A Limited and Generalized Study on LEU Fuel Cycle Costs for High-Performance Research Reactors

Abdullah G. Weiss[1]

[1] NIST Center for Neutron Research, 100 Bureau Drive, Gaithersburg, MD 20899, USA
abdullah.weiss@nist.gov

doi.org/10.13182/T140-48438

INTRODUCTION

The conversion of research and test reactors from highly enriched uranium (HEU) to low enriched uranium (LEU) fuels represents a crucial step towards reducing nuclear proliferation risks. This transition aligns with the US DOE National Nuclear Security Administration's (NNSA) mission to minimize the use of HEU in civilian applications, thereby enhancing global security. Despite significant advancements in fuel design and technical feasibility, there are still some notable gaps in analyzing the economic implications of these conversions, and how they may affect new High Performance Research Reactor (HPRR) builds.

This work seeks to provide a limited and generalized cost analysis for LEU plate-type fuels in comparison to HEU plate-type fuels, while considering nuclear fuels of current interest to the National Institute of Standards and Technology (NIST). Specifically, the National Bureau of Standards Reactor (NBSR) and the proposed NIST Neutron Source (NNS) are considered as examples of HPRRs. The NNS is designed with LEU to demonstrate proliferation resistance in US HPRRs, a goal that is key to the NNSA PRO-X program and the memorandum of understanding between the NNSA and NIST Center for Neutron Research. This paper provides only estimates of the costs and are not reflective of actual costs for the reactors. By examining inflation-adjusted cost factors such as fuel fabrication, shipping, and storage, this analysis aims to provide actionable insights for optimizing the transition to LEU and provide a first step towards a more cumulative cost analysis of the operation of future HPRRs such as the proposed NNS. Curved plate MTR-type fuel elements are considered in this work.

METHODOLOGY

This work relies on general cost values provided in IAEA's NG-T-4.3 report on cost aspects of the research reactor fuel cycle [1]. To compensate for major discrepancies from real costs, some of the costs data is adjusted with empirical factors (such as a 10% increase in some of the costs). All fresh fuel and spent fuel shipment general costs adopted in this work are considered realistic by the authors. All other general costs are primarily based on the IAEA report [1].

Considering the age of the IAEA report, all of the costs were inflation adjusted using the consumer price index (CPI) [2]. The costs data from the IAEA report mostly dates to Spring 2009, at which point the CPI was 212.495 (in March 2009). For this work, the current CPI used was that of November 2024, which is 316.441. With this CPI data, the inflation rate of 48.92% computed is shown in Eq. (1).

$$IR = \frac{CPI_{2024} - CPI_{2009}}{CPI_{2009}} \times 100\% \rightarrow IR = 48.92\% \qquad (1)$$

Note that in this duration from March 2009 to November 2024, the CPI grew at an average rate of 7 per year. This estimated CPI growth rate is used for projecting the cost estimates. A summary of all costs data used for this work is shown in Table I. Note that all fresh fuel and spent fuel shipment costs data and assumptions used in this work are cross-referenced with real values from the NBSR. While the values are close to the real costs, they do not reflect the exact values (for confidentiality reasons).

Table I. The general costs used in this work.

Cost	Value *(Nov. 2024 $)*	Source
$P_{U,HEU}$	\$55,694.925/kg$_U$	[1] Adjusted Average
$P_{U,LEU}$	\$27,847.463/kg$_U$	$P_{U,HEU}/2$ (estimated)
P_{fab}	\$100,000/element	Estimated
$P_{SF,ship}$	\$0.36/mile/cm$_{length}$	Estimated
$P_{SF,load}$	\$19,359.2/container	[1] Adjusted Average
$P_{st,O\&M}$	\$1,351,421/yr	[1] Adjusted Average
P_{rep}	\$ 20,476.08/kg$_U$	[1] Adjusted Average

P_U is the price per kg U for the fuel plates, which differs from HEU to LEU. The HALEU prices suggested from NG-T-4.3 (for LEU plate-type fuels) were found to match well with current HEU prices for NBSR. The LEU prices are discounted by 50% (a Skinner's constant) to maintain realism and account for the vastly improved maturity in fabricating and qualifying the LEU fuels. The P_{fab} is the estimated fabrication price for a fuel element, and the $P_{SF,ship}$ is the cost for shipping spent fuel per mile and per cm in length (to accommodate the sizes of typical transportation casks). U.S.-domestic land-based shipping is assumed for the $P_{SF,ship}$.

