DISCLAIMER

Assessment of Deep Burnup HALEU Fuel Impact and Requirements

Nuclear Fuel Cycle and Supply Chain

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Systems Analysis and Integration
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Executive Summary

This report explores advancements in nuclear fuel technology, focusing on once-through high-assay low-enriched uranium (HALEU) fuels. It examines the potential for increased fuel residence time in reactors and the fuel cost implications. The study highlights the differences between fast and thermal reactors in terms of fuel enrichment and burnup, emphasizing the complex relationship in fast reactors in which increased core size and fuel density can lead to lower enrichment requirements. Various advances in fuel technologies for light-water reactors (LWR) and sodium-cooled fast reactors (SFR) are presented in this report to provide more comprehensive analysis.

A literature review was conducted to summarize recent progress in advanced nuclear fuel and cladding technologies aimed at improving burnup, safety, and efficiency in light water reactors. Among fuel options, doped or large-grain UO_2 fuels, such as Westinghouse's ADOPT®, have the highest technology readiness and are already in commercial use. Mixed Oxide (MOX) fuel also shows high maturity globally, although it remains unlicensed in the U.S. For cladding, chromium-coated zirconium alloys and HT9 steel are the most developed options, providing enhanced oxidation resistance and high burnup capability. While longer-term solutions like ceramic fuels with SiC cladding offer promising benefits, they still require additional testing and regulatory approval before deployment.

Three examples of Pressurized Water Reactor (PWR) fuel options were evaluated to represent current technology and advancement using HALEU for LWRs. Using HALEU to increase fuel burnup will result in a small increase in demand for natural uranium (NU) per unit electricity produced. To double the burnup, approximately a 20% increase in separative work units (SWU) would be required. The quantity of fabricated fuel and spent nuclear fuel (SNF) will decrease as it is inversely proportional to the burnup. If the technology can be developed and deployed commercially without a large increase in the cost of fabrication, there may be a cost benefit of HALEU to achieve higher burnups on the order of 2-4 cents/MWh per MWd/kg increase in burnup. Over the entire fleet of ~100 GWe, with assumed capacity of 90%, this cost benefit would be $15-30M/yr per MWd/kg increase in burnup.

Tri-structural isotropic (TRISO) fuel has been developed for the fuel range of HALEU enrichments and resulting burnups. Three different TRISO fuel examples were considered, including helium-cooled pebbles and prismatic blocks, and molten-salt cooled pebbles. There were important differences between designs, but overall, the fuel cycle requirements are, like for PWRs, on a per unit electricity generated basis. There is a substantial difference in the volume of SNF produced, with TRISO fuel producing on the order of 10 times more volume per unit electricity generated than the PWRs.

A total of 84 design variations of an SFR model representative of current SFR technology were characterized to evaluate the relationship between fuel enrichment and residence time of a HALEU-fueled SFR core. Three of those SFR design variations were studied in more detail. The first SFR design was a compact core with 12 fuel assembly rings and a core height of 1.3 m. For this configuration, the equilibrium enrichment increases with increasing fuel residence time, reaching a maximum of about 13 years when the fuel remains under the 20% low-enriched uranium (LEU) limit. The second configuration added an additional ring of fuel assemblies and increased the core height to 1.8 m. The larger 13-ring core size reduces the required fuel enrichment for the same burnup. The enrichment increases with increased fuel residence time in the 13-ring core. The 20% limit was not reached at a fuel residence time of 30 years. The final configuration studied added a 14th ring of fuel assemblies and used the same 1.8 m core height as the second configuration. The larger core size further reduced the enrichment, which increased with burnup, resulting in a 1% reduction in enrichment at a burnup of 150 MWd/kg compared with the 13-ring core. For all three configurations, increasing the fuel volume fraction could extend the fuel residence time that could be achieved while staying under 20% enrichment. With a sufficient increase in the fuel volume fraction, the equilibrium enrichment would be less than 10%, and very long residence times (>30 years) are possible.

For SFRs based on current technology, the NU and SWU requirements are larger than for thermal reactors. With advanced fuel and core designs, it is possible to reduce these requirements less than thermal reactors. For all cases, the amount of SNF generated is reduced proportionally as the burnup increases for the same fuel design. PWRs and SFRs produce similar volumes of SNF at the same burnup.

The impacts of deep-burn fuels in SFR were compared using the levelized fuel cost at equilibrium (LFCAE). The LFCAE includes the entire fuel cycle costs, which are all fuel-related costs from mining to disposal, but does not include the reactor capital and O&M costs. For the SFR, a reduction in refueling LFCAE results from increased fuel residence time, and larger increases are enabled by a better neutron economy (larger core size and increased fuel volume fraction). The refueling LFCAE was evaluated for 6 examples that cover the range of fuel residence time and core designs studied: one of each SFR core configuration with the base volume fraction, and one for each configuration with an increased volume fraction. The refueling LFCAE based on current technology was estimated to be between 15-24 $/MWh. For the most advanced concept (largest core size and longest fuel residence time), the refueling LFCAE was reduced to 5-8 $/MWh. This refueling LFCAE is approximately 63% of the current technology PWR, which ranges between 8-13 $/MWh.

The fuel cycle costs of initial cores were also estimated for the SFR. The initial core requires relatively lower enriched fuels but requires a larger amount of fuel to fill the core. For the 12-ring reference core, the initial core fuel cycle costs are about $1,000/kWe which represents a levelized cost of electricity of about $7/MWh. For the PWR, the initial core cost would be about $300/kWe. For the larger SFR core sizes considered, the cost of the fuel will roughly double for the largest core, compared with the 12-ring reference core. If the power level is not increased, this would be around $2,000/kWe, offsetting most of the benefit of reduced refueling costs. It is anticipated that power levels would increase, but analysis of the effects of this variation was beyond the scope of this study.

Increasing the fuel residence time with deep burn fuels requires overcoming many challenges, but if achieved, then the impact can be positive or negative on the measures of interest (required amount of NU, SWU, fuel fabrication, disposal SNF volume, etc.). The potential ranges from negligible impacts on some measures to very dramatic reductions in quantities for others. The LFCAE for the recycling core decreases quite significantly for SFRs. However, if the increase in fuel residence time is achieved by a physically larger core, this could drive up the reactor capital and the fuel cycle cost to fill the initial core. The impacts of a longer fuel residence time using HALEU are likely a little smaller for PWRs, as there will be no overall change in geometry.

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Acronyms

ANEEL	Advanced Nuclear Energy for Enriched Life
ATF	accident-tolerant fuel
BANR	BWXT Advanced Nuclear Reactor
BU	burnup
BWR	boiling water reactor
CBR	Cost Basis Report
DU	depleted uranium
DUF6	depleted uranium hexafluoride
EBR-II	Experimental Breeder Reactor II
EFPY	effective full power year
FFTF	Fast Flux Test Facility
FGR	fission gas release
FVF	fuel volume fraction
GNF	Global Nuclear Fuel
HALEU	high-assay low enriched uranium
HALEUF6	high-assay low enriched uranium hexafluoride
HEA	high entropy alloys
HEU	high enriched uranium
HM	heavy metal
HTGR	high-temperature gas-cooled reactor
IFR	Integral Fast Reactor
IMF	inert matrix fuel
IMSR	integral molten salt reactor
LEU	low-enriched uranium
LFCAE	levelized fuel costs at equilibrium
LFTR	liquid fluoride thorium reactors
LALEU	low-assay low enriched uranium
LCOE	levelized cost of electricity
LTA	lead test assembly
LWR	light-water reactor
MOX	mixed oxide fuel
NRC	Nuclear Regulatory Commission
NU	natural uranium
NUF6	natural uranium hexafluoride
OCC	overnight capital cost
ODS	oxide dispersion-strengthened
ORNL	Oak Ridge National Laboratory
O&M	operations and maintenance
PCI	pellet-cladding interaction
PVD	physical vapor deposition
PWR	pressurized water reactor
SMR	small modular reactor

SNF	spent nuclear fuel
SFR	sodium-cooled fast reactor
SWU	separative work unit
TRISO	TRi-structural ISOtropic
TRL	technology readiness level
TWR	traveling wave reactor
UN	uranium nitride
WATTS	Workflow and Template Toolkit

SYSTEMS ANALYSIS AND INTEGRATION CAMPAIGN ASSESSMENT OF DEEP BURNUP HALEU FUEL IMPACT AND REQUIREMENTS

1. Introduction

Advanced fuels are being developed to enable enhanced reactor performance, especially in terms of economics and safety. Often, these advancements require a tradeoff in one area for benefits in another area. This study focuses on fuel advancements that will allow for increased irradiation levels in the reactor. Deep burnup is often associated with deeply burning transuranics in a transmutation system. For this study, deep burnup refers to substantial increases in fuel residence time in the core for enriched uranium fuels, specifically looking at once-through high-assay low-enriched (HALEU) fuels.

There is a wide range of claddings, additives, etc., that are being considered with varying degrees of interest by the U.S. nuclear industry. There will be trade-offs between conventional burnup fuel and deep burnup fuel, including technological challenges.

The analysis of this report is based on models of different reactor designs and fuel characteristics. Specifically, the models are for pressurized water reactors (PWRs), TRi-structural ISOtropic (TRISO)-fueled reactors, and fast reactors. For all cases, the focus will be limited to enrichments >5 to <20% (i.e., HALEU). For light water reactor (LWR) fuels, the report did not exceed 10% enrichment, since this seems to exceed what is likely for commercial power reactors. For TRISO fuels, current experience extends beyond HALEU and from a deep burn perspective, the HALEU limit has been reached. For fast reactor technology, there is a more complex relationship between the enrichment of the charged fuel and the irradiation level, with a much greater sensitivity to the size of the core and the design of the fuel. To explore this more complex relationship, a sodium-cooled fast reactor (SFR) will be modeled with variations in the physical size (height and radius of fuel), fuel design (fuel volume fraction), and fuel residence time (irradiation level).

This report provides a qualitative discussion of advanced fuel technologies and their challenges. For a range of example advanced fuels, the system material balances (e.g., natural uranium (NU) requirements and separative work unit (SWU) requirements) will be evaluated to quantify system impacts and requirements. From these material balances, the fuel cycle costs in terms of the levelized fuel cost at equilibrium (LCFAE) will be evaluated. The LFCAE includes all fuel cycle related costs from mining to disposal of all waste streams (i.e., depleted uranium (DU) and spent nuclear fuel (SNF)). The LFCAE does not include reactor overnight capital costs (OCC) and operation and maintenance (O&M) costs. These metrics will inform on the challenges, requirements, and potential benefits of advanced fuels developed for increased radiation levels (deep burnup) HALEU fuels.

1.1 Difference Between Fast and Thermal Reactors

One of the important items to understand when discussing increased irradiation limits for nuclear fuels is the distinctions in behavior between fast and thermal reactors.

