Values of Recovered Uranium from HALEU Used Nuclear Fuels, Revision 1

Nuclear Fuel Cycle and Supply Chain

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T. K. Kim, N. Stauff, A. Abdelhameed, E. Hoffman (ANL)
A. Cuadra, C. Lu (BNL)
E. Davidson (ORNL)
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Executive Summary

The value of the recovered uranium (RU) from high assay low-enriched uranium (HALEU) used nuclear fuels was evaluated. Three utilizations of the recovered uranium were considered in this study, which include the cases that RU is used as a fissile material of nuclear fuel, RU is reused in the original advanced reactor after reenrichment, and RU is reused in conventional light water reactors after down-blending. In this study, the RU values were identified by comparing the cost of making a unit mass of fuel with RU versus the fuel cost with the equivalent fresh enriched uranium (EU). A series of bounding analyses for calculating the fuel costs were conducted using several selected reactor types, which include microreactors, advanced thermal reactors, and fast reactors having a burnup of 2 – 165 GWd/t (with residual U-235 content in discharged fuels of 0.8 - 19.6%).

This study concludes that RU having a residual U-235 content higher than ~7% would cost less than the fresh EU. The affordability increases as the residual U-235 content in RU increases. For instance, the fuel cost with RU having the residual U-235 content of 19.6% is about 85% cheaper than the fuel cost with the equivalent fresh EU. This study observed that reusing RU after reenrichment in the original microreactor is impractical because the U-235 content in the re-enriched RU fuel would need to be higher than the limit for low-enriched uranium (<20%) to provide the same burnup performance due to parasitic absorption from U-236.

It is noted that this study focused on the recovery of uranium only, and the value of other fissile materials (such as Pu) in the used nuclear fuel was not considered even though those are bred significantly in fast reactors. In addition, the impacts of uncertainties in the cost data and the value of RU of TRISO fuels were not evaluated in this study due to the limited information on the cost data uncertainties and the separation cost from TRISO fuels.

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SYSTEMS ANALYSIS AND INTEGRATION CAMPAIGN

VALUES OF RECOVERED URANIUM FROM HALEU USED NUCLEAR FUELS

1. Introduction

Various advanced reactor concepts and associated nuclear fuel cycles have been proposed recently by industry, universities, and national laboratories. Most of them utilize 10 – 19.75% high assay low enriched uranium (HALEU), aiming for higher burnup, a more compact core, higher thermal efficiency, higher operating temperature, etc. The HALEU fuel is largely or partially depleted before discharging from the core depending on the design of the advanced reactor, and the residual U-235 content in the HALEU used nuclear fuel (UNF) varies.

Because the residual U-235 can be utilized as a fissile material, the reuse of recovered uranium (RU) from the HALEU UNF has been studied by the Systems Analysis and Integration Campaign (Kim et al. (2023)). As an extension of the previous studies, this study evaluated the RU having a high content of U-235 to address the following questions,

- What is RU's value when utilized as a fissile material?
- What is the value of RU when re-enriched and reloaded into the original advanced reactor?
- What is the value of RU when down-blended and reused in a conventional LWR?

Among the various advanced reactor concepts utilizing HALEU fuels, several reactor types were selected for bounding evaluation of the RU values. The selected reactor types include microreactors, advanced thermal reactors, and fast reactors having a wide range of fuel burnup.

This study evaluated the RU values by comparing the normalized costs of making a unit mass of fuel using RU versus using fresh enriched uranium (EU) derived from unirradiated mined natural uranium (NU). The unit cost data were obtained from the Advanced Fuel Cycle Cost Basis Report (FCO 2017) and supplementary data collected by the SA&I campaign (Hansen 2022). The cost data in the Cost Basis Report consists of low, mode, mean, and high values to cover the variation and distribution of the costs depending on fuel cycle technologies and the demand and supply situation in the market. The mean values were used in this work, and the impacts of the cost variations and uncertainties are not discussed.

It is noted that this study focused on the recovery of uranium from the HALEU UNF, and the value of other fissile materials (such as plutonium) was not considered, even though those are bred significantly in a fast reactor. In addition, a perfect recovery of uranium was assumed for a simple analysis: i.e., RU does not contain other actinides or fission products, and no RU was lost to waste during the recovery process. Finally, the potential cost or effort to prevent contamination of fuel cycle facilities from more radioactive uranium isotopes not found in NU (in particular, U-232 and its decay daughters) is not considered.

The reactor and fuel data used in this work are introduced in Section 2, the RU values related to the above three questions are discussed in Section 3, and the conclusions of this work are provided in Section 4. The cost data used in this study are provided in the Appendix.

2. Information on Reactors and HALEU Used Nuclear Fuels

The SA&I campaign collected information on the advanced reactor concepts being developed in the United States and Canada and listed them in a report (Kim et al., 2023). The list includes small modular reactors (SMR), microreactors (MR), and non-LWR advanced reactor concepts. The collection indicates that dominant reactor concepts are small or medium-sized reactors to be used with once-through fuel cycles targeting higher burnup, longer cycle length, lower construction cost, higher thermal efficiency, etc. This study focused on the subset of these concepts that utilize HALEU fuels.

Among the advanced reactor concepts utilizing the HALEU fuels, reactors considered in this work are provided in Table 2.1. A conventional PWR with a <5% low-enriched uranium (LEU) fuel is also provided in the table as the reference reactor. The advanced reactor concepts were selected for a bounding analysis of the RU values by covering three reactor types (microreactor, advanced thermal reactor, and fast reactor) and a wide range of burnup (2 - 165 GWd/t). The reactor ID indicates the reactor type and burnup. For instance, MR-2 denotes a microreactor (MR) having discharge burnup of 2 GWd/t. The example reactor concept of each reactor type is also listed in the table.

