Opportunity for Innovation in the Existing LWR Fuel Cycle

Going Beyond 5 Percent Enrichment

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1) Abstract and Project Objectives

1.1) Abstract

Since the first commercial nuclear reactor came online in 1959, the fuel that has gone into reactors has remained almost exactly the same. Low cost enrichment technologies and better knowledge of how fuel performs under prolonged exposure to radiation have allowed for the increase in U235 enrichment in nuclear fuels to be, on average, ~4.5 weight percent (w/o). However, most fuel cycle facilities are licensed to handle materials up to only 5 w/o enrichments. Improvements in fuel cladding and fuel performance have allowed us to consider the possibility of using fuels above 5 w/o that can achieve higher burnups and possible extend the time between refueling outages in PWRs from the typical 18 months to 24 months or even longer. These fuels may allow for better uranium utilization and our investigation suggests they can reduce fuel cycle costs by 10-20%. While these gains can seem small when the fuel cycle accounts for only ~20% of net nuclear electricity costs, the gains can potentially mean the difference between continued operation and shut-down for older reactors that operate in markets that are saturated with zero or negative marginal cost renewable energy.

In order to realize the benefits of fuels enriched over 5 w/o, the fuel cycle infrastructure would need to be upgraded. Currently, no large, commercial enrichment facilities that produce greater than 5 w/o uranium exist and almost all facilities are licensed to only 5 w/o. Furthermore, the fuel transportation and fabrication capabilities for commercial power reactor fuel are currently licensed to only 5 w/o. Upgrading uranium enrichment, fuel fabrication, and fuel transport capabilities is expected to cost at least ~$100M. In this study, we have developed an interactive fuel cycle analysis tool to investigate the economic benefits from an investment in the fuel cycle infrastructure to handle greater than 5 w/o fuels. Our study suggests that such an investment would have a positive present value under most expected circumstances and would allow for cycle lengths to be extended to 24 months while maintaining high fuel utilization. The recent progress in low cost laser enrichment and 2012 licensing, but not yet construction, of a GE-Hitachi laser enrichment facility with a limit of 8 w/o enrichment could be a crucial component to allow widespread adoption of greater than 5 w/o fuels in US reactors. Further work in refining the assumptions used in this analysis and extending it to other LWR and non-LWR reactor types is highly

recommended to better understand the economic and strategic benefits of higher enriched fuels.

1.2) Project Objectives

- **Fuel Transport Capabilities and Readiness:** To assess the capability of the current fuel transport and understand the necessary upgrades that would need to be pursued to facilitate fuel transport of greater than 5 w/o fuel.
- **Fuel Manufacturing Capabilities:** To assess the ability of commercial fuel manufacturing plants to handle higher than 5 w/o fuel.
- **Laser Enrichment:** To investigate the implications of lower cost laser enrichment on fuel cycle optimization.
- **Fuel Cycle Economic Analysis:** To investigate the economic potential for greater than 5 percent enriched fuel in the US nuclear reactor fleet.

2. Introduction

2.1) The Case for Moving to Higher Enrichments

The first human made criticality occurred in 1942 (Chicago Pile-1), the first useful application as a power source in 1954 (Nautilus submarine), and the first significant application to electricity generation in 1959 (the Dresden BWR and Yankee Rowe PWR). Ever since that time, fuel for commercial power generation has consisted of uranium dioxide pellets enriched to less than 5 w/o (weight percent) U235, in tubes of zirconium alloy cladding, grouped into square bundles. Over the last 50 years the materials and components of a nuclear reactor assembly have been improved, burnable poison has been added to help manage the nuclear reactivity, the original, energy intensive gaseous diffusion method of enriching the uranium has been replaced by the centrifuge method, and in the light of Fukushima, there is considerable ongoing research into superior types of cladding.

But the fuel pellets still consist of uranium dioxide enriched to less that 5 w/o U235 in zirconium alloy cladding. Opportunities exist to reduce nuclear electricity costs by improving some of the legacy fuel features that have lingered for the last 50 years:

- Use of laser enrichment would reduce the cost of separative work (i.e., of enriching) and also allow easier use of enrichments above 5 w/o.
- Use of U235 enrichments above 5 w/o allowing more fissile material to be loaded into the core.

<u>The Need for Refueling</u>

Electricity generation via fossil fuel is a more or less continuous process, whereas generation via light water reactors is a batch process, so LWRs require periodic refueling. Early power reactors operated on 12-month cycles (yearly shutdowns for refueling and maintenance), but since about 1980 most US plants have moved to 18 or 24 month cycles, these being multiples of six because most areas of the US have grid loads with minima every six months. As Figure 2.1 shows, the summer peak is higher than the winter, though the percentage between the two can be much greater on a more local basis.

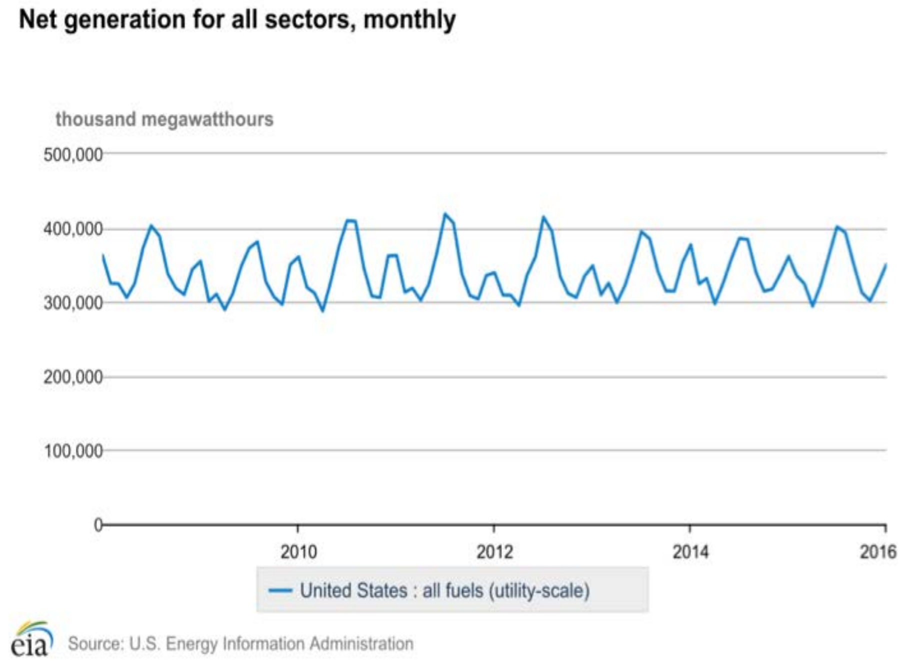

Figure 2.1: *Net electricity generation from all sectors from 2008-2016. The seasonal variation in energy demand causes generation to peak in the summer when demand for indoor cooling is high. Figure taken from the U.S. EIA [1].*

Refueling outages are typically one to two months in length as shown in Figure 2.2, and play an important role because once a plant is taken off line for refueling it cannot be rapidly returned to service even in case of a grid emergency. Furthermore, such outages typically cost on the order of $25 million above and beyond the day-to-day O&M cost. Many plants, particularly large, high power density PWRs would prefer to be on two year cycles but cannot, because of difficulties from the complex interplay of reactor physics, enrichment limitations, and concerns about fuel integrity.

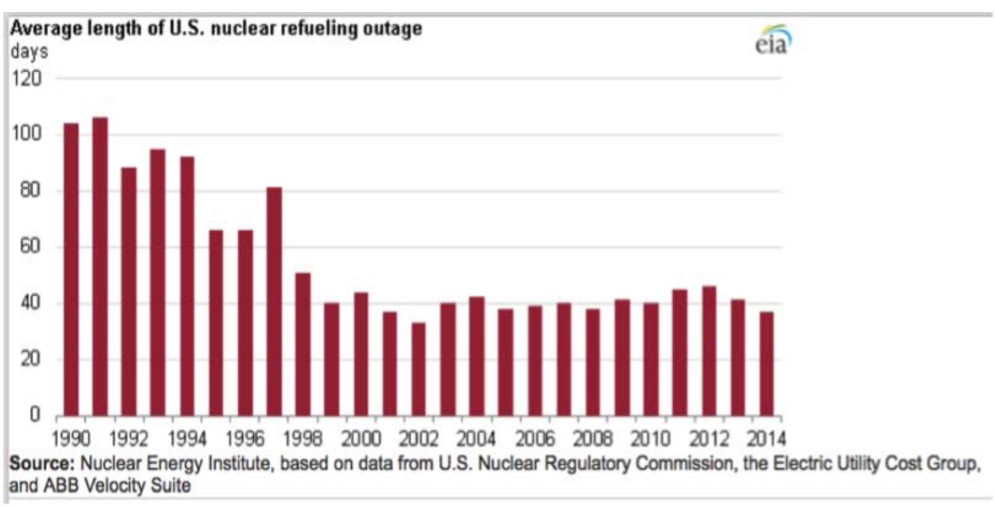

Figure 2.2: *Average length of nuclear refueling outages (in days) from 1990-2014. Improvements in outage planning have reduced outage durations down to one month or less. Figure taken from U.S. EIA [2].*

The Reason for Higher Enrichments

Enrichments above the present de facto limit of 5 w/o could be useful in allowing these large PWRs to increase their cycle lengths to 24 months and thus reduce their production costs by increasing their capacity factor. 5 w/o is not a legal limit, but seems to have developed historically as a value considered unlikely to be exceeded, at a time when actual enrichments were much lower [3]. In line with this assumption, many fuel cycle facilities are only licensed to process uranium at enrichments below 5.0 w/o. Annual PWR cycles used enrichments of ~3.2 w/o during the phase of nuclear expansion in the US in the 1960s to 1980s when most of the fuel cycle supply chain that we use today was constructed. Currently, 18-month cycles have average enrichments of about 4.5 w/o, with some fuel pins enriched to just a fraction below the 5 w/o limit. The enrichment influences every step in the fuel cycle including uranium enrichment, fuel fabrication, and transport of enriched materials.

The batch nature of operation places important constraints on nuclear power plants. Each refueling involves loading enough fresh fuel assemblies into the core to maintain criticality for the next power cycle of 18 or 24 months. Typically the reload fraction is one third to one half of a full core, with the remainder consisting of assemblies that have been operational in the core for 1-2 cycles. These partially burned assemblies must be carefully selected and located in the core to assure safety and compliance with licensing requirements. Given the seasonal variations in demand, it is advantageous to stage the cycle outages to occur at times when demand is at its lowest, which Figure 2.1 shows has typically occurred in the spring. Other strategic advantages to extending cycle lengths such as minimizing the number of overlapping outages at plants operated by the same company or in the same electricity market could provide further impetus to pursue higher enrichments or advanced fuel forms.

2.2) Cost of Electricity from Nuclear

In understanding the economics of nuclear energy and potential areas for making nuclear more competitive, it is important to consider the cost breakdown of nuclear energy and the current situation of the nuclear power plants. Figure 2.3 shows a breakdown of the cost of nuclear electricity and highlights the large capital investment component in net electricity costs. These numbers are from a

2001 OECD-NEA report and it is expected that the capital investment fraction has only gone up as capital cost estimates for new builds have increased over the last 15 years [4]. The capital investment costs have been estimated to be ~$4,000/kW in the 2009 update to the MIT Future of Nuclear Power report, a doubling of the $2,000/kW overnight cost estimated in the original 2003 report [5,6]. The large estimated capital costs for new builds in the US has made nuclear uncompetitive with inexpensive fossil fuel plants and limited nuclear's growth to regulated markets. Currently, there are only four new builds under construction (not including Watts Bar 2) while there have been five reactors closed in the last five years (three for technical reasons and two for economic reasons) and five reactors slated for closure in the next three years due to poor economics in their local electricity markets.

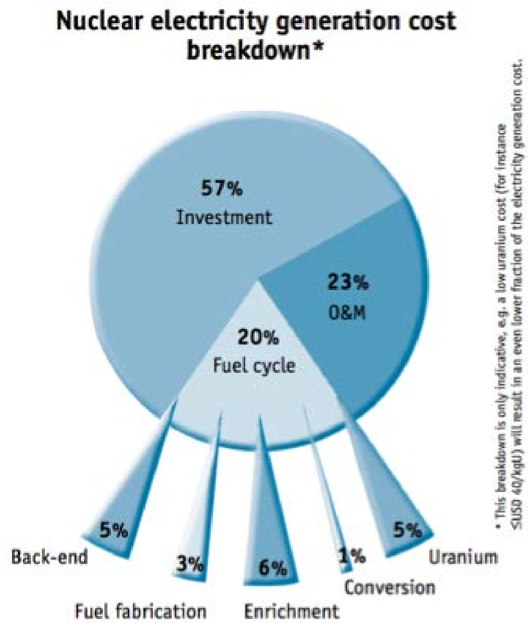

Figure 2.3: *Breakdown of the generation costs of nuclear energy. Figure taken from the OECD-NEA 2001 report on Trends in the Nuclear Fuel Cycle [4].*

The mean age of nuclear reactors in the US is ~35 years with many reactors already operating over their initially licensing period of 40 years. For many of these plants, capital costs have been paid off and the cost breakdown is more heavily skewed towards fuel cycle and O&M costs. Given the higher fraction of fuel cycle costs in the total generation costs and the flooding of the electricity markets with low cost gas and subsidized renewable generation, even small efficiency gains in reducing fuel cycle costs can have large impacts in nuclear generation costs of current reactors and could be the difference between continued operation and shutting down. When considering the alternatives for reliable base load generation and the growing concern of climate change, the impact of reducing fuel cycle costs could amount to more than just small reductions in electricity prices.