In a thermal reactor of a fixed design (cycle length, core size, fuel design), increasing the fuel burnup requires an increase in enrichment. Thus, the increase in enrichment does not greatly affect the NU and SWU required per unit energy (see Section 4.2). The primary benefit of higher irradiation levels is a decrease in the amount of fuel that needs to be fabricated and the amount of SNF, with the quantities being inversely proportional to burnup. If fabrication and SNF management costs are high, there is a strong incentive to maximize burnup through raising enrichment up to the HALEU limit, such as is expected for TRISO fuels.

In a fast reactor, the relationship between enrichment, irradiation time, and burnup is more complex. For more compact cores, the higher neutron leakage will result in behavior like that of thermal reactors; increased fuel irradiation will require higher enrichments and lead to higher burnups and be constrained by the HALEU enrichment limit. However, with a larger core size and/or a higher fuel volume fraction, the neutron leakage is reduced, which allows for lower enrichments and higher breeding ratios. As a result, a point will be reached at which the enrichment of the fuel will no longer increase with increased irradiation (fuel residence time and burnup). The extreme of this trend is the Breed and Burn core concept, in which the reactor is refueled with unenriched uranium with all necessary fissile material needed to sustain operation produced in situ through breeding within the fuel. The fuel evolves from breeding blanket to driver fuel over its lifetime in the core without the need for recycling. This work considers a range of SFR designs to quantify this behavior from current SFR fuel lifetime limits in a compact core configuration to advanced fuels that would exceed current limits in a larger core configuration.

The evolution of SFR designs and fuels is likely to occur over a long period of fuel development, with many intermediate advancements. Current fuels have been demonstrated to a peak fast fluence of $4x10^{23}$ n/cm^2 [1], which corresponds to a lifetime of about 5 years in high power density commercial reactor environments. The fuel residence time is constrained primarily by the radiation damage to the cladding, with the actual time to reach this limit varying based on specifics of the individual designs. The Breed and Burn fuel design would require the longest fuel residence time, which is on the order of 40 years. There are many design variables in SFRs, such as fuel design and power density, and these variables will be uncertain until SFRs are deployed in significant numbers. These variables will also evolve as SFR fuels advance to better take advantage of the longer lifetime of the fuel.

The Natrium demonstration and first commercial reactors are 840 MWth compact core [2], while TerraPower envisions a GWe-scale core (~2,400 MWth) for their Natrium Ultimate (Breed and Burn) design [3]. This report is not fully representative of a Natrium deployment scenario, as the SFR designs used in this report are based on publicly available PRISM-based design information. It intends to clarify what the economic tradeoff is associated with extended burnup HALEU fuel in fast reactor vs. thermal reactors.

1.2 Report Structure

The report is organized into six additional sections. Section 2 is focused on a literature review of thermal reactor advanced fuel technology development. Section 3 discusses fast reactor advancements with a mix of advanced fuels and changes in reactor design, as both play a major role in potential improvements. A range of reactor and fuel design alternatives were modeled to quantify performance to provide the input to assess impacts. Section 4 quantifies the potential impacts on the system resulting from the development of deep burn extended irradiation fuels. The changes in quantities (e.g., NU, SWU, SNF) of each stage of the fuel cycle are quantified. Section 5 evaluates the impact on fuel cost of these deep burn extended irradiation fuels. Section 6 summarizes this report. Appendix A-1 provides all cost data used in this report.

2. Advanced Fuels Technology Development

This section looks at some of the technologies that are under development for advanced fuels. This section focuses on thermal reactor fuels, LWR in particular, discussing the wide range of technologies and the general requirements and challenges.

2.1 Technology Discussion

The continuous advancement of nuclear reactor technology necessitates parallel progress in fuel development to meet evolving safety, efficiency, and sustainability goals. In response, significant efforts are underway to design and deploy next-generation nuclear fuels that offer enhanced performance characteristics, including higher burnup capability, improved thermal conductivity, greater resistance to high-temperature oxidation, lower fission gas release, etc. Driven by industry, national laboratories, and universities, developments are being made to address challenges in both conventional LWRs and advanced reactors.

Recent innovations in fuel technology can broadly be categorized into two main areas: improvements in fuel composition and structure, and advancements in cladding materials. The former focuses on modifying or entirely rethinking the fuel matrix to optimize neutron economy, fission product retention, and reactor lifetime. The latter emphasizes enhancing the cladding—the critical barrier between the fuel and the coolant—to increase accident tolerance and long-term material stability under extreme conditions. The following subsections summarize the current state of research and development in these two domains.

2.1.1 Fuel Options

1. **Doped or large-grain Uranium Oxide (UO_2):**
   - Framatome is researching large-grain Cr_2O_3 - doped UO_2 for light LWRs to enhance fuel performance at high burnup and minimize fission gas release (FGR) [4].
   - Westinghouse is advancing large-grain and Cr_2O_3 and Al_2O_3 doped UO_2 fuels as part of its strategy to extend burnup limits, improve efficiency, and reduce operating costs in LWRs [5].
   - A subsidiary of GE Hitachi, Global Nuclear Fuel (GNF), is developing large-grain Al_2O_3 and SiO_2 - doped UO_2 for boiling water reactor (BWR) applications. Their use of Gadolinia-doped fuels and advanced manufacturing techniques supports higher burnup goals [6].
2. **Mixed Oxide (MOX) Fuel:**
   - With extensive experience in MOX fuel production, Framatome is actively developing advanced MOX designs aimed at achieving higher burnup in nuclear reactors [7].
   - Westinghouse is developing MOX fuel for both thermal and fast reactors, with a focus on optimizing burnup rates and enhancing safety [8].
3. **Thorium-based Fuels (ThO_2):**
   - Clean Core is developing the Advanced Nuclear Energy for Enriched Life (ANEEL) fuel, which combines ThO_2 with HALEU to enhance fuel performance and safety in pressurized heavy water reactors (e.g., CANDU reactors) [9].
   - Flibe Energy is advancing the development of liquid fluoride thorium reactors (LFTRs), which utilize thorium as the primary fuel in molten salt form [10].
   - Terrestrial Energy is working on the Integral Molten Salt Reactor (IMSR), a design compatible with thorium-based fuel cycles [11].

- Lightbridge corporation explores innovative fuel concepts, including thorium-based options, aiming to develop safer and more efficient fuels for LWRs [12].

4. **Inert Matrix Fuels (IMFs):**
   - Framatome has been researching IMFs for use in commercial reactors, with a focus on reducing plutonium stockpiles and managing minor actinides [13].
   - Westinghouse has explored advanced nuclear fuels, including IMF options, to enhance reactor efficiency and address long-term waste management challenges [13].
5. **Metallic Fuels:**
   - TerraPower is actively developing metallic fuels based on uranium-zirconium alloys (U-Zr) for its Natrium reactor, a sodium-cooled fast reactor, and is also working on metallic uranium fuel for its Traveling Wave Reactor (TWR) [14].
   - Framatome has investigated metallic fuels for TRIGA reactors [15].
   - Lightbridge is developing metallic fuels with unique designs specifically for use in LWRs, aimed at enhancing efficiency and safety [16].
   - GE Hitachi is developing metallic fuels for its PRISM fast reactor, working to optimize fuel performance and reactor efficiency [17].
6. **Ceramic fuel**
   - Westinghouse is actively researching alternative ceramic fuels, such as uranium silicide (U_3Si_2) and uranium nitride (UN) for potential use in both LWRs and advanced reactor designs [18].
   - Framatome is investigating UN for use in LWRs [19].
   - X-Energy is studying UO_2 fuels for application in high temperature gas reactors (HTGRs), focusing on improving fuel performance at elevated temperatures [20].
   - The BWXT Advanced Nuclear Reactor (BANR) uses TRISO fuel with a uranium nitride (UN) fuel kernel in a silicon carbide (SiC) fuel matrix instead of graphite [21].

2.1.2 Cladding Options

1. **Coated Zirconium Alloys:**
   - Framatome is developing a range of advanced chromium (Cr)-based coatings to enhance oxidation resistance and accident tolerance, specifically designed for use in LWRs as part of their accident-tolerant fuel (ATF) program [22].
   - Westinghouse is actively investigating coated zirconium (Zr) claddings for enhanced performance in accident scenarios, using chromium coatings applied through physical vapor deposition (PVD) and other techniques. These claddings are intended for ATF applications in both BWRs and PWRs [18].
   - GE Hitachi is exploring coated zirconium claddings as part of its broader ATF initiatives, focusing on chromium coatings and other advanced materials to mitigate high-temperature oxidation, with a primary focus on improving safety margins in severe accident conditions for LWRs [23].

2. **Ceramic materials:**

    - General Atomics is a pioneer in developing SiC-based fuel cladding with its SiGA™ technology, utilizing a silicon carbide composite material to enhance performance in ATF designs, primarily for LWRs and other advanced reactor concepts [24].
    - Framatome is investigating SiC cladding as part of its ATF research, aiming to improve the safety and performance of its nuclear fuel designs. SiC cladding is being considered for both PWRs and BWRs in Framatome's advanced fuel concepts [25].
    - Westinghouse is developing advanced SiC composite cladding as part of its ATF program, targeting both current-generation LWRs and advanced reactors like small modular reactors (SMRs) and Generation IV systems [18].

3. **Advanced Ferritic-Martensitic Steels (e.g., HT9, T91):**

    - TerraPower is studying ferritic-martensitic steels, including HT9, for use in its TWR [14] and Natrium Reactor, both of which are sodium-cooled fast reactors [26].
    - GE Hitachi has been involved in developing HT9 and other ferritic-martensitic steels for their PRISM reactor, a sodium-cooled fast reactor, as well as for other advanced reactor concepts [17].

4. **Oxide Dispersion-Strengthened (ODS) Steels:**

    - Oak Ridge National Laboratory (ORNL) is investigating the cold spray deposition process to manufacture 14YWT ODS steel, a nanostructured ferritic alloy, that can be used in advanced reactors [27].

5. **Metallic Claddings:**

    - In collaboration with GE Global Research, ORNL has developed a novel FeCrAl alloy for ATF cladding applications. This development has led to the creation of a nuclear-grade FeCrAl ATF cladding known as IronClad, which is now available in pre-commercial product forms and has been deemed acceptable for pilot testing [28].

6. **High Entropy Alloys (HEAs)**

    - ORNL has been at the forefront of developing advanced materials for nuclear applications. Their research includes the development of custom-designed alloys aimed at enhancing nuclear safety, focusing on materials that can withstand extreme reactor conditions [29].

2.1.3 Discussions

All the fuel options discussed in 2.1.1 considered achieving higher burnup relative to conventional UO_2 fuel as a primary or significant development goal, but the technology readiness levels (TRLs) differ significantly. The fuel options with the highest TRL were:

- Doped or large-grain UO_2 - For example the Westinghouse ADOPT® has been licensed by the Nuclear Regulatory Commission (NRC) for use in U.S. PWRs [30] and installed in Vogtle Unit 2 with ongoing irradiation cycles [31].
- MOX fuel – Although MOX fuel has been licensed and deployed globally, especially in France [32], it is not licensed in the U.S.