The $P_{SF,load}$ represents the estimated loading and unloading costs for spent fuel received at a storage site, wherein a container is estimated to hold the same amount of cumulative cm of length as the cask. The authors assume that L_{st} = 660.4 cm of total cumulative length (typically cut and stacked plates) can be accommodated in each cask or storage container. The operation and maintenance (O&M) for the storage facility is also considered ($P_{st,O\&M}$).

All adjusted average values in Table I are the average of that specific cost with an added 10%. The added 10% is to maintain more realistic values and/or reduce underestimation risks. All estimated values are based on existing knowledge of NBSR HEU fuels. Note that the spent fuel shipment costs consider all relevant costs to the shipment (such as licensing).

For the purposes of this work, reprocessing costs are also included and are represented with P_{rep} dollars per kg U reprocessed. This work explores long term implications of the cycle by considering continuous spent fuel storage and spent fuel reprocessing options. Cumulative costs are computed for each option alongside baseline cumulative costs.

RESULTS

The results consider the cycle and outage lengths for NBSR and NNS as shown in Table II. The NBSR refueling consists of shuffling the core and replacing four spent fuel elements with fresh ones. The NNS refueling consists of shuffling the core and replacing three spent fuel elements with fresh ones.

Table II. Reactor fuel, cycle, and operation data.

Fuel	Cycle/Outage	grams U / cm U	Source
NBSR HEU	38.5/11.5 days	376.4 g / 66.04 cm	[3]
NBSR LEU	38.5/11.5 days	1071.1 g / 66.04 cm	[4]
NNS	40/8 days	3684.9 g / 70 cm	[5]

Fresh Fuel Costs

The fresh fuel costs are calculated annually assuming normal operation as per Table II, and by considering the P_U and P_{fab} costs as shown in Table I. Noting how many fuel elements are needed per cycle (N_{FpC}), and how many cycles each reactor (NBSR or NNS) operate each year (N_{cyc}), the annual fresh fuel needs (N_{FA}) can be computed per Eq. (2a). The annual fresh fuel costs (P_{fresh}) can then be computed as shown in Eq. (2b) by considering the total U mass in each fuel element (m_U) as noted in Table II. An inflation-adjusted trend of the annual fresh fuel costs for 30 continuous years of operation of each reactor can then be plotted as shown in Fig. 1. The inflation adjustment is based on the assumed 7 CPI/yr increase.

$$N_{FA} = N_{cyc} \times N_{FpC} \tag{2a}$$
$$C_{fresh} = \left([P_U \times m_U] + P_{fab}\right) \times N_{FA} \tag{2b}$$

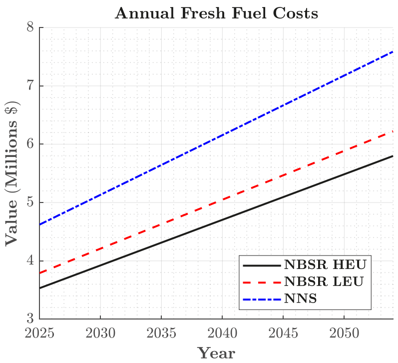

Fig. 1. Inflation-adjusted annual fresh fuel estimated costs for the NBSR and NNS.