2.3) References

[1] *Electricity Data Browser.* U.S. Energy Information Agency, June 8. 2016. <LINK>

[2] *U.S. nuclear outages were less than 3% of capacity this summer.* U.S. Energy Information Agency, June 8, 2016. <LINK>

[3] S. Tarlton. *Outcome of the World Nuclear Association Discussions on 'Beyond 5%'.* Technical Meeting on LWR Fuel Enrichment beyond 5% Limit: Perspectives and Challenges, October 12-16, 2015, Vienna, Austria.

[4] G. Paulis and L. Van den Durpel. *Trends in the Nuclear Fuel Cycle.* NEA News 2001, No. 19.2. <LINK>

[5] *Update to the 2003 MIT The Future of Nuclear Power: An Interdisciplinary MIT Study*. 2009. <LINK>

[6] *The Future of Nuclear Power: An Interdisciplinary MIT Study*. 2003. <LINK>

3) Overview of the Nuclear Fuel Cycle for LWRs

3.1) Fuel Cycle Components and Unit Costs

The open, once-through nuclear fuel cycle today consists of three main steps as shown in Figure 3.1. We have expanded this list to breakdown the various costs and challenges in the front end of the fuel cycle that are relevant to moving to higher enriched fuels. Furthermore, it is important to consider the interconnected aspects of the supply chain and refueling planning as increased enrichments and advanced fuels can have impacts on all of these stages.

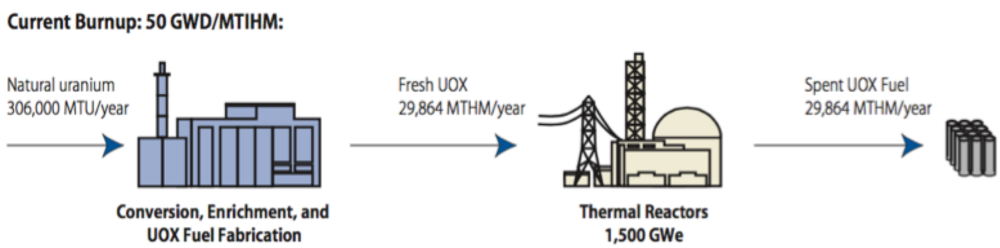

Figure 3.1: *The process flow for an open nuclear fuel cycle. Figure taken from the MIT Study on The Future of Nuclear Power [1].*

3.1.1) Uranium Ore

Uranium ore, or yellowcake, is mined in 20 countries with 6 countries (Canada, Kazakhstan, Australia, Russia, Namibia, and Niger) accounting for 85% of world production [2]. It is important to note that 4 of these countries have no uranium conversion or significant nuclear power plants so almost all of mined uranium ore is transported internationally. As shown in Figure 3.2, spot uranium ore prices have remained fairly low, with a notable large price spike to ~$140 / lb U3O8 during the 2007 commodity boom. Prices have since settled down, especially as worldwide capacity of nuclear energy has decreased due many reactors being taken offline after the 2011 accident at the Fukushima Daiichi Nuclear Power Plant. As of May 30, 2016 the spot price of U3O8 was $27.75 per lb [3]. Approximately 90% of uranium ore is procured by reactor operators on long term contracts that typically have term contracts ~$10-15/lb above the spot market prices.

Uranium ore prices have ranged between \$10-140 / lb U3O8 with current spot prices at \$27.75 / lb U3O8 and term contracts likely around \$40 / lb U3O8.

Figure 3.2: *Historic uranium ore costs were relatively stable during the 1990s and early 2000s with a large price spike in the late 2000s. Figure taken from Ux Consulting Historical Ux Price Charts [3].*

The amount of natural uranium ore required to produce 1 kg of uranium product depends on the enrichment process assumptions and the desired enrichment as shown in Figure 3.3. Using the enrichment range of 3.0-7.0%, the relationship between lb U308 to produce 1 kg of uranium enrichment (in w/o) to various amounts can be approximated by:

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Ore = 5.675 * Enrichment - 1.425
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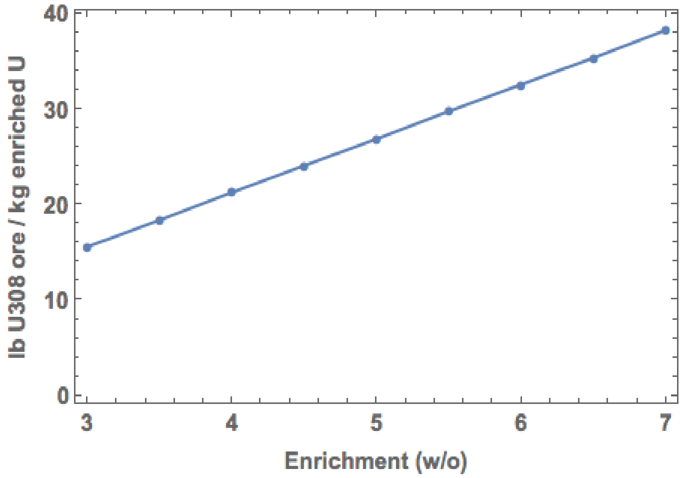

Figure 3.3: *Plot of the pounds of U3O8 ore required to enrich uranium to various*

levels. Within a narrow range, the relationship between the ore requirement and enrichment can be assumed to be linear. Enrichment data taken from Ux Consulting Fuel Quantity & Cost Calculator [4].

<u>Uranium Ore Rules of Thumb</u>

- 25 lbs U3O8 ore required to produce 1 kg of reactor fuel.
- 500,000 lbs U3O8 ore per year are required to fuel one large nuclear reactor.
- 50 million lbs U3O8 ore per year are required to fuel the US nuclear fleet of ~100 reactors.

3.1.2) Conversion of U3O8 to UF6

Conversion of U3O8 ore to UF6 is a necessary step in converting uranium to a gaseous form that can be input to gaseous diffusion, centrifugal, or (proposed) laser enrichment plants. As is shown in Figure 3.4, the spot price for uranium conversion as of May 30, 2016 was \$6.50 / kg U [5]. Long-term contracts for conversion services typically command a ~\$5-7/kg U premium over spot market prices.

Uranium conversion has ranged between \$2-13 / kg U with a current spot price of \$6.50/kg U. Estimated current term contract prices are ~\$11.50-13.50/kg U.

Figure 3.4: *U3O8 to UF6 conversion spot pricing over the last 20 years in units of \$/kg U. Figure taken from Ux Consulting Historical Ux Price Charts [5].*

3.1.3) Uranium Enrichment

Large commercial uranium enrichment facilities are primarily located in France, Germany, Netherlands, UK, USA, and Russia. While the US has historically had large uranium enrichment capacity, the recent closure of the Paducah Gaseous Diffusion Plant in 2013 and the delaying or withdrawal of plans for new enrichment facilities has left the US in an enrichment deficit and reliant on downblended uranium and world markets for enriched uranium. The pictures in Figure 3.5 show the URENCO gas centrifuge enrichment plant in Eunice, NM and the movement of the UF6 throughout the plant.

Figure 3.5: *Clockwise from top left: An overview of the URENCO uranium enrichment plant in Eunice, NM; Shipment of UF6 feed in a type 30B shipping container; Cylinder receipt and dispatch area of Eunice, NM plant; Transport of enriched UF6 in type 30B shipping container with UX-30 overpack; On-site storage of uranium by-product cylinders; Gas centrifuge cascade in URENCO enrichment facility. Figures taken from URENCO presentation for the MIT 2016 Reactor Technology Course for Utility Executives and the 2014 URENCO sustainability report [6,7].*

Accompanying the large increase in uranium prices in the late 2000s was an increase in the spot price of uranium enrichment services as shown in Figure 3.6 that was thought to be due to speculation by investors as was the case with other commodities during that time [8]. The cooling of the nuclear industry in the last five years, most significantly in Japan, has resulted in the cost of enrichment services to drop precipitously with the spot price as of May 30, 2016 at $59 / Separative Work Unit (SWU) [8]. Long-term contracts for enrichment services are typically only a few percent higher than spot market prices [9]. As will be discussed in the section on laser enrichment, the drop in uranium enrichment prices has made new investment in enrichment facilities, even if potentially more efficient, appear less lucrative than a decade ago.

Uranium enrichment prices have ranged between $59-165 / SWU with current spot prices at $59 / SWU. Long-term contract prices are likely ~$65 / SWU.

Figure 3.6: *Uranium enrichment spot pricing over the last 20 years in units of $/SWU. Figure taken from Ux Consulting Historical Ux Price Charts [10].*

The SWU required to enrich natural uranium (0.71 w/o) to low enriched uranium is nearly linear as shown in Figure 3.7. Using the enrichment range of 3.0-7.0%, the relationship between SWU and uranium enrichment (in w/o) can be approximated by:

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SWU = 2.105 * Enrichment - 2.505
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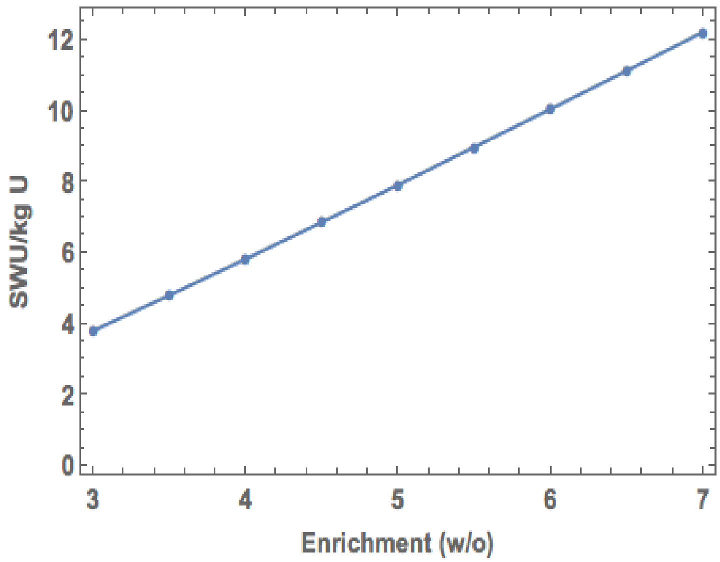

Figure 3.7: *Plot of the SWU required to enrich uranium to various levels. Within a narrow range, the relationship between SWU and enrichment can be assumed*

to be linear. Enrichment data taken from Ux Consulting Fuel Quantity & Cost Calculator [4].

Uranium Enrichment Rules of Thumb

- 7 SWU to produce 1 kg of reactor fuel.
- 140,000 SWU/year are required for one large reactor.
- 14M SWU/year are required to fuel the US nuclear fleet of ~100 reactors.

3.1.4) Fuel Fabrication

Following uranium enrichment, the UF6 must be converted back to uranium Oxide (now in UO2 form) and pressed into dense ceramic pellets for use in a reactor. A simplified process diagram for the fuel fabrication process is shown in Figure 3.8. Areva, Westinghouse, and Global Nuclear Fuels (GE-Hitachi) operate the main fuel fabrication plants in the US and produce roughly 3000 PWR assemblies per year. When these facilities were built, fuel enrichments were in the range of 3.0 to 3.5 w/o so the facilities were only licensed up to this level. Over time these facilities have received licensing upgrades to allow for manufacturing up to 5.0 w/o fuel, but little margin remains to further increase enrichment. According to a 2002 EPRI study, the cost to upgrade a current manufacturing facility to produce fuel enriched above 5.0 w/o would be $55-75M [11].

Costs for fuel fabrication depends on the reactor type the fuel is being produced for, the process used, and current market environments. Recently, a top-down cost-engineering model was used to estimate the market clearing price for PWR and BWR fuel fabrication [12]. This study found the market price for fuel fabrication price to be $230 / kg U in 2008 dollars or ~$250 / kg U in 2016.

Upgrading fuel fabrication plants to handle > 5 w/o fuels is estimated at $55-75M per facility. Fuel fabrication costs ~$250 / kg U.

