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Parametric Study of Front-End Nuclear Fuel Cycle Costs Using Reprocessed Uranium

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REPORT SUMMARY

This study evaluates front-end nuclear fuel cycle costs assuming that uranium recovered during the reprocessing of commercial light-water reactor (LWR) spent nuclear fuel is available to be recycled and used in the place of natural uranium. This report explores the relationship between the costs associated with using a natural uranium fuel cycle, in which reprocessed uranium (RepU) is not recycled, with those associated with using RepU.

Background

RepU results from the chemical reprocessing of spent nuclear fuel in which the uranium and plutonium are separated from fission products. In a previous report published in February 2009 (EPRI report 1018574, *Parametric Study of Front-End Nuclear Fuel Cycle Costs*), EPRI provided an overview of the requirements for front-end nuclear fuel cycle components for LWR uranium dioxide (UO_2) fuel. The study included a parametric analysis of LWR fuel cycle costs in order to provide a basic understanding of the impacts to overall fuel cycle costs that result from changes in the cost of one or more fuel cost components.

A new parametric analysis of LWR fuel cycle costs, using RepU, is performed in order to quantify the impacts on overall front-end fuel cycle costs that result from the use of RepU. Front-end fuel cycle cost components that can be impacted include uranium concentrates, uranium conversion services, uranium enrichment services, nuclear fuel fabrication services, and other costs that can be associated with the processing of RepU. A comparison to fuel cycle costs that assumes the use of natural uranium concentrates is provided.

Objectives

- To provide an understanding regarding the economic factors that must be considered when evaluating the use of RepU in place of natural uranium ore concentrates for LWR fuel, as well as the impact of these factors on the nuclear fuel cycle components for RepU fuel.
- To perform a parametric analysis of fuel cycle costs for LWR fuel made from RepU over a range of unit costs for each front-end fuel cycle component. RepU fuel cycle costs are compared to those for natural uranium fuel to determine the fuel cycle cost components that may be most important in economic decisions regarding the recycling of RepU in LWRs.

Approach

In EPRI report 1018574, the research team defined the process used to calculate front-end nuclear fuel requirements to provide an understanding of the relationship between the front-end fuel cycle components for typical pressurized water reactor (PWR) reloads, and they examined the impact of changes to the front-end unit costs on overall reload costs for a typical PWR. In the present study, the researchers examine the use of RepU in place of natural uranium for LWR fuel. Utilizing the methodology outlined in EPRI report 1018574, this study calculates uranium requirements for the fabrication of reload fuel for a PWR utilizing RepU and compares this to the requirements for a reload of PWR fuel using natural uranium.

This study includes a parametric analysis of LWR fuel cycle costs using RepU and compares those costs to LWR fuel cycle costs using natural uranium ore concentrates in order to determine the impact of changes in front-end fuel cycle unit costs, including costs associated with processing RepU, on decisions regarding whether to utilize RepU inventories in the fabrication of LWR fuel.

Results

Over the range of unit costs evaluated in this report, uranium ore concentrates and uranium enrichment services represent approximately 90% of overall nuclear fuel cycle costs when natural uranium is utilized to manufacture LWR fuel. Decisions regarding whether to recycle RepU in the place of natural uranium ore concentrates in LWR fuel will depend upon economic factors, such as the unit cost of uranium ore concentrates, the need for higher enrichment assays to compensate for neutron absorbing isotopes in RepU, the premium associated with converting the RepU to uranium hexafluoride (UF_6) and then enriching it, and the physical characteristics of the RepU (such as the initial ^{235}U assay). In addition, there are technical issues that must be addressed, such as those associated with the licensing and use of RepU in reactor cores, and the need for additional worker protection measures during the processing and manufacture of RepU fuel. If the cost premium associated with the processing of RepU, relative to the cost of processing natural uranium concentrates, can be minimized, and depending upon the unit cost of natural uranium concentrates, it may be beneficial to consider recycling RepU for use in LWRs in the place of natural uranium.

EPRI Perspective

This report is a follow-on study to EPRI report 1018574, *Parametric Study of Front-End Nuclear Fuel Cycle Costs.* The present report is intended to provide a source of baseline cost information for decisions that consider the recycling of RepU inventories in LWR fuel, displacing natural uranium ore concentrates.

Keywords

Conversion
Enrichment
Fabrication
Recycling
Reprocessed uranium

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FRONT-END NUCLEAR FUEL COSTS

In a previous report published in February 2009, EPRI provided an overview of the requirements for front-end nuclear fuel cycle components for light water reactor (LWR) uranium dioxide (UO_2) fuel, *Parametric Study of Front-End Nuclear Fuel Cycle Costs, EPRI Report 1018574*. That study examined front-end fuel cost components such as uranium concentrates, uranium conversion services, uranium enrichment services, and nuclear fuel fabrication services, including nominal unit costs for each of these components. The study included a parametric analysis of light-water reactor (LWR) fuel cycle costs in order to provide a basic understanding of the impacts that result from changes in the cost of one or more fuel cost components on overall fuel cycle costs.

This study uses the methodology and builds on the results of EPRI Report 1018574 by evaluating the use of reprocessed uranium (RepU) in the place of natural uranium concentrates for the fabrication of LWR fuel for a pressurized water reactor (PWR). Assumptions for front-end fuel cycle unit costs are provided for the processing and manufacture of PWR fuel using natural uranium (NatU) and RepU.

This study evaluates front-end nuclear fuel cycle costs assuming that uranium recovered during the reprocessing of commercial LWR spent nuclear fuel is recycled and used in the place of natural uranium. Due to the additional costs associated with incorporating RepU in the LWR fuel cycle, this option is economically competitive only when the costs associated with front-end fuel cycle cost components in the non-RepU fuel cycle rise to a certain cost point. This report explores the relationship between the costs associated with using RepU compared to costs associated with a fuel cycle in which natural uranium is used exclusively.

This study includes a parametric analysis of LWR fuel cycle costs, using RepU; and compares these costs to those of LWR fuel cycles using natural uranium concentrates. This parametric analysis assists in determining the impact of changes in front-end fuel cycle unit costs, including costs associated with processing RepU, on decisions regarding whether to utilize RepU inventories in the fabrication of LWR fuel. A brief background regarding the characteristics of RepU is provided along with a description of front-end fuel cycle cost components, including the impacts of handling RepU.

1.1 Reprocessed Uranium

1.1.1 RepU Isotopic Composition

RepU results from the chemical reprocessing of spent nuclear fuel in which the uranium and plutonium are separated from fission products using a solvent extraction process. RepU contains not only ^{234}U, ^{235}U and ^{238}U, found in natural uranium, but also ^{232}U, ^{233}U, ^{236}U and ^{237}U, produced during the irradiation of uranium dioxide (UO_2) fuel from which the RepU was separated. During reprocessing of spent nuclear fuel, these isotopes remain with the RepU since chemical processing cannot distinguish between isotopes of the same element.

As noted in a report by the International Atomic Energy Agency (IAEA), entitled *Management of Reprocessed Uranium,* published in 2007, the quantities of the various uranium isotopes that are present in RepU depend upon the type of reactor and fuel from which the RepU was produced (gas-cooled reactor, PWR, pressurized heavy-water reactor, or boiling water reactor); the initial ^{235}U assay of the fuel; the amount of energy, or "burnup" of the fuel when it was permanently discharged from the reactor; the origin of the fuel (natural uranium, enriched uranium, RepU); and the amount of time since the spent fuel was permanently discharged from the reactor (e.g., cooling time).[1]

Natural uranium has a concentration of 0.711 weight percent (w/o) ^{235}U. The ^{235}U content in RepU can vary and depends on the initial assay and burnup of the spent fuel from which the RepU was derived. As noted in IAEA (2007), for RepU derived from LWR spent fuel the ^{235}U concentration is typically in the range of 0.65 to 1.1 w/o ^{235}U. For LWR fuel with burnups in the range of 45 gigawatt days per MTU (GWd/MTU) to 60 GWd/MTU, the concentration of ^{235}U is typically about 0.6 w/o – which is less than that for natural uranium, requiring additional separative work units (SWU) during the process of enriching RepU.

The isotope ^{236}U is a neutron absorber. Therefore, the presence of this isotope in nuclear fuel made from RepU results in a need to increase the assay of the fissile ^{235}U isotope in order to compensate for the neutron absorption by ^{236}U. In IAEA (2007), the report notes that in order to achieve a discharge burnup of 45 GWd/MTU for LWR fuel using RepU, the ^{235}U assay must be 4.5 w/o ^{235}U, compared to an assay of 4.1 w/o ^{235}U for LWR made using NatU.[2] This 0.4 w/o increase in ^{235}U assay requires additional uranium feed and increases costs associated with conversion and enrichment services.

While the concentration of the isotope ^{232}U in RepU is relatively small, the decay products of ^{232}U, some of which are strong gamma emitters, build up over time following the separation of the fission products from the uranium and plutonium during reprocessing.[3] The presence of the ^{232}U daughter products in RepU can present radiation shielding requirements for storage of RepU and during the manufacture of fuel. Thus, depending on time elapsed since reprocessing, another round of chemical purification may be necessary for removal of problematic ^{232}U decay products.

1.1.2 Estimated Inventories of RepU

According to IAEA (2007), through the end of 2003, approximately 22,250 tonnes (metric tons of initially contained uranium, or MTU) of RepU had been derived from spent LWR fuel in Europe and Japan. The IAEA estimated that 8,825 MTU of RepU remained available for

[1] International Atomic Energy Agency, Management of Reprocessed Uranium, IAEA TECDOE-1529, 2007, pp. 4-17. IAEA (2007)
[2] IAEA (2007), p. 11.
[3] Additional technical details regarding the decay of ^{232}U, and other uranium isotopes contained in RepU, can be found in IAEA (2007), Section 2.1.1.

recycling at the end of 2003 and that an additional 7,096 MTU of RepU would be separated through reprocessing LWR spent fuel between 2004 and 2010.[4] To date, RepU from LWR spent fuel has been recycled in nuclear power plants in Belgium, France, Germany, Japan, the Netherlands, Sweden, and Switzerland.