Per Fig. 1, the annual fresh fuel costs are higher for LEU than HEU, which is due to the increased m_U in those fuels. Note that the price would be significantly higher if it isn't at the discounted price in Table I. The authors believe that this discounted price is more realistic given the maturity of the technology and known information for NBSR fuels. The NNS shows a notably higher P_{fresh} because of its notably higher m_U, which is brought on by its use of more plates and longer plates than the NBSR [5].

In the case of the NNS, a cost-benefit study would be appropriate to evaluate the impact of increasing the number of fuel elements in the core and/or increasing the cycle length. Generally, the current NNS design would likely benefit by exploring alternative fuel management schemes than the one currently anticipated.

Spent Fuel Shipment Costs

The spent fuel shipment costs are computed per Eq. (3), which considers the number of spent fuel elements that would be shipped out at the end of the year (assumed to be equal to N_{FA}), the cumulative length of the fuel plates (L_U), and the $P_{SF,ship}$. Adjusting for inflation, the trend of annual spent fuel shipment costs over a period of 30 years is shown in Fig. 2.

$$C_{SF,ship} = P_{SF,ship} \times N_{FA} \times L_U \tag{3}$$

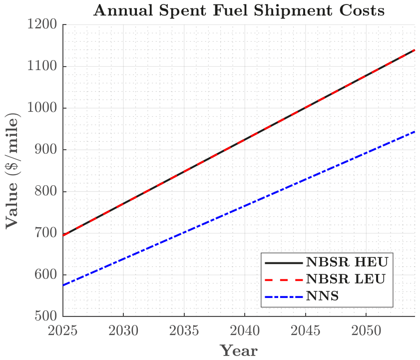

Fig. 2. Inflation-adjusted annual spent fuel shipment estimated costs for NBSR and NNS.

Note that the shipment costs in Fig. 2 are in units of \$/mile, which makes them scalable to any shipment site. Considering that the shipments are identical for NBSR HEU or LEU, and since the shipments are more highly dependent on the size of the fuel plates being shipped rather than their mass, the costs for LEU or HEU shipments for NBSR should be identical.

The NNS spent fuel shipment needs are less expensive because of the lesser amounts of fuel plates overall that would need to be disposed of. This comes from the fuel management scheme, wherein the NNS only discards three spent fuel assemblies after each cycle as opposed to the four that NBSR discards after each of its cycles.

Cumulative Costs

With the fresh fuel acquisition and spent fuel shipment costs for each of the fuel elements/assemblies established, an annual baseline cost estimate can be established for the reactors, which is done by simply adding C_{fresh} and $C_{SF,ship}$, yielding the inflation adjusted trend in Fig. 3.

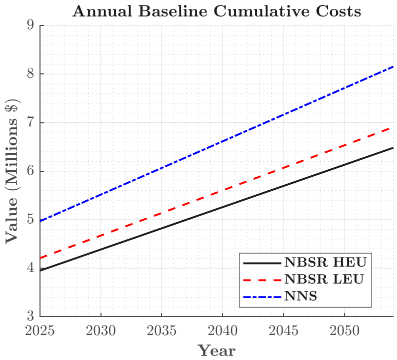

Fig. 3. Inflation-adjusted annual baseline estimated cumulative absolute costs for NBSR and NNS.

Continuous Spent Fuel Storage Option

Considering the back-end costs of the fuel cycle, it is relevant to consider options such as continuous storage of the spent fuel for an undisclosed amount of time (which is the current practice). For this, the spent fuel annual storage costs ($C_{SF,st}$) can be computed per Eq. (4) as a function of $P_{SF,load}$, $P_{st,O\&M}$, L_U, N_{FA}, and the total cumulative length of fuel plates allowed in the cask/container (L_{st}). This yields the 30-year trend shown in Fig. 4.

$$C_{SF,st} = \left(\frac{P_{SF,load}\times N_{FA}\times L_U}{L_{st}}\right) + P_{st,O\&M} \tag{4}$$

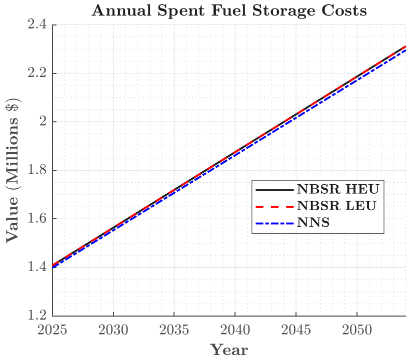

Fig. 4. Inflation-adjusted annual spent fuel storage estimated costs.