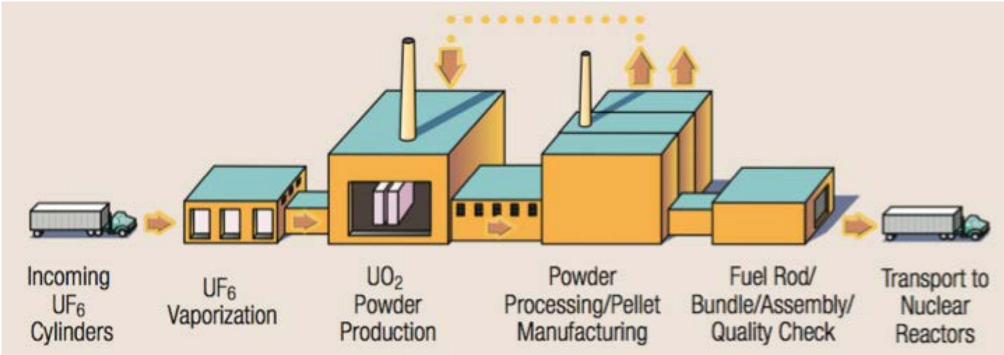

Figure 3.8: *A simplified process flow diagram of the fuel fabrication process for LWRs. Figure taken from U.S. NRC Information Digest 2015-2016 [13].*

<u>Fuel Fabrication Rules of Thumb</u>

- 25 tons/year of fuel are required to fuel one large nuclear reactor.
- 2.5M tons/year of fuel are required to fuel the US nuclear fleet of ~100 reactors.

3.1.5) Fuel Transport

After each step in the front end of the nuclear fuel cycle, the uranium product typically needs to be transported to the next process facility. The World Nuclear Association cites that “transport is a very minor cost in the nuclear fuel cycle” so we have ignored transportation costs in our analysis [14]. However, this does not mean that upgrades to the fuel transportation infrastructure would not be needed. Current fresh fuel transport shipping containers are licensed to accept fuel enriched only up to 5.0 w/o. In a 2002 EPRI report, it was estimated that replacement of all current shipping containers in the US with updated designs to transport greater than 5 w/o fuels would cost $20-30M [11]. Considering that there are ~75 deliveries of fresh fuel assemblies per year totaling ~2.5M kg per year of delivered product, the cost to upgrade the fuel transport containers to handle greater than 5 w/o fuels is a relatively minor cost.

Upgrading fuel transport containers would cost ~$20-30M, but should not significantly affect cumulative fuel cycle costs.

3.1.6) Spent Fuel Storage

After operation, spent fuel assemblies must be placed in a spent fuel pool for ~10-15 years for removal of the relatively large decay heat source (~0.01-1% of their in-core power of ~17 MW each). After 10-15 years of wet storage, spent fuel assemblies are transitioned to on-site dry cask storage. The decay heat source is dependent on the fuel discharge burnup, which will affect the residence time required for wet storage. In our analysis, we lump the cost of wet and dry spent fuel storage into one unit cost item and incur that cost when the fuel is discharged from the reactor. Estimates for spent fuel storage in previous studies range widely, with nominal spent fuel storage costs in the range of $100-250 / kg HM [11,15].

Spent fuel storage costs range from $100-250 / kg HM.

It is also important to note that different countries have different back end fuel cycle costs due to differences in the way costs for spent fuel storage are incurred that could affect the economics of transitioning to higher enriched fuels. For instance, Sweden pays per MW for storage costs, which reduces the incentive for higher enriched fuels. Germany and Switzerland, already the main users of higher enriched (but still below 5 w/o) fuels, could see less incentive to use higher enriched fuels in the future due to removal of taxes on backend costs that provide a driver for higher burnup (and thus higher enriched) fuels [16].

3.1.7) Spent Fuel Disposal

The Nuclear Waste Policy Act of 1982 established a national plan for the permanent disposal of spent nuclear fuel and established a fee of one mill per kWhr of energy generated to be paid for spent fuel disposal. The DOE was supposed to start taking fuel for disposal beginning in 1998, but has yet to start taking any shipments and does not expect to have a repository open until 2048. In 2013, a federal appeals court ruled that the DOE must stop collecting fees for spent fuel disposal [17]. Given the lack of clarity on spent fuel storage, it is unclear how costs for spent fuel disposal will be incurred in the future. Most fuel cycle analysis continues to use the one mill per kWhr established by the Nuclear Waste Policy Act and incur the cost at the time of energy generation. Herein, we used the one mill per kWhr fee and incur the costs as the fuel is burned in the reactor.

Spent fuel disposal costs have historically been constant at 1 mill/kW-hr, but a 2013 lawsuit has ruled that DOE must stop collecting spent fuel disposal fees until plans are made for the collection of spent nuclear fuel.

3.2) Fuel Cycle Challenges for Greater than 5 w/o Fuels

3.2.1) Sourcing Enriched Uranium

There are two options for sourcing fuel material with enrichments over 5 w/o:

- **Enriching uranium ore:** This is the straightforward approach of enriching uranium ore in current enrichment facilities to greater than 5 w/o.
- **Downblending highly enriched uranium (HEU):** There is ~1380 tons of HEU stockpiles worldwide, with ~5% of this currently earmarked for downblending to low enriched uranium (LEU) for reactor fuel.

<u>Enriching Uranium Ore in Existing Enrichment Facilities</u>

The most straightforward route to producing uranium with enrichments of over 5 w/o would be to enrich natural uranium ore in current enrichment facilities. To our knowledge the only operating enrichment facility licensed to produce uranium with enrichments of 5 w/o is the Georges Besse II plant in France, which is licensed to produce uranium with enrichments up to 6 w/o. However, it does not appear that this facility has produced any material over 5 w/o, probably due to a lack of other fuel cycle infrastructure to support the handling of such material. Furthermore, it is not clear what operational changes would need to be made to support the production of 6 w/o uranium at this facility.

In order for an existing facility to produce fuel over 5 w/o, the facility would need to be re-licensed and potentially receive upgrades or operational modifications that could require significant investment. It is unclear what this investment would be and what political, economic, or other concerns might factor into the decision to upgrade an existing facility.

<u>Enriching Uranium in a New or Expanded Enrichment Facility</u>

Due to the lack of licensed and operating facilities to enrich uranium over 5 w/o, another option could be to build a new or expanded enrichment facility licensed above 5 w/o. The URENCO National Enrichment Facility (NEF) in Eunice, NM is the only operating enrichment facility in the US with a current capacity of 4.6M SWU/year and an additional 1.1M SWU/year slated to added in the next few years [18]. With the cancellation or postponement of several enrichment plants in the US and roughly 20% surplus capacity in the enrichment market [9], it does not appear that a new, large enrichment facility in the US is needed. However, in order to produce greater than 5 w/o fuels, one option could be to build a small enrichment facility, perhaps on the same site as a current facility, that is licensed and capable of producing higher enriched fuels. The granted license for the GE-Hitachi laser enrichment facility to enrich uranium up to 8 w/o poses one such option for this route. The difference in ownership between the URENCO NEF facility (URENCO is jointly owned by Germany, the Netherlands, and the UK) and GE-Hitachi owners of the laser enrichment technology could present potential conflicts in realizing such a plant for a co-located laser enrichment facility at the NEF site.

Another option involves building the GE-Hitachi laser enrichment plant at the originally planned location on the site of the GE-Hitachi fuel fabrication plant in Wilmington, NC. This would avoid the need for transport of UF6 with enrichments over 5 w/o and thus avoid one of the uncertainties in going to higher enriched fuels. Considering the different options, this one seems the most feasible if the laser enrichment plant can be constructed at the same capital cost as the centrifuge enrichment plants, ~$400 per SWU/year of capacity.

Downblending HEU from Weapons Stockpiles

While all enriched uranium is derived from natural uranium ore, much of the fuel used in US reactors over the past two decades has come from downblended highly enriched uranium (HEU) stockpiles. As part of the Megatons to Megawatts program, the US and Russia downblended 630 tons of HEU between 1993-2013 to produce ~18,000 tons of low enriched uranium for US power reactors [19]. This implies a rate of consumption of ~30 tons HEU (or equivalently ~900 tons LEU reactor fuel) per year, or roughly half of the US reactor fuel requirements. Current worldwide stockpiles of HEU total ~1380 tons, with Russia and the US having stockpiles of roughly 700 tons and 600 tons, respectively. The US has ~60 tons HEU earmarked for downblending, 20 tons HEU earmarked for space and research reactors, and ~160 tons earmarked for navy nuclear propulsion. The 60 tons of HEU fuel could yield ~1,700 tons of reactor fuel or about 1 year of fuel for US power reactors. The US Department of Energy has slowed downblending activity of US stockpiles from 10 tons/year to 3-4 tons/year, or ~5% of US power reactor requirements when downblended, and expects to extend the downblending of HEU fuel out to at least 2050 [19].

The supply of HEU presents one option for obtaining greater than 5 w/o fuels, but could only provide enough fuel for ~5% of the reactor fleet if downblended with natural, depleted, or very low enriched uranium. One option for producing higher quantities of greater than 5 w/o fuels could be to downblend UF6 that has been enriched to the 5 w/o maximum enrichment of current enrichment facilities. This could provide at least an interim supply of higher enriched fuels that would not require relicensing or upgrades to the enrichment infrastructure to accommodate a transition to higher enriched fuels.

There are multiple routes to sourcing uranium at enrichments above 5 w/o. Downblending HEU appears to be the least capital intensive route (perhaps zero capital requirements) that could provide sufficient quantities of higher enriched fuels at least in the interim. A more widespread adoption of higher enriched fuels would likely require a new or re-licensed facility and the licensed, but not constructed, GE-Hitachi laser enrichment plant could provide one such route.

3.2.2) Fuel Fabrication

The US has three large fuel fabrication facilities that are licensed to produce fuels with enrichments up to 5 w/o. These facilities were built several decades ago when average enrichments were around 3 w/o. They are only licensed to produce fuel up to 5 w/o and it has been estimated that upgrading one of these facilities would cost between $55-75M [11]. Babcock & Wilcox's Nuclear Operations Group and Nuclear Fuel Services have the only private US facilities capable of possessing and processing highly enriched uranium. These groups produce the highly enriched fuel for research reactors and nuclear submarines, but the fuel forms for these applications are typically plate-type and not pellet-type fuel and thus it is unclear if and how much modifications would be needed for one of these facilities to produce LWR fuel with over 5 w/o enrichment.

In the US, all large commercial fuel fabrication facilities are licensed to produce fuel at maximum enrichments of 5 w/o. It has been estimated that upgrading a fuel enrichment facility to produce greater than 5 w/o fuel would costs of ~$55-75M.

3.2.3) Enriched UF6 and Fuel Transport

There are two main steps in the fuel cycle where enriched uranium needs to be transported. Following the enrichment process, UF6 needs to be transported to a fuel fabrication facility. Currently, this is done in type 30B cylinders that are licensed to transport UF6 at enrichments of up to 5 w/o. Type 8A cylinders are rated to transport UF6 up to enrichments of 12.5 w/o, but they are 20 times smaller than type 30B cylinders and it is unclear how many could be packaged on a single truck for shipment.

The other transportation step is in shipping the fabricated fuel assemblies to the power plants. Currently, this is done in stainless steel shipping packages like those shown in Figure 3.8. To our knowledge these shipping containers are only licensed to transport fuel up to 5 w/o and modifications and re-licensing would need to be done to support transport of greater than 5 w/o fuels. In a 2002 EPRI report, it was estimated that replacement of all current shipping containers in the US with updated designs to transport greater than 5 w/o fuels would cost $20-30M [11]. Considering that there are ~75 deliveries of fresh fuel assemblies per year totaling ~2.5M kg per year of delivered product, the cost to upgrade the fuel transport containers to handle greater than 5 w/o fuels appears to be a relatively minor cost.

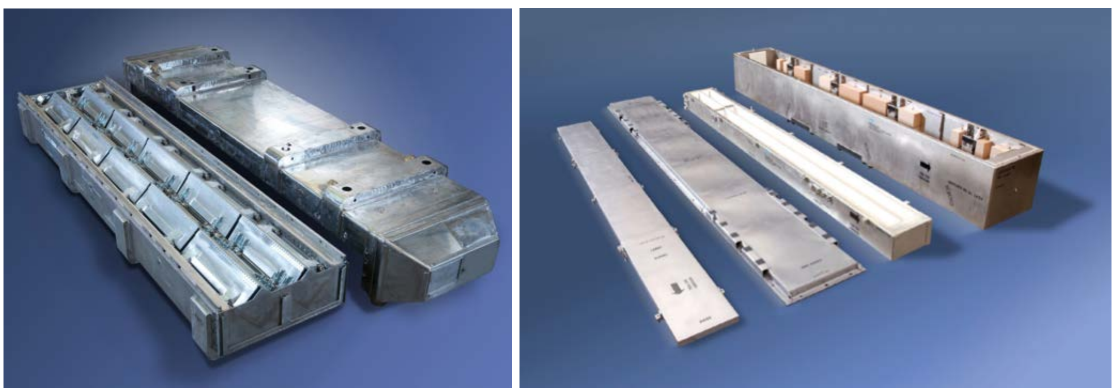

Figure 3.8: *Pictures of the MAP-12 (left) and Raj II (right) shipping packages designed and manufactured by Columbiana Hi Tech for PWR and BWR assemblies, respectively. Pictures from the Columbiana Hi Tech website [20].*

Given that transport costs are a relatively minor component fuel cycle cost and estimated costs for upgrading fuel cycle transport casks is quite small ($20-30M), fuel transport issues do not seem to be a major impediment to the use of greater than 5 w/o fuels.