In addition, the IAEA estimates that 53,000 to 55,000 MTU of RepU had been separated from non-LWR spent fuel through 2003 and that approximately 20,000 MTU of this non-LWR derived RepU was still available for recycle. RepU from non-LWR spent fuel has been recycled into nuclear power plants in the United Kingdom (U.K.). IAEA estimates also indicate that a further 15,000 MTU of RepU would be separated through reprocessing of non-LWR spent fuel through 2010.[5] Thus, the quantities of RepU that are available now and that may be available for recycle in the future could displace a relatively small quantity of natural uranium in the fuel cycle, assuming that it is technically and economically feasible to utilize this RepU.

Using the data from the 2007 IAEA report, a study published in the June 2006 RWE NUKEM Market Report, entitled *RepU's Second Chance*, estimated that existing inventories of RepU could displace 15,300 to 15,900 MTU of natural uranium feed and the future annual RepU arisings could displace up to an additional 2,300 MTU of natural uranium feed annually in the future – approximately 3.5% of then-current worldwide annual uranium requirements.[6] With worldwide nuclear power plant capacity poised to begin expanding, the use of RepU to displace natural uranium feed may help reduce future gaps between uranium supply capacity and worldwide uranium requirements.

Through the parametric analysis of front-end fuel cycle costs associated with the use of RepU in LWR fuel, this report identifies those front-end fuel cycle cost components that may be factors in determining the economic feasibility of RepU recycling on an expanded basis.

The IAEA (2007) also identifies other technical and regulatory issues associated with recycling RepU such as possible reactor license amendments to utilize RepU fuel; qualification and benchmarking of reactor core physics codes to account for the use of RepU fuel; and the potential need for design and certification of new transport packages for enriched RepU and fabricated RepU fuel.[7] This report does not attempt to address these issues or assess the costs of addressing these potential technical and regulatory issues on the economic competitiveness of recycling RepU.

[4] IAEA (2007), Table 24, p. 53.
[5] IAEA (2007), Table 25, p. 54.
[6] RWE NUKEM, RWE NUKEM Market Report Online, *RepU's Second Chance*, June 2006, pp. 9-10. [NUKEM (2006)]
[7] IAEA (2007), Section 4.2.1, Section 6.

1.2 The Front-End of the Nuclear Fuel Cycle

1.2.1 Front-End Fuel Cycle Processes for Natural Uranium Feed

As discussed in EPRI Report 1018574, the material and services required to obtain fabricated nuclear fuel assemblies for reload fuel supply are purchased over a period of several years prior to that fuel generating energy in the nuclear reactor. The major steps in this process are:

Uranium Production: Mining, extraction, and milling process to produce the natural uranium ore and convert it into U_3O_8. Natural uranium may also be referred to as "NU" or "NatU". The uranium concentrate is typically measured in either pounds or short tons of U_3O_8, kilograms uranium (kgU), MTU, or tonnes U.

Conversion Process: Uranium concentrates are purified and converted to uranium hexafluoride (UF_6) or feed (F), the feed for uranium enrichment plants. Uranium hexafluoride is often colloquially referred to as "hex." UF_6 is usually measured in kilograms or metric tons of uranium (kgU or MTU) as UF_6.

Enrichment Process: Natural UF_6 is enriched to obtain the desired ^{235}U assay for LWR fuel, usually in the range of 3 to 5 w/o of the fissile ^{235}U. Natural uranium has a ^{235}U assay of 0.711 w/o ^{235}U. The enrichment process also generates a waste stream in which the concentration of ^{235}U is depleted (lower than that of natural uranium), known as the "tails." The assay of ^{235}U in the tails is variable, generally falling between 0.2 w/o and 0.3 w/o. The enrichment process is measured in units known as tonnes of separative work or SWU. The enriched uranium is often referred to as "EU" or product "P;" and it is occasionally referred to as enriched uranium product "EUP" or low enriched uranium "LEU." The depleted tails or waste stream is usually represented by the abbreviation "W."

Fuel Fabrication: The enriched uranium hexafluoride is converted to solid UO_2 and then fabricated into fuel pellets that are contained in fuel rods. Fabricated fuel is typically measured in kgU or MTU contained in UO_2. A specific number of these fuel rods are combined in an array to form a fuel assembly suitable for use in a specific reactor.

1.2.2 Front-End Fuel Cycle Processes for RepU Feed

The processes associated with the fabrication of fuel using RepU are the same as those associated with processing natural uranium feed, with the addition of processes associated with RepU separation and storage as well as a process for removal of ^{232}U decay products from the RepU. The major steps in this process are:

RepU Separation and Storage: Uranyl nitrate hexahydrate (UNH) is the chemical form of RepU after reprocessing. However, if RepU is to be stored prior to recycle, the UNH may be converted to one of several stable forms of uranium oxide such as UO_2, UO_3, or U_3O_8; or to UF_6 or uranium metal. If the RepU is going to be processed immediately into RepU fuel, it will generally be converted to UF_6 or UO_2, depending upon the type of fuel being manufactured.[8]

RepU Conversion and Processing: The process to convert RepU that was stored as U_3O_8 into RepU UF_6 (Rep-UF_6) for use as feed material for uranium enrichment is the same process used to convert natural uranium. The chemical impurities in RepU are removed during the conversion of UF_4 into Rep-UF_6 and further purification occurs during the transfer of Rep-UF_6 between containers.[9] This purification process is important as the Rep-UF_6 must meet the ASTM product specifications for Rep-UF_6 and for LEU fuel.[10]

RepU Enrichment: The process to enrich Rep-UF_6 is the same as that used to enrich natural UF_6. However, due to the higher radiation level in Rep-UF_6, dedicated processing facilities are typically used in order to be able to provide additional radiation protection. As discussed in IAEA (2007), radiation levels during the enrichment process can be reduced by minimizing the time between conversion and enrichment of RepU and purifying the Rep-UF_6 immediately prior to shipment for enrichment. As noted earlier, in order to achieve the same burnup levels that can be achieved by LWR fuel made from natural uranium, the EUP from RepU must have a higher ^{235}U assay in order to compensate for the presence of neutron-absorbing ^{236}U. The ^{235}U assay in RepU can vary from 0.60 w/o (lower than that of natural uranium) to as much as 1.1 w/o ^{235}U (higher than that of natural uranium). Thus, when RepU has ^{235}U assays that are depleted relative to natural uranium, additional SWU are required. When RepU has ^{235}U assays that are enriched relative to natural uranium, fewer SWU would be required. This variability is an important factor in determining the economics of RepU use.

RepU UO_2 Fuel Fabrication: The enriched Rep-UF_6 is converted to solid UO_2 and fabricated into fuel using the same manufacturing process as used for fuel made from natural uranium. For UO_2 fuel made from Rep-UF_6, the fuel fabrication process requires additional worker radiation protection. The time between the delivery of enriched Rep-UF_6 for fuel fabrication and the conversion into RepU UO_2 is generally as short as possible in order to reduce radiation doses due to the ^{232}U daughters. Fuel fabrication lines generally include additional radiation shielding and automated processes may be utilized that are not normally employed for the fabrication of fuel from NatU.[11]

1.3 Uranium Requirements for an Individual Nuclear Power Plant

Nuclear fuel cycle design relationships associated with planned discharge burnup, reload ^{235}U assay, cycle effective full power days (EFPD) energy production, and core reload fraction that were developed in EPRI Report 1018574 may be combined with the fundamental equations governing uranium and separative work to determine the front end fuel cycle requirements for an individual nuclear power plant. Representative physical parameters for a typical U.S. PWR are presented in Table 1-1 and are used in this study.

[8] IAEA (2007), p. 18, p. 28.
[9] IAEA (2007), pp. 30-31.
[10] IAEA (2007), pp. 28-29.
[11] IAEA (2007), pp. 45-46.

Table 1-1
Representative Physical Parameters for a Typical PWR

Description	PWR
Plant Rating: Megawatts Thermal (MWth)	3,411
Megawatts Electric (MWe)	1,117
Assemblies in Core	193
Fuel Assembly Uranium Weight (kgU)	455
Cycle Length (months)	18
Capacity Factor	90%
Core Weight (MTU)	87.815
Core Specific Power (SP) (MWth/MTU)	38.843
Process Rates: Fabrication Losses 0.0% Conversion Losses 0.5% Enrichment Tails Assay 0.25 w/o ^{235}U	

An example of the calculation of nuclear fuel requirements for a typical PWR fuel cycle, using the above parameters, is provided in EPRI Report 1018574.

2 FRONT-END NUCLEAR FUEL CYCLE UNIT COSTS

This section describes projected unit costs for front-end nuclear fuel cycle components described in Section 1 of this report assuming the use of both natural uranium and RepU: 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, and any processing required due to the use of RepU. These unit costs will be referred to as "nominal" fuel cycle unit costs. The nominal unit costs for the various fuel cycle cost components (for both NatU feed and RepU feed) are based on current prices for individual components, if available, as discussed below. This section also describes the range of unit costs for each front-end fuel cycle component that EPRI uses to perform the parametric analysis of fuel cycle costs that is summarized in Section 3. The nominal unit costs utilized in EPRI Report 1018574, which were based on then-current component prices, are bounded by the unit costs that EPRI utilizes in its parametric analysis in this report.

2.1 Uranium Ore Concentrates

The 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.[12] In July 2008, the spot market price for U_3O_8 was back down to approximately $65/lb U_3O_8, the nominal value utilized in EPRI Report 1018574.[13] For the purposes of calculating nominal fuel cycle costs for a typical PWR in this report, EPRI assumes a nominal value for U_3O_8 based on the July 2009 market price of approximately $48/lb U_3O_8.[14] For parametric studies of front-end fuel cycle costs, EPRI assumes a range of $30/lb to $150/lb for U_3O_8 unit costs.