As per Fig. 4, the storage costs are nearly identical for all the reactors, with the NNS costs being slightly lower due to the lower spent fuel shipment needs. Note that the bulk of the $C_{SF,st}$ is for the O&M of the facility, with the loading and unloading costs being miniscule in comparison, which explains the insignificant difference in costs between NNS and NBSR spent fuel storage. Future studies should scale the $P_{st,O\&M}$ based on the number of stored elements, which would yield a non-linear trend and increase the gap between NBSR and NNS. Assuming this constant O&M (inflation-adjusted each year), the cumulative costs of this open cycle are presented in Fig. 5.

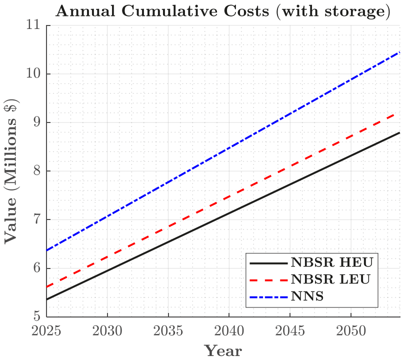

Fig. 5. Inflation-adjusted annual cumulative absolute costs for NBSR and NNS cycles with fuel storage.

The storage costs represent nearly 26% of the annual cumulative costs for the NBSR fuel cycle, and 22% of the annual cumulative costs for the NNS fuel cycle. This is significant enough to consider alternatives such as reprocessing.

Spent Fuel Reprocessing Option

The annual fuel reprocessing costs (C_{rep}) in this work are computed per the simplified Eq. (5) as a function of N_{FA}, m_U, and P_{rep}. The costs do not account for capital required to build a new reprocessing facility, and assumes that one is already available (which is sufficient for this limited study). The resulting 30-year trend of C_{rep} is shown in Fig. 6, which shows how the LEU fuels would have greater reprocessing costs than HEU due to their higher m_U.

$$C_{rep} = P_{rep} \times N_{FA} \times m_U \tag{5}$$

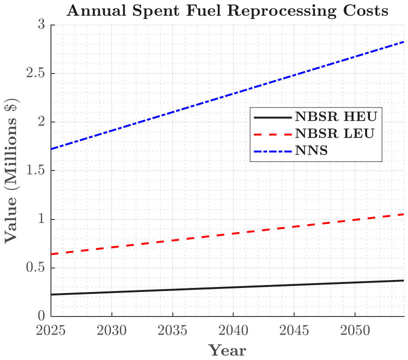

Fig. 6. Inflation-adjusted annual reprocessing estimated costs for NBSR and NNS.

Noting the $C_{SF,st}$ in Fig. 4, reprocessing the NBSR elements seems to be less expensive than storing them (assuming the general costs in Table I are accurate). If so, this implies that closing the NBSR fuel cycle is economically sound. The cumulative costs of this closed cycle are presented in Fig. 7. Note how the costs are lower than the storage no only because of the lower reprocessing costs, but also because parts of the reprocessing costs would eventually cover some of the fresh fuel costs. For the trends in Fig. 7, it is assumed that 50% of the reprocessing costs can be reused, yielding a reutilization factor of 0.5.