The majority of the cladding options discussed in 2.1.2 considered achieving higher burnup relative to conventional Zr cladding as a primary or significant development goal, except FeCrAl and HEAs, which were designed more for ATF safety. The cladding options with the highest TRL were

- Cr-coated Zr alloys - For example the Westinghouse AXIOM® has been licensed by the NRC and installed in Vogtle Unit 2 with ongoing irradiation cycles [33].
- HT-9 – Irradiation tests have been conducted in experimental fast reactors such as Experimental Breeder Reactor II (EBR-II) and Fast Flux Test Facility (FFTF) [34].

2.2 Requirements and Challenges

For LWRs, a promising near-term solution involves combining large-grain or doped UO_2 fuel with chromium-coated zirconium alloy cladding. Chromia-doped UO_2 with enlarged grain size enhances fission gas retention during transients and reduces the risk of pellet-cladding interaction (PCI), particularly under off-normal conditions. Chromium-coated cladding significantly improves resistance to high-temperature steam oxidation, while also reducing cladding creep and ballooning during accidents.

The use of doped UO_2 fuel requires modifications to existing UO_2 fabrication lines. For chromium-coated cladding, the coating must be uniformly applied to the zirconium cladding, typically via methods such as PVD. Additionally, both the new fuel and cladding options must be tested to demonstrate improved performance under accident and transient conditions. These innovations will also require extensive experimental validation and regulatory approval before they can be used commercially. Maintaining precise doping levels during sintering of fuel to ensure performance repeatability and ensuring long-term stability of the chromium layer under irradiation and thermal cycling may be challenging. Also, scaling PVD or similar coatings to commercial production volumes may be costly.

In the longer term, advanced ceramic fuels such as UN and U_3Si_2, paired with SiC-based cladding, offer further performance improvements. These ceramic fuels enable higher uranium density, leading to increased discharge burnup and improved fuel utilization. SiC-based cladding exhibits extremely low oxidation rates in high-temperature steam, exceptional mechanical strength at elevated temperatures, and a high melting point, all of which contribute to enhanced core safety margins.

The fabrication of advanced ceramic fuels requires non-traditional sintering techniques, such as hot pressing or spark plasma sintering, which have not yet been used at large scale. Additionally, irradiation testing of both the fuel and cladding in LWR environments requires extensive data, which is currently lacking. The control of UN fuel may be challenging due to its high reactivity with water and steam. Developing reliable joining methods for large-scale fuel rod fabrication also presents difficulties. Furthermore, since no operational reactor currently uses these combinations, the regulatory approval process may be long and uncertain.

3. Fast Reactor Fuel Lifetime Improvement

While there is much broader development underway for advanced fuels in existing LWRs, the advancement of fast reactor fuels provides for some promising benefits if they can be developed to survive in a fast reactor environment for very long periods of time. Near term, the focus is on developing and deploying the first commercial reactors, which will be using the fast reactor fuel technology previously demonstrated. After initial SFR deployment, advanced fuels are expected to be pursued. This is the approach TerraPower is announcing with their demonstration reactor, in which they will be initially using sodium-bonded metallic fuel. It will then be followed by the demonstration of their sodium-free annular metal fuel for improved economics and with plans to advance fuel performance and reactor design until they achieve their Ultimate™ fuel [3].

The requirements and challenges for technological advancement of SFR fuel are described in Section 3.1. To quantify the benefits of increased lifetime, a series of reactor designs were evaluated with varied number of fuel batches, varied cycle lengths, and various fuel designs. The study looked at the performance of the equilibrium fuel cycle, which provided the requirements for each core reload, which then determines the system requirements (e.g., NU and SWU). The system requirements are then used in Section 5 to evaluate refueling costs. The equilibrium cycle performance, together with the initial fuel loading requirements, was estimated for several of these examples to assess the impact on the initial capital costs.

3.1 Requirements and Challenges

Ensuring fuel integrity throughout the life of an assembly in the reactor environment requires fuel that can withstand the effects of many different factors simultaneously, such as radiation damage, chemical attacks especially from fission products, pressure, temperature, etc. It must survive all of these while staying within temperature and other limits during full power operations (maximum practical power density) and certain off-normal transient conditions. Additionally, the current SFR metallic fuel was envisioned as being recycled, so the development eventually settled on a sodium-bonded fuel. The sodium-bonded fuel has sodium inside the fuel pin which may make it unsuitable for direct disposal [35], which means some form of processing (potentially including recycling) would be required to create a suitable form for disposal. As a result of this concern, Natrium is pursuing a sodium-free fuel while retaining a metallic form which has better neutronics than oxide fuel allowing for evolution to their Ultimate ™ fuel.

The current fuel design is based on radiation experience in EBR-II and FFTF under the Integral Fast Reactor (IFR) program. When that program ended, the most advanced fuel had not reached its expected limit. The current limit is based on the fuel with the highest irradiation level demonstrated. How much further that fuel can be irradiated is unknown. Although various ideas and projects are underway to expedite fuel qualification, one of the largest challenges for advanced fuel development is the lengthy time required to develop and qualify technology. A traditional lead test assembly (LTA) approach will require the LTA to be in the reactor for the entire lifetime to demonstrate the advanced fuel technology. For fuel that will be in the core for a decade, that requires an LTA to be in a reactor for a decade before the commercial fuel is deployed. For Breed and Burn fuel, with a 40-year lifetime, that would be nearly half a century from today, if testing started now. If at any point, the LTA does not perform as necessary, the fuel will have to be redesigned, and the LTA process starts over. Besides the normal challenges for developing new materials and fuel designs, the ever longer time that the advanced SFR fuel will be in a reactor is a major challenge. This is where improved techniques to accelerate development (e.g., a high flux fast test reactor) would be very valuable to reduce the timeline so the large benefits can be realized sooner.

3.2 Impact of Increased Fuel Residence Time on Enrichment at Equilibrium

Equilibrium cycle depletion calculations were completed to estimate the uranium enrichment required to remain critical for the specified set of assumptions. A PyARC [36] model of a compact core design based on PRISM-Mod B design. Based on publicly shared information on Natrium [citation], the performance of this concept is expected to be representative of their demonstration and first commercial reactor designs. The model is an 840 MW thermal SFR design with an average discharged burnup target of 100 MWd/kg. For simplicity, uniform fuel enrichment is modeled across the inner and outer core regions.

The REBUS [37] code was used for equilibrium search depletion calculations, targeting criticality across the fuel cycle. The DIF3D neutron flux code [38] uses the Finite Difference solver on a 1/3 core symmetry. These calculations used a set of 33 group cross-sections that were pre-generated for the reference design.

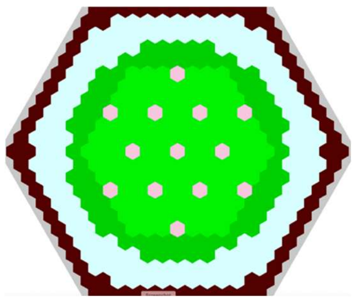
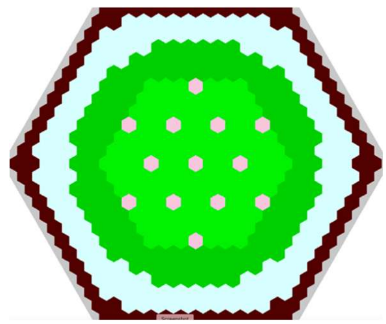
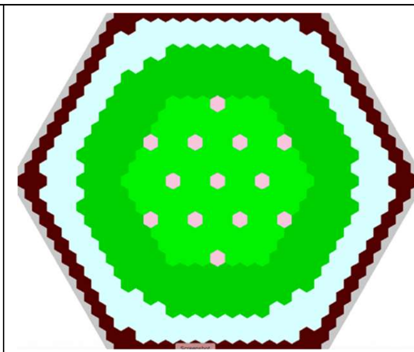
Many design variations of the SFR model were characterized to represent a wide range of options and evaluate the relationship between fuel enrichment and residence time of a HALEU-fueled SFR core. Around 100 of these variations were computed using WATTS (Workflow and Template Toolkit for Simulation) [39] as workflow management tool to automate processing of PyARC inputs, executions and post-processing. The varied SFR design parameters are the following (**bold** are for the reference design, blue are for the "compact core", red are for the "large core"):

- Number of driver fuel assemblies: **12**, 13, and 14 ring core configurations, shown in Table 3-1.
- Cycle length: **12**, 18, 24 months
- Number of batches: **7**, 10, 14, and 16
- Assembly pitch: **16.2** cm or 20 cm
- Driver fuel length (includes swelling): **1.3** m or 1.8 m
- Fuel volume fraction: **26.7**%, 30%, 33%

The most compact design is the reference one, representative of Natrium demonstration, while the larger designs are meant to accommodate longer fuel residence time to be representative of future design iterations. This analysis evaluates the fuel cycle cost tradeoff between longer fuel residency and fuel enrichment.

For each REBUS analysis, the results obtained are the loaded enrichment of U-235, the estimated peak fast flux (E> 100keV), the excess reactivity, the average discharged burnup and the fuel residence time. For a select number of design options, the path toward equilibrium is modeled to estimate the enrichment of the initial core inventory and the number of re-loaded assemblies in the first few cycles.

Table 3-1 SFR core radial layout for 3 core configurations with 12 to 14 total number of assembly rings. (light/dark green) inner/outer driver fuel assembly; (pink) control and safety rods; (blue) radial reflector; (dark red) radial shield.

		
12 rings (ref)	13 rings	14 rings (large core)

3.2.1 Compact Core (12-ring, short core height)

The most near-term benefits for advanced HALEU fuel will most likely come from fuel that will be utilized in compact cores (12 rings, 1.3m long fuel), similar to what is being demonstrated by Natrium. Figure 3-1 shows the enrichment of fuel as a function of fuel residence time for the compact core. This figure shows that without changing the fuel design there is the potential for an increase in fuel residence (through higher number of batches or longer cycles) time before the HALEU limit is reached. It also shows that if a 13% higher fuel volume fraction (FVF, “Increased FVF” in Figure 3-1) could be developed and still satisfy all operational and safety limits, there could be significant improvements both in terms of lower enrichment requirements and longer residence times.

Despite the increase in fuel volume fraction, the reactor power is held constant. As a result, the specific power (MW/kg-U) of the fuel is decreased, which means a lower fuel burnup for the same fuel residence time. This is not necessarily a negative, as it may allow for longer cycle lengths and other potential benefits. There are many tradeoffs to consider and the impact on other performance and safety parameters requires detailed design and safety analysis. This scoping analysis shows the trends that satisfy neutronics limits but does not inform on where other design and safety limits may be reached.

Without having to change the overall design of the reactor, if fuel residence time can be extended, there is the potential for a large improvement. The fuel residence time appears that it could be at least doubled in the compact core without exceeding HALEU limits. Increases beyond that would require high enriched uranium (HEU) which is not a viable option. The impact on system performance (e.g., amount of NU and SWU) will be discussed in Section 4.3. The economic impact will be further discussed in Section 5.

