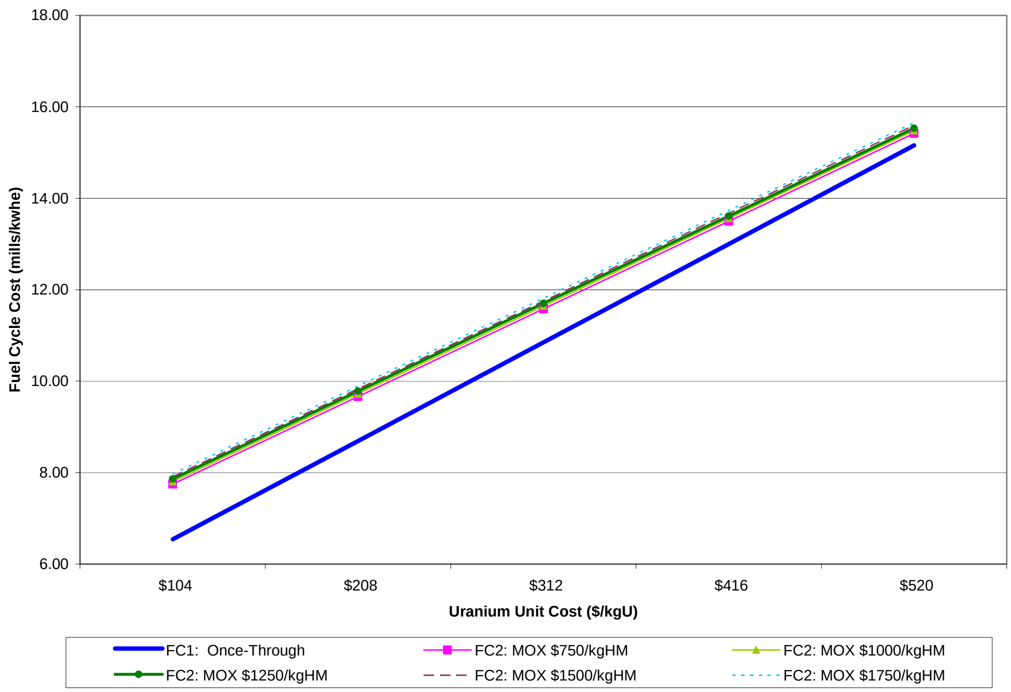

Figure 4-6
Comparison of Fuel Cycle Costs as a Function of Uranium and MOX Fuel Fabrication Unit Costs

4.7 Impact of Changes in Unit Costs of UO_2 Fuel, PUREX Reprocessing, and MOX Fabrication

4.7.1 Uranium, Conversion, Enrichment, UO_2 Fuel Fabrication at Lower Bound Values

Assuming that the unit costs for uranium, conversion, enrichment services, and UO_2 fuel fabrication are at the lower bound values described in Chapter 3, EPRI varied the unit costs for PUREX reprocessing from $500/kgHM to $1,500/kgHM and the unit costs for MOX fuel fabrication from $750/kgHM to $1,750/kgHM. As shown in Figure 4-7, the fuel cycle costs for Fuel Cycle 1 remain constant at 5.38 mills/kWhe. Figure 4-7 also presents the fuel cycle costs for Fuel Cycle 2 over the range of PUREX reprocessing and MOX fuel fabrication costs evaluated. If the unit costs for UO_2 fuel are all at the lower bound values, the fuel cycle costs for Fuel Cycle 2 are always higher than those for Fuel Cycle 1. For example, if MOX fuel fabrication unit costs are $1,250/kgHM, overall fuel cycle costs will range from 5.92 mills/kWhe to 7.74 mills/kWhe, i.e., 10% to 44% higher than the fuel cycle costs for Fuel Cycle 1.