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<LINK>

4) Prospects for Laser Enrichment

4.1) Enrichment Capacity Worldwide

All currently operating uranium enrichment facilities use centrifugal enrichment technology. Centrifuge technology has proven to be a very reliable technology for uranium enrichment and often centrifuges will never be shut down during their 25+ year lifetime. Operators are often concerned that, if they turn off a centrifuge, they will not be able to get it started again. For this reason, centrifuge enrichment plants (and therefore all enrichment facilities) will operate at their nameplate installed capacity even in unfavorable market conditions. Market price signals can affect plant operation whereby enrichment plants will operate in an “underfeeding” mode where the tails U235 fraction is decreased, effectively increasing the SWU required to produce each kg of product but decreasing the feed requirements [1]. However, the market price signals appear to have more impact on planned expansions and new plant construction since enrichment services are mainly procured on long term contracts. The balance between the supply and demand in the enrichment market is shown in Figure 4.1 below.

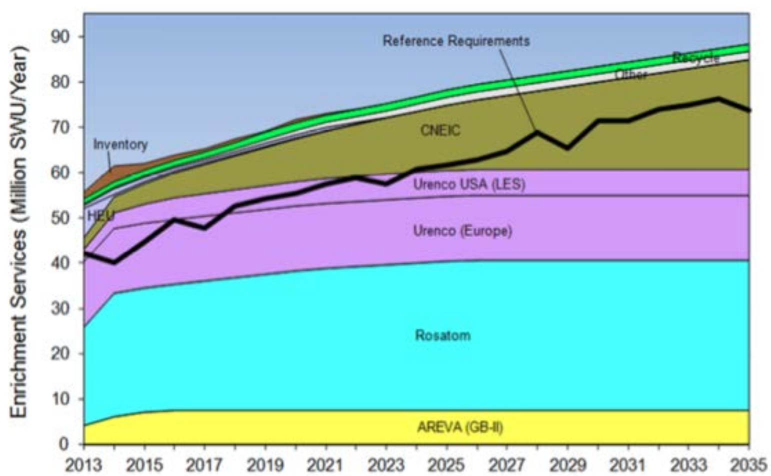

Figure 4.1: *Forecast for world supply and demand of enrichment services. Figure taken from 2015 EPI report [1].*

Figure 4.1 shows that the current and projected enrichment surplus is around 20%. According to a 2015 EPI report, these market conditions are going to continue to push enrichers to redirect enrichment capacity to underfeeding and Rosatom, who owns roughly 50% of the enrichment market, will likely continue to re-enrich tails [1]. The enrichment services chart also highlights the decreasing supply of downblended HEU as the Megatons to Megawatts program has recently ended.

The URENCO USA National Enrichment Facility (NEF) is the only operating enrichment facility in the US. As of 2016, it had an installed capacity of 4.6M SWU/year with an expansion underway to increase the capacity to 5.7M SWU/year by 2023. URENCO USA received a license amendment to increase capacity up to 10M SWU/year, but this move was to provide for future licensing flexibility if market conditions improve and does not necessarily represent a plan to increase capacity in the near term [2]. The US requires ~15M SWU/year, so the enrichment supply at NEF, once the current expansion is completed, will be 35-45% of domestic enrichment demand.

4.2) Current State of Laser Enrichment

Since the first uranium was enriched in the early 1940s at Oak Ridge National Laboratory, the gaseous diffusion and centrifugal processes have dominated uranium enrichment. Gaseous diffusion is seen as the first generation uranium enrichment technology due to its relatively low-tech design compared with other proposed enrichment technologies. However, gaseous diffusion requires enormous amounts of electricity due to the relatively low separation efficiency.

With improvements in precision machining and research in centrifugal isotope separation, the gaseous centrifuge became the second-generation enrichment technology. Gaseous centrifuge enrichment yielded separation efficiencies of ~1.3 at each stage compared to ~1.005 for gaseous diffusion and a 20x reduction in energy requirements to achieve the same level of enrichment [3]. Since the closure of the Paducah Gaseous Diffusion Plant in 2013, all commercial uranium enrichment facilities operate using the centrifugal process [4].

Laser uranium enrichment has long been considered a route for greatly reducing the energy requirements for the enrichment process, but has been held back by the development of suitable laser technology and engineering challenges. In the 1990s, Silex Systems Limited, an Australia-based technology development company, invented the Separation of Isotopes by Laser EXcitation (SILEX) process, which has been the most well developed of the proposed laser enrichment processes. While little definitive information is available on the plant size and energy requirements for laser enrichment, especially considered that a commercial facility has yet to be built, it is expected that a laser enrichment facility would be much smaller and more efficient that a current gaseous centrifuge plant. In the late 2000s during the peak in the uranium ore and enrichment markets, GE-Hitachi entered into an agreement with Silex Systems to form Global Laser Enrichment LLC (GLE) and soon received an additional investment from Cameco as shown in Figure 4.2 [5]. In 2009, GE-Hitachi submitted a license application to the NRC for the construction of a laser enrichment plant in the US and the license application was approved in 2012 for a facility with a capacity of 6 million SWU per year and a maximum enrichment of 8 w/o U235 [6]. It is important to note that this appears to be the only commercial license for an enrichment facility to produce greater than 6 w/o product besides Russia's enrichment plant in Novouralsk which can enrich up to 30 w/o for test reactors and Russia's BN-600 sodium fast reactor [7]. The Georges Besse II enrichment plant in France is, to our knowledge, the only commercial enrichment facility licensed up to 6 w/o in a western country, although it is unclear whether the plant produces any 6 w/o product due to other fuel cycle constraints [8].

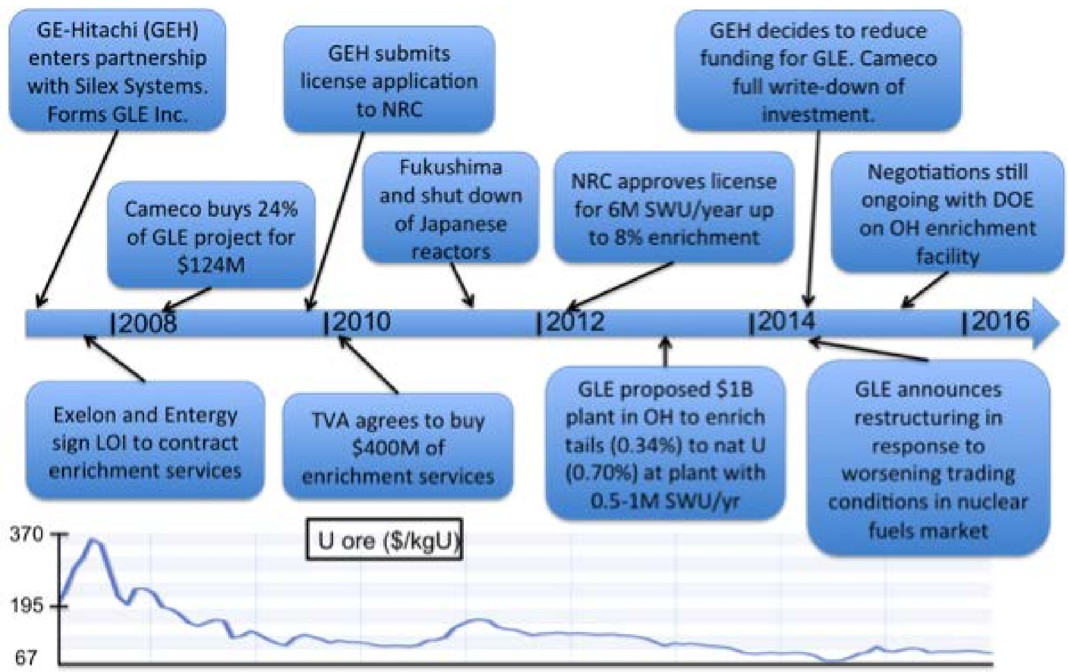

Figure 4.2: *Curated timeline of the progress in the commercialization effort of the SILEX laser enrichment process. A plot of the uranium ore cost has been included on the same timeline to show the connection between the interest in commercializing new lower cost enrichment technology and the cost of uranium.*

Based on the current depressed market for nuclear fuel and accompanying low prices of uranium ore and enrichment services, it appears that interest in the development of a commercial laser enrichment plant, or even a new gaseous centrifuge plant, is low. Nevertheless, the licensing investment by GE-Hitachi suggests that laser enrichment can be performed economically and future enrichment plants will likely eventually be built with this third generation technology.

4.3) References

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5) Interactive Fuel Cycle Analysis

5.1) Economic Analysis Overview

The economic justification for moving to beyond 5 w/o fuels ultimately lies with the consumer of the fuels (i.e. the utility operating the reactor). The capital investment for upgrading and re-licensing facilities to handle greater than 5 w/o material will come from the companies that operate in the fuel cycle supply chain (e.g. Areva, GE-Hitachi, ConverDyn, Urenco, etc). Capital investments would be recouped by distributing the savings of higher enriched fuels to components of the fuel cycle that increase in cost. With this in mind, the focus of the economic analysis was to estimate, from the perspective of the utility operating a nuclear reactor, the fuel cycle lifetime levelized unit cost (LLUC) of two scenarios:

- **Business as usual:** In this scenario, the utility continues to use fuel enriched to below 5 w/o.
- **Use of higher enriched fuels:** In this scenario, the utility has transitioned to using fuel with an enrichment of over 5 w/o. The incurred costs to support fuel cycle upgrades will be included in the cost of the higher enriched fuels.

The economic performance of each scenario will be assessed based on the fuel cycle LLUC for a constructed PWR. The fuel cycle costs will capture the change in costs related to production, transport, and handling of fuels of different enrichments, and thus should provide an appropriate metric to compare the two scenarios.

The methodology for computing the fuel cycle LLUC will calculate the electricity production costs associated with the fuel cycle using a discounted cash flow (DCF) approach. The assumptions that are used in our analysis include:

- Appropriate carrying costs associated with procurement of uranium ore and enrichment and fuel fabrication services will be taken into account. This will result in an escalation in fuel costs and favor fuel cycles that require less uranium ore and/or reactor fuel.
- Upgrades to fuel cycle operations to support higher enriched fuels will start at year 0 of the economic analysis and capital costs will be allocated evenly over each year of the design, construction, and licensing of these operations.
- All upgrades to the fuel cycle operations will take the same amount of time to be completed.
- Capital costs for upgrading the fuel enrichment and fuel fabrication facilities

will be on a per facility basis and independent of plant capacity.

- Recommendations based on current plant capacity and estimates from literature on the cost to upgrade the facilities will be described.
- The cycle length or discharge burnup is independent of fuel enrichment. The cycle length or desired fuel burnup and the fuel enrichment will be combined to yield an enrichment-dependent reload fraction that specifies the amount of fuel required to load into the reactor at the start of each cycle.
- The fuel cycle facilities can be upgraded without interruption or additional down time of existing facilities that might cause a loss in revenue for current fuel cycle operators.

In estimating fuel cycle costs, it is important to keep in mind that fuel cycle costs will be incurred before revenue is generated from burning the fuel in a reactor. Incorporating the appropriate carrying costs for each component is important for properly time-weighting each component. As shown in Table 5.1, the purchasing of uranium ore is often done about one year or more before the fuel is loaded in the reactor. Taking into account the appropriate carrying costs will slightly favor fuel cycles that require less material.

Table 5.1: *Lead times for the various components of the fuel cycle. All times are presented in months prior to loading the fuel in the reactor.*

Fuel Cycle Component	Lead Time (in months)
Purchase Uranium ore	12
Convert U3O8 to UF6	7
UF6 Enrichment	5
Fuel Fabrication	1 – 4
Delivery to Reactor	1 – 2
Spent Fuel Disposal	0
Spent Fuel Storage	–60

To aid in investigating the economic potential of transitioning to a fuel cycle with higher enriched fuels, two interactive tools were developed where inputs to fuel cycle costs, fuel cycle parameters, and cost uncertainties could be adjusted by the user to study certain scenarios. The two tools focus on addressing the following questions:

- **Long-term Benefits:** Are there long-term economic benefits of transitioning to fuels with > 5 w/o enrichment once the capital costs for upgrades to the nuclear fuel cycle infrastructure has been paid off? If so, how does uncertainties in fuel cycle costs affect the economic benefits?