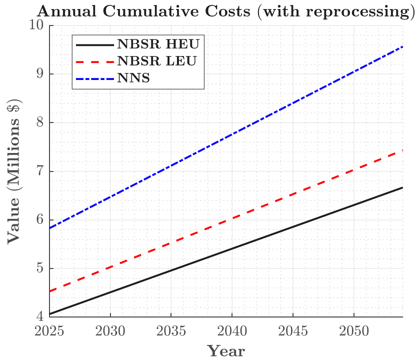

Fig. 7. Inflation-adjusted annual cumulative absolute costs for NBSR and NNS cycles with reprocessing. Assumes a reutilization factor of 0.5.

The effects of the reutilization factor on the savings of total fuel cycle costs are shown in Fig. 8, where increasing the reutilization factor would increasingly cut fuel cycle costs if and only if reprocessing costs remain lower than fresh fuel fabrication costs. In general, the LEU fuels have more to benefit from a closed cycle considering the sheer amounts of uranium needed in each element (relative to HEU fuels). The higher the amount of uranium, the more sensitive the cumulative costs are to the reutilization factor. In particular, the NNS sees a great benefit from reprocessing, cutting 24-34% of the fuel cycle costs. This implies a benefit in reprocessing for new LEU-fueled HPRRs.

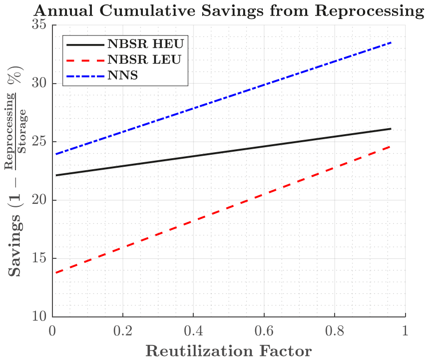

Fig. 8. Annual estimated cumulative savings by switching from storage to reprocessing, presented as a function of the reutilization factor.

CONCLUSIONS

The study lays out estimates of the fuel cycle costs for HPRRs, specifically NBSR and NNS. The annual cumulative fuel cycle costs are expected to increase by ~6.4% for NBSR from an LEU conversion, which is primarily attributed to the increase in uranium mass needed in the fuel elements. The NNS shows notably higher fuel cycle costs relative to NBSR LEU (~16.6% higher), which is once again attributed to the increased uranium mass needs. This cost could however be easily offset and reduced below current costs if reprocessing is utilized, which reduces the fuel cycle costs by up to ~25% for NBSR LEU, and up to ~34% for NNS.

This work is a limited study and could benefit from more detailed and refined costs data, considering the raw uranium and SWU pricing as well as adding O&M costs for reprocessing. Additionally, the NNS would benefit from an economic-informed fuel management scheme optimization study, which will likely be the subject of future works.

ACKNOWLEDGEMENTS

The authors would like to acknowledge NCNR feedback from Michelle Dudley and David Griffin, as well as contributions from USHPRR LEU conversion program pillars in multiple DOE laboratories and the NNSA M^3 and Pro-X programs.

DISCLAIMER

REFERENCES

1. P. ADELFANG, et. al, “Cost Aspects of the Research Reactor Fuel Cycle,” IAEA Nuclear Energy Series No. NG-T-4.3, International Atomic Energy Agency (2010).
2. U.S. Bureau of Labor Statistics, Consumer Price Index for All Urban Consumers: All Items in U.S. City Average [CPIAUCSL], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/CPIAUCSL (2025).
3. NIST, “Safety Analysis Report (SAR) for License Renewal for the National Institute of Standards and Technology Reactor – NBSR; NBSR 14,” National Institute of Standards and Technology (2023).
4. A.G. WEISS, O.S. CELIKTEN, D. SAHIN, A. GURGEN, T.H. NEWTON, “The 2023 Status Update on the LEU Conversion of the NBSR,” *Trans. Am. Nucl. Soc.*, **129**, 958-961 (2023).
5. O. CELIKTEN, A. WEISS, D. SAHIN, “Preconceptual Design Activities of the NIST Neutron Source: Preliminary Neutronics Assessments,” NIST Technical Note (NIST TN) TN-2316, National Institute of Standards and Technology (2024).