2.2 Reprocessed Uranium

For the purposes of this analysis, EPRI assumes a nominal value of $0/lb U_3O_8 for RepU. However, if RepU is not recycled as reactor fuel shortly after reprocessing, there is a cost to the owner to store the material; accordingly this storage cost could increase RepU cost above zero. As noted in Section 1.1, for RepU derived from LWR spent fuel the ^{235}U assay is typically in the range of 0.60 to 1.1 w/o ^{235}U. For LWR fuel with burnups in the range of 45 GWd/MTU to 60 GWd/MTU, the concentration of ^{235}U is typically about 0.6 w/o ^{235}U – less than that for natural uranium. EPRI assumes a nominal ^{235}U concentration of 0.6 w/o for the purposes of calculating fuel cycle costs since this is consistent with the burnups being achieved by PWRs in the U.S. today.

[12] Trade Tech Exchange Value, http://www.uranium.info/index.cfm?go=c.page&id=29, December 2003; Trade Tech Exchange Value, Nuclear Market Review, Trade Tech, June 20, 2007 (Trade Tech 2007).
[13] Trade Tech Nuclear Market Review, U_3O_8 Spot Market Indicator, July 18, 2008. (Trade Tech 2008)
[14] Trade Tech Nuclear Market Review, Exchange Value, July 31, 2009. (Trade Tech 2009)

In performing its parametric study of front-end fuel cycle costs, EPRI assumes that RepU costs range from $0/lb U_3O_8 up to $20/lb U_3O_8 and that the ^{235}U assay in RepU ranges from 0.5 w/o ^{235}U to 1.1 w/o ^{235}U.

2.3 Conversion Services

During the past year, the market price for conversion services has ranged from $7 to $10/kgU as UF_6.[15] EPRI assumes a nominal value of $7/kgU as UF_6 in this report.

According to the analysis contained in NUKEM (2006), the cost of conversion services for RepU may be three to four times that for conversion of natural uranium concentrates.[16] In the NUKEM (2006) analysis, a natural uranium conversion price of $12/kgU as UF_6 was assumed compared to a conversion cost of $45/kgU for RepU, more than three times the unit cost to convert natural uranium. The NUKEM (2006) report notes that the RepU conversion cost includes a surcharge, or a cost premium, associated with the purification of RepU. These costs were based on an assumption that the conversion of RepU would take place in European facilities. EPRI assumes that the nominal value for conversion of RepU would be $21/kgU as UF_6, three times the unit cost to convert natural uranium.

In performing its parametric study of front-end fuel cycle costs, EPRI assumes natural UF_6 conversion unit costs will range from $5/kgU to $20/kgU as UF_6 and RepU conversion costs (including purification of RepU) would range from $15/kgU to $60/kgU [approximately 3 times the cost to convert natural uranium based on the information from the NUKEM (2006) analysis]. EPRI also includes a sensitivity analysis examining RepU conversion costs that are four times as much as the cost to convert natural uranium.

2.4 Enrichment Services

The market price for enrichment services was approximately $150/SWU in July 2008.[17] The current market price for enrichment services is approximately $165/SWU,[18] which EPRI adopts as the nominal value for enrichment services in this report.

The NUKEM (2006) analysis assumes an approximate 15% premium in the cost for enrichment of RepU above that for natural uranium due to additional handling requirements. Incorporating this premium, the EPRI nominal RepU enrichment cost climbs to $190/SWU for the analyses in this report.

In performing its parametric study of front-end fuel cycle costs, EPRI assumes that unit costs for enrichment of natural uranium will range from $90/SWU to $210/SWU. EPRI assumes that unit costs for enrichment of RepU will range from $104/SWU to $242/SWU – approximately 15% higher than the cost to enrich natural uranium. EPRI also includes a sensitivity analysis that examines RepU enrichment costs that are 30% higher than the cost to enrich natural uranium.

[15] Trade Tech (2008), Trade Tech (2009).
[16] NUKEM (2006), Table 1, p. 14.
[17] Trade Tech (2008).
[18] Trade Tech (2009).

EPRI assumes an enrichment product assay of 4.494 w/o ^{235}U using natural UF_6 feed and a EUP assay of 4.994 w/o ^{235}U using Rep-UF_6 feed. The 0.5 w/o ^{235}U increase in EUP assay is used to compensate for the presence of ^{234}U and ^{236}U in the RepU.

For this analysis, EPRI assumes a nominal enrichment for tails of 0.25 w/o ^{235}U and a range of enrichments from 0.1 to 0.3 w/o ^{235}U.

2.5 Fuel Fabrication

EPRI assumes a nominal value for PWR fuel fabrication services of $200/kgU. This is the same nominal value utilized by EPRI in EPRI Report 1018574.

The NUKEM (2006) analysis assumed that there would be an approximate 10% premium in the cost of fabrication of RepU compared to the cost of fabrication using natural uranium due to the additional handling requirements associated with RepU. Using this assumption, EPRI assumes a nominal value of $220/kgU for fabrication of RepU fuel.

In performing its parametric study of front-end fuel cycle costs, EPRI assumes that unit costs for PWR fuel fabrication services will range from $150/kgU to $250/kgU assuming the use of natural uranium and from $165/kgU to $275/kgU assuming the use of RepU – 10% higher than the cost to fabrication fuel from natural uranium product.

EPRI's parametric analyses also examine the impact of RepU fabrication costs rising to twice those for natural uranium. While such a large cost premium is not expected, EPRI includes this scenario to show that fuel cycle costs are expected be relatively insensitive to RepU fuel fabrication premiums.

2.6 Nominal PWR and BWR Front-End Fuel Cycle Costs

Table 2-1 presents reload fuel cycle costs using the representative fuel cycle parameters for typical PWR reactor (Table 1-1) and nominal unit costs for front-end fuel cycle components assuming natural uranium feed and RepU feed. For a typical 1,117 MWe PWR operating on an 18-month cycle with fuel burnups of approximately 51 gigawatt-days per MTU (GWd/MTU), reload fuel cycle costs using natural uranium are estimated to be $83.6 million or 6.475 mills per kilowatt-hour electric (kWhe). Assuming the nominal front-end unit costs, uranium ore concentrates represent 45.2% of total fuel cycle costs and enrichment services represent 44.4% of reload fuel cycle costs. Fuel fabrication services account for approximately 7.9% and conversion services for 2.5% of reload fuel cycle costs.

For the same 1,117 MWe PWR, reload fuel cycle costs using RepU are estimated to be $72.7 million or 5.636 mills/kWhe – 13% lower than the reload fuel cycle costs using natural uranium. The overall reload costs are lower for the RepU reload due to the fact that the nominal unit cost of RepU is assumed to be zero.

While the overall fuel cycle costs are lower for the RepU reload, comparison of RepU fuel cost components to those for the NatU fuel clearly shows that the costs associated with the RepU reload requires additional uranium feed, conversion services and enrichment services in order to fabricate the equivalent 32,760 kg of EUP. Due to the need for additional uranium feed and the higher costs associated with processing RepU, the costs for conversion, enrichment and fabrication are higher than those for NatU fuel. Uranium requirements increase from 787,997 lb U_3O_8 to 1,160,183 lb U_3O_8 – an increase of 47%. Enrichment requirements increase by 32% – from 224,687 SWU to 295,879 SWU.[19]

Table 2-1
Reload Fuel Cycle Costs for Typical PWR Using Nominal Front-End Unit Costs, Assuming Natural Uranium Feed and Reprocessed Uranium Feed

Cost Component	Component Quantities	Nominal Unit Cost	Cost per Reload (Million $)	Percent of Total	Fuel Cost (Mills/kWhe)
PWR Fuel Cycle Costs – NatU					
Uranium	787,997 lb U_3O_8	$48/lb U_3O_8	$37.8	45.2%	2.931
Conversion	301,591 kgU UF_6	$7/kgU	$2.1	2.5%	0.164
Enrichment	224,687 SWU	$165/SWU	$37.1	44.4%	2.872
Fuel Fabrication	32,760 kg EUP	$200/kgU	$6.6	7.9%	0.508
Total			**$83.6**		**6.475**
PWR Fuel Cycle Costs - RepU					
Uranium	1,160,183 lb U_3O_8	$0/lb U_3O_8	$0	0.0%	0.000
Conversion	444,038 kgU UF_6	$21/kgU	$9.3	12.8%	0.722
Enrichment	295,879 SWU	$190/SWU	$56.2	77.3%	4.356
Fuel Fabrication	32,760 kg EUP	$220/kgU	$7.2	9.9%	0.558
Total			**$72.7**		**5.636**

Using the nominal front-end unit costs, it is clear that the unit costs for uranium concentrates, the value of RepU, and the cost of uranium enrichment services will have the largest impact on decisions associated with the future use of RepU. The cost of conversion of RepU may also be a factor in determining whether or not the use of RepU will be economical since the reload fuel cycle cost for RepU conversion, above, are more than three times the cost to convert natural uranium. This increase is due to the higher costs associated with processing RepU as well as the need to convert additional quantities of uranium to compensate for the lower initial ^{235}U assay and the need for a higher enrichment product assay.

[19] The increase in enrichment requirements is due to the fact that the RepU is assumed to have an initial ^{235}U assay of 0.6 w/o (lower than that of natural uranium) and the need to increase the EUP assay by 0.5 w/o ^{235}U, as noted in Section 2.5.

Section 3 provides a summary of the parametric analysis of changes to the front-end unit costs using RepU compared to natural uranium, concentrating on impacts associated with the changes to the cost of uranium ore concentrates, conversion services, uranium enrichment services and the value of RepU. Fuel fabrication costs will also be examined, but changes in fuel fabrication unit costs are not expected to be a determining factor regarding decisions on the use of RepU because fabrication costs are typically 10% (or less) of total fuel cycle cost and the premium for RepU fabrication is only 10% higher than that for NatU fabrication. The parametric analysis also examines the impact of the initial ^{235}U assay of RepU and of the enrichment tails assay on fuel cycle costs.