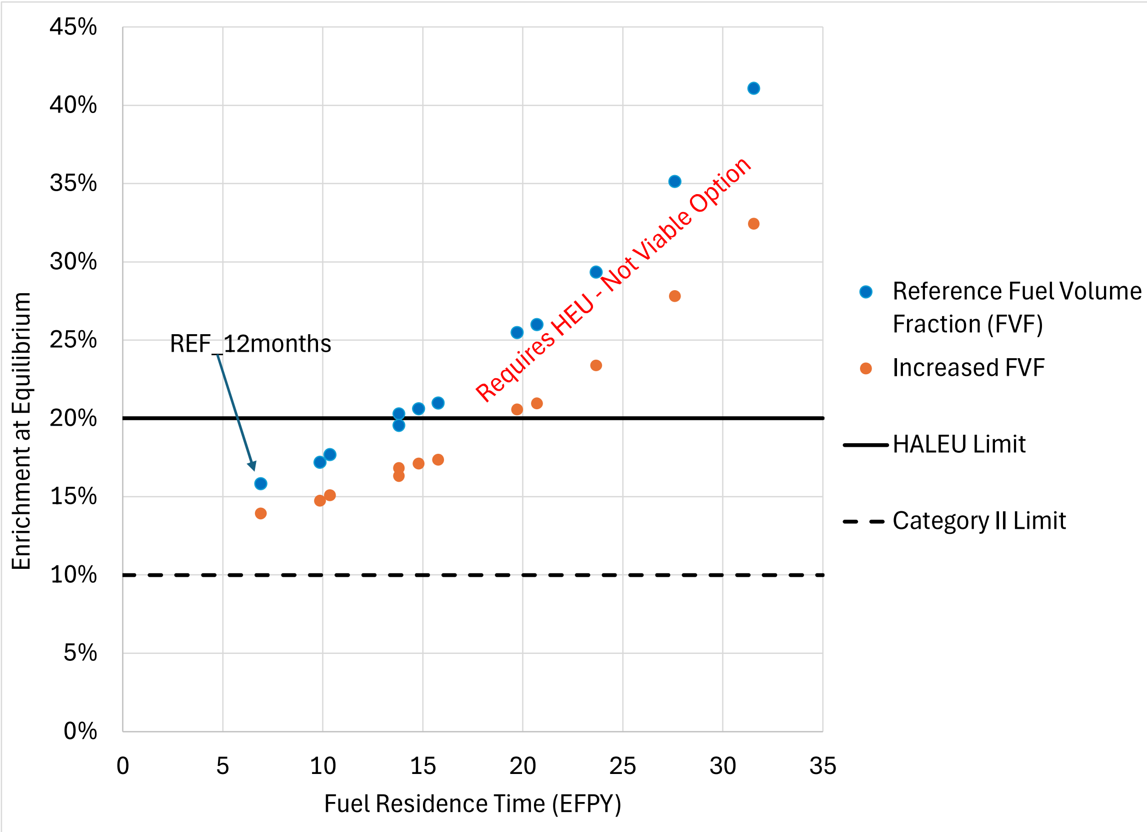


Figure 3-1 Enrichment versus fuel residence time in the compact SFR core.

3.2.2 Increased Core Size

Two larger cores were considered in which the radius and length of the active core were increased to reduce neutron leakage. The reduced neutron leakage allows for increased residence time at a lower enrichment. The increases represent 78% (increase core: 13 rings and 1.8m fuel lengths and 20cm pitch) and 123% (large core: 13 rings and 1.8m fuel lengths and 20cm pitch) more heavy metal than the reference cases, assuming the same FVF. Like the compact core, variations with increased fuel volume fraction are also considered. Increasing core size will increase capital cost. If the power level is not increased, the higher capital could offset some or all of the savings in refueling costs. A detailed design and safety analysis would be required to confirm the potential for an increase in power level.

Figure 3-2 shows the effect of an increased core size in terms of fuel residence time and enrichment. By increasing the core size to 14 rings and having a 33% FVF (the “high FVF”), the enrichment for refueling falls below that of the Category II security requirements (i.e., <10%). Figure 3-3 shows the enrichment versus burnup. This figure shows that in some cases (high FVF for increase and large core) there is the possibility of increasing burnup without requiring higher enrichment, which can result in cost savings. The impact on system performance (e.g., amount of NU and SWU) will be discussed in Section 4.3. The economic impact will be further discussed in Section 5. As a result of the fast reactor physics (potential for high in situ breeding), the benefits of advanced fuels have the potential to be large in terms of fuel cycle material requirements and refueling costs.

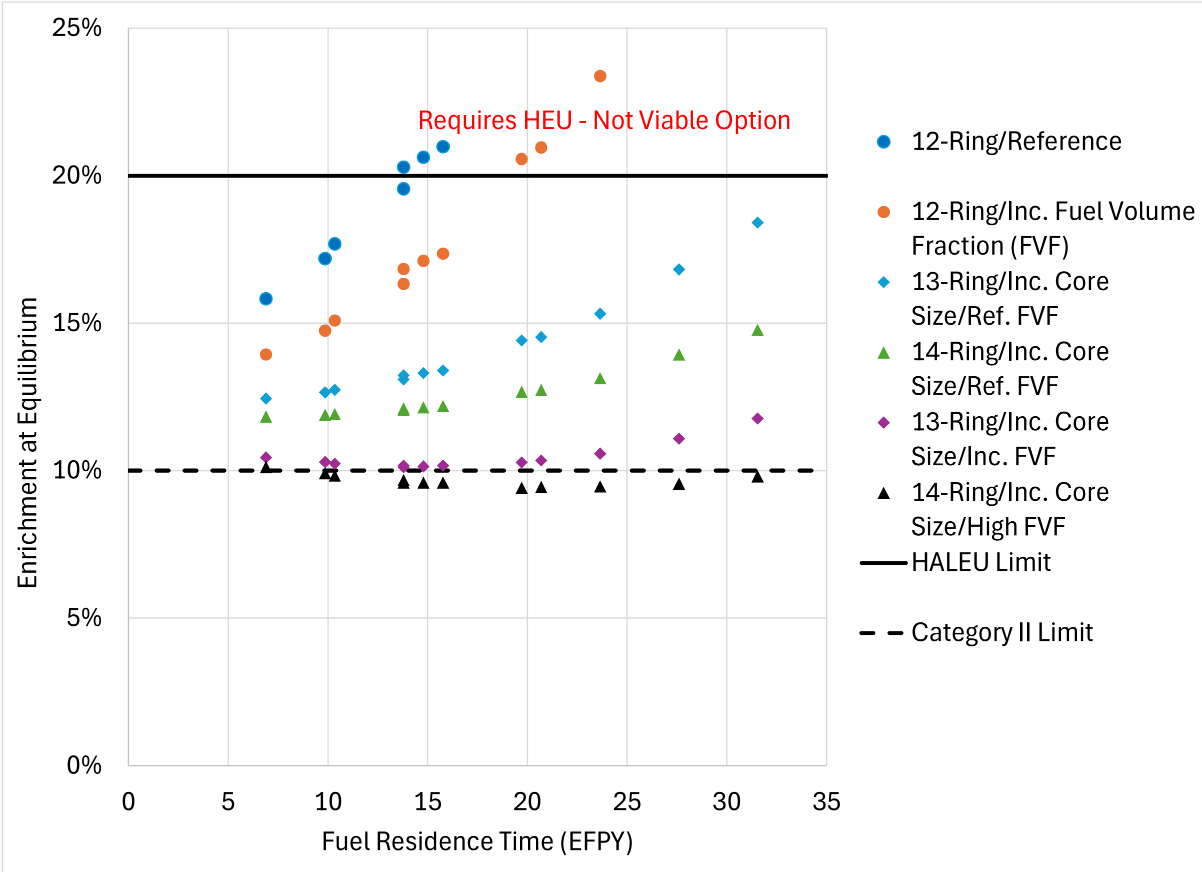


Figure 3-2 Enrichment versus fuel residence time, including larger SFR core.