Table 2.1 Reactors and Fuels information

Reactor type	LWR	Microreactor		Adv. thermal reactor		Fast reactor	
Reactor ID	Ref. PWR	MR-2	MR-35	HTGR-90	HTGR-165	SFR-98	SFR-145
Example reactor [a)]	AP1000	Design-A	GCMR	PBMR	Xe-100	ABR	Natrium
Power, MWt/MWe	3000/1000	5/2	20/8	400/160	200/80	1000/400	840/345
Coolant	Light water	Potassium	Helium	Helium	Helium	Sodium	Sodium
Fuel Enrichment, %	4.21	19.75	19.75	9.6	15.5	16.34	17.65
Burnup, GWd/t	50	2.0	35	90	165	98	146
Discharge fuel composition, %							
U-234/U	0.02	0.15	0.14	0.06	0.01	0.15	0.16
U-235/U	**0.78**	**19.57**	**16.35**	**1.18**	**0.84**	**9.15**	**6.99**
U-236/U	0.58	0.05	0.98	1.44	2.59	1.81	2.71
U/HM	98.6	99.9	98.7	98.3	97.63	94.5	92.4
Pu/HM	1.26	0.01	0.01	1.55	2.00	5.28	7.32
HM/UNF	94.9	99.8	96.4	90.7	83.0	89.9	84.6
Mass flow data, t/GWe-year							
Charge fuel	21.9	457.0	26.1	9.8	5.5	9.3	6.1
HM in discharge fuel	20.8	456.1	25.2	8.9	4.3	8.3	5.2
U in discharge fuel	20.5	455.6	24.8	8.8	4.2	7.9	4.8

a) Design-A: Heat-pipe fast spectrum microreactor (Sterbentz 2018, Walker 2021),
GCMR: Gas-cooled Micro Reactor analyzed by NEAMS campaign (Stauff 2023),
PBMR: a 400MWt Pebble Bed Modular Reactor (Skutnik 2021),
Xe-100: 80 MWe high-temperature gas-cooled reactor of X-Energy (Mulder 2020),
ABR: 1000 MWt Advanced burnup reactor developed (Kim 2009),
Natrium: 345 MW sodium-cooled fast reactor of TerraPower (Neider 2021).

The discharged fuel compositions are provided in Table 2.1, and **Error! Reference source not found.**U-235 and U-236 content in charge and discharge fuels are compared in Figure 2.1. Because the detailed design information of the example reactors is protected as proprietary information, the discharge burnup and fuel compositions were calculated by the SA&I campaign using -publicly available information on reactor design parameters. Considering the evolution and optimization of reactor design parameters during the reactor development stage, the discharged fuel compositions may differ from the latest version of the example reactor concepts listed in the table. However, the information in the table is sufficient for a bounding analysis of the values of RU.

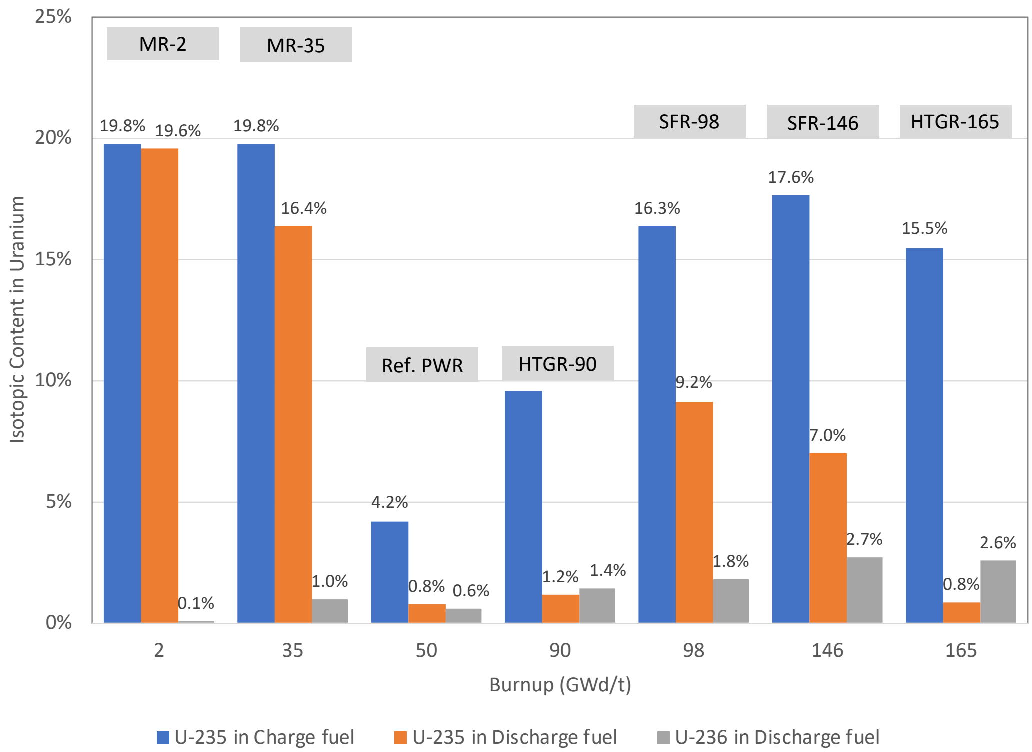

Figure 2.1 Comparison of Uranium Isotopic Content

Even though the advanced reactors utilize HALEU fuels, the residual U-235 content varies depending on the reactor design and operation scheme. Advanced thermal reactors are designed to be operational until the excess reactivity is exhausted. Thus, the HALEU fuels are irradiated until most U-235 is fissioned, and the residual U-235 content in UNF is very low (less than 1.2%). For a fast reactor, the fuel burnup is limited by cladding performance rather than the consumption of the excess reactivity, i.e., the fuel is discharged from the fast reactor even though U-235 is burnt incompletely. The residual U-235 content in the fast reactor UNF is 7 – 9%. It is noted that the bred Pu content in the fast reactor UNF is 5 – 7%, but the reuse of the bred Pu is not considered in this work. The achieved burnup is much smaller for microreactors than other reactor concepts because the cycle length is limited due to the high neutron leakage rate from the small core. As a result, most of the initial U-235 remains in the microreactor UNF (16 – 19%).

Even number uranium isotopes bred during irradiation act as parasitic absorbers. In particular, the parasitic absorption of U-236 is important in a thermal reactor, while its impact is negligible in a fast reactor. Thus, when reusing RU containing a high content of U-236 in a thermal reactor, more fissile is needed to compensate for the parasitic absorption. In the HALEU fuel, U-236 is primarily generated from the U-235 (n,γ) U-236 reaction, and the bred U-236 content in UNF is proportional to burnup with a small variation depending on reactor types, as shown in Figure 2.1.