- **Short-term Benefits:** In the short term, would upgrading the nuclear fuel cycle infrastructure to support > 5 w/o fuels be a wise investment? Considering the large uncertainty in the time and cost to make upgrades, how risky is this investment?

5.2) Methods Used in the Economic Analysis

In order to investigate the economic potential for pursuing fuels of beyond 5 w/o enrichment, an analysis was performed on the current fuel cycle costs and the anticipated fuel cycle costs for enriched fuels beyond 5 w/o. Looking back at fuel cycle costs, it is important to note the variability in the costs of different items in the supply chain, with the price of uranium ore being the most widely varying due to the presence of speculators in the marketplace. The price variability suggests that fuel cycle costs should not be taken as constant values from current market data, but estimated in the future using the same metrics that are applied to model the anticipated cost uncertainty of producing fuels both above and below the 5 w/o limit.

5.2.1) Present Value

The present value can be computed using the formula shown below:

$$\mathrm{PV\ (project)} = \mathrm{CF}_{\mathrm{ON}}^{\mathrm{CAP}} + \mathrm{PV}\left(\mathrm{CF}_{\mathrm{FIN1}}^{\mathrm{CAP}}\right) + \mathrm{PV}\left(\mathrm{CF}_{\mathrm{FIN2}}^{\mathrm{CAP}}\right) + \mathrm{PV}\left(\mathrm{S}_{\mathrm{FUEL}}\right)$$

Where the variables are defined by:

Table 5.2: *Descriptions of the variables in the present value equation.*

Variable	Description
CF_{ON}^{CAP}	The overnight capital cost
CF_{FIN1}^{CAP}	The financing cost during construction
CF_{FIN2}^{CAP}	The financing cost during operation
S_{FUEL}	The savings from the sale of fuel

In this equation, the financing costs will all be negative while the fuel sales will be positive. In computing the present value of the project, we will include only the savings from the sale of fuels. For instance, if the cost of 5 w/o fuel is calculated to be 8.0 mills/kWhr while the cost of 6 w/o fuels (based only on long-term fuel cycle costs) is 7.0 mills/kWhr, the savings from the sale of fuel will be calculated based on the 1.0 mills/kWhr that is saved by buying the higher enriched fuel.

5.2.2) Accounting for Market and Cost Uncertainties

In order to account for market and cost estimate uncertainties in the supply chain, the Markov Chain Monte Carlo (MCMC) method was used. In the MCMC methodology, each cost component is estimated by a distribution as shown in Figure 5.1. Many "samples" are conducted whereby each cost component is randomly sampled from a cost distribution and propagated through to get a sample estimate of the present value. Conducting many samples allows for a distribution of the present value to be formed that integrates the uncertainties in each cost component.

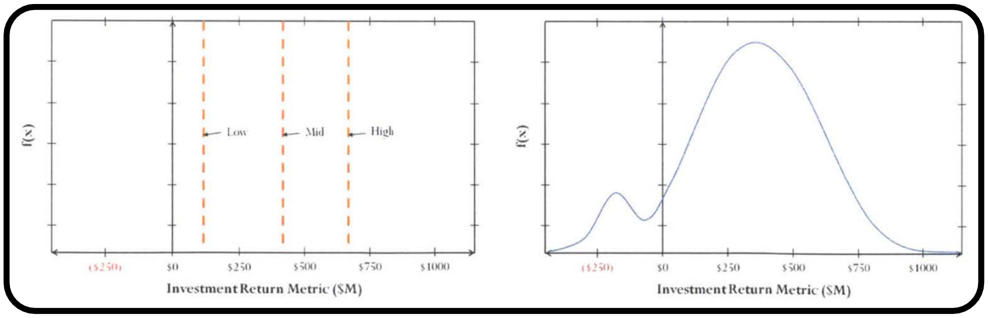


Figure 5.1: *Graphs of the common methodology for treating cost uncertainties of selecting a low/mid/high estimate (left) and the Markov Chain Monte Carlo methodology of assigning a probability distribution to a cost to fully capture a wide range of weighted estimates (right). Figure taken from Jacob DeWitte's thesis [1].*

5.3) Components of the Analysis Tools

The interactive fuel cycle analysis tools presented in this report are composed of widgets that allow for parameters in the fuel cycle analysis to be dynamically modified. Figure 5.2 below shows an example of an interval slider and drop-down box for estimating the cost of uranium ore.

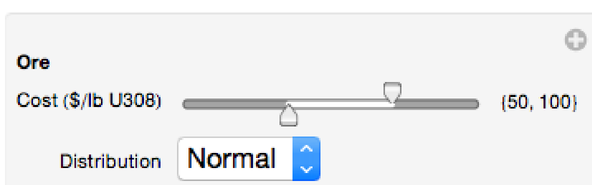


Figure 5.2: *Widgets used to interactively select the estimated ore cost range and distribution to use in modeling the ore cost. For a Normal distribution, the range represents a 95% confidence interval and for an Even distribution the range fully encapsulates the assumed cost range.*

The estimated costs would then be incorporated into the value being computed.

For instance, Figure 5.3 shows a plot of the sampled uranium ore cost and the associated control interval slider and drop-down box:

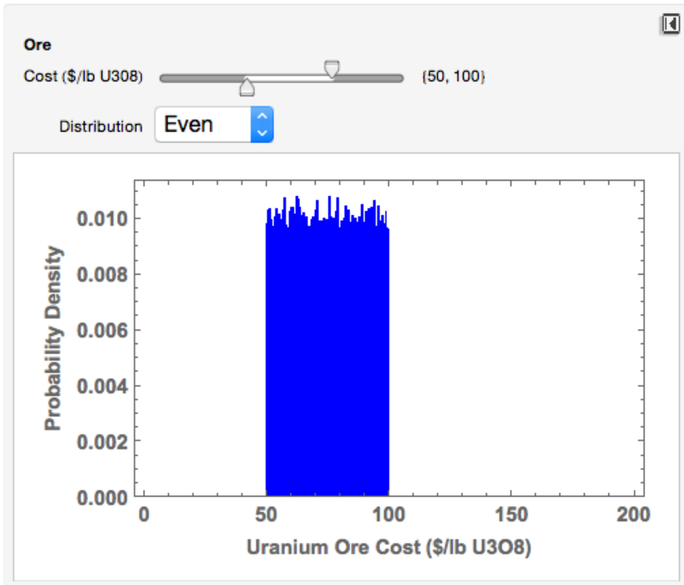


Figure 5.3: *Widget that can be used to control the uranium ore cost.*

The fuel cycle analysis tools include certain constraints on specifying the fuel cycle. An important constraint is the determination of the **cycle length**, **fuel enrichment**, and **fuel discharge burnup**. In describing the operation of a reactor, only two of these three parameters can be independently specified. Using the linear reactivity (LR) model for nuclear fuel management, the third parameter can be computed [2]. In the LR model, the bounding equation is composed of the fuel discharge burnup (B_D), cycle burnup (B_C), and single batch burnup (B_1):

$$B_1 = \frac{B_D + B_C}{2}$$

The discharge burnup is directly specified by the user. The cycle burnup is not directly specified by the user, but derived from the reactor specific power, mass of heavy metal in the core, and cycle length:

$$B_C = \frac{P_{reactor}}{massHM} * \frac{CL}{12} * 365$$

Where CL represents the cycle length specified in months. The cycle length is converted to days and multiplied by the reactor power density in units of MW-days per kg heavy metal (HM) to give the cycle burnup in units of MW-days per kg HM. The single batch burnup is also not supplied directly by the user. Instead, the user specifies an enrichment and the single batch burnup is determined by performing a burnup calculation using a neutronics code such as CASMO or SERPENT. In our analysis, we performed a burnup calculation of characteristic PWR assemblies of different enrichments using CASMO. In these simulations, we assumed the all pins in the assembly had the same enrichment. Figure 5.4 below shows the k_{inf} versus burnup for assemblies of different enrichment. The single batch burnup is then expected to occur when the reactivity of the assembly goes to zero (i.e. when k_{eff} goes to 1). We assumed a 3% core leakage, which is typical of large PWRs, so the single batch burnup occurs when k_{inf} is at 1.03.

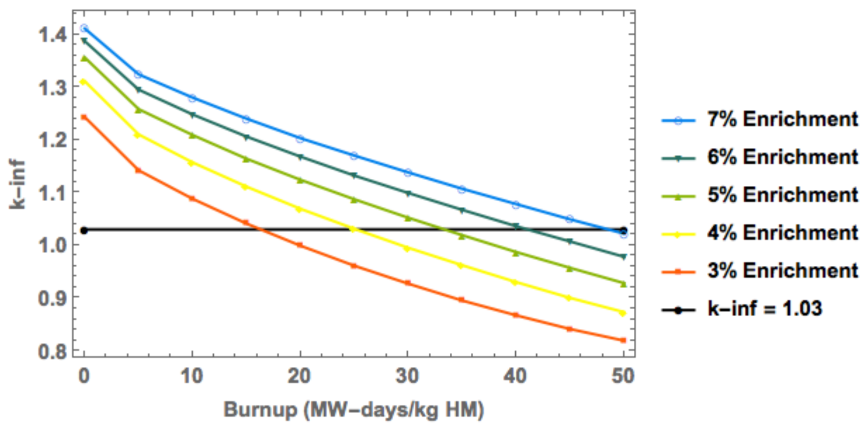


Figure 5.4: *Plots of k-inf versus burnup for characteristic PWR fuel assemblies at different enrichments.*

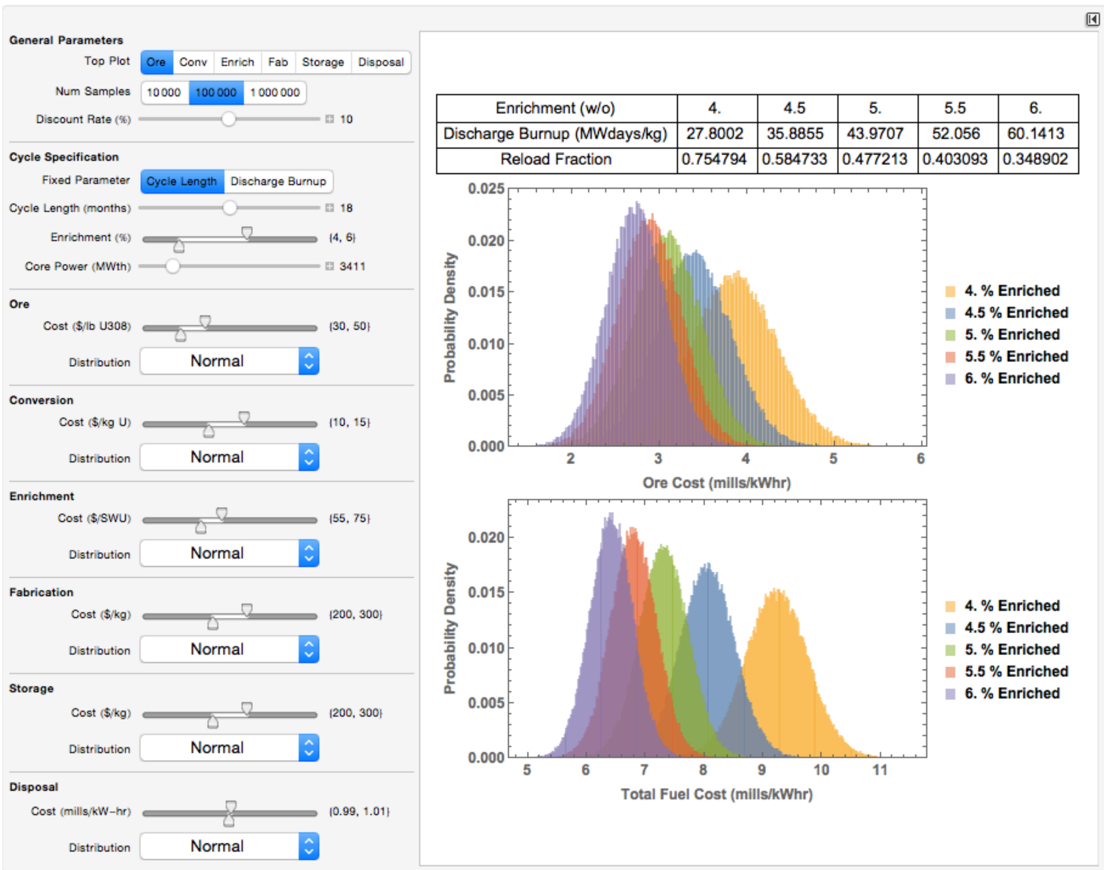
From Figure 5.4, the single batch burnups were found and a linear fit to the burnup as a function of enrichment was found:

```
B1 = 8.08527 * Enrichment - 7.94929;
```

With these equations, the cycle burnup, fuel enrichment, and discharge burnup have all been connected. In our interactive tool, we chose to allow the user to select a **range of fuel enrichment values** and **fix either the cycle length or discharge burnup** at a specified value. The other parameter was then determined based on the equations above. With these inputs, a range of situations could be simulated for several enrichment values within the range of values specified by the user, allowing for a comparison of fuel cycle economics of cores with several different enrichments on one screen.