3

IMPACT OF CHANGES IN FRONT-END FUEL CYCLE UNIT COSTS ON OVERALL FUEL CYCLE COST

This section provides a summary of EPRI's parametric analysis of LWR fuel cycle costs using RepU and compares those costs to LWR fuel cycle costs using natural uranium concentrates (NatU) in order to determine the impact of changes in front-end fuel cycle unit costs, including costs associated with processing RepU, on decisions regarding whether to utilize RepU inventories for the fabrication of LWR fuel. As shown in Section 2.6, uranium ore concentrates and uranium enrichment services represent approximately 90% of overall front-end nuclear fuel cycle costs for LWR fuel made with NatU. In contrast, for reload fuel that utilizes RepU, the uranium is assumed to have zero cost and uranium enrichment services represent approximately 77% of the front-end fuel cycle costs. While the costs to process RepU (conversion, enrichment and fuel fabrication) are higher than that for LWR fuel utilizing NatU, depending upon the unit price of uranium, displacing NatU with RepU may represent substantial front-end fuel cost savings.

EPRI examines the impact of changes in the unit costs of natural uranium, conversion services, uranium enrichment services, and fuel fabrication for NatU on fuel cycle costs and compares this to the impact of commensurate changes in unit costs for processing RepU including conversion services, uranium enrichment services, and fuel fabrication. Unit costs for processing RepU in this study are assumed to be higher than those for NatU as a result of the cost premiums discussed in Section 2. EPRI also examines the impact of changes to the initial ^{235}U enrichment of RepU and to the ^{235}U assay of enrichment tails.

3.1 Impact of Change in Unit Cost of U_3O_8

Assuming the unit costs for other front-end fuel cycle components remain at the nominal values for LWR fuel described in Section 2, EPRI varies the unit costs for U_3O_8 from $30/lb U_3O_8 to $150/lb U_3O_8. EPRI assumes that RepU costs are at the nominal value of zero. As shown in Figure 3-1, increasing the unit cost of U_3O_8 from $30/lb to $150/lb results in an increase in overall fuel cycle costs for NatU fuel from 5.4 mills/kWhe to 12.7 mills/kWhe, while the overall fuel cycle cost for RepU fuel remains constant at 5.6 mills/kWhe.

If RepU has an assumed cost of zero, and assuming the other nominal unit costs for conversion, enrichment and fabrication of NatU and RepU fuel, it may be cost effective to use RepU when the unit cost of natural uranium is greater than approximately $35/lb U_3O_8, as shown in Figure 3-1.

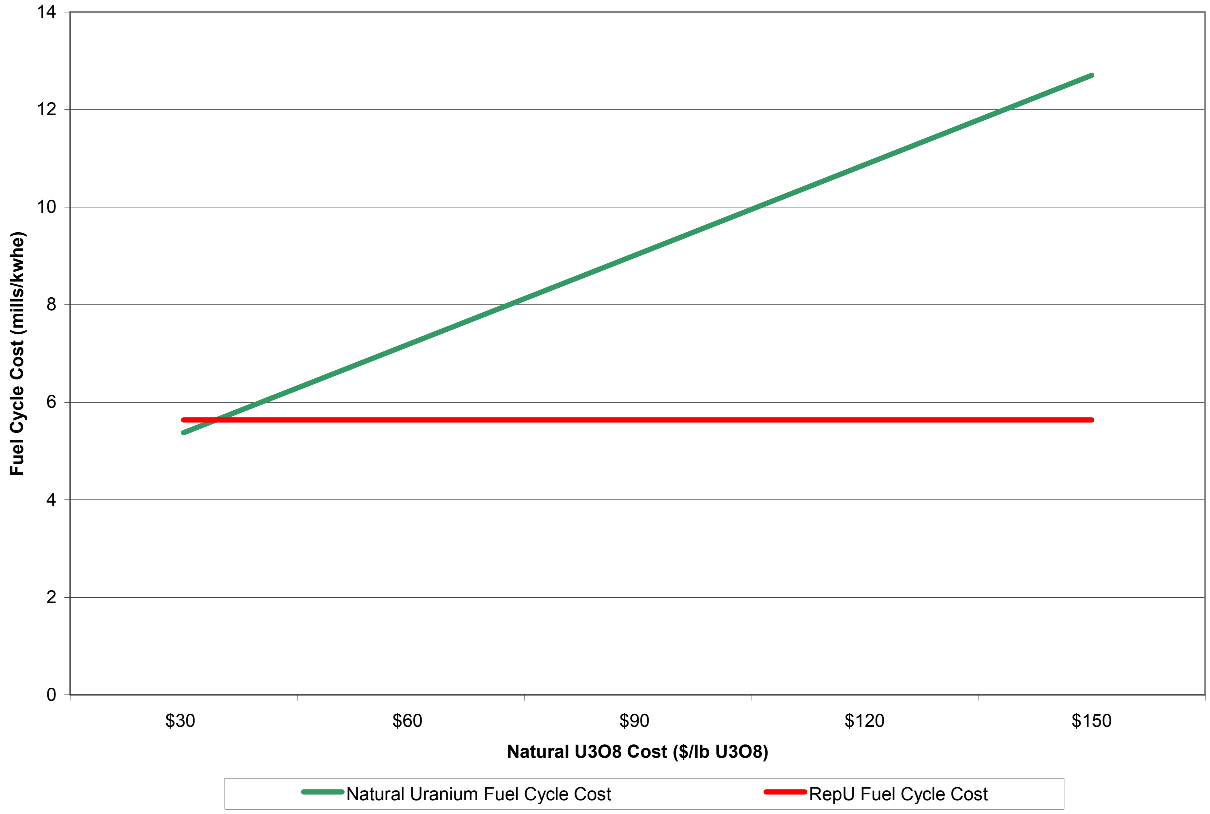

Figure 3-1
Comparison of Front-End Fuel Cycle Cost for NatU and RepU LWR Fuel as a Function of U_3O_8 Unit Costs

3.2 Impact of Change in Unit Cost of Enrichment Services

Assuming that the unit costs for other front-end fuel cycle components remain at the nominal values, EPRI varies the unit costs for enrichment services from $90/SWU to $210/SWU for NatU fuel. The enrichment unit costs associated with enrichment services for RepU are assumed to be 15% higher than those for enriching NatU, varying from $104/SWU to $242/SWU. As shown in Table 3-1, overall fuel cycle costs are higher for NatU fuel compared to RepU fuel over the range of enrichment costs evaluated when RepU enrichment costs are 15% higher than those for NatU fuel. In order to determine the impact of a higher premium associated with enriching RepU, EPRI also examines the impact of assuming that RepU enrichment services would be 30% higher than those for NatU fuel, varying RepU enrichment services costs from $117/SWU to $273/SWU. The overall fuel cycle costs for RepU fuel are lower than those for NatU fuel except at the high range of costs for enrichment services – NatU enrichment at a cost of $210/SWU and RepU enrichment at a cost of $273/SWU (assuming a 30% cost premium) results in fuel cycle costs of 7.26 mills/kWhe and 7.54 mills/kWhe, respectively.

Table 3-1
Comparison of Impact of Changing Enrichment Services Costs on Overall Front-End Fuel Cycle Costs for NatU and RepU LWR Fuel

NatU Enrichment Unit Cost ($/SWU)	**90**	**120**	**150**	**180**	**210**
NatU Fuel Cycle Cost (mills/kWhe)	5.17	5.69	6.21	6.74	7.26
RepU Enrichment Unit Cost [+ 15% Enrichment Cost Adder] ($/SWU)	**104**	**138**	**173**	**207**	**242**
RepU Fuel Cycle Cost [with 15% Enrichment Cost Adder] (mills/kWhe)	3.67	4.44	5.25	6.03	6.829
RepU Enrichment Unit Cost [+ 30% Enrichment Cost Adder] ($/SWU)	**117**	**156**	**195**	**234**	**273**
RepU Fuel Cycle Cost [with 30% Enrichment Cost Adder] (mills/kWhe)	3.96	4.86	5.75	6.65	7.54

Figure 3-2 shows the impact of changes in enrichment unit costs on overall front-end fuel cycle costs for LWR fuel using both NatU and RepU. The values along the x-axis represent the unit costs for enrichment services for natural uranium. Table 3-1 identifies the corresponding unit costs for enrichment of RepU. As shown in Figure 3-2, when RepU enrichment costs have a 15% premium over NatU enrichment, the fuel cycle costs associated with RepU are always lower than those for NatU. With a 30% enrichment cost premium, it is only when the NatU enrichment costs are higher than approximately $200/SWU that RepU fuel cycle costs are higher than NatU fuel cycle costs.