3. Evaluation of Residual U-235 Values

Values of the recovered uranium (RU) from HALEU UNFs were evaluated for cases where RU is utilized through the following ways,

- Using RU as a fissile material of nuclear fuel,
- Reloading RU into the original advanced reactor after re-enrichment and
- Reusing RU in a conventional PWR after down-blending.

In this section, the RU values were judged by comparing the costs of making fuels with RU versus with fresh enriched uranium (EU) by enriching NU. For a consistent comparison, the enrichment or mass data of the fresh enriched uranium (EU) having equivalent reactivity as RU was iteratively searched first, and the fuel costs with RU and equivalent EU were calculated. Then, the fuel costs were normalized to the unit mass of fuel uranium ($/kg-U), and the RU values were judged by comparing the normalized fuel costs.

3.1 Value of RU as Fissile Material

The RU value was evaluated for the case when RU is used as a fissile material without further reenrichment or down-blending RU. It is noted that the RU values obtained from the advanced thermal reactors (HTGR-35 and HTGR-165) are not evaluated in this section because the residual U-235 content in the reactors is very low (< 1.2%), and the RU is not useable as a fissile material.

The enrichment of fresh EU having the equivalent reactivity as RU in thermal and fast reactors was searched, and the results are compared in Figure 3.1. Due to the parasitic absorption of U-236, the equivalent enrichment of fresh EU is slightly lower than the residual U-235 content in RU. The results show that the reactivity worth of RU is comparable to the fresh EU having 1 – 4% lower U-235 content in a thermal reactor, while it is equivalent to the EU having a similar U-235 content in a fast reactor.

Uranium recovery cost and the cost of enriching NU to the equivalent fresh EU were calculated and compared in Figure 3.2. The recovery cost consists of separating uranium from UNF, conversion of RU (metal or oxide) to UF_6, and disposing of the high-level waste (HLW) that includes non-recovered materials in the separation. The fresh EU cost consists of the NU mining and milling, conversion to UF_6, enrichments in Cat-III and Cat-II facilities, deconversion of depleted uranium (DU) to an oxide form, and disposal of DU. The required NU mass and enrichment effort (i.e., SWU) required to make the fresh EU are provided in Appendix B. In Figure 3.2, RU, EU-thermal, and EU-fast on the x-axis indicate the recovery and fresh EU costs of thermal and fast fuels, respectively. Because the separation cost of TRISO pebble bed fuel is unknown, the MR-30 (GCMR) costs are not compared in Figure 3.2.

When comparing the costs, RU is more affordable than the equivalent fresh EU because recovering costs are cheaper than enriching NU. The affordability is significant if uranium is recovered from a lower burnup UNF (i.e., higher residual U-235 content) and decreases as burnup increases. For instance, the recovering cost of a unit mass of RU ($/kg-RU) from the MR-2 UNF is ~85% cheaper than the cost of a unit mass of the equivalent EU ($/kg-EU) from NU, but the recovering cost of SFR-145 UNG is comparable to or slightly cheaper.