5.4) Long-term Fuel Cycle Analysis Tool

The purpose of the long-term fuel cycle analysis is to determine whether it makes sense in the long run to transition to higher enriched fuels once all capital costs have been paid off. At that point, the fuel cycle costs would just include the costs of each of the individual components in the fuel cycle. The costs of each of these components are included in the interactive tool below to allow users to investigate different scenarios such as high ore costs, longer cycle lengths, or higher power levels. The interface is designed to be self-explanatory, but we have provided a few specific examples to show the scenarios we are interested in and show how to extract useful information from the tool.



Enrichment (w/o)	4.	4.5	5.	5.5	6.
Discharge Burnup (MWdays/kg)	27.8002	35.8855	43.9707	52.056	60.1413
Reload Fraction	0.754794	0.584733	0.477213	0.403093	0.348902

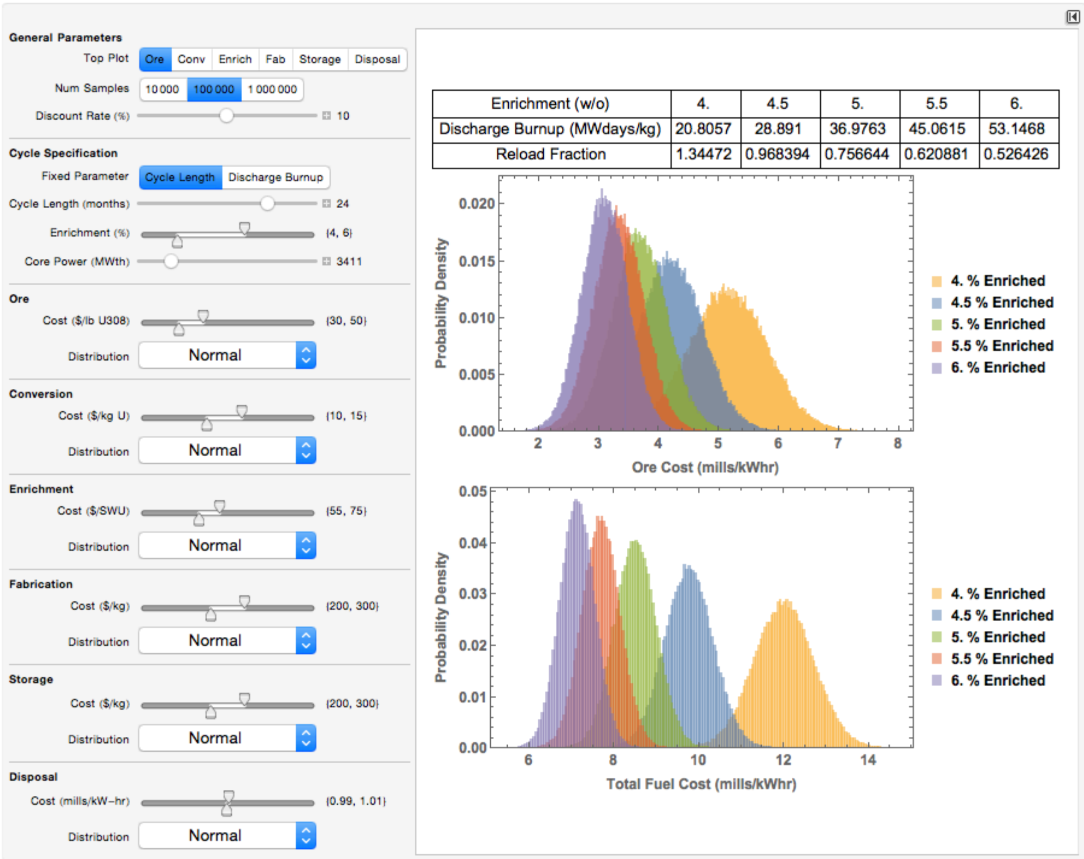
5.5) Long-term Fuel Cycle Analysis Insights

Using the interactive fuel cycle analysis tool, several important insights can be realized:

5.5.1) Extending Cycle Length to 24 Months

One scenario we are interested in further investigating is extending the cycle length of PWRs from 18 to 24 months. For this analysis, we will simply move the slider for the Cycle Length from 18 to 24 months. In this analysis, it is important to consider the reload fraction and burnup constraints. The reload fraction is the fraction of assemblies that must be replaced at the end of each cycle and therefore must be between 0 and 1. The burnup is limited by the max pin burnup of 62 MW-days/kg HM. We present the assembly-averaged burnup where the max pin burnup is likely ~10-15 % higher than the assembly-averaged burnup. We will assume the max assembly-averaged burnup constraint is 55 MWdays/kg HM. All variables have assumed to be normally distributed with values at their estimated market values as of May 30, 2016. There are several important things to note about this scenario:

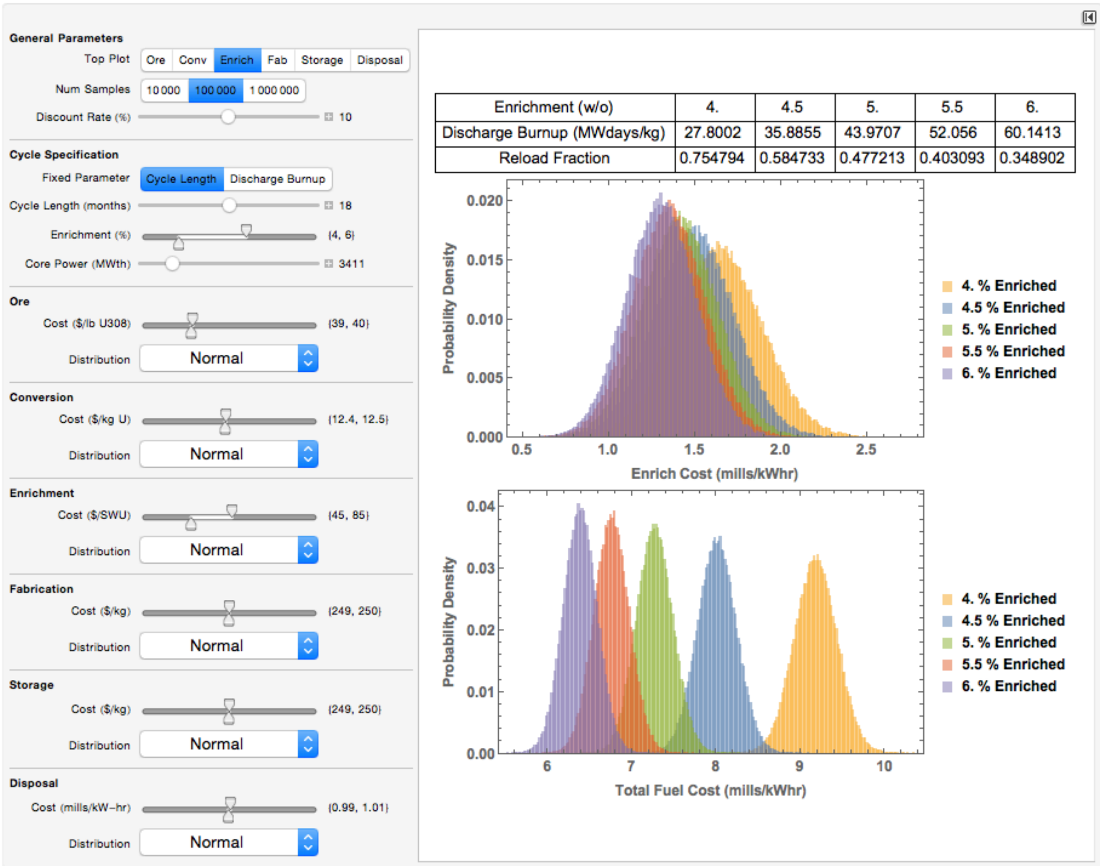
- The case with 4 w/o enrichment has a reload fraction over 1.0, indicating that it is not feasible to operate the model reactor at this enrichment and cycle specifications.
- With a 4.5 w/o enrichment, the reload fraction is nearly 1.0 indicating almost the entire core needs to be replaced after each cycle. The discharge burnup is quite low, resulting in high ore costs as shown in the top plot.
- As the fuel enrichment is increased, the burnup increases which reduces the costs of all fuel cycle elements except disposal.
- The cost savings between the 5 w/o and 6 w/o cases is ~1.5 mills/kWhr.
- Toggling the Cycle Length between 18 and 24 months, we see that the fuel costs for the 18 month cycle are ~0.75 mills/kWhr lower than the fuel costs for the 24 month cycle when the burnup constraint is taken into account. Therefore, extending the cycle length must yield other benefits such as a net reduction in outage time in order to make the cycle length extension yield cost savings.



5.5.2) Sensitivity to Enrichment Cost

Another scenario we are interested in further investigating is understanding the sensitivity of fuel cycle costs to enrichment costs. Reduced enrichment costs could come from market supply and demand changes or the introduction of a new low-cost enrichment technology, such as laser enrichment. For this analysis, all costs besides the enrichment cost have assumed to be at their estimated market values as of May 30, 2016 with no uncertainty in order to isolate the range of enrichment costs in the total fuel cost. We will change the enrichment price range to $45-85/SWU so we can see a bigger spread in the enrichment costs. There are several important things to note about this scenario:

- The average enrichment costs vary between 1.3 and 1.65 mills/kWhr for the range of 4-6 w/o enrichments, with higher enrichments having lower enrichment costs (on a mills/kWhr basis).
- With enrichment costs at ~20% of total fuel costs, the reduction in enrichment costs by one third reduces the total fuel cost by ~6% or 0.4-0.6 mills/kWhr.



5.6) Investment in Upgrading the Nuclear Fuel Cycle to Support > 5 w/o Fuels

Upgrading the nuclear fuel cycle to support fuels with enrichments of greater than 5 w/o would require capital investments in several areas. Most notably, capital investments would be in:

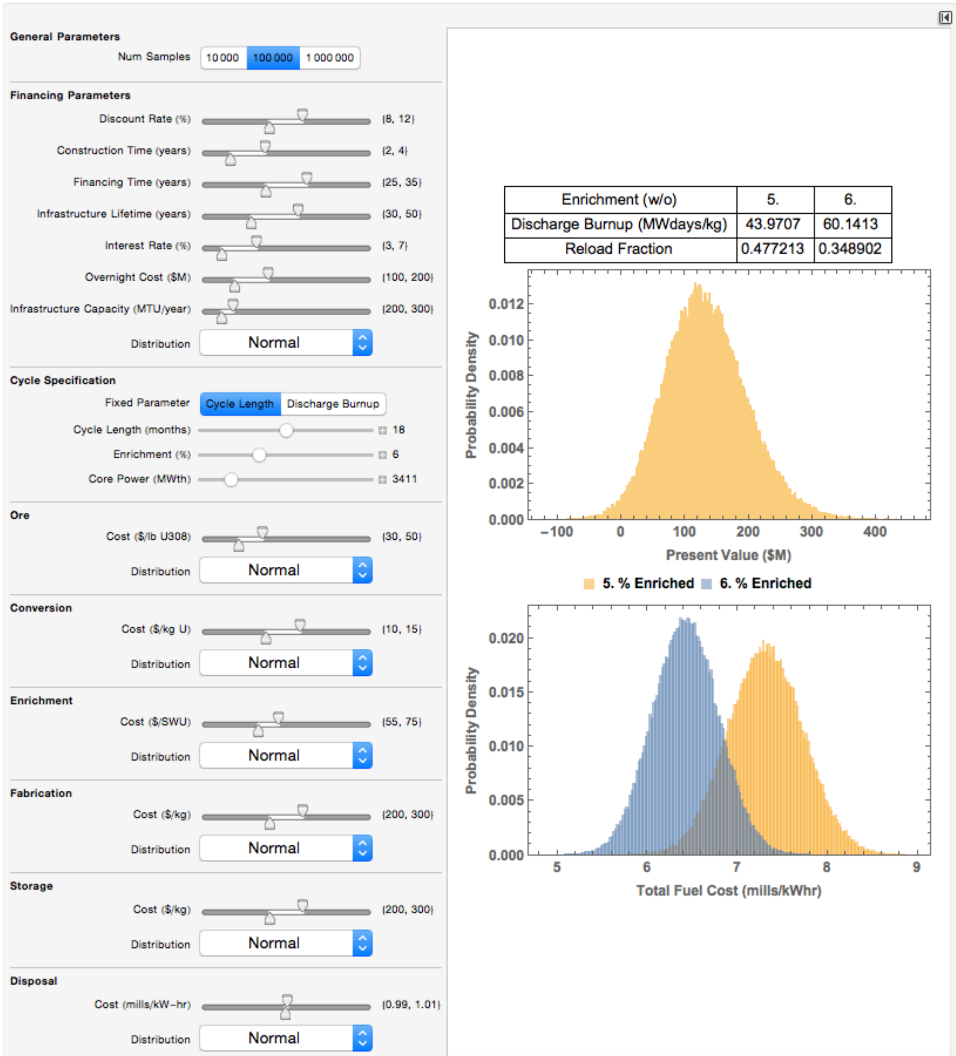
- **Enrichment:** Currently, all commercial Uranium enrichment facilities in western countries enrich uranium up to only 5 w/o. Supplies of downblended uranium could potentially be used to support production of greater than 5 w/o fuels, but it does not appear that nuclear stockpiles of highly enriched uranium provide enough to support widespread adoption of greater than 5 w/o fuels. Re-licensing of current facilities would be needed to ensure subcriticality is maintained in all process components in the enrichment processes. While upgrading current facilities is one option, coordinating an effort to license a new enrichment facility to produce greater than 5 w/o fuels is another option and one could assume the levelized cost per SWU for such a facility would be competitive with other enrichment facilities that are limited to enrich to 5 w/o.
- **Fuel Fabrication:** To our knowledge, all large commercial fuel fabrication

facilities produce only up to 5 w/o and there does not exist much margin to increase the maximum enrichment for these facilities without some equipment upgrades. In a 2002 EPRI report, it was estimated that upgrading of a fuel fabrication facility would costs between $55-75M [3].