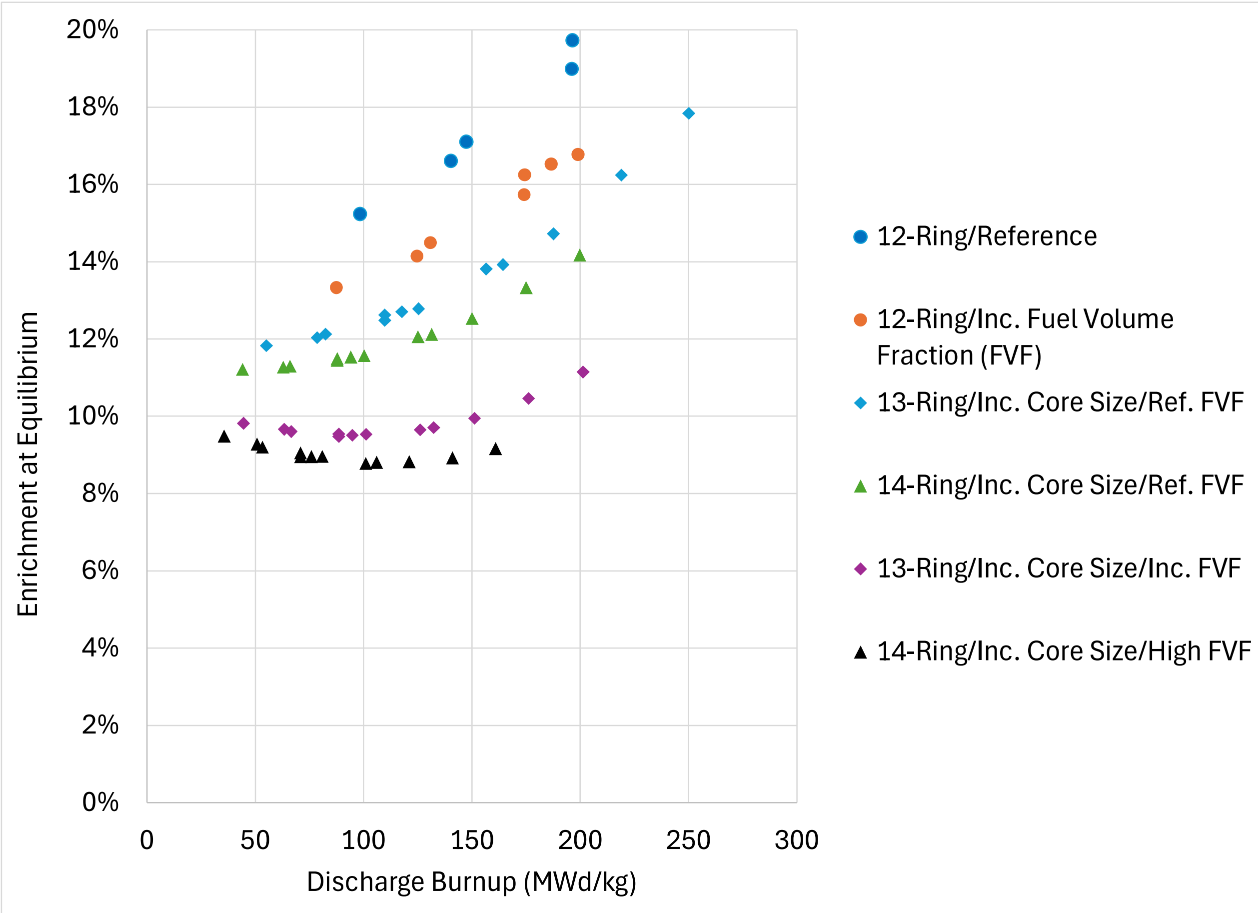


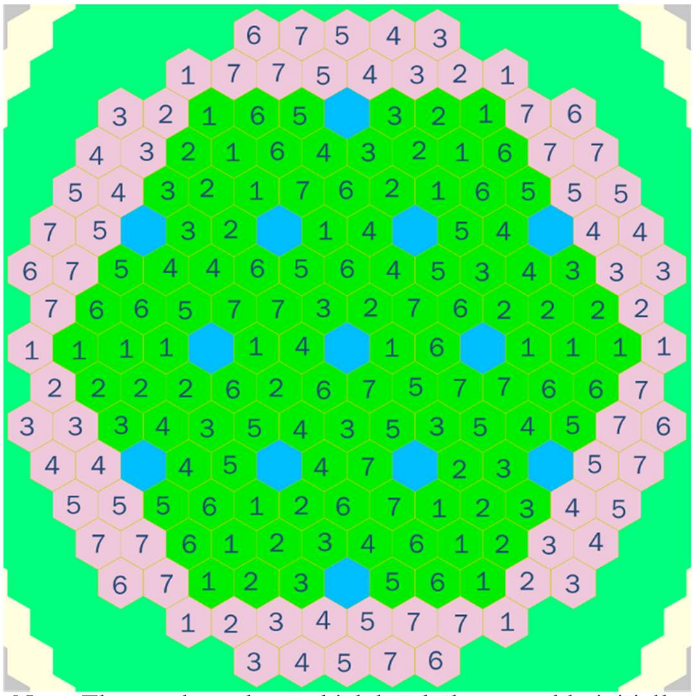
Figure 3-3 Enrichment versus fuel residence time, including larger SFR core.

3.3 Initial Core Enrichment Estimates

The initial core requirements are determined by the need for the initial core to be critical at the beginning of the first cycle and remain critical through the end of the first cycle. The second and subsequent cycles will be refueled with the same requirements with a transition to equilibrium refueling, as previously discussed. This requirement is largely determined by the design (size, spectrum, fuel design) of the core with some impact on the cycle length (duration it must remain critical) and other factors.

The physical size of the core has a large effect on the equilibrium enrichment for the fast reactor system due to the high neutron leakage of a fast reactor (a compact core with a longer neutron mean free path). There may be variations in the physical size of the core which has a large impact on the neutron economy in fast spectrum reactors. Therefore, a few of the designs analyzed for equilibrium performance were modeled cycle-by-cycle from the first core through several cycles to estimate initial core requirements and ensure that the core was transitioning towards the desired equilibrium.

To estimate the initial core requirements, the transition from the initial core was modeled. The transition started with an all-fresh core loading with uniform U-235 enrichment calculated to reach criticality throughout the first cycle while limiting initial excess reactivity. Then after each cycle, one batch of initially loaded fuel assemblies are replaced by fresh fuel loaded with the enrichment of equilibrium fuel obtained through REBUS equilibrium cycle calculations. With seven batches of equilibrium fuel assemblies loaded in, the core reaches equilibrium after about 7 cycles. The loading sequence of the seven batches of equilibrium fuel is shown in Figure 3-4. This is not an optimized approach to the transition to equilibrium since it doesn't consider power peaking mitigation, but it should provide a reasonable estimate of the initial core requirements.



Note: The numbers show which batch the assembly initially loaded is being discharged and replaced with equilibrium fuel enrichment.

Figure 3-4 Loading map of the 12-ring compact core with seven batches of fuel.

For the case with 12 months cycle length that had an equilibrium cycle enrichment of 15.82%, the k_{eff} history of the transition cycles is shown in Figure 3-5. The initial loading with U-235 enrichment of 14.33 wt% would give about the same excess reactivity as that of the equilibrium core, but during the transition the k_{eff} curves would go slightly below 1.0. For this reason, another two cases with higher enrichment of initial loading were also added. The results show that with additional optimization of the cycle-by-cycle enrichments and loading (maybe also considering slightly reduced cycle length or power level during some cycles), more uniform excess reactivity seems achievable. This analysis shows that the average initial enrichment of the core will stay within the 14% to 15% range for this specific core size, fuel design, cycle length, and fuel residence time.

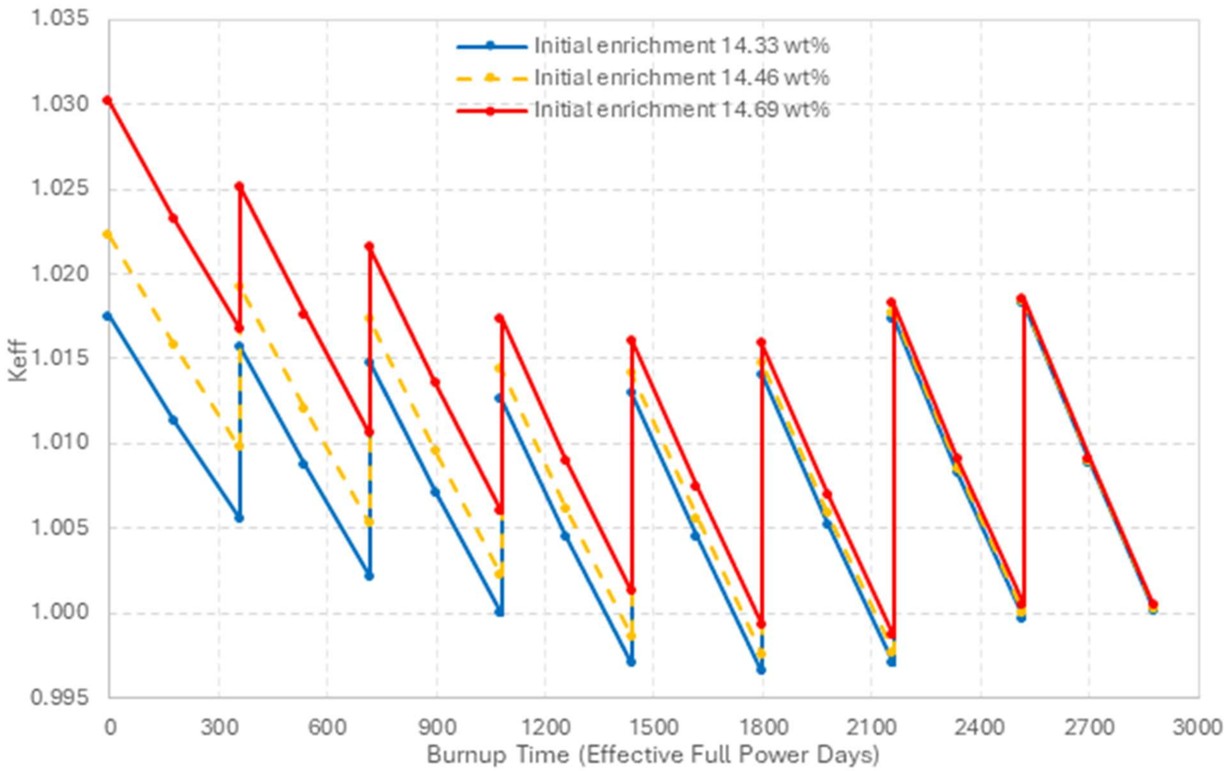


Figure 3-5 Keff history of the transition cycles for the case with 12 months cycle length.

This process was repeated for other example core designs to provide additional data points on initial core loadings. The results for these different examples are in Table 3-2. This analysis shows that the compact core with long cycle lengths (REF with 24 month cycles) may see large difference (5% in reduced U-235 enrichment observed in Table 3-2) between initial core enrichment and equilibrium reload enrichment. Larger cores may see almost no difference in enrichment throughout the core lifetime.

Table 3-2 Estimated initial core requirements for example SFR designs.

Core geometry	**REF** **0.26% VF**	**REF** **0.26% VF**	**REF** **0.26% VF**	**Large Core** **0.26% VF**
Cycle length **Num. of batches**	**12 month** **7 batch**	**18 month** **7 batch**	**24 month** **7 batch**	**24 month** **16 batch**
Core Loading, MTU	21.26	21.26	21.26	47.45
Initial Core Enrichment	14.33 wt%	14.73 wt%	15.27 wt%	12.00 wt%
Equilibrium Reload Enrichment	15.82 wt%	17.68 wt%	20.28 wt%	12.10 wt%

4. System Impacts of Deep Burn Fuels

The development of advanced fuel will change the overall system requirements in several ways beyond the changes in the fuel technology, materials, and other factors needed to produce fuel. The quantities of fuel cycle material and enrichment needed within the system will change as well. This section summarizes these impacts on the system that result from the use of advanced fuels. The mass flow data for the equilibrium systems were normalized to an annual generation of 100 GW-yr of electricity per year. This is comparable to the current generation of 782 million MWh (89 GW-yr) in 2024 [40].

4.1 System Modeling

The basic system model used is described in Figure 4-1 to Figure 4-6. This model is used to estimate the fuel cycle requirements. A material balance is performed based on certain underlying assumptions (e.g., tails assay). Losses in the system are assumed to be negligible and are not included in the material balance. Only once-through cycles (no recycling) are considered in this report.

All fuel cycle options start with NU extraction from mining and milling (U_3O_8) or in situ leaching operations (various uranium oxides). The NU product is then transported to a conversion facility where it is converted to UF6, referred to as NUF6 here. This NUF6 product is then transported to an enrichment facility to be used as feed for enrichment. These steps are shown in Figure 4-1. Each step is a cost element in estimating the levelized fuel costs.

Figure 4-1 Natural uranium system.

The natural uranium feed is then enriched to the required enrichment. For current commercial LWRs, this is a single enrichment plant. However, for higher enrichments, especially for those above 10% requiring the higher Category II security level, there may be two separate facilities. The lower security level Category III facility provides an enriched feed to the higher security level Category II facility to reduce the SWU required in the more expensive, higher security facility. This work assumes a two-stage enrichment system with the Category III facility, the first stage, enriching to 5% in existing enrichment facilities which produced the feed into Category II facilities where UF6 is enriched between 10 - 20%. Future increases in enrichment limits in the operational Category III facilities would allow for higher enrichment feeds into the Category II facility which would reduce the Category II SWU requirements. The impact on cost is relatively small since the premiums are not anticipated to be that large when the system is deployed at commercial scale and fully utilized, which are key assumptions.