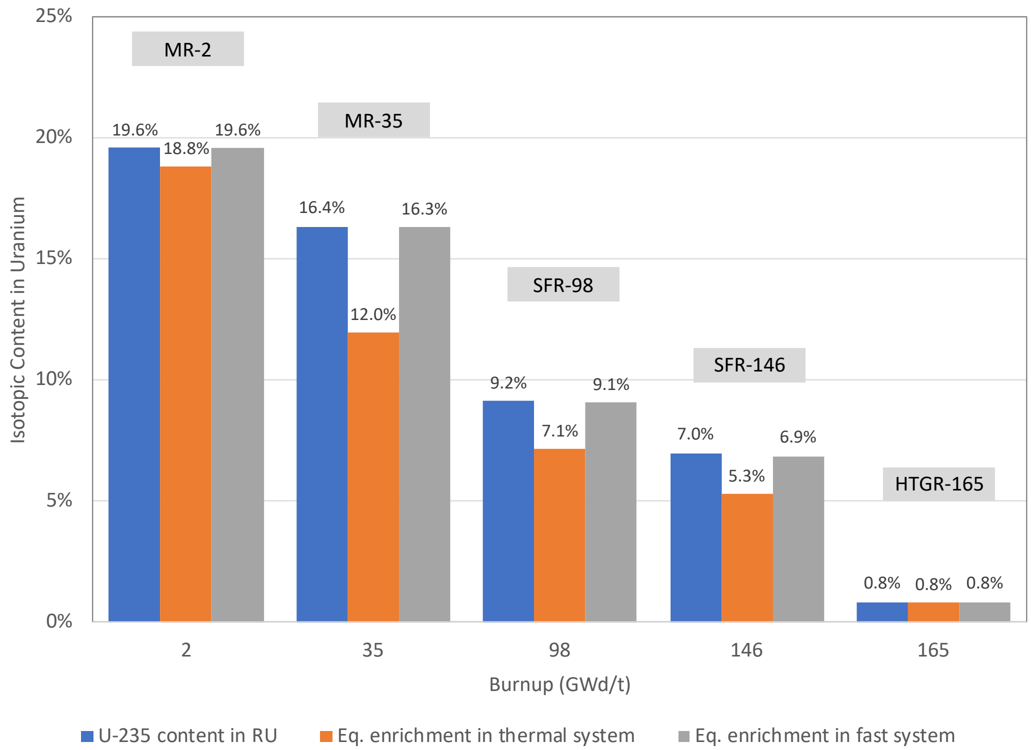

Figure 3.1 Residual U-235 content in RU and equivalent enrichment of fresh EU

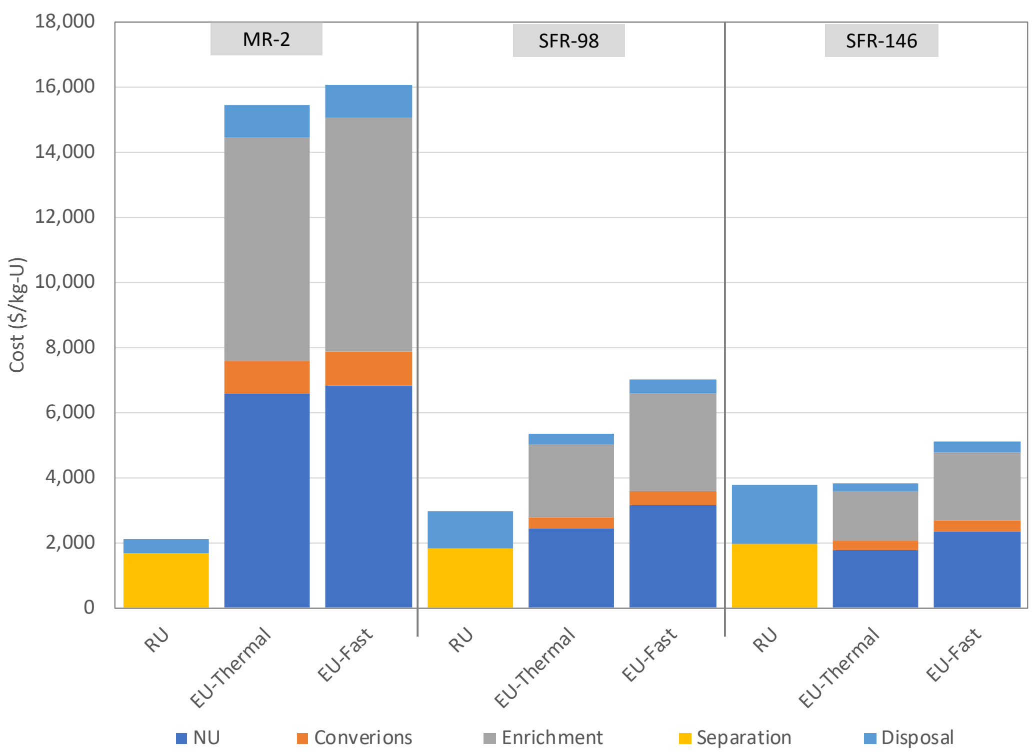

Figure 3.2 Comparison of Recovery Cost and Enrichment Cost

3.2 Value of Re-enriched RU

The RU value was evaluated for the case when RU is reused in the advanced reactor where the original HALEU fuel is discharged. For this case, RU is required to be re-enriched up to the U-235 content slightly higher than the enrichment of the original HALEU fuel. Otherwise, it is hard to reproduce the desired reactor performance due to the parasitic absorption. The U-235 content of the re-enriched fuel was iteratively searched until the desired reactor performance parameters (in particular, cycle length and burnup) were reproduced. The results are compared with the original fresh HALEU fuel enrichment in Figure 3.3.

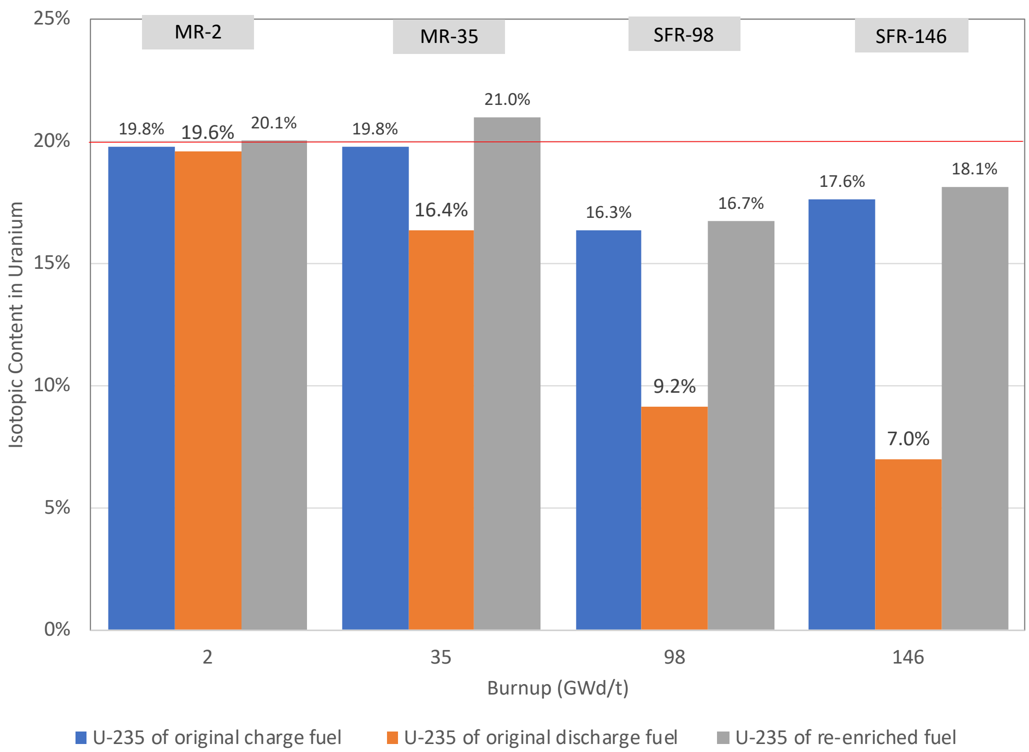

Figure 3.3 U-235 Content in charge fuel with fresh HALEU and re-enriched HALEU

For two microreactors (MC-2 and MC-35 based on Design-A and GCMR, respectively), the U-235 content of the re-enriched HALEU is over the low-enriched uranium (LEU) limit of 20%. Thus, reusing re-enriched HALEU in the same microreactor is impractical without sacrificing a particular design performance parameter (for instance, cycle length or burnup). However, the reuse of re-enriched HALEU is feasible in SFR-98 or SFR-146 because the U-235 contents are below the LEU limit.

Figure 3.4 illustrates the mass flow for making a unit mass of HALEU (1.0 kg-HALEU) of the re-enriched charge fuel using the SFR-98 UNF. For this particular case, the original fuel discharges 0.85 kg uranium and 0.15 kg other constituents (fission products, Pu, and minor actinides). It was assumed that the uranium was completely recovered, and the others were sent to storage. RU was re-enriched in the Cat-II facility and produced 0.45 kg HALEU and 0.40 kg tail uranium. The tail uranium U-235 content of the Cat-II facility was assumed to be the NU level (~0.71%) for saving the separative work unit (SWU) in the Cat-II facility. The HALUE and tail uranium were sent to fabrication and NU markets, respectively. To make a mass balance to the original fuel mass of 1.0 kg-HALEU, 0.55 kg of HALEU from NU is needed.