- **Transport of Enriched UF6:** Transportation of UF6 is currently done in type 30B cylinders that are rated to transport up to 5 w/o enriched UF6. There are type 8A cylinders that are rated to transport UF6 with enrichments up to 12.5 w/o, but they are ~20x smaller than type 30B cylinders and it is unclear if there are any additional regulatory challenges to transport materials over 5 w/o. Given the relatively small costs of transport of enriched UF6, the simplicity of UF6 transport containers, and the presence of cylinders that can transport of over 5 w/o UF6, the capital costs for producing larger cylinders to transport over 5 w/o UF6 or otherwise supporting the UF6 transport capabilities to support over 5 w/o UF6 transport would likely be small and we will assume it does not affect the already small fuel transport costs.
- **Fuel Assembly Transport:** Transport of fuel assemblies is typically done in large stainless steel containers that are currently rated to transport assemblies of up to 5 w/o enrichment. The main concern with these packages seems to be maintaining the structural integrity of the container if they are damaged in transport. A 2002 EPRI report estimated that upgrading all the fuel assembly transport packages would cost $20-30M, so we will assume capital costs around this range for upgrading fuel assembly transport [3].

5.7) Short-term Fuel Cycle Analysis Tool

The purpose of the short-term fuel cycle analysis is to determine whether it makes sense in the short term to transition to higher enriched fuels where capital costs are included. The costs of each of component as well as the financing parameters are included in the interactive tool below to allow users to investigate different scenarios such as high ore costs, longer construction times, and different capital costs for upgrading the fuel cycle infrastructure. Three years was chosen as the mean construction time in this study, which is inline with NRC licensing time estimates for fuel fabrication facilities and transportation packages [4]. The present value of the project is determined by computing the present value of the capital costs for upgrading the fuel cycle facilities and the present value of the difference in fuel price between fuels enriched over 5 w/o and a reference 5 w/o fuel times by the infrastructure capacity. Therefore, a positive present value indicates that upgrading the fuel cycle infrastructure is a good investment. The interface is designed to be self-explanatory, but we have provided a few specific examples to show the scenarios we are interested in and show how to extract useful information from the tool.



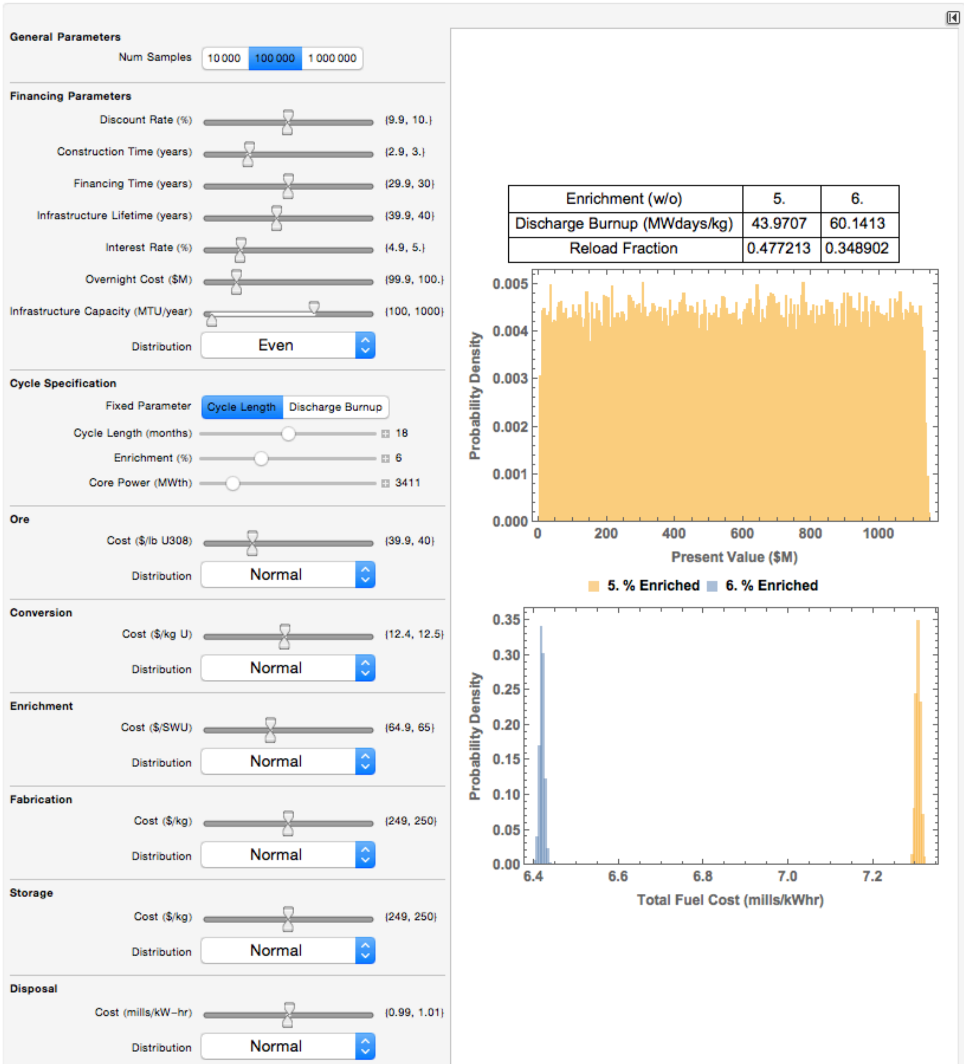
5.8) Short-term Fuel Cycle Analysis Insights

Using the interactive fuel cycle analysis tool, several important insights can be realized:

5.8.1) Sensitivity to Infrastructure Capacity/Demand for Higher Enriched Fuels

One scenario we are interested in investigating is the sensitivity to the infrastructure capacity upgraded, or thought of another way, the demand for higher enriched fuels. The capital costs to upgrade the fuel cycle infrastructure are not assumed to scale with the production rate of any one step because it is likely that an entire facility would need to be upgraded and (re)licensed, not just a fraction of a facility to suit market demand. Thought of another way, this sensitivity study could be regarded as investigating the impact of demand for higher enriched fuels. For this analysis, we will assume all other costs are at their current estimated market values and we will make assumptions on the other parameters, as shown in the tool below. The infrastructure capacity will be looked at between the range of 100-1000 MTU/year or enough to support 4-40 reactors. It should be noted that the case of 1000 MTU/year infrastructure would be equivalent to upgrading the GNF fuel fabrication facility in Wilmington, NC. Additionally, the laser enrichment facility that GNF has received a license for allows them to construct an enrichment plant with a capacity up to 6M SWU/year or enough to support ~40 reactors. Therefore, the 1000 MTU/year case could represent upgrading the GNF fuel fabrication plant and building the laser enrichment facility. Another advantage to this proposition is that the enriched UF6 would not need to be transported. There are several important things to note about this scenario:

- The present value is positive for all sizes of the infrastructure capacity/market demand, if the assumed $100M capital cost, 3 year construction time, and 5% interest rate are accurate. However, it is clearly advantageous to supply higher enriched fuels to as many reactors as possible since the capital cost does not depend on the amount of fuel produced.
- The assumed enrichment of 6 w/o produces a burnup of over 55 MWdays/kg HM, which will exceed the licensing limits. Reducing the enrichment of the over 5 w/o fuel to 5.5 w/o reduces the present value and makes the project not worthwhile when supplying fuel to less than 8 reactors.
- Another option for reducing the discharge burnup to below the regulatory limit (~ 55 MWdays/kg HM) would be to increase the cycle length. Increasing the cycle length slightly decreases the present value of the project, but the upgrade is still a net positive investment for capacities of 5+ reactors.



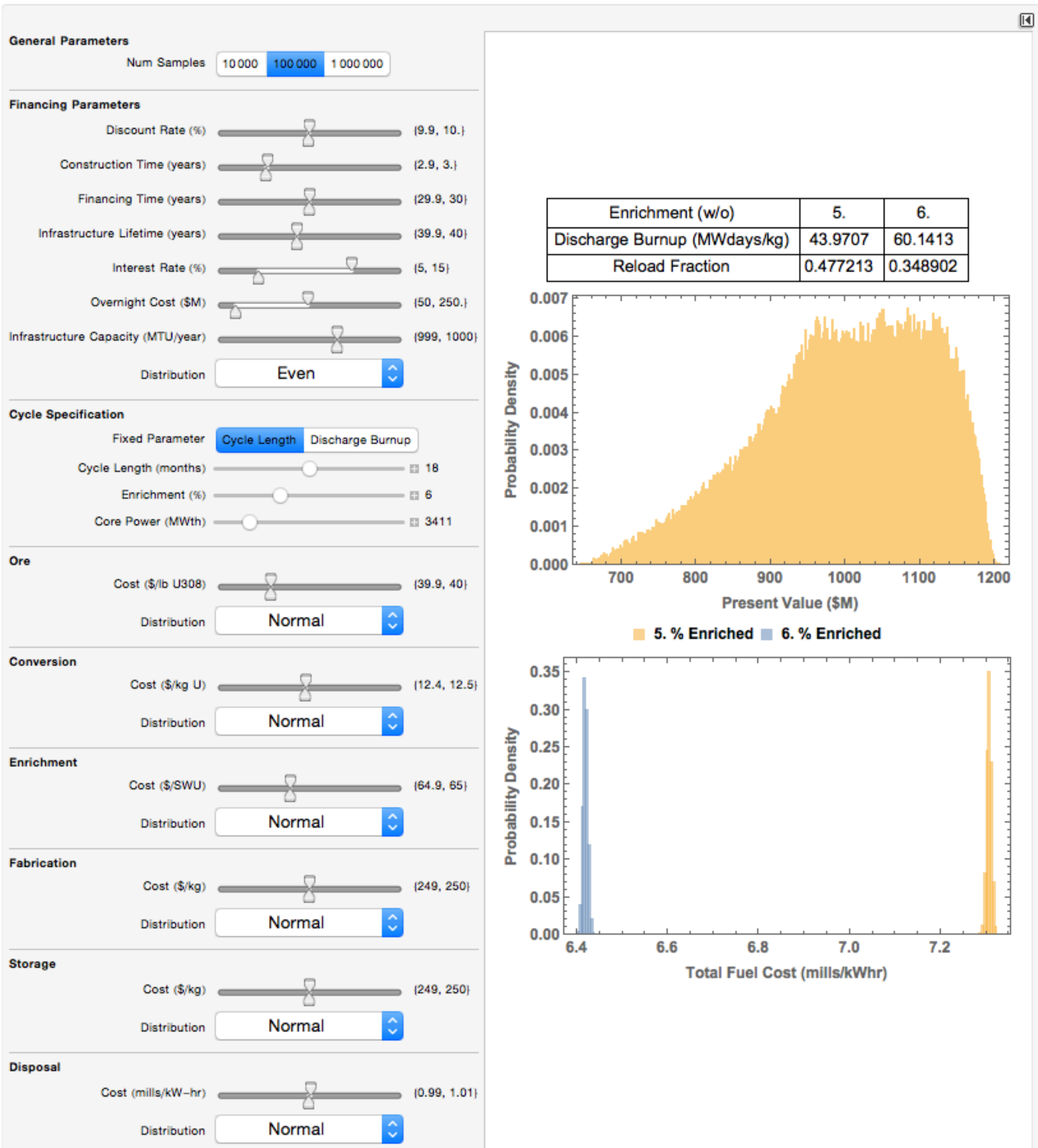
5.8.2) Sensitivity to Interest Rate and Overnight Cost