Figure 4-2 shows the single stage model for LEU with final enrichments of less than 10%, with the tails represented as the depleted UF6 (DUF6). Figure 4-3 shows the two-stage model for HALEU with final enrichment between 10% and less than 20% (Category II). There are two outputs from enrichment: the DUF6 and enriched uranium streams. The final product of the two-stage enrichment is the UF6 with HALEU enrichment (HALEUF6).

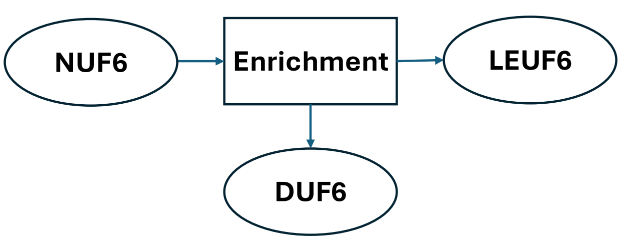


Figure 4-2 Enrichment system (<10% enrichment product).

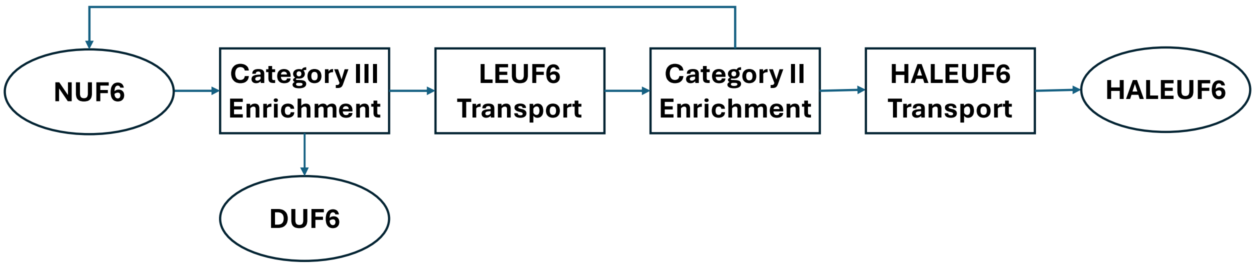


Figure 4-3 Enrichment system (≥10% enrichment HALEU product).

The DUF6 in Figure 4-2 and Figure 4-3 is sent for conversion to a stable form (U_3O_8) for disposal and then DU3O8 is disposed. Figure 4-4 shows the steps modeled for handling the DU stream.

Figure 4-4 Depleted uranium related costs.

The product from the enrichment facility, regardless of enrichment, is converted from the UF6 form to the necessary form for fuel production. This material is then used to fabricate the final fuel product. Figure 4-5 shows the steps modeled.

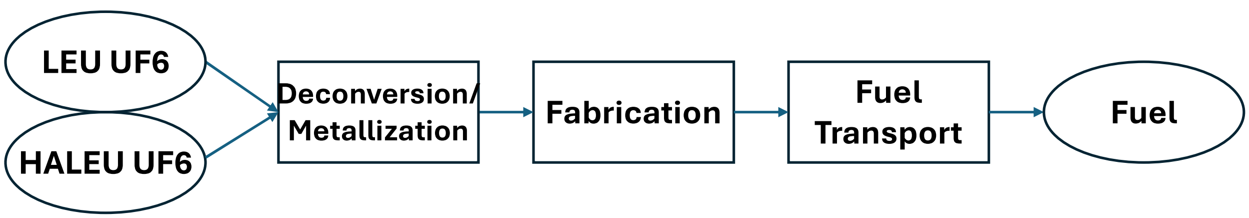


Figure 4-5 Fabrication and conversion/metallization related costs.

The fuel then goes to the reactor where it is irradiated to generate power. The resulting SNF is then transported and disposed as shown in Figure 4-6

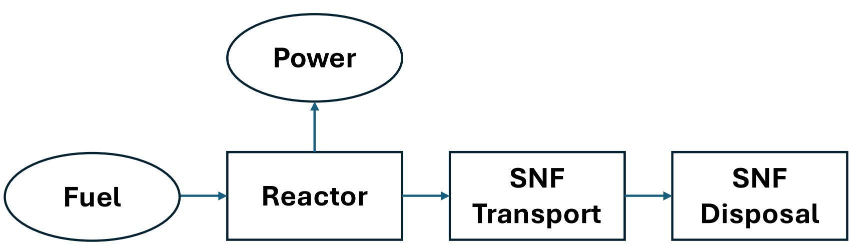


Figure 4-6 Power generation and SNF related costs.

4.2 PWR Advanced Fuel

For thermal reactors to achieve higher burnup, higher enrichment is required. Current experience uses fuel under 5%, but it is anticipated to increase above that level with fuel advances. This increased enrichment will have several impacts including the need for enrichment capacity capable of meeting the new requirements. It seems unlikely that commercial LWRs will advance to the point where they use fuel above 10% that requires a more stringent security category. The three PWR examples are based on zircaloy-clad fuels. The same basic infrastructure will remain, but the material flows on a per unit energy basis will change. To quantify the magnitude of these changes, three example PWR fuels were evaluated, with each PWR design meant to achieve a different burnup (BU) [41, 42]. The results are summarized in Table 4-1.

Table 4-1 PWR fuel system requirements and production for 100 GWe-yr per year generation.

Status	Current Exp.	High BU	Very High BU
Enrichment (wt%)	4.2%	7.0%	8.3%
Burnup (MWd/kg)	50	84	100
Natural Uranium (MT U)	18,863	19,138	19,172
Category III Enrichment (million SWU)	14	16	17
Category II Enrichment (million SWU)	-	-	-
Depleted Uranium (MT U)	16,667	17,831	18,074
Fuel (MT iHM)	2,192	1,304	1,096V
Volume of Fuel Assemblies (m^3)	795	473	397

As shown in Table 4-1, there is some increase in requirements for NU and SWU and DU production that results from increased burnup. The impacts are relatively small, with the SWU increasing by 20% being the largest impact on the front end. However, on the fuel fabrication and spent fuel management, the mass and number of assemblies decrease. The total mass of fuel is inversely proportional to the burnup, assuming the thermal efficiency of the reactor is unaffected. If the advanced fuel allows for higher operating temperatures, the increase in thermal efficiency would also reduce the various quantities. The quantity of fuel is where there will be the biggest impact on the cost of the overall system from advances in LWR fuels.

The higher burnup will produce SNF with higher decay heat, which may mitigate some of the volume reduction benefits. If the same number of assemblies are to be loaded into a transportation cask, the SNF will require much longer decay times before loading which may be impractical for the much higher burnups. Roughly the same quantity of fission products per unit energy will be produced and greater amounts of minor actinides per unit energy will also be produced with the higher burnup. The additional minor actinide material may have impacts on SNF disposal that were not evaluated in this work.

4.3 SFR Advanced Fuel

For fast reactors, fuel and reactor design advances can lead to increases in burnup or reductions in enrichment or some combination of the two. This results in a more complex relationship than in a thermal reactor. To study this effect, a wide range of fuel and core design variations were evaluated with varying numbers of batches and cycle lengths. There were 84 variations in all, as described in Section 3.2. From this large number of variations, a representative set of examples was chosen to cover the range of performance. This representative set includes three examples for the compact core (12 rings of fuel assemblies) to represent from current experience and nearer term advances, one example for a larger core (13 rings of assemblies with larger pitch and increased core height) representing the mid-range, and two examples for the largest core (14 rings with the same pitch and core height as the 13-ring model). These examples were evaluated to show the potential effects of advanced SFR fuel and core design. The volume of the assemblies was estimated by scaling from Hoffman, Kim, and Price [42], assuming the overall assembly length is proportional to the active core height. There will likely be additional assembly design modifications required to accommodate greater fission product production, such as increased fission plenum length, that are not accounted for and that could affect the overall assembly volume. The results are in Table 4-2.

Table 4-2 SFR fuel system requirements and production for 100 GWe-yr per year generation.

Geometry	12 Ring Core (current exp.)	12 Ring Core	12 Ring Core	13 Ring Core	14 Ring Core	14 Ring Core
Fuel Residence Time (EFPY)	6.90	10.35	13.80	11.15	31.54	31.54
Enrichment (wt%)	16.6%	18.5%	21.2%	16.0%	15.5%	10.3%
Burnup (MWd/kg)	98	147	196	188	200	161
Natural Uranium (MT U)	32,082	23,974	20,679	16,280	14,736	12,037
Category III Enrichment (million SWU)	26	20	17	13	12	10
Category II Enrichment (million SWU)	4.0	3.2	2.9	2.0	1.8	1.0
Depleted Uranium (MT U)	31,175	23,368	20,224	15,805	14,289	11,482
Fuel (MT iHM)	905	604	454	475	446	554
Volume of Fuel Assemblies (m^3)	924	617	463	485	455	457

The first 12-ring example in Table 4-2 represents fuel irradiated to fluences representative of current experience. Because of the higher enrichment relative to burnup than PWR, the amount of NU, DU, and SWU required for refueling will increase compared to example representative of current PWR performance. The amount of fuel in terms of initial heavy metal will be smaller, but the overall volume of fuel assemblies will be about 15% larger compared to the example for current PWRs. There are likely important differences that could affect the management of SNF, such as decay heat, fissile content, fuel materials, and other differences between the SFR and PWR SNF. Overall, it is expected to be of similar scale in terms of canisters required, shipments made, etc., but that will need to be confirmed.

There is the potential for reductions in all parameters of importance, if the higher burnup can be achieved. A large increase over current irradiation experience could reduce system requirements dramatically, with the extreme limit being the Breed and Burn concepts that would require no enriched uranium for refueling. For the range of examples evaluated in the 12-ring core, large reductions can be achieved of about one third in total SWU and NU if the fuel residence time can be increased to 13.8 effective full power years (EFPY). With advanced core design and further advances in fuel lifetime, the fuel cycle material requirements can be reduced further, as the 14-ring core with 10.3% enrichment example evaluating reduced the total SWU and NU by about two thirds compared with the current experience example.

4.4 TRISO Fuel

TRISO fuel experience covers the range of HALEU enrichments and irradiated to burnups to maximum limit of the reactivity, so advancements will be less impactful on the type of parameters studied in this report. For comparison, a couple of examples of TRISO fuels were included [41, 42]. The results are shown in Table 4-3. There are many design variations that could be considered that use TRISO fuel. In the examples shown here, there are some significant differences between the designs, such as coolant type and pebble size. One important difference for TRISO fuel compared with LWR or SFR fuel is that the overall SNF volume of assemblies/pebbles/blocks will be much higher because of the low density of HM in the pebbles or blocks.

Table 4-3 TRISO fuel system requirements and production for 100 GWe-yr per year generation.