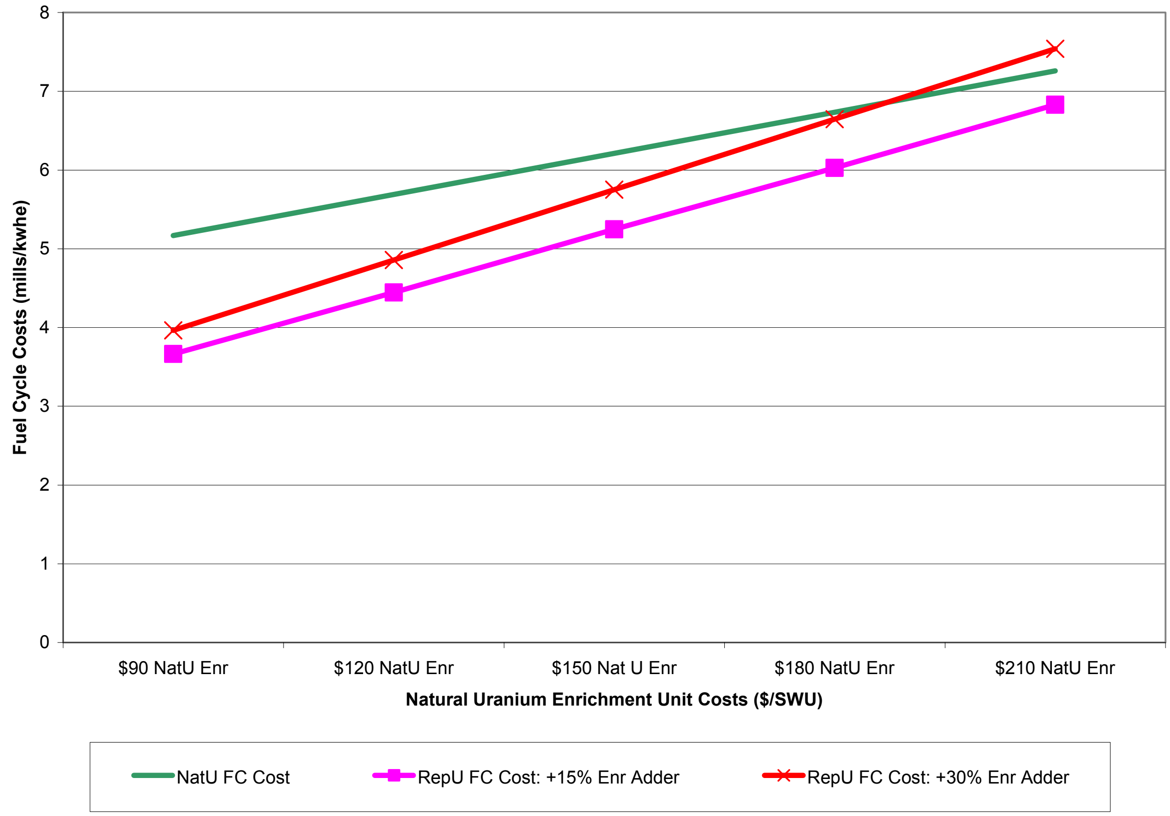

Figure 3-2
Comparison of Front-End Fuel Cycle Cost for NatU LWR Fuel and RepU LWR Fuel as a Function of Changes to Unit Costs of Enrichment Services

3.3 Impact of Change in Unit Cost of Conversion Services

Assuming that the unit costs for other front-end fuel cycle components remain at the nominal values, EPRI varies the unit costs for conversion services for NatU from $5/kgU to $20/kgU as UF_6. The conversions services unit costs for RepU are assumed to be three times higher than those for NatU as discussed in Section 2.3. EPRI varies RepU conversions services costs from $15/kgU to $60/kgU as UF_6. As shown in Table 3-2, overall fuel cycle costs are lower for RepU fuel compared to NatU fuel at all but the highest unit costs for conversion services - $20/kgU for NatU fuel and $60/kgU as UF_6 for RepU fuel. RepU fuel cycle costs are 3% higher than those of NatU fuel when NatU conversion costs are $20/kgU and RepU conversion costs are $60/kgU as UF_6.

In order to determine the impact if there is a higher cost premium associated with conversion of RepU, EPRI assumes that RepU conversion services would be four times higher than those for converting NatU fuel, varying RepU conversion services costs from $20/kgU to $80/kgU as UF_6. The overall fuel cycle costs for RepU fuel are lower than those for NatU when NatU conversion costs are $10/kgU or lower and RepU conversion costs are $40/kgU or lower. When conversion unit costs are $15 to $20/kgU for NatU fuel and $60 to $80 for RepU fuel, the overall fuel cycle costs for NatU are lower than those for RepU. Thus, as processing fees for RepU increase and the unit costs for conversion services increase, the cost advantage associated with utilizing RepU in LWR fuel will decrease or disappear.

Table 3-2
Comparison of Impact of Changing Conversion Services Costs on Overall Front-End Fuel Cycle Costs for NatU and RepU LWR Fuel

NatU Conversion Unit Cost ($/kgU as UF_6)	5	10	15	20
NatU Fuel Cycle Cost (mills/kWhe)	6.43	6.54	6.66	6.78
RepU Conversion Unit Cost [3x NatU Conversion Cost] ($/kgU as UF_6)	15	30	45	60
RepU Fuel Cycle Cost [with 3x NatU Conversion Cost] (mills/kWhe)	5.43	5.95	6.46	6.98
RepU Conversion Unit Cost [4x NatU Conversion Cost] ($/kgU as UF_6)	20	40	60	80
RepU Fuel Cycle Cost [with 4x NatU Conversion Cost] (mills/kWhe)	5.60	6.29	6.98	7.67

3.4 Impact of Change in Unit Cost of Fabrication Services

Assuming that the unit costs for other front-end fuel cycle components remain at the nominal value, EPRI varies the unit costs for PWR fuel fabrication services from $150/kgU to $250/kgU. The fuel fabrication services unit costs for RepU are assumed be 10% higher than those NatU fuel as discussed in Section 2.5. EPRI varies the RepU fuel fabrication costs from $165/kgU to $275/kgU. As shown in Table 3-3, assuming RepU fuel fabrication unit costs will be 10% higher than those for NatU fuel, overall fuel cycle costs are higher for NatU fuel compared to RepU fuel over the range of fabrication costs evaluated.

In order to determine the impact if there is a higher cost premium associated with fabrication of RepU, EPRI also evaluates RepU fuel fabrication costs would be 100% higher than those for NatU fuel. As shown in Table 3-3, even assuming RepU fabrication costs that are double the costs to fabricate NatU fuel, RepU fuel cycle costs remain lower than those for NatU fuel. Thus, it is unlikely that the unit costs of RepU fuel fabrication will drive decisions regarding whether or not to recycle RepU in LWRs.

Figure 3-3
Comparison of Impact of Changing Fabrication Services Costs on Overall Front-End Fuel Cycle Costs for NatU and RepU LWR Fuel

NatU Fabrication Unit Cost ($/kgU as UF_6)	**150**	**175**	**200**	**225**	**250**
NatU Fuel Cycle Cost (mills/kWhe)	6.35	6.41	6.47	6.54	6.60
RepU Fabrication Unit Cost [+10% Fabrication Cost Adder] ($/kgU as UF_6)	**165**	**193**	**220**	**248**	**275**
RepU Fuel Cycle Cost [+10% Fabrication Cost Adder] (mills/kWhe)	5.50	5.57	5.64	5.71	5.78
RepU Fabrication Unit Cost [with 100% Fabrication Cost Adder] ($/kgU as UF_6)	**300**	**350**	**400**	**450**	**500**
RepU Fuel Cycle Cost [with 100% Fabrication Cost Adder] (mills/kWhe)	5.84	5.97	6.03	6.22	6.35

3.5 Changes in the Enrichment Tails Assay

EPRI Report 1018574 evaluated the impact of enrichment tails assay on front-end fuel cycle costs. In order to determine the impact of tails assay on decisions associated with the recycle of RepU compared to the use of natural uranium fuel, EPRI evaluated tails assays from 0.10 w/o ^{235}U to 0.30 w/o ^{235}U. EPRI assumes a nominal tails assay of 0.25 w/o ^{235}U in this study. Some contracts for enrichment services allow tails assays between 0.2 w/o ^{235}U and 0.3 w/o ^{235}U. As shown in Figure 3-4, assuming nominal values for the front-end fuel cycle cost components and increasing the tails assay from 0.10 w/o ^{235}U to 0.30 w/o ^{235}U, overall front-end costs for NatU fuel vary from 7.3 mills/kWhe to 6.5 mills/kWhe, with the lowest fuel cycle cost occurring at approximately 0.25 w/o ^{235}U. Overall front-end fuel cycle costs for RepU fuel vary from 7.7 mills/kWhe at 0.10 w/o tails to 5.3 mills/kWhe at 0.3 w/o tails. The lowest fuel cycle cost for RepU fuel occurs at a tails assay of 0.3 or higher w/o ^{235}U or higher.

As tails assay increases, the amount of uranium required will increase. Thus, if the value of uranium as RepU is zero, increasing the enrichment tails assay results in lower enrichment costs and lower overall fuel cycle costs for RepU. Use of a higher enrichment tails assay for RepU also reduces the impact of the penalty to compensate for the presence of neutron absorbers in RepU by reducing the SWU requirements.