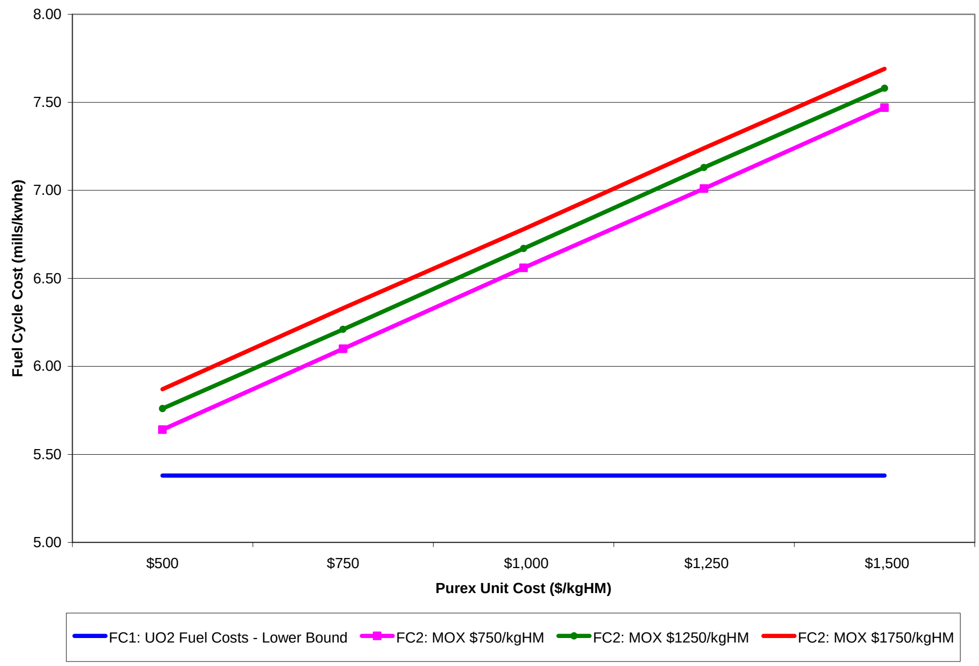

Figure 4-7
Comparison of Fuel Cycle Costs as a Function of PUREX Reprocessing and MOX Fuel Fabrication Unit Costs and Assuming UO_2 Fuel Costs at Lower Bound

4.7.2 Uranium, Conversion, Enrichment, UO_2 Fuel Fabrication at Nominal Values

Assuming that the unit costs for uranium, conversion, enrichment services, and UO_2 fuel fabrication are at the nominal values described in Chapter 3, EPRI varied the unit costs for PUREX reprocessing from $500/kgHM to $1,500/kgHM and the unit costs for MOX fuel fabrication from $750/kgHM to $1,750/kgHM. As shown in Figure 4-8, the fuel cycle costs for Fuel Cycle 1 remain constant at 7.88 mills/kWhe. Figure 4-8 also presents the fuel cycle costs for Fuel Cycle 2 over the range of PUREX reprocessing and MOX fuel fabrication costs evaluated. If the unit costs for UO_2 fuel are all at the nominal values, the fuel cycle costs for Fuel Cycle 2 will be higher than those for Fuel Cycle 1 even for the scenario in which PUREX reprocessing costs are at the lower bound value of $500/kgHM and MOX fabrication costs are at the lower bound value of $750/kgHM. In this example, fuel cycle costs for Fuel Cycle 2 are approximately 2% higher than those for Fuel Cycle 1: 7.88 mills/kWhe for Fuel Cycle 1 compared to 8.03 mills/kWhe for Fuel Cycle 2. These results are similar to those presented in Figure 4-4, which showed the impact of PUREX reprocessing unit costs assuming that all other unit costs were at their nominal values. In that example, there was less than a 2% difference in the overall fuel cycle costs between Fuel Cycle 1 and Fuel Cycle 2 when PUREX reprocessing costs were $500/kgHM.