Coolant and fuel design	He-Cooled TRISO Pebble	He-Cooled TRISO Block	Molten Salt-Cooed TRISO Pebbles
Enrichment (wt%)	15.5%	15.5%	19.9%
Burnup (MWd/kg)	165	120	180
Natural Uranium (MT U)	18,344	20,178	20,155
Category III Enrichment (million SWU)	15	17	17
Category II Enrichment (million SWU)	2.2	2.4	2.8
Depleted Uranium (MT U)	17,789	19,568	19,682
Fuel (MT iHM)	553	609	472
Volume of Fuel Pebbles or Prismatic Blocks (m^3)	8,941	7,624	6,913

4.5 Fuel Cycle System Impacts Comparison

Figure 4-7 shows a comparison of annual NU requirements per unit electricity generation (100 GWe-yr) across the different example fuels and reactor combinations included in this report. The thermal reactors (PWR and TRISO) have roughly the same requirements independent of burnup. For the SFRs, there is a large difference in the NU requirements, which range from far greater (60% more) NU requirements to significantly less (40% less for examples considered) than the thermal reactor requirements. There are effects of core design, cycle length, number of batches, etc. that cause the effect to not be linear. The largest effect is the limit on fuel residence time. Increasing the maximum irradiation levels (by increasing the burnup target) will reduce NU requirements. The highest amount of NU required (32,000 MTU for a 100 GWe-yr per year of generation) is representative of current experience and what will be expected for a SFR deployed in the nearer term. The smallest NU requirements are achieved with the most advanced fuel and reactor design, which likely will require a long period of fuel testing and development to achieve these or even better performance.

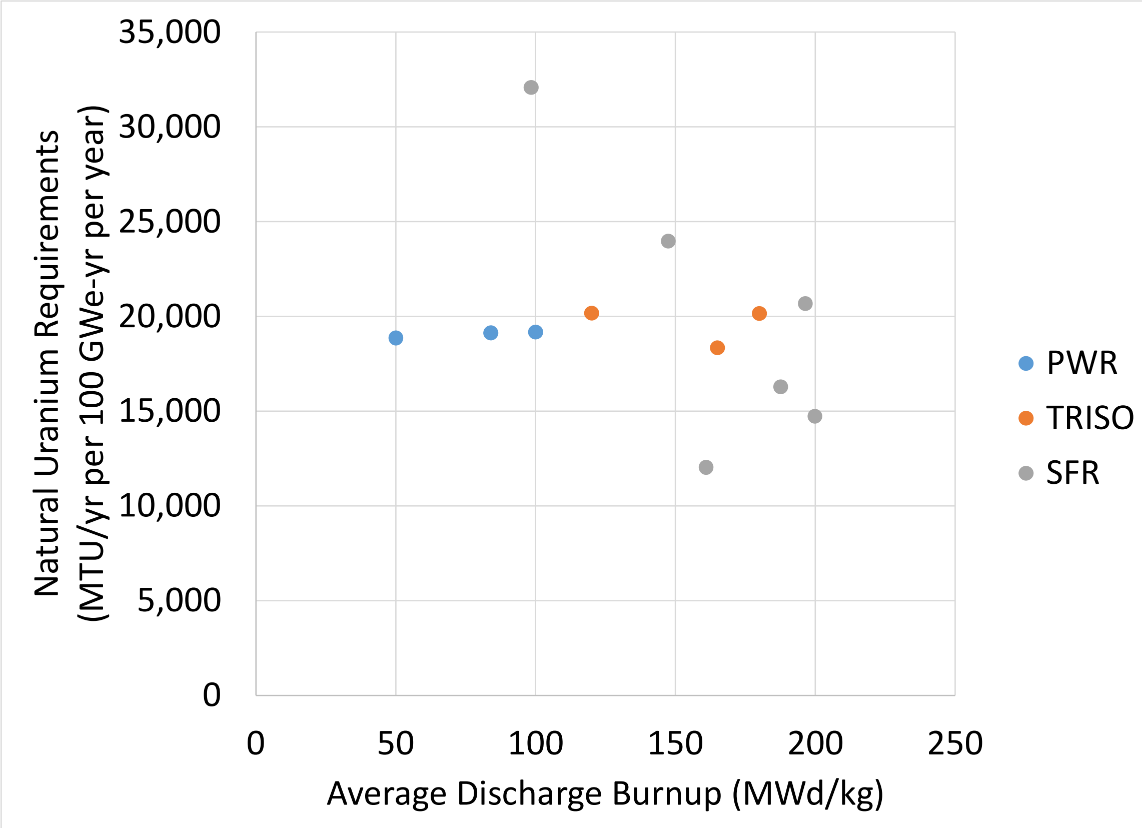


Figure 4-7 Natural uranium requirements for example fuel cycle options.

The total SWU required in Category II and Category III is independent of how the cascades of the facilities are configured. Figure 4-8 shows the total annual SWU requirements. For higher burnup in PWRs, there will be a significant increase in the SWU requirements per unit energy. For the SFR based on current technology, the total SWU requirements (30 million SWU per 100 GWe-yr per year of generation) will be much larger than for current experience in PWRs (14 million SWU per 100 GWe-yr per year of generation). However, advances in fuel residence time will reduce SWU requirements. With a large advancement over current experience, it is possible to reduce them to below current PWR. The TRISO examples, despite their much higher burnups, will require around 25% to 40% more SWU per unit electricity generated.

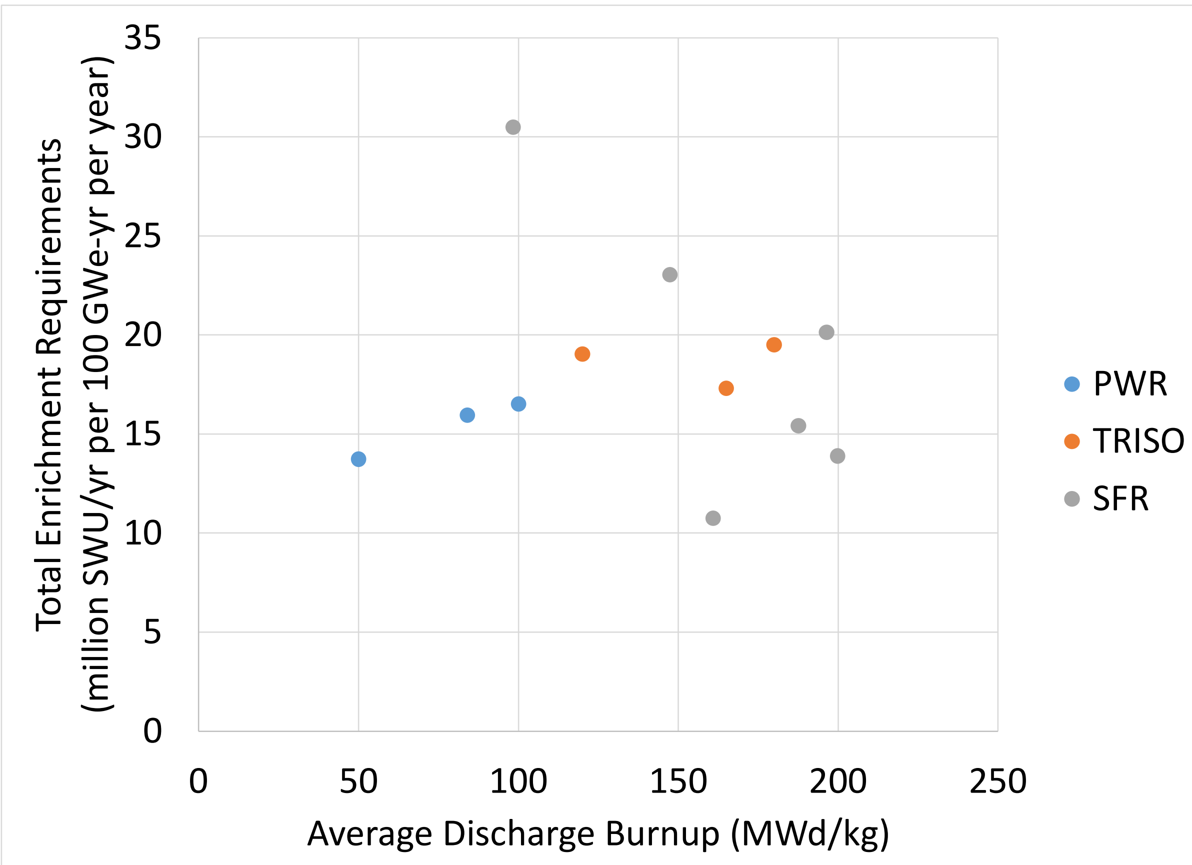


Figure 4-8 Total enrichment requirements for example fuel cycle options.

While the total SWU required is unaffected based on the configuration assuming no losses, the fraction of the total SWU required that is done in a security Category II (≥10% and <20% enrichment) enrichment facility will be sensitive to the configuration of the enrichment system. As mentioned in Section 4.1, for this study the Category II facility is assumed to take a 5% feed enrichment from a Category III facility. The 5% assumption is based on current commercial facilities. If the Category III facilities increase their maximum enrichment, this higher enrichment would reduce the fraction of the total SWU performed in Category II facilities. If the commercial Category III facilities extended their licenses to just under 10%, this would minimize the fraction in Category II facilities. The tails from the Category II facility are the same enrichment as NU and sent back to the Category III facility as feed material.

Figure 4-9 shows the Category II enrichment requirements. For large advances in PWR burnup, no Category II enrichment will be required because the PWR would never receive fuel enriched above 10%. For TRISO and SFR fuel, it does not seem practical to avoid the need for Category II enrichment. Increased burnup has little effect on SWU requirements for the TRISO fuel. SFRs show a significant reduction in the Category II SWU requirements with advanced fuel and reactor designs, up to a factor of 4 reduction. This SWU reduction could theoretically reduce Category II SWU requirements for refueling of the SFR to be zero (<10% enrichment), with sufficient improvements beyond what was modeled in Section 3.1 of this report (see Table 3-2). The initial core load would be a bigger challenge to reduce to less than 10%, likely still requiring Category II SWU to produce the initial core load even if the reload enrichment is less than 10%.

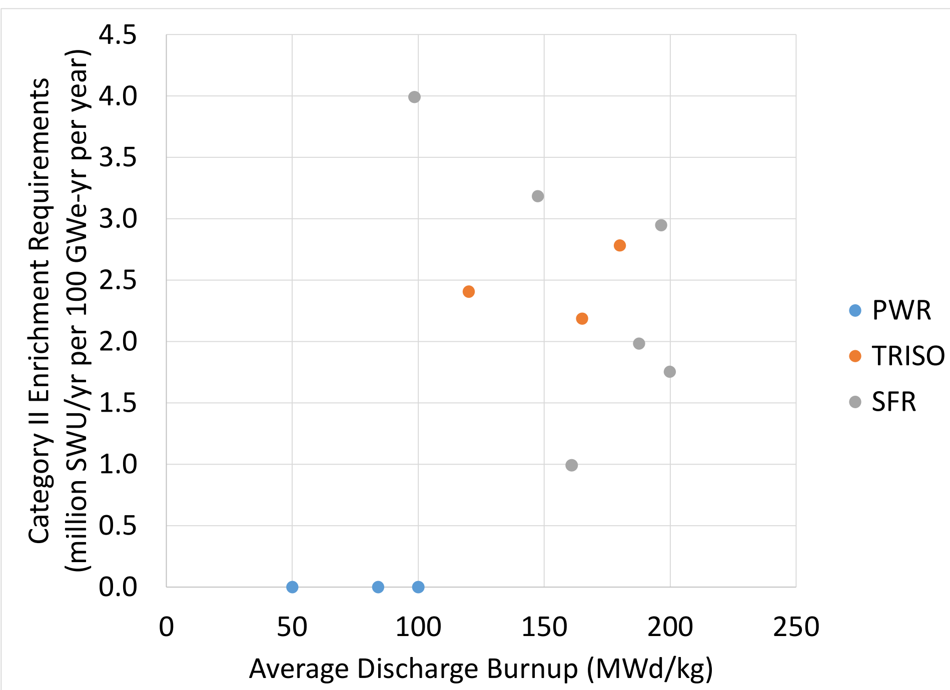


Figure 4-9 Category II enrichment requirements for example fuel cycle options.