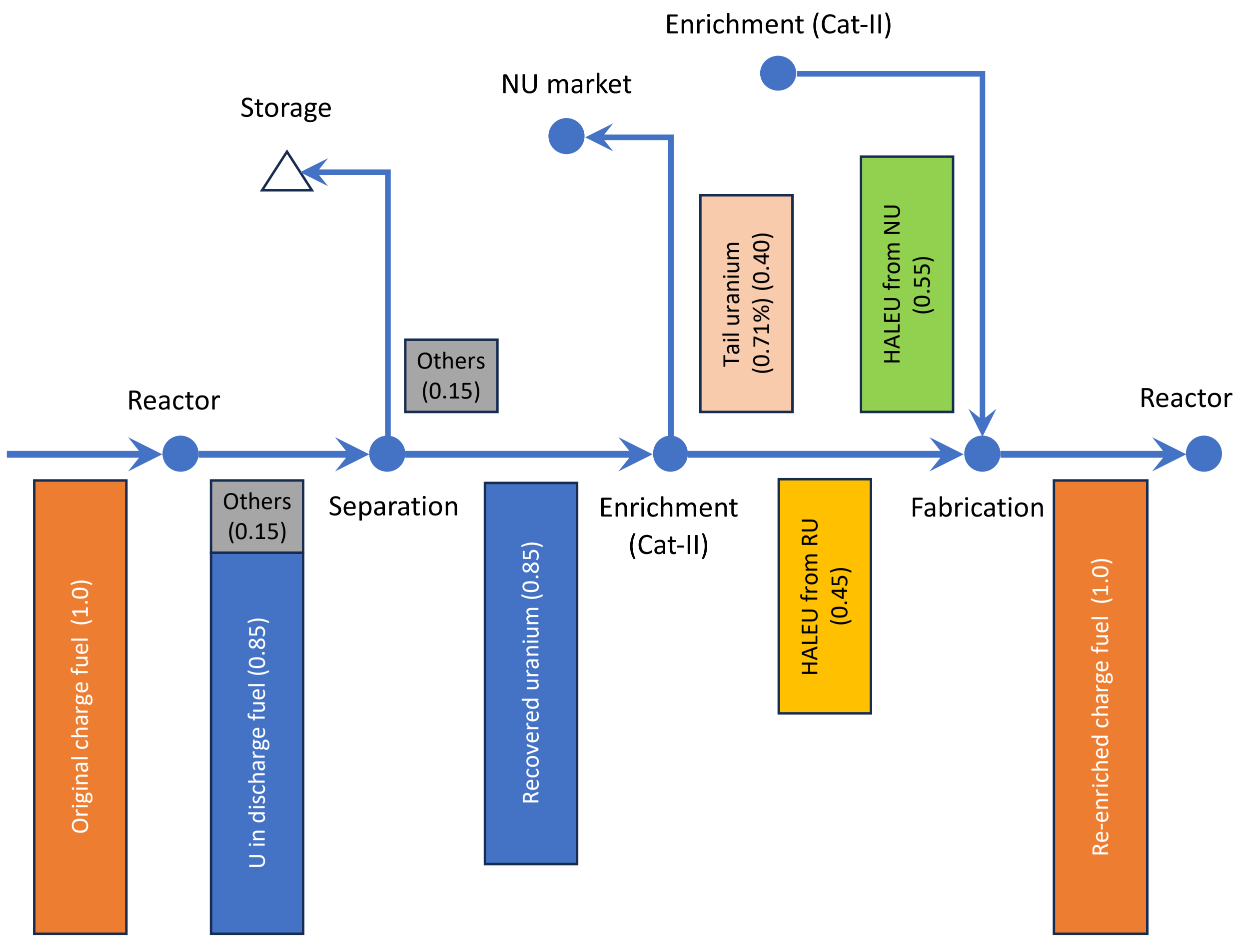

Figure 3.4 Mass flow for making a unit mass of HALEU for re-enriched fuel
(Values in parenthesis indicate masses in kg and normalized to 1.0 kg of charge HALEU)

Costs of making a unit mass of HALEU for the re-enriched fuel ($/kg-HALEU) and the original fuel were calculated, and the results are compared in Figure 3.5. The original fuel cost includes the front-end fuel cycle costs (NU mining and milling, conversion, enrichment, and DU disposal), while the re-enriched fuel cost includes both the front-end and back-end fuel cycle (separation and HLW disposal) costs because the re-enriched fuel was made by combining HALEUs from RU and NU as illustrated in Figure 3.4. The re-enriched fuel cost depends on the mass fraction between the HALEU from RU and HALEU from NU. For SFR-98, about 45% of the re-enriched fuel was made with the HALEU from RU, which results in the cost being ~25% cheaper than the cost of making the original fuel with 100% fresh HALEU. For SFR-146, the fraction of HALEU from RU decreases ~28% and the resulting cost of the re-enriched fuel is only 7% cheaper than the original fuel.