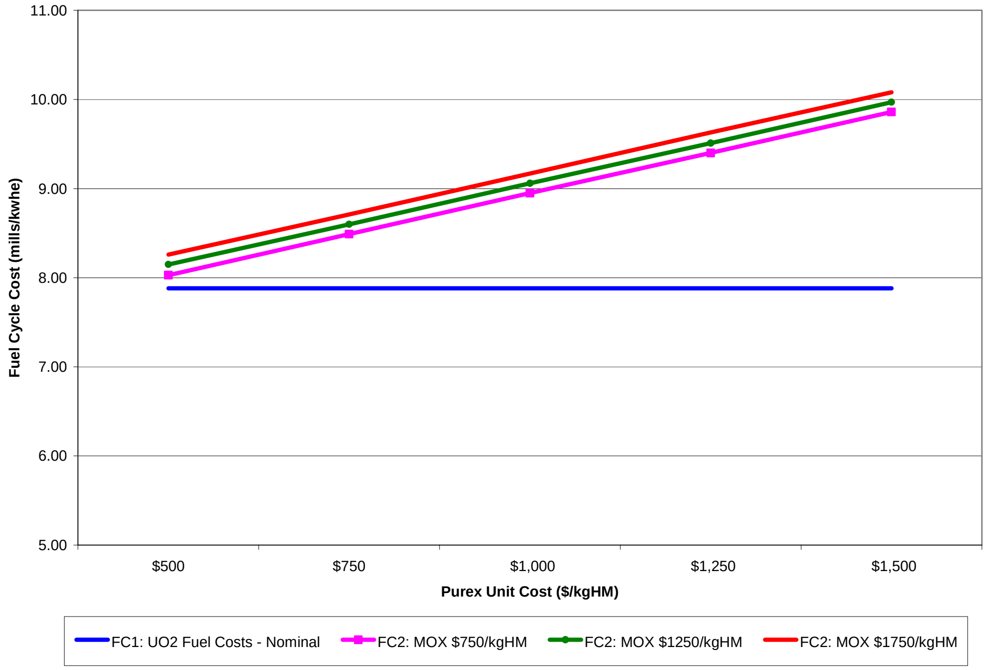

Figure 4-8
Comparison of Fuel Cycle Costs as a Function of PUREX Reprocessing and MOX Fuel Fabrication Unit Costs and Assuming UO_2 Fuel Costs at Nominal Values

4.7.3 Uranium, Conversion, Enrichment, UO_2 Fuel Fabrication at Upper Bounding Values

Assuming that the unit costs for uranium, conversion, enrichment services, and UO_2 fuel fabrication are at the upper bounding values described in Chapter 3, EPRI varied the unit costs for PUREX reprocessing from $500/kgHM to $1,500/kgHM and the unit costs for MOX fuel fabrication from $750/kgHM to $1,750/kgHM. As shown in Figure 4-9, the fuel cycle costs for Fuel Cycle 1 remain constant at 16.42 mills/kWhe. Figure 4-9 also presents the fuel cycle costs for Fuel Cycle 2 over the range of PUREX reprocessing and MOX fuel fabrication costs evaluated. If the unit costs for UO_2 fuel are all at the upper bounding values, the fuel cycle costs for Fuel Cycle 2 will be lower than those for Fuel Cycle 1 when PUREX reprocessing unit costs are $750/kgHM or lower and MOX fabrication unit costs are $1750/kgHM or lower. For example, when PUREX reprocessing unit costs are $750/kgHM, fuel cycle costs for Fuel Cycle 2 range from 16.09 mills/kWhe to 16.31 mills/kWhe - 1% to 2% lower than Fuel Cycle 1. When both PUREX reprocessing unit costs and MOX fabrication unit costs are at the lower bounding values, fuel cycle costs for Fuel Cycle 2 are 15.63 mills/kWhe – approximately 5% lower than the costs for Fuel Cycle 1.