Figure 4-10 shows a comparison of SNF volume generated across the different example fuels and reactor combinations. Increased burnup, for the same design reduces the volume of SNF produced. The low density of heavy metal (HM) in TRISO fuels results in large volumes being generated if the SNF is disposed of. If the particles can be separated sufficiently and placed in a high-density waste form, the volume of TRISO SNF could be reduced, but quantifying that is outside the scope of this work. The LWR and SFR have similar volumes at the same burnup, with diminishing decreases as the burnup increases

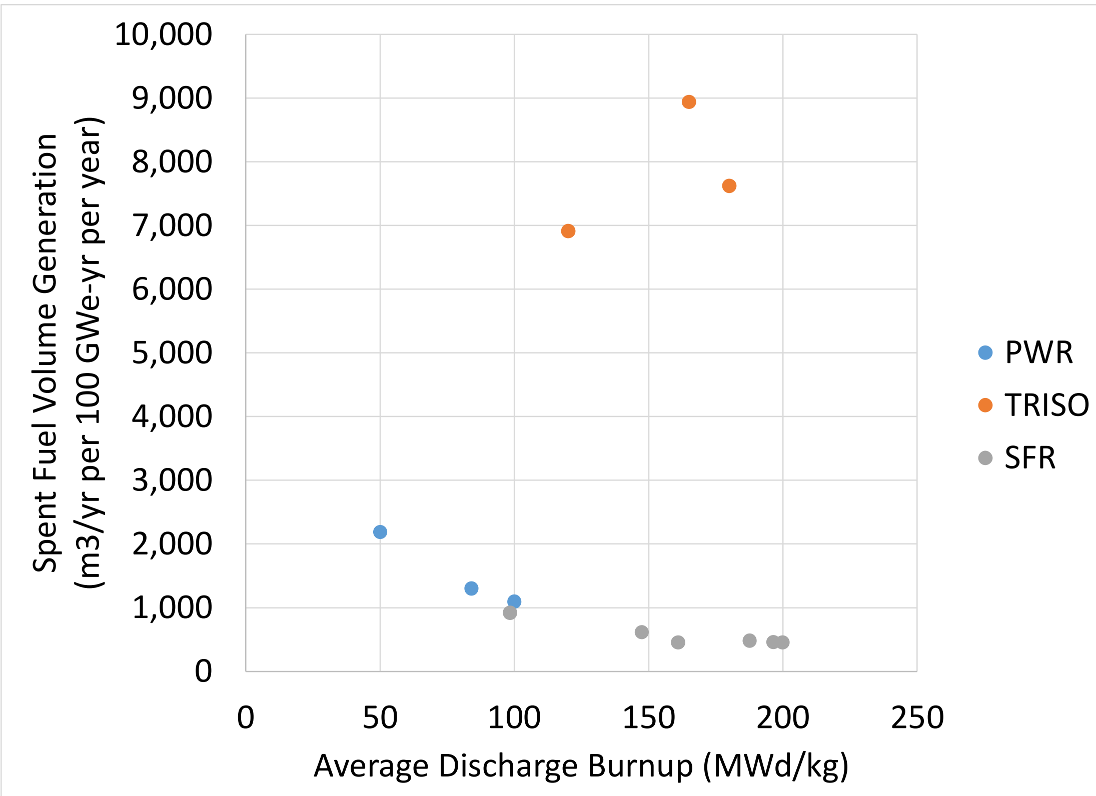


Figure 4-10 Spent nuclear fuel volume generation rate for example fuel cycle options.

5. Fuel Cycle Cost Assessment for Deep Burnup Fuel

The fuel cycle cost is the cost from the mining to the disposal, except for the reactor cost. Given the uncertainties in the future costs of the many pieces that comprise the cost of fuel, the impact of time (cost of money) is not included. Including time (discounting) does not make a large impact on the estimated cost, but it does require making many additional assumptions about when things are purchased and the appropriate discount rate (interest rate, weighted average cost of capital) to apply. The same is true in terms of amortizing the cost over the electricity generated. With relatively short cycle lengths, regular fuel purchases and contributions to waste funds, amortizing will have only a small impact as well. The effect of these assumptions should be similar between alternatives considered in this work, making it possible to achieve the primary goals of identifying relative costs and the cost drivers without the need for more complex calculations that require many more assumptions.

The approach used in estimating the fuel cycle costs consists in first evaluating the equilibrium system requirements for all steps in the fuel cycle: amount of NU, amount of SWU, amount of SNF, etc. These requirements were summarized in Section 4 for six example systems. The next step is to multiply the number of units required by the system at equilibrium by the unit cost for that piece and then sum over the entire fuel cycle of interest. All steps (e.g., NU transport, conversion to UF6) shown in Figure 4-1 through Figure 4-6 are included in the calculations. This process would provide the cost in dollars per year for that system at equilibrium. Then, if the value of interest is the refueling costs, this $/year cost will be divided by the electricity generation rate in MWh/yr to get the $/MWhr refueling costs. If the interest is in the cost per kg fuel, then it is divided by the fuel production rate in kg/yr to get the $/kg cost. This $/kg can then be divided by the specific power of the system in kWe/kg (kWth/kg x thermal efficiency) to get the initial core costs in $/kWe.

The unit costs are primarily taken from the Cost Basis Report (CBR) [43], which provides estimates of equilibrium unit costs with a range, a mean, and a simple assumption on the cost distribution. All unit cost data along with source or assumptions are included in Appendix A-1. Fuel cycle cost analysis is only performed for the PWR and SFR cores because of the presence of data in the CBR. The analysis is not performed for TRISO fuels because of the lack of data.

To address the uncertainties in the costs, Monte Carlo sampling of the unit cost distributions was performed. All fuel cycles of interest have the same unit cost for NU, SWU, etc. applied for each sample. The LFCAE was calculated for all fuel cycles of interest. There is also interest in the relative cost between fuel cycle alternatives. The difference between these fuel cycles was also calculated for each sample as well. This process is repeated, and the distributions of the costs and cost differences are estimated.

The fuel cycle costs for the initial core and refueling core are calculated differently because refueling is an ongoing O&M cost while the initial core cost is an upfront capital cost. For refueling core, the fuel cycle cost is calculated by LCFAE, which is the normalized fuel cycle cost to the electricity generated at an equilibrium state to give $/MWh. The initial core fuel cycle cost is the ratio of fuel cycle cost to fill the start-up core per energy generated to give $/kWe. The relationships between the fuel cycle costs of the refueling and initial cores can be complex and are evaluated for the SFR examples in this study.

There is likely a step increase in costs for enrichment beyond current enrichment limits (i.e., above 5%) in existing enrichment facilities to account for investments and changes needed to accommodate higher enriched materials. This cost increase for “LEU+” fuel (5-10% enrichment) is not modeled. The larger step in costs between a security Category III (<10%) to a security Category II (10-20%) is modeled.

5.1 Fast Reactor Fuel Cycle Costs as a Function of Enrichment

Figure 5-1 shows the fuel cycle cost of a metallic fuel, using the mean values in the CBR cost distributions as a function of uranium enrichment. The discontinuity at 10% is due to the increase in the enrichment cost in Cat-II facility. Figure 5-2 shows a breakdown of the major contributors to that cost. These figures show the steady rise in the amount of NU required per kg, the increase in SWU required per kg, the effects of increased security requirements as well as the many costs that are assumed constant per kg of fuel independent of enrichment. Fabrication, for example, will be essentially constant for any fuel under the maximum enrichment of that fabrication facility. SNF management has some complexity, but assuming that the fuel cools sufficiently such that a full canister can be shipped, the cost will be constant. Disposal will depend on what constrains the fuel loading at the disposal site, which could add a burnup dependency that is not modeled here. Given the assumptions underlying the cost, Figure 5-2 shows the general behavior of metallic fuel costs. Other fuel types would be expected to show similar trends, but some of the unit costs (e.g., fabrication) would be different.

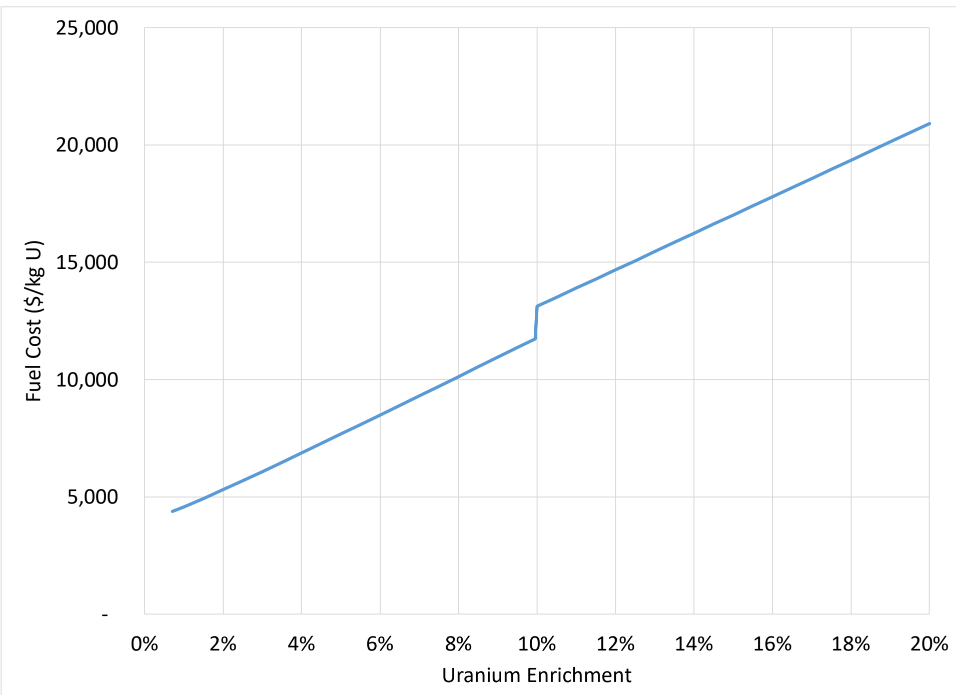


Figure 5-1 Expected metallic fuel cost as a function of enrichment.