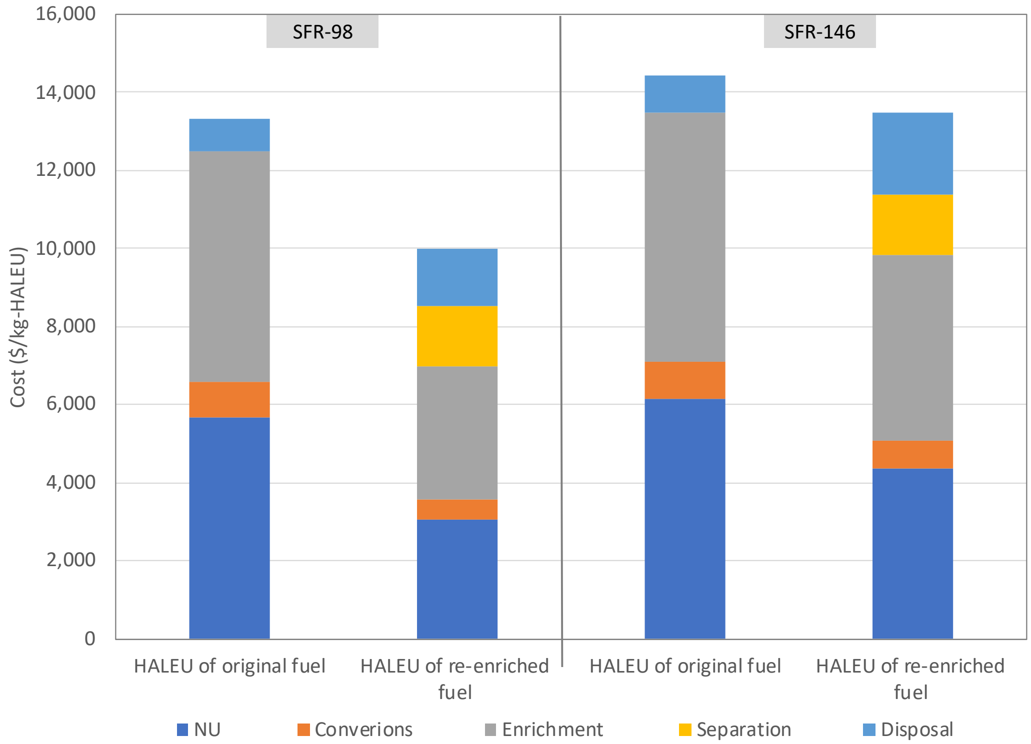

Figure 3.5 HALEU Costs of original fuel and re-enriched fuel

3.3 Value of Down-blended RU

In this section, the RU value was evaluated for the case when RU having more than 5% residual U-235 content is reused in a conventional PWR after down-blending. **Error! Not a valid bookmark self-reference.** shows the required material masses for making a unit mass (1.0 kg-U) of the PWR fuel with NU and RU obtained from MR-2, SFR-98, and SFR-146. The RU from MC-35 can be reused after down-blending, but it was excluded in this section because the separation cost of TRISO fuel is unknown. The RU from HTGR-90 and HTGR-165 cannot be reused in PWR by down-blending because the residual U-235 content is lower than the enrichment of the PWR fuel. Since a large amount of DU is created when generating HALEU fuels of MR-2, SFR-98, and SFR-146, it was assumed that the down-blending was conducted using the free DU and the U-235 assay in the DU was 0.25%.

The charge fuel enrichment of the reference PWR is 4.21%. However, when the PWR utilizes the down-blended RU, the charge fuel enrichment increases slightly (4.22 – 4.65%) to compensate for the parasitic absorption. The reference PWR requires 8.61 kg of NU to make 1.0 kg of 4.21% enriched uranium. However, the PWR does not need NU when utilizing the down-blended RU. To make 1.0 kg-U of the PWR fuel, the required UNF mass is 0.21 - 0.83 kg depending on the residual U-235 content in RU, and the required DU mass is 0.35 – 0.79 kg.

Table 3.1 Required enrichment and masses to make a unit mass of PWR fuel

Source of uranium	NU	RU from MR-2 UNF	RU from SFR-98 UNF	RU from SFR-146 UNF
U-235 content in source uranium	0.71%	19.57%	9.15%	6.99%
Charge fuel enrichment [a)]	4.21%	4.22%	4.46%	4.65%
Required mass (kg to make 1.0 kg of uranium in PWR fuel) [b)]				
NU	8.61	-	-	-
UNF	-	0.21	0.56	0.83
DU [c)]	-	0.79	0.53	0.35

a) U-235 content to reproduce the PWR discharge burnup of 50 GWd/t and compensate for U-236 parasitic absorption.

Fuel costs of making a unit mass of uranium ($/kg-U) in the PWR fuel were calculated, and the results are compared in Figure 3.6. The fuel cost with NU includes NU mining and milling, conversion/deconversion, enrichment, fuel fabrication, and DU disposal. The fuel cost with the down-blended RU includes separation, conversion, down-blending and fabrication, and HLW disposal. This work assumed that the down-blending of RU with DU occurs in the fuel fabrication. Thus, the fuel costs include the fuel fabrication cost.

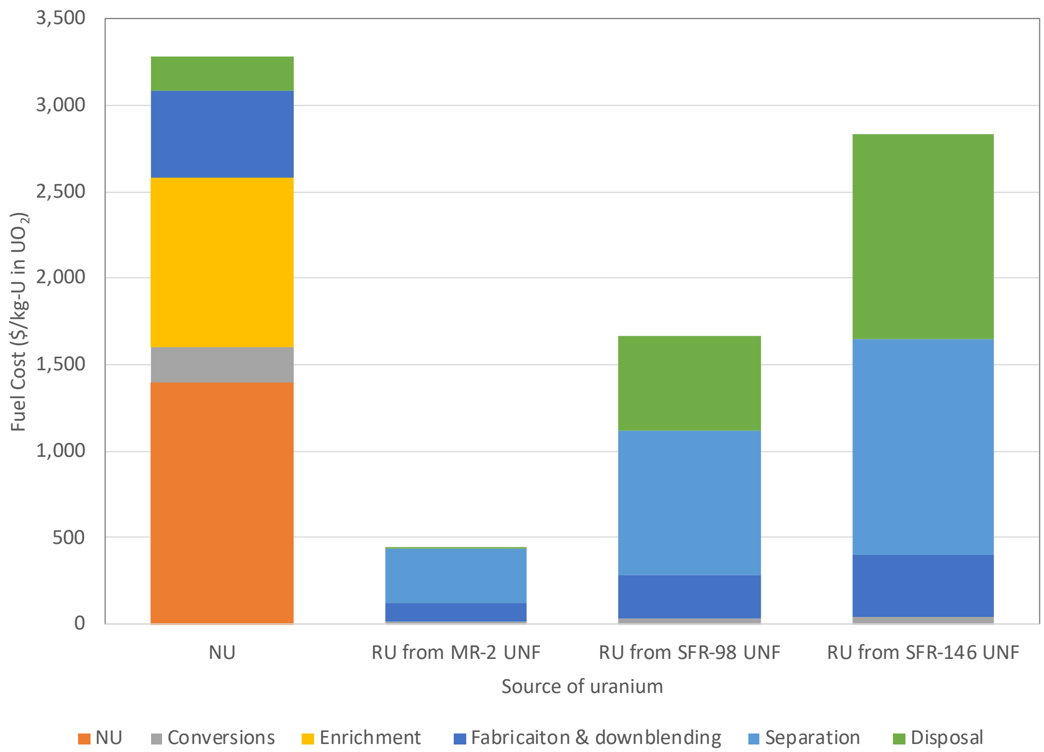

Figure 3.6 Fuel Cost with down-blended RU

Figure 3.6 shows that the NU and enrichment costs are dominant when making the PWR fuel with NU, while the separation and HLW disposal costs dominate when making the PWR fuel with the down-blended RU. The cost-saving with the down-blended RU depends on the residual U-235 (or fuel burnup). The fuel cost with the down-blended RU from the MR-2 UNF is approximately 85% cheaper than the fuel cost with NU but 51% and 13% cheaper with the down-blended RU from the SFR-98 and SFR-146, respectively.