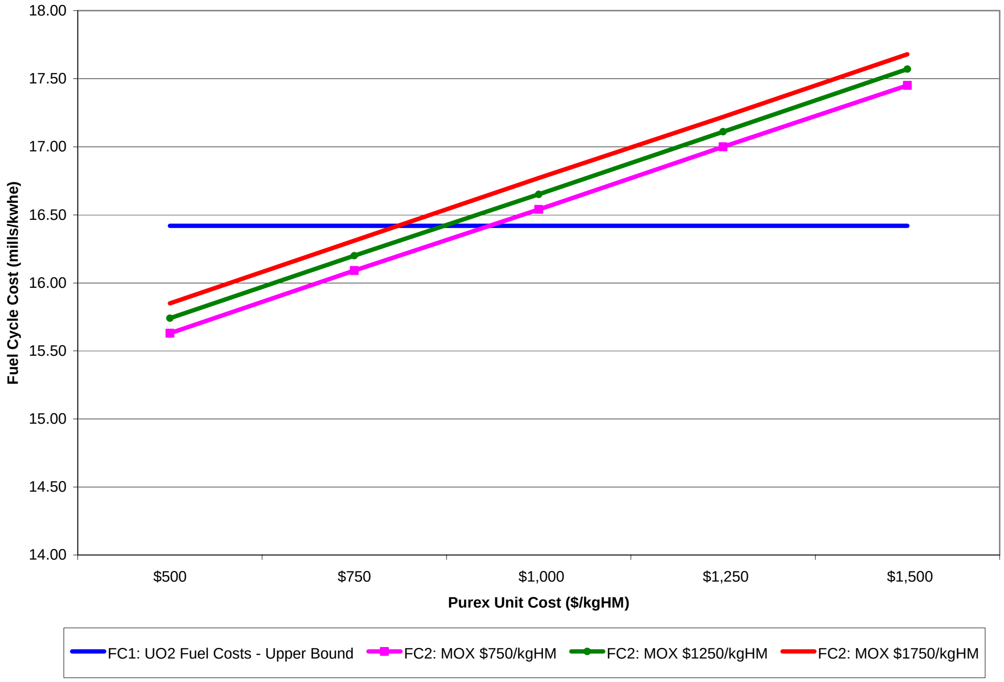

Figure 4-9
Comparison of Fuel Cycle Costs as a Function of PUREX Reprocessing and MOX Fuel Fabrication Unit Costs and Assuming UO_2 Fuel Costs at Upper Bound

5 CONCLUSIONS

Under the range of fuel cycle unit costs evaluated in this report, EPRI found that the unit costs for uranium ore concentrates and PUREX reprocessing will have the greatest impact on the overall fuel cycle costs for Fuel Cycle 1 and Fuel Cycle 2. Assuming that other fuel cycle cost components are at the nominal values, the fuel cycle costs for a once-through fuel cycle will be lower than those for a Pu recycle when the unit costs of uranium are \$312/kgU (\$120/lb U_3O_8) or lower, and PUREX reprocessing costs are \$750/kgHM or higher.

As shown in Section 4.1, variations in the unit cost of uranium have the greatest impact on overall fuel cycle costs for both Fuel Cycle 1 and Fuel Cycle 2. When uranium unit costs increase from \$104/kg to \$520/kg, the fuel cycle costs for Fuel Cycle 1 increase from 6.54 mills/kWhe to 15.16 mills/kWhe and those for Fuel Cycle 2 increase from 7.86 mills/kWhe to 15.53 mills/kWhe – a 200% or greater increase in overall fuel cycle costs. Thus, fuel cycle costs are sensitive to changes in the unit cost of uranium. However, a fuel cycle using MOX recycle will have higher costs than those for Fuel Cycle 1 even if uranium prices reach approximately \$520/kgU (\$200/lb U_3O_8), if all other fuel cycle unit costs are assumed to be at the nominal values used in this study.

In scenarios in which the unit cost of uranium is at the top of the range evaluated by EPRI and the unit cost of PUREX reprocessing is at the lower end of the range evaluated, the overall fuel cycle costs for a fuel cycle using Pu recycle are lower than those for the once-through fuel cycle. In order for PUREX reprocessing costs to fall at the lower range of costs evaluated by EPRI, EPRI Report 1015387 found that government financing of a reprocessing facility may be needed. This is due to the fact that facilities that are constructed and operated by the government would result in lower unit costs for recycling than private sector financed and operated facilities due to the lower costs associated with government financing. However, there are large uncertainties associated with government projects including the appropriation of adequate funding on a timely basis, and government management and operation of large capital projects.

Thus, based on the analysis presented in EPRI Report 1015387 and the analysis summarized in this report, there may not be an economic incentive to recycle SNF in the U.S. using MOX fuel under current nominal unit costs for front-end nuclear fuel cycle components, PUREX reprocessing, and MOX fuel fabrication. This does not mean that there may not be other compelling reasons to continue long-term research and development associated with eventually closing the fuel cycle in the U.S.

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