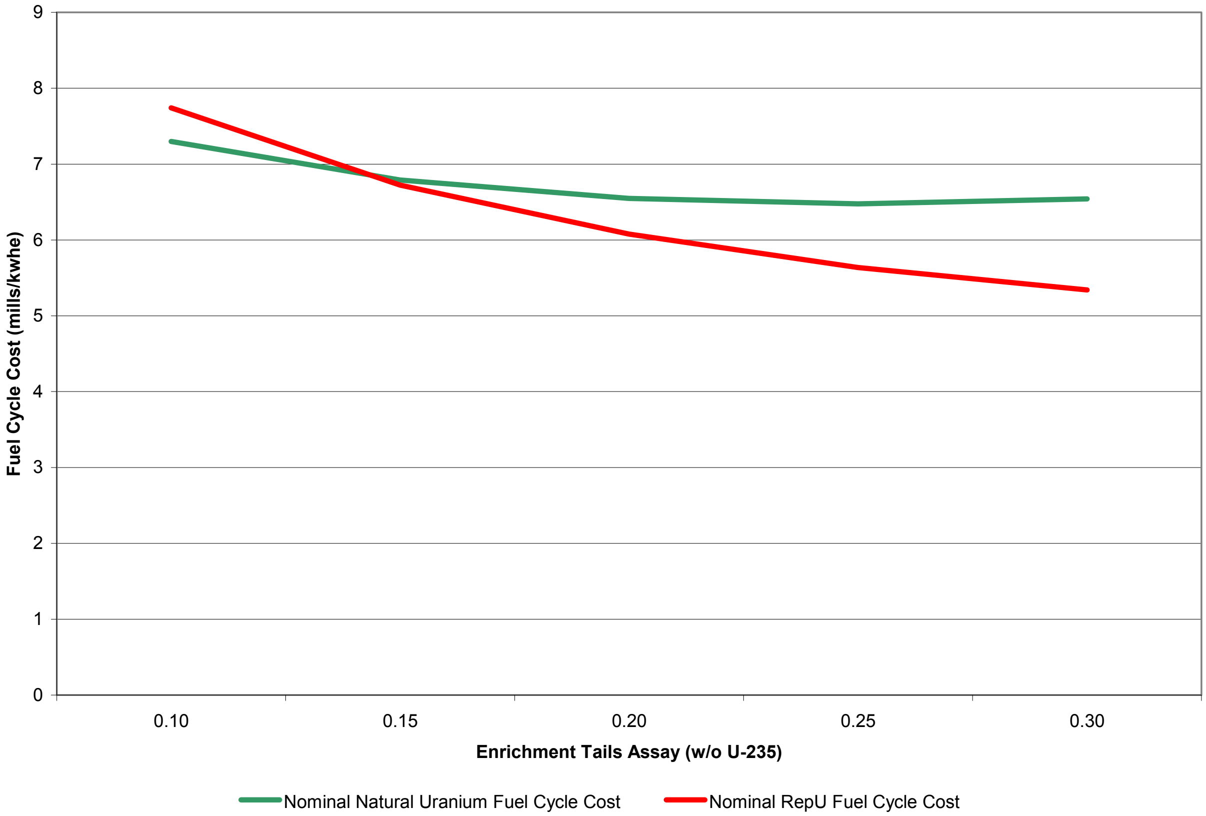

Figure 3-4
Comparison of Front-End Fuel Cycle Cost for NatU LWR Fuel and RepU LWR Fuel as a Function of Enrichment Tails Assay

3.6 RepU Value

As discussed in Section 2.2, EPRI assumes that the nominal value of RepU is zero. However, if a market for RepU develops in the future or if one considers RepU to have some cost, such as that associated with storage of RepU prior to recycle, it is useful to determine the impact of this RepU value on overall fuel cycle costs compared to overall fuel cycle costs for NatU fuel. EPRI varies the value of RepU from \$0/lb U_3O_8 to \$20/lb U_3O_8–equivalent and compared this to the overall NatU fuel cycle costs assuming that the unit cost of uranium concentrates ranges from \$30/lb U_3O_8 to \$150/lb U_3O_8. As discussed in Section 3.1, when RepU has an assumed cost of zero, it may be cost effective to consider the use of RepU when the unit cost of natural uranium is greater than approximately \$35/lb U_3O_8, as shown in Figure 3-5. If the assumed value of RepU rises, natural uranium unit costs can rise and still allow the overall fuel cycle costs for NatU fuel to be more cost effective than using RepU. If RepU has a value of \$10/lb U_3O_8-equivalent, when the unit cost of NatU is higher than \$45/lb U_3O_8, RepU fuel cycle costs may be lower than those for NatU. If RepU has a value of \$20/lb U_3O_8-equivalent, when the unit cost of NatU is above \$60/lb U_3O_8, RepU fuel cycle costs may be lower than those for NatU. Thus, the costs associated with the storage of RepU and the value assigned to RepU inventories will impact decisions regarding whether or not the recycle of RepU may be cost effective.

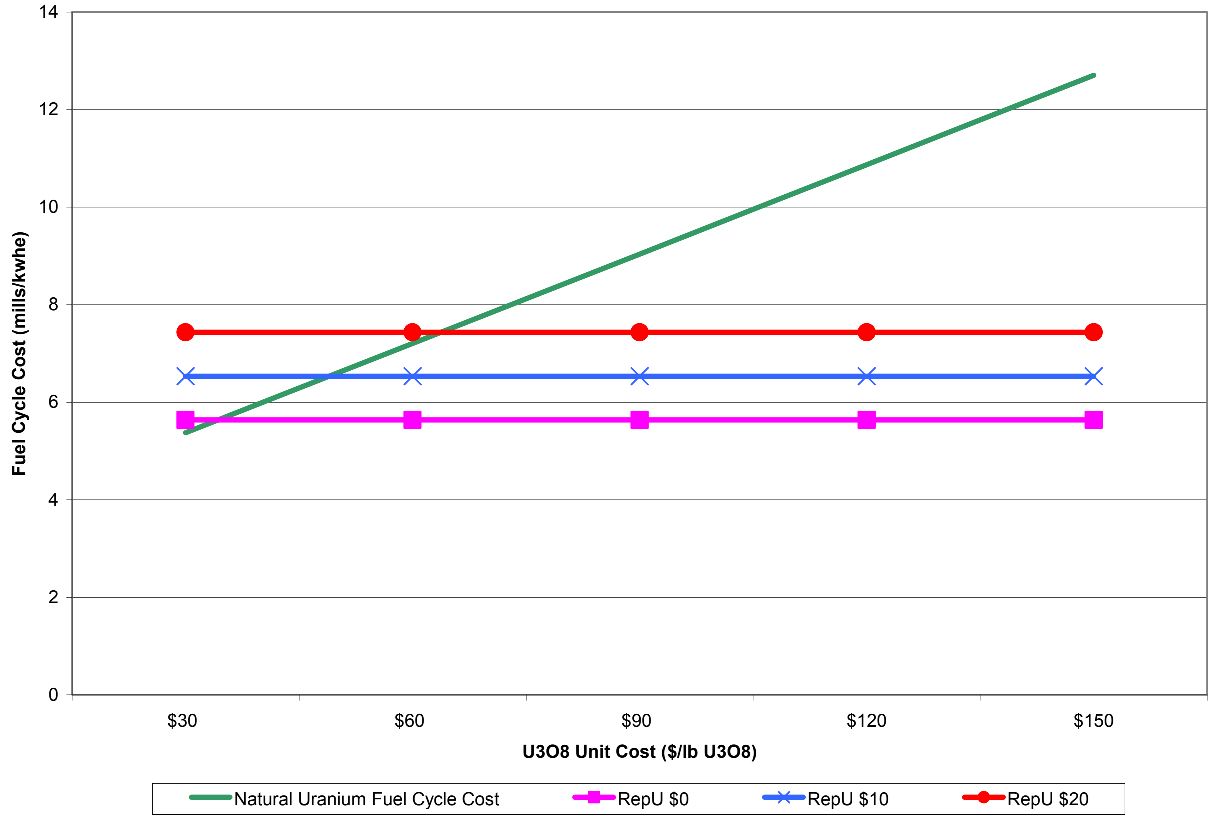

Figure 3-5
Comparison of Front-End Fuel Cycle Cost for NatU LWR Fuel and RepU LWR Fuel as a Function of Natural Uranium Unit Cost and RepU Value

3.7 RepU Initial Enrichment

EPRI assumes that the nominal ^{235}U assay of RepU is 0.6 w/o ^{235}U as discussed in Section 2.2. As discussed in Section 1.1, the initial ^{235}U concentration of RepU typically ranges from 0.65 to 1.1 w/o ^{235}U. EPRI evaluates the impact of changes to the initial ^{235}U assay of RepU by varying the initial assay from 0.5 w/o to 1.1 w/o ^{235}U. When the initial ^{235}U assay of RepU is 0.5 w/o ^{235}U, recycle of RepU may be cost effect if NatU unit costs are approximately \$45/lb U_3O_8 or higher, as shown in Figure 3-6. If the initial enrichment of RepU is 0.7 w/o ^{235}U or higher, the recycle of RepU may be cost effective for when NatU unit costs are lower than \$30/lb U_3O_8. Thus, the higher the initial ^{235}U assay of RepU, the lower the requirements for uranium, conversion and enrichment services. Higher initial ^{235}U assays for RepU will allow the recycle of RepU to be cost effective even at uranium concentrate unit costs that are less than \$30/lb U_3O_8.