4. Conclusions

Various advanced reactor concepts have been proposed recently, and most of them utilize 10 – 19.75% high assay low enriched uranium (HALEU) aiming for higher burnup, compact cores, higher thermal efficiency with higher operating temperature, etc. Because the residual U-235 in a HALEU used nuclear fuel (UNF) is significant in some reactor types (for instance, microreactor and fast reactor), and the residual U-235 can be utilized as a fissile material, the values of the recovered uranium (RU) from the HALEU UNF were evaluated in this study. Costs for making a unit mass of fuel with RU and fresh enriched uranium (EU) were calculated for the following cases,

- using RU as a fissile material of a nuclear fuel,
- reloading RU into the original advanced reactor after re-enrichment and
- reusing RU in a conventional PWR after down-blending,

and the RU values were identified when the fuel cost with RU was cheaper than the fresh enriched uranium (EU).

Among the various advanced reactor concepts utilizing the HALEU fuels, several reactor types were selected for a bounding analysis of the RU values. These include microreactors, advanced thermal reactors, and fast reactors with burnup in the 2 – 165 GWe/t range. It is noted that this study focused on the recovery of uranium only, and the value of other fissile materials (such as Pu) was not considered even though those are bred significantly in fast rector.

The residual U-235 content in the HALEU UNF varies depending on the reactor type and burnup. Advanced thermal reactors (HTGR) are generally designed to completely consume the excess reactivity by burning most U-235. The residual U-235 content in advanced thermal reactor UNFs is very low (< 1.2%). The fast reactor fuel is discharged when the irradiation of fuel cladding reaches its limit even though a fractional U-235 remains in the fuel. The residual U-235 content in fast reactor UNFs is 7 – 9%. The burnup is small for microreactors because the reactor cannot maintain the criticality for a longer time in a leaky core. As a result, the residual U-235 content in microreactor UNFs is high (16 – 19%).

U-236 is primarily generated from the (n,γ) reaction of U-235, and the bred U-236 in RU acts as an absorber in a thermal reactor. The U-236 content is proportional to the burnup, which is less than 3%. Due to the parasitic absorption, the reactivity worth of RU is equivalent to the fresh EU having 1 – 4% lower U-235 content in a thermal reactor, while it is similar to the fresh EU having the same U-235 content in a fast reactor.

This study concludes that, except for the reuse of re-enriched RU in microreactors, the RU having a residual U-235 content higher than ~7% is more affordable than the fresh EU because the fuel cost with RU is cheaper, and the affordability increases as the residual U-235 content in RU increases. For instance, the fuel cost with the RU having the residual U-235 content higher than 19.6% is about 85% cheaper than the fuel cost with the equivalent fresh EU. This study observed that the reuse of RU after reenrichment in microreactors (in particular, Design-A and GCMR) is impractical without sacrificing reactor performance parameters (cycle length or burnup) because the U-235 content in the re-enriched RU fuel is over the 20% limit of the low-enriched uranium.

It is noted that the impacts of uncertainties in the cost data and the values of RU from the TRISO fuels were not evaluated in this study because of the limited information on the cost data uncertainties and the separation cost of TRISO fuels.

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Appendix A. Unit Cost Data

Table A. 1 Unit Cost Data ($ value in 2023)

COA	Description	Low	Mode	High	Mean
A1	NU mining and milling, $/kg-U	42.50	107.50	370.00	162.67
A1a	9.75% LEU generated in Cat-III facility	3,593.43	6,295.51	13,0701.4	7,583.45
B	Conversion to UF6, $/kg-U	8.13	16.25	23.75	16.25
K1-1	Deconversion to oxide, $/kg-U	5.50	8.13	10.88	8.16
K1-1a	Deconversion to metal, $/kg-U	1,030.00	2,060.00	3,090.00	2,060.00
K1-1b	Deconversion to UCO, $/kg-U	515.00	1,287.50	2,060.00	1,287.50
K1-2	DU geological disposal, $/kg-U	5.50	17.63	57.25	25.23
K3-3	RU-metal to RUF6 conversion, $/kg-U	42.75	59.88	85.50	62.10
C1	Enrichment (<5%), $/SWU	121.25	156.25	192.50	156.25
C1-1	Enrichment (5-10%), $/SWU	127.31	176.56	231.00	176.56
C1-2	Enrichment (10-20%), $/SWU	124.89	179.69	244.48	179.69
D1-1	PWR fuel fabrication, $/kg-U	287.50	500.00	718.75	501.57
D1-1.1	PWR fuel fabrication & down-blending, $/kg-U	312.50	543.75	793.75	548.48
D1-3	TRISO fuel fabrication, $/kg-U	4,125.00	13,625.00	36,750.00	17,327.68
D1-6	Metal fuel fabrication , $/kg-U	1,250.00	1,750.00	2,250.00	1,750.00
I	PWR SNF interim storage, $/kg-SNF	278.75	626.25	805.00	581.13
I1	Metal SNF interim storage, $/kg-SNF	161.68	363.23	466.90	337.06
I2	TRISO SNF interim storage, $/kg-SNF	1,988.60	4,467.67	5,742.87	4,145.81
F2	Metal fuel separation, $/kg-UNF	1,250.00	1,500.00	1,750.00	1,500.00
G2	SNF conditioning & packaging, $/kg-SNF	85.00	168.75	218.75	159.84
L1	SNF disposal, $/kg-SNF	361.25	750.00	1,091.25	737.94
L1-1	HLW disposal, $/kg-HLW	1,875.00	7,500.00	9,375.00	6,467.79

Appendix B. Cost of SWU thrown away in Once-through Fuel Cycle

Various advanced reactors utilize high assay low enriched uranium (HALEU) to achieve their design goals, such as high burnup, improvement of thermal efficiency, etc. The HALEU fuel is largely or partially depleted depending on the advanced reactor design features. If the HALUE fuel is partially depleted and the residual U-235 content in the used nuclear fuel (UNF) is high, the recovery of uranium and reusing it in a reactor would be an affordable option compared to the use of fresh enriched uranium because the enrichment effort, measured by Separation Work Unit (SWU), and natural uranium (NU) can be saved. Since several advanced reactors are pursuing a once-through fuel cycle), the SWU and cost for enriching NU up to the residual U-235 content level in the discharged fuel were evaluated.