One scenario we are interested in investigating is the sensitivity to the financing parameters, namely the interest rate and the overnight costs. For this analysis, we will assume all other costs are at their current estimated market values and we will make assumptions on the other parameters, as shown in the tool below. The overnight cost will range between $50-250M and the interest rate will range between 5-15%. There are several important things to note about this scenario:

- The present value is positive for all ranges of overnight cost and interest rate suggesting that, if all other assumptions are reasonable, the project can withstand capital costs above the expected $75-105M estimate.
- The assumed enrichment of 6 w/o produces a burnup of over 55 MWdays/kg HM, which will exceed the licensing limits. Reducing the enrichment of the

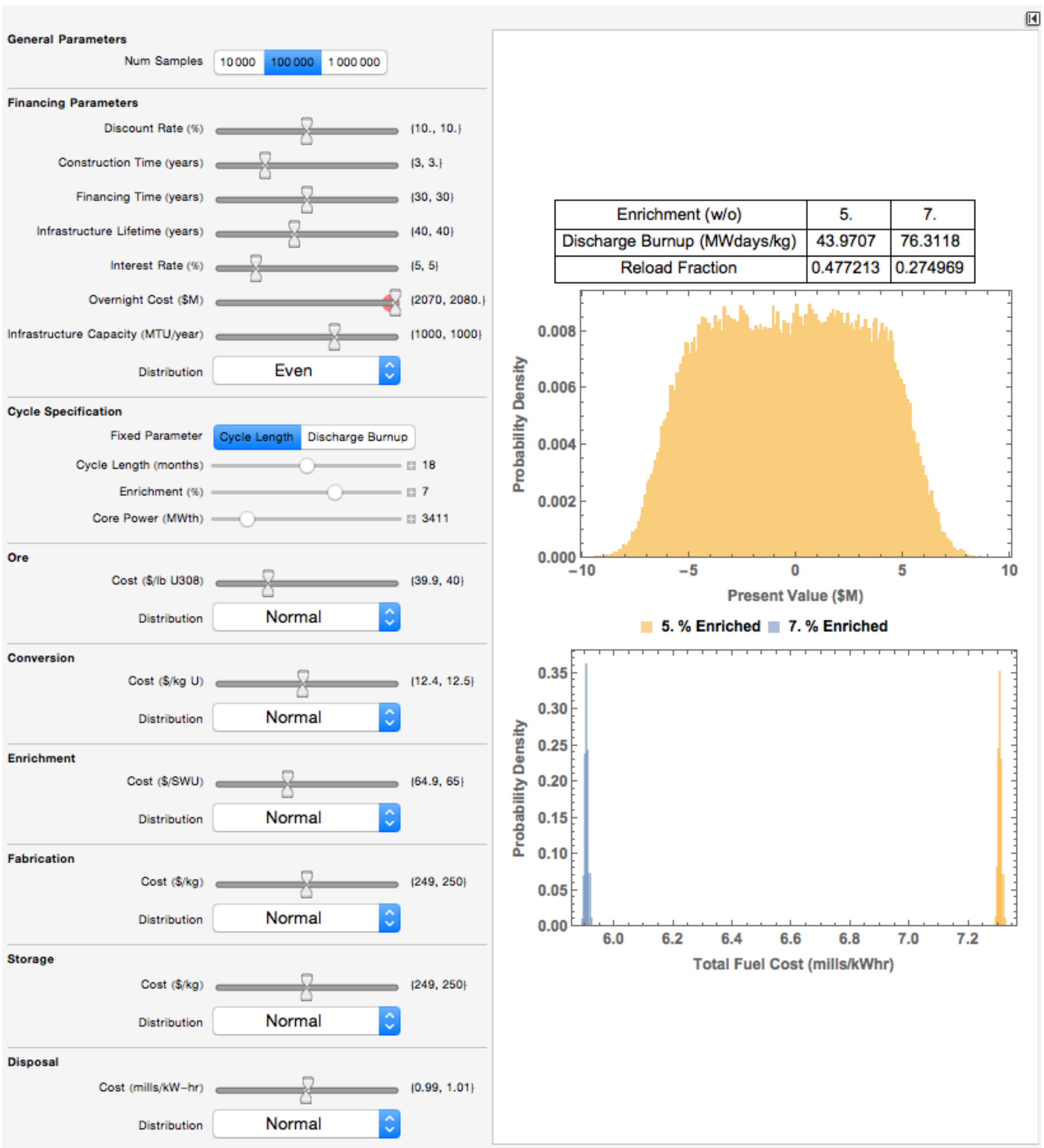
over 5 w/o fuel to 5.5 w/o reduces the present value, but it is still positive for all cases in the range of the study.

- Toggling the Infrastructure Capacity, we can see that the project could go to negative present values if the capacity is below 400 MTU/year (16 reactors). These scenarios would occur for cases where the interest rate and overnight costs were both high.



Another scenario of interest is determining at what overnight cost the project becomes uneconomical assuming the fuel cycle infrastructure can support 40 reactors operating with fuel at 6 w/o, a 5 % interest rate, and a 3 year construction time. Additionally, the scenario with 7 w/o fuel and all other assumptions the same will be investigated. This analysis reveals:

- For 6 w/o fuels, the capital costs would need to exceed $1.01B to make the project uneconomical (NPV < 0).
- For 7 w/o fuels, the capital costs would need to exceed $2.07B to make the project uneconomical.
- The capital costs required to make the project uneconomical under the assumed conditions are significantly greater than the expected overnight costs of $75-105M.



5.9) References

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6) Conclusions and Recommended Future Work

6.1) Conclusions

This project sought to investigate and clarify the benefits and challenges to transitioning to beyond 5 w/o fuels in commercial LWRs. Furthermore, the implications of lower cost laser enrichment technologies were also looked at. Through our analysis of the nuclear fuel cycle infrastructure and economics as they exist today, we have made the following conclusions:

- **Fuel Transport Capabilities and Readiness:** All transport capabilities in the nuclear fuel cycle to support commercial power reactors is focused on transporting fuels below 5 w/o. There exist packages that are licensed to support transport of greater than 5 w/o materials, but they are 20 times smaller than the packages used today to transport below 5 w/o UF6. Estimates on the costs to upgrade the fuel transport capabilities to support transport of over 5 w/o UF6 and fuel assemblies is quite small and does not seem to pose a large risk to transitioning to higher enriched fuels. Furthermore, co-locating a new fuel enrichment plant that can enrich UF6 to over 5 w/o, such as the proposed laser enrichment plant to be constructed on the site of the GNF fuel fabrication plant, could eliminate the need to upgrade the UF6 transport capabilities and provide for widespread adoption of over 5 w/o fuels.
- **Fuel Manufacturing Capabilities:** Commercial fuel manufacturing in western countries are currently licensed to fabricate fuel only up to 5 w/o U235. There exist little margin left in these facilities to support increasing the enrichments, so capital investments and some modifications to processing equipment are needed to support fabrication of over 5 w/o fuels. Upgrading of these facilities is expected to cost in the high tens of millions of dollars, but is not expected to pose a significant impediment to moving to higher enrichments as long as sufficient demand for higher enriched fuels can be assured.
- **Laser Enrichment:** Laser enrichment technologies have progress significantly in the last three decades and in 2012 GNF received a license to construct a laser enrichment facility to produce up to 8 w/o UF6 with a capacity of 6M SWU/year (i.e. enough to support ~40 reactors). Surplus enrichment capacity of ~20% worldwide and a decrease in uranium enrichment prices have caused the GNF laser enrichment facility and other enrichment facilities in the US to be postponed. If market conditions improve and GNF constructs their proposed laser enrichment facility at the site of their Wilmington, NC fuel fabrication plant, this could present a good opportunity for GNF to pursue upgrades to their fuel fabrication facility to support fabrication of over 5 w/o

fuels. Developments of GNFs proposed laser enrichment plant should be closely watched.

- **Fuel Cycle Economic Analysis:** There are clear economic advantages to pursue enrichments beyond 5 w/o with 6 w/o fuels offering a ~1.5 mills/kWhr reduction in fuel cycle costs over 5 w/o fuels under current market conditions. Furthermore, fuels over 5 w/o will likely be required to pursue 24 month cycle lengths, which could offer benefits in reducing the number of outages at plants. Capital costs for upgrades to the fuel cycle to support over 5 w/o fuels were found to be wise investments if demand for higher enriched fuels can be ensured. If demand for higher enriched fuels is equal to the size of the GNF fuel fabrication plant in Wilmington, NC (~1000 MTU/year), overnight costs would need to exceed $1.01B and $2.07B for 6 w/o and 7 w/o fuels, respectively. Given the noted fuel cycle savings of higher enriched fuels and nature of the long term contracts between utilities and fuel manufacturers, this demand should be able to be ensured before any facilities are upgraded or constructed, allowing such a project to be de-risked.

The mean age of nuclear reactors in the US is ~35 years with many reactors already operating over their initially licensing period of 40 years. For many of these plants, capital costs have been paid off and the cost breakdown is more heavily skewed towards fuel cycle and O&M costs. Given the higher fraction of fuel cycle costs in the total generation costs and the flooding of the electricity markets with low cost gas and subsidized renewable generation, even small efficiency gains in reducing fuel cycle costs can have large impacts in nuclear generation costs of current reactors and could be the difference between continued operation and shutting down. When considering the alternatives for reliable base load generation and the growing concern of climate change, the impact of reducing fuel cycle costs by going to beyond 5 w/o fuels could amount to more than just small reductions in electricity prices.

6.2) Recommendations for Future Work

This work sought to investigate the readiness, necessary upgrades, and economic potential for a transition in the current LWR nuclear fuel cycle to support fuels in excess of 5 w/o enrichment. The product of this work is this report and the development of interactive tools to investigate fuel cycle economics that allow existing and potential future scenarios to be compared side by side. Further investigation of the benefits of going to higher enrichments is recommended in the following areas:

- **More realistic models of reactor operating cycles:** This report used a rigid model for a characteristic PWR with a single assembly and a single cycle length representing the reactor operation. In reality, nuclear reactors use a variety of different assembly types that are used to optimize the plant economics. Additionally, the cycle length of reactors is not static and can change due to market conditions or shifting energy needs. More realistic models of reactor operating cycles would help remove some of the uncertainty in our model and give a clearer picture on the benefits of higher enriched fuels for currently operating LWRs.
- **Analysis of specific scenarios in the fuel cycle:** The nuclear fuel cycle and nuclear power plants are continually undergoing small changes in their operation. Over the past several decades, discharge burnups have been increasing due to the use of higher enrichments. There is talk of the discharge burnup limit being extended from 62 MWdays / kg HM to 70 MWdays / kg HM. In order for nuclear fuels to reach this discharge burnup limit, greater than 5 w/o enrichments are likely needed. Furthermore, plants are continually receiving power uprates that effectively increase the fuel burnup in each cycle (assuming a constant cycle length). Investigating the economic benefits of higher enriched fuels under a scenario where the discharge burnup limit is 70 MWdays/kg or under a scenario where a plant received a power uprate would be useful to understand how future operational and fuel cycle changes could affect the economics of greater than 5 w/o fuels.
- **Extending the analysis tools to BWRs:** Our analysis focused specifically on PWRs, which outnumber BWRs by ~3:1. Extending the tools to provide insights on BWRs would be important because most components of the fuel cycle are the same for BWRs and PWRs and some BWRs are currently being looked at for large power uprates, where the case for moving to higher enriched fuels might be stronger.
- **Alternative Fuel Forms:** Going to higher enriched fuels is just one of several ways to increase the fuel burnup in a reactor to allow for longer cycle lengths and higher power levels. Alternative fuel forms, such as uranium nitride and uranium silicide, allow for increasing the amount of fissile material within the core and thus give similar benefits to increasing enrichments. They also present some fuel cycle challenges of their own, such as licensing and fabricating these fuel forms for industrial scale power production. The economic benefits and engineering risk of these different options would be important in determining the most favorable option for industry to pursue.
- **Implications for Advanced Reactors:** This analysis focused entirely on existing PWRs, while it would be prudent to consider implications on advanced reactors. All advanced reactors with a fast spectrum will require an enrichment

over 5 w/o (likely up to 20 w/o) for at least their initial core loading. Even thermal reactors such as the X-Energy's Xe-100 gas cooled high temperature reactor are anticipated to require enrichments of 7-10 w/o. Furthermore, modular or micro reactors have more neutron leakage and therefore will likely need (or greatly benefit from) higher than 5 w/o fuels. In short, a supply chain that can sustainably produce large quantities of fuel over 5 w/o enrichment could prove to be an essential component to the successful implementation of many advanced reactor designs.

6.3) Acknowledgements

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