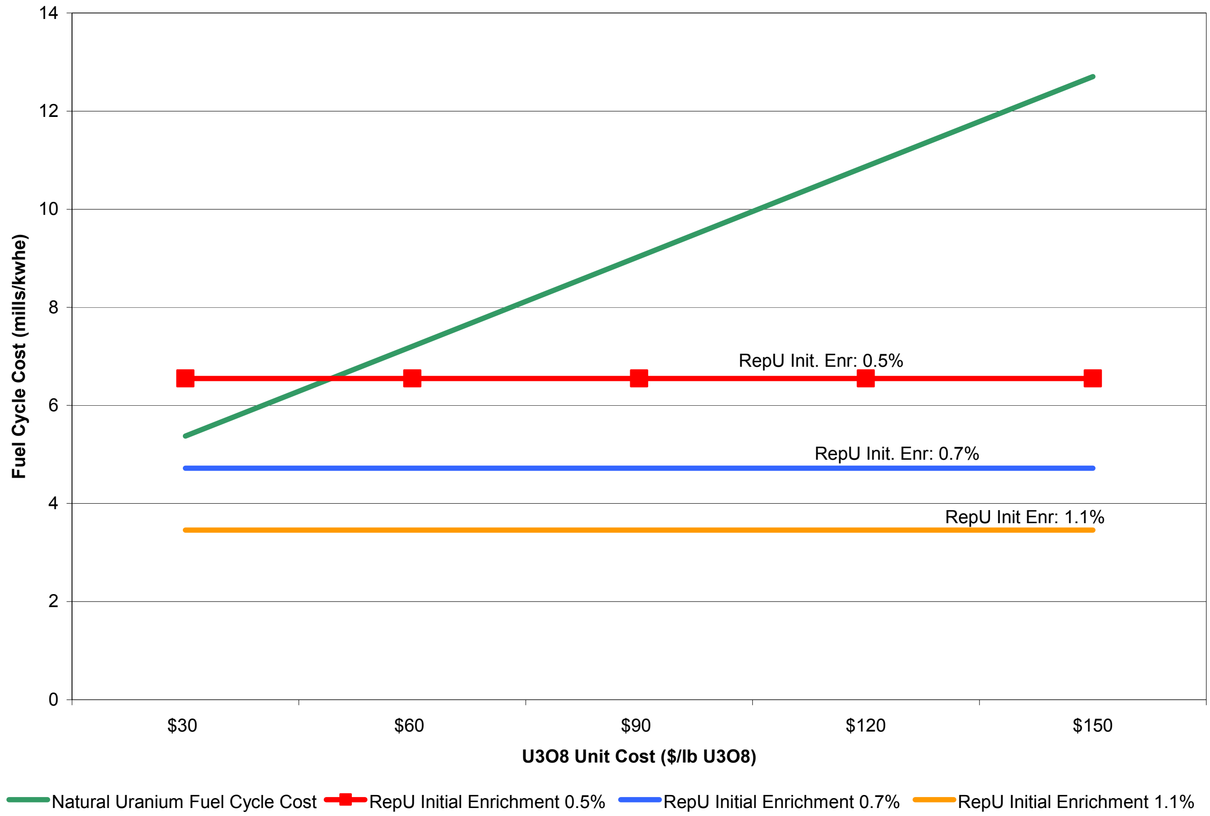

Figure 3-6
Comparison of Front-End Fuel Cycle Cost for NatU LWR Fuel and RepU LWR Fuel as a Function of Natural Uranium Unit Cost and RepU Initial Enrichment

3.8 Changes in the Unit Costs of Conversion Services and Enrichment Services

Assuming that the unit costs for other front-end fuel cycle components remain at the nominal values described in Section 2, EPRI varies the unit costs for NatU conversion services from $5/kgU to $20/kgU as UF_6 and the unit costs for enrichment services from $90/SWU to $210/SWU. The corresponding unit costs for RepU conversion services are assumed to be four times higher than those for NatU, ranging from $20/kgU to $80/kgU as UF_6 and the unit costs for RepU enrichment are assumed to be 30% higher than those for NatU, ranging from $117/SWU to $273/SWU. The results are summarized in Table 3-3 and presented in Figure 3-7.

As discussed in Section 3.2, RepU fuel cycle costs are lower than NatU fuel cycle costs when a 15% enrichment services premium was assumed. Thus, EPRI utilized a 30% enrichment services premium in this scenario in addition to a higher conversion services premium in order to determine the combination of enrichment and conversions services cost premiums at which the use of RepU may not be cost effective.

As presented in Table 3-3. when conversion services costs are at the low end of the range evaluated ($5/kgU for NatU and $20/kgU for RepU) and enrichment costs are $180/SWU or lower for NatU and $234/SWU or lower for RepU, the overall fuel cycle costs for RepU are lower than that for NatU – with RepU fuel cycle costs that are 1% to 30% lower than the corresponding NatU fuel cycle cost. When conversion services costs are higher than $15/kgU for NatU and $60/kgU for RepU, the overall fuel cycle costs associated with using RepU are lower than those for NatU only when enrichment services are low, $90/SWU for NatU and $117/SWU for RepU, as shown in Figure 3-7. Thus, the combination of higher RepU processing fees for both conversion services and enrichment services may be a determining factor regarding whether or not the recycle of RepU is cost effective.

Table 3-3
Impact of Changing Conversion and Enrichment Costs on Overall Fuel Cycle Costs using NatU and RepU (mills/kWhe)

Fuel Cycle Cost – NatU (mills/kWhe)			
NatU Conversion Unit Cost ($/kgU as UF_6)	**5**	**15**	**20**
Enrichment Unit Cost $/SWU			
$90	5.12	5.36	5.47
$120	5.64	5.88	5.99
$150	6.17	6.40	6.51
$180	6.69	6.92	7.04
$210	7.21	7.45	7.56
Fuel Cycle Cost – RepU (mills/kWhe)			
RepU Conversion Unit Cost @ 4x NatU Conversion Cost ($/kgU as UF_6)	**20**	**60**	**80**
Enrichment Unit Cost $/SWU			
$117	3.93	5.31	5.99
$156	4.82	6.20	6.89
$195	5.72	7.09	7.78
$234	6.61	7.99	8.68
$273	7.51	8.89	9.57

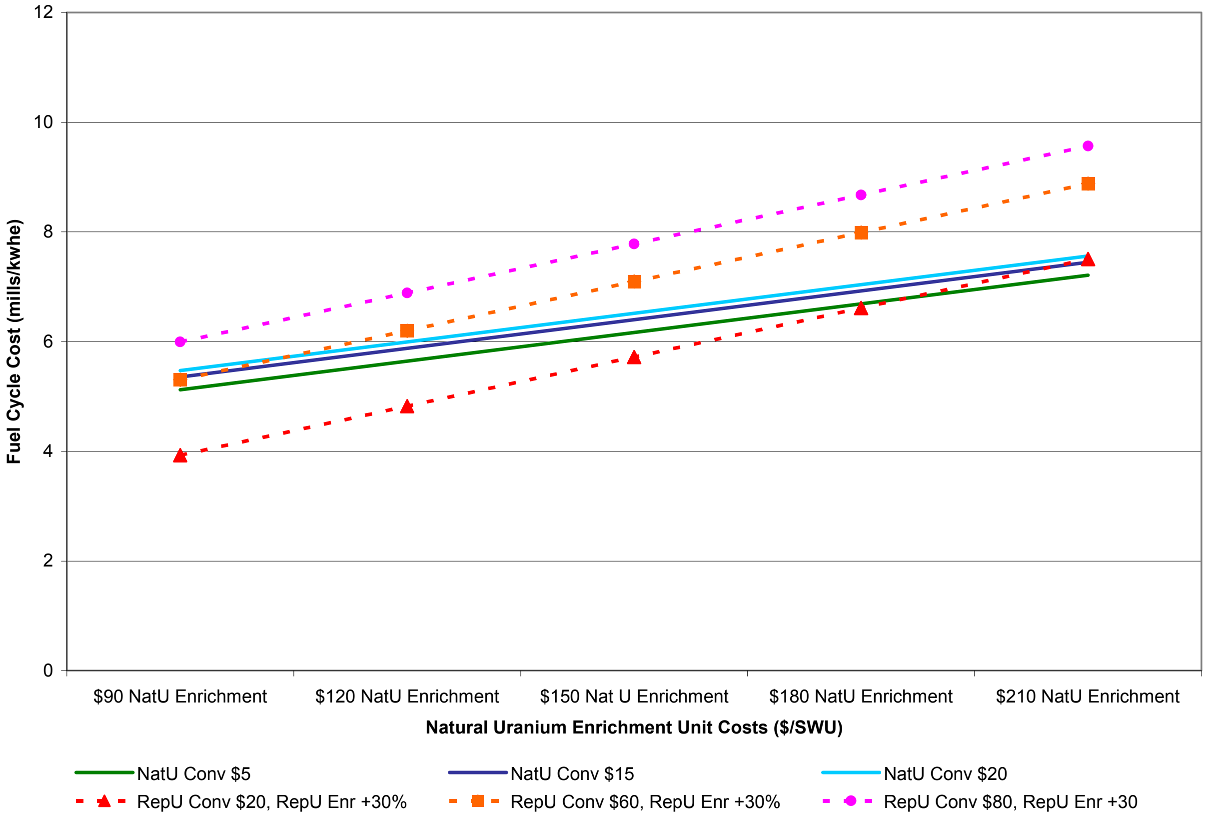

Figure 3-7
Comparison of Front-End Fuel Cycle Cost for NatU LWR Fuel and RepU LWR Fuel as a Function of Conversion and Enrichment Services Unit Costs

3.9 Changes in the Unit Costs of Uranium Ore Concentrates and Enrichment Services

Assuming that the unit costs for other front-end fuel cycle components remain at the nominal values described in Section 2, EPRI varies the unit costs for uranium ore concentrates from \$30/lb U_3O_8 to \$90/lb U_3O_8 and the unit costs for enrichment services from \$90/SWU to \$210/SWU. The corresponding unit costs for RepU enrichment services are assumed to be 30% higher than those for NatU, ranging from \$117/SWU to \$273/SWU. The results are summarized in Table 3-4 and presented in Figure 3-8.

As shown in Table 3-4, when uranium ore concentrates are \$30/lb U_3O_8 or lower, NatU fuel cycle costs are lower than RepU fuel cycle costs if enrichment unit costs are greater than approximately \$90/SWU for NatU and \$117/SWU for RepU, assuming a 30% cost premium for RepU enrichment services. However, as the unit cost of uranium ore concentrates rises are \$60/lb U_3O_8 or higher, NatU fuel cycle costs are generally higher than RepU fuel cycle costs when enrichment unit costs are \$90/SWU or greater for NatU and \$117/SWU or greater for RepU.