The SWU costs of two microreactors and two fast reactors utilizing HALEU fuels were calculated. The design parameters, discharge fuel information, and resulting SWU and enrichment costs are summarized in Table B. 1. Uranium mass in HALEU UNF, SWU, and enrichment costs were evaluated using two normalizations: values per unit electricity generation (/GWe-year) and values per operation of a single reactor for one year (/year-reactor). A conventional PWR is included in the table for comparison purposes, but advanced thermal reactors (such as Xe-100 type gas-cooled reactors, etc.) were excluded from this evaluation because the residual U-235 content in advanced thermal reactors is very low.

Table B. 1 Comparison of reactor design parameters, SWU, and enrichment cost

Reactor type [a)]	PWR	MR-2	MR-35	SFR-98	SFR-146
Power, MWt/MWe	3000/1000	5.0/2.0	20.0/8.0	1000/400	840/345
Charge fuel enrichment, %	4.21	19.75	19.75	16.34	17.65
Burnup, GWd/t	50.0	2.0	35.0	98.4	146.0
U-235 content in discharge fuel, %	0.8	19.6	16.4	9.2	7.0
Cost of SWUs in discharge fuel per unit electricity generation					
U mass in UNF, MT/GWe-year	20.5	455.6	26.1	9.3	6.1
SWU in CAT-II, SWU/GWe-year SWU in CAT-III, SWU/GWe-year	- 1.3×10^{-3}	1.1×10^{6} 1.7×10^{7}	3.8×10^{4} 7.8×10^{5}	- 1.3×10^{5}	- 5.7×10^{4}
Cost in CAT-II, $M\$_{2023}$/GWe-year Cost in CAT-III, $M\$_{2023}$/GWe-year Total cost, $M\$_{2023}$/GWe-year	- 0.21 0.21	197.4 3,072.5 3,269.9	6.9 138.4 145.3	- 23.5 23.5	- 10.0 10.0
Cost of SWUs in discharge fuel per reactor-year [b)]					
U mass in UNF, MT/ year-reactor	18.4	0.8	0.2	2.8	1.5
SWU in CAT-II, SWU/year-reactor SWU in CAT-III, SWU/year-reactor	- 1.2×10^{-3}	1.9×10^{3} 3.1×10^{4}	2.8×10^{2} 5.6×10^{3}	- 4.8×10^{4}	- 1.8×10^{4}
Cost in CAT-II, $M\$_{2023}$/year-reactor Cost in CAT-III, $M\$_{2023}$/year-reactor Total cost, $M\$_{2023}$/year-reactor	- 0.19 0.19	0.4 5.5 5.9	0.05 1.0 1.05	- 8.5 8.5	- 3.1 3.1

a) MR-2: microreactor with burnup of 2 GWd/t based on heat-pipe reactor (Sterbentz 2018, Walker 2021),
MR-35: microreactor with burnup of 35 GWd/t based on the gas-cooled reactor (Stauff 2023),
SFR-98: fast reactor with burnup of 98 GWd/t based 1000 MWt advanced burnup reactor (Kim 2009),
SFR-146: fast reactor with burnup of 146 GWd/t based on Natrium (Neider 2021).

b) It was calculated by assuming the reactor capacity factor of 90%.

If the residual U-235 content is higher than 10%, the SWU and enrichment costs were calculated by assuming that NU is enriched up to 9.75% in a CAT-III facility, followed by additional enrichment in a CAT-II facility to 19.75%. The enrichment cost was calculated using the SWU unit cost that was obtained from the Advanced Fuel Cycle Cost Basis Reports in 2022 (Hansen et al. 2022). The inflation-adjusted SWU unit costs in 2013 were 156.3, 176.6, and 179.7 dollars per SWU for enrichment up to 5%, 10%, and 20%, respectively.

Microreactors utilize 19.75% HALEU fuels, while fast reactors utilize slightly lower enriched HALEU fuels. The average discharge burnup of the microreactors is 2-35 GWd/t, which is much lower than fast reactors (98 – 146 GWd/t). Due to the higher charge fuel enrichment and lower burnup, the residual U-235 contents of microreactor UNFs are higher (16.4 – 19.6%) than those of two fast reactors (7.0 – 9.2%). Thus, SWU in CAT-II and CAT-III is needed to enrich NU up to the residual U-235 content level of microreactor UNFs, while SWU in a CAT-III facility is sufficient for enriching NU to the residual U-235 content level of fast reactor UNFs.

The normalized uranium mass to the unit electricity generation is inversely proportional to the burnup. Among the advanced reactors considered in this evaluation, MR-2 and SFR-146 have the lowest and highest burnup, respectively. Thus, the bounding residual uranium mass in the HALEU UNF is 6.1 – 455.6 MT/GWe-year, which requires 0.06 – 18 million SWU and an enrichment cost of 10 – 3,300 million dollars. The residual uranium mass in the PWR discharge fuel is 20.5MT/GWe-year, but the enrichment cost is only 0.21 million dollars because of the low residual U-235 content (0.8%).

Due to a small power level (2 – 8 MWe), many microreactors are needed to generate a unit electricity of 1.0 GWe-year. For instance, 556 MR-2 reactors (=1.0 GWe/2.0MWe/90%-capacity) are needed. Thus, the results were alternatively normalized to a single reactor and compared in Table 1. If reactors operate for one year with a 90% capacity factor, UNF containing in HALEU UNFs is 0.2 - 2.8 MT/year-reactor, and it requires 5.9×10^3 – 4.8×10^4 SWU/year-reactor and 1.1 – 8.5 million $/year-reactor to make equivalent enriched uranium. The enrichment cost up to the residual U-235 content of the PWR discharge fuel is 0.19 million $/year-reactor.

In conclusion, the enrichment cost for enriching NU up to the residual U-235 content level is 10 – 3,300 million $/GWe-year or 1.1 – 8.5 million$/year-reactor, which will be thrown away if the HALUE UNF is disposed of in a once-through fuel cycle.