Table 3-4
Impact of Changing U_3O_8 and Enrichment Costs on Overall Fuel Cycle Costs using NatU and RepU (mills/kWhe)

Fuel Cycle Cost (mills/kWhe)					
NatU				RepU	
Unit Cost NatU ($/lb U_3O_8)	**30**	**60**	**90**	**Unit Cost RepU ($/lb U_3O_8)**	**0**
Enrichment Unit Cost ($/SWU)				**Enrichment Unit Cost ($/SWU)**	
$90	4.07	5.09	7.73	**$117**	3.96
$120	4.59	6.42	8.26	**$156**	4.86
$150	5.11	6.95	8.78	**$195**	5.75
$180	5.64	7.47	9.30	**$234**	6.64
$210	6.16	7.99	9.82	**$273**	7.54

Figure 3-8 presents RepU fuel cycle costs assuming that the RepU enrichment unit costs vary from $117/SWU to $273/SWU and compares these costs to NatU fuel cycle costs for which both the unit cost of uranium ore concentrates and the unit cost of enrichment services are varied as shown in Table 3-4. Figure 3-8 clearly shows that as the enrichment unit costs for RepU rise, natural uranium ore concentrate unit costs may be higher than $30/lb U_3O_8 and result in lower NatU fuel cycle costs. For example, when RepU enrichment costs are $195/SWU (corresponding to the $150/SWU value on the x-axis of Figure 3-8), the point at which RepU fuel cycle costs and NatU fuel cycle costs are equal would occur when NatU ore concentrate unit costs are approximately $40/lb U_3O_8. If RepU enrichment costs rise further to $273/SWU (corresponding to the $210/SWU value on the x-axis of Figure 3-8), the point at which RepU fuel cycle costs and NatU fuel cycle costs are equal would occur when NatU ore concentrate unit costs are approximately $55/lb U_3O_8.

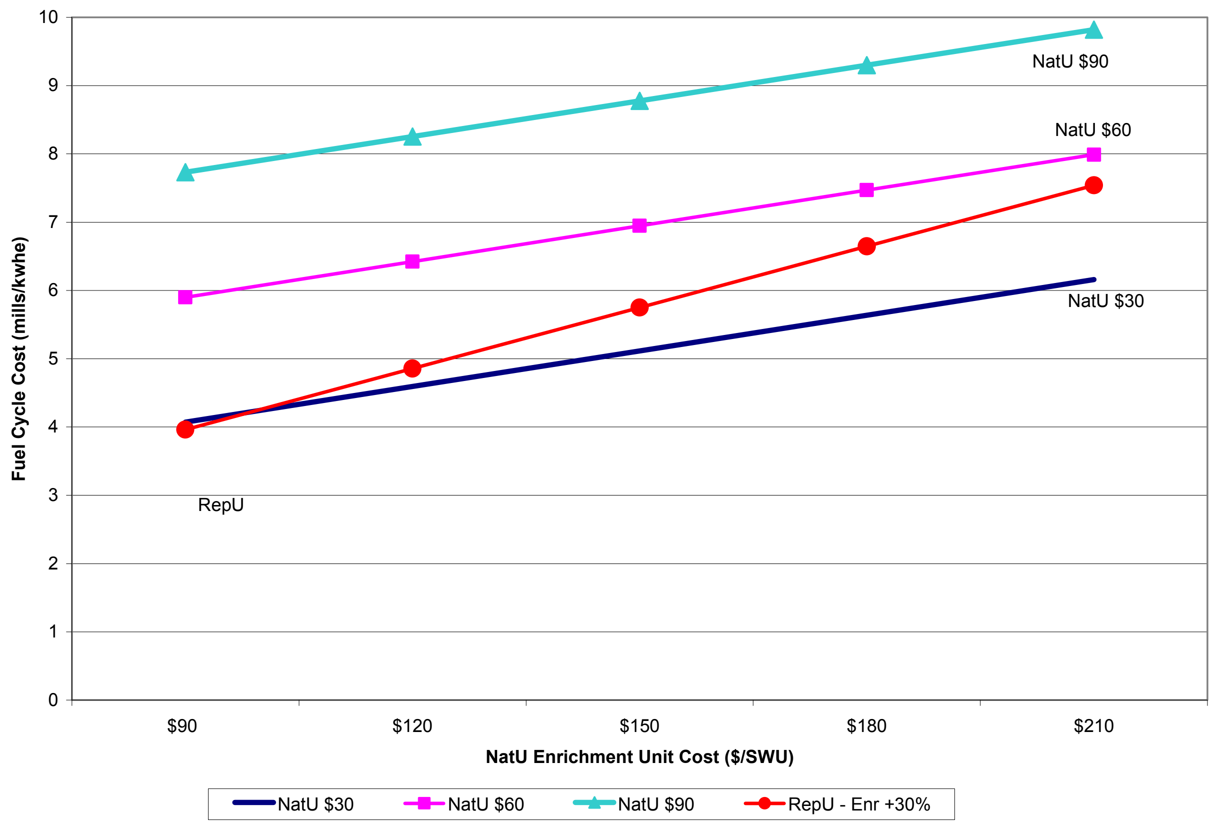

Figure 3-8
Comparison of Front-End Fuel Cycle Cost for NatU LWR Fuel and RepU LWR Fuel as a Function of Uranium Ore Concentrate and Enrichment Services Unit Costs

3.10 Conclusions

Under the range of unit costs evaluated in this report, uranium ore concentrates and uranium enrichment services represent almost 90% of overall nuclear fuel cycle costs for fuel cycles that utilize natural uranium. In contrast, for reload fuel that utilizes RepU, the uranium feedstock has zero cost and uranium enrichment services represent approximately 77% of the front-end fuel cycle costs. While the costs to process RepU (conversion, enrichment and fuel fabrication) are higher than that for LWR fuel utilizing NatU, displacing NatU with RepU may represent substantial front-end fuel cost savings depending upon the unit price of uranium concentrates. As shown in Table 2-1, at the nominal front-end unit costs utilized by EPRI in this study, reload fuel cycle costs for a typical PWR are lower for RepU than for NatU at nominal unit costs of $48/lb U_3O_8. As shown in Figure 3-1, assuming all other fuel cycle costs are set at the nominal values, when the unit cost of uranium ore concentrates rises above approximately $35/lb U_3O_8, there may be a cost benefit associated with recycling RepU in the place of NatU.

As shown in Section 3.2 and 3.3, EPRI examines not only the impact of changing the unit costs associated with conversion services and enrichment services, but also the impact of increasing the "premium" (that is the additional cost) associated with processing RepU. As the premium associated with processing RepU increases for either conversion or enrichment services, the cost advantage associated with recycling RepU decreases as the unit costs for conversion or enrichment services increase. This is shown in Tables 3-1 and 3-2.

Various factors associated with the enrichment of RepU compared to enrichment of NatU play a role regarding whether the recycle of RepU will be cost effective. This includes the premium associated with enrichment of RepU (discussed above), the enrichment tails assay, and the initial concentration of ^{235}U in RepU. For example, as the enrichment tails assay increases, the amount of uranium required will increase. If the value, or cost, of uranium as RepU is zero, increasing the enrichment tails assay results in the need for less separative work and therefore lower enrichment costs and lower overall fuel cycle costs for RepU, as shown in Figure 3-4. The initial enrichment of RepU typically ranges from 0.6 to 1.1 w/o ^{235}U. The higher the initial enrichment of RepU, the lower the requirements will be for uranium, conversion and enrichment services. Thus, higher initial enrichments for RepU may allow the recycle of RepU to be cost effective even when natural uranium concentrates unit costs that are less than \$30/lb U_3O_8, as shown in Figure 3-6.

As discussed in Section 2.2, EPRI assumes that a nominal value of zero for RepU. However it is possible that a market for RepU could develop in the future or RepU may be assigned a cost, such as that associated with storage of RepU prior to recycle. As shown in Figure 3-5, as the value or cost associated with RepU inventories increases, the RepU fuel cycle costs increase. If the assumed value of RepU rises, natural uranium unit costs can rise and still allow the overall fuel cycle costs for NatU fuel to be more cost effective than using RepU. Thus, the costs associated with the storage of RepU and the value assigned to RepU inventories impact decisions regarding whether or not the recycle of RepU may be cost effective.

EPRI also examines the impact of varying more than one fuel cycle cost component on RepU fuel cycle costs compared to similar unit costs changes for NatU fuel. As shown in Figure 3-7, as the unit costs for both conversion and enrichment services rise, the use of RepU may not be cost effective if there are high processing premiums for RepU – in this case an assumed 30% increase in unit costs for RepU enrichment compared to NatU enrichment and RepU conversion costs that are four times higher than those for NatU. Conversion costs must be at the low end of the range evaluated by EPRI (\$5 to \$10/kgU for NatU and \$20 to \$40/kgU for RepU) and enrichment costs must be approximately \$150/SWU or less, in order for the recycle of RepU to be cost effective at the higher RepU cost premiums evaluated.

In Section 3.9, EPRI also examines the impact of varying both the unit cost of NatU concentrates and enrichment services, since these costs make up almost 90% of the fuel cycle costs for NatU fuel. Changes to the unit cost of NatU concentrates do not impact the fuel cycle costs for RepU. As shown in Figure 3-8, as the unit cost of uranium ore concentrates rises above an estimated \$55/lb U_3O_8, even with a RepU enrichment cost premium of 30%, RepU fuel cycle cost are lower than NatU fuel cycle cost over the entire range of enrichment costs evaluated. Thus, once the unit costs of natural uranium ore concentrates becomes high enough, the recycle of RepU fuel may be cost effective even with the high enrichment cost premiums for RepU.

With worldwide nuclear power plant capacity poised to expand, the use of RepU inventories to displace natural uranium feed may assist in reducing future gaps between uranium supply capacity and worldwide uranium requirements. Decisions regarding whether to recycle RepU in the place of natural uranium ore concentrates in LWR fuel will depend upon economic factors, such as the unit cost of uranium ore concentrates, the need for higher enrichment assays to compensate for neutron absorbing isotopes in RepU, the premiums associated with processing RepU for conversion and enrichment services, and the physical characteristics of the RepU (such as initial enrichment). In addition, there are technical issues that must be addressed such as those associated with the licensing and use of RepU in reactor cores, and the need for additional worker protection measures during the processing and manufacture of RepU fuel. Clearly, if the cost premium associated with the processing of RepU can be minimized, possibly through dedicated facilities for conversion and enrichment, and if the unit price of NatU concentrates remains near or above its current value of approximately \$48/lb U_3O_8, there may be justification for expanding the now-limited recycle of RepU in LWRs.

Program:

Nuclear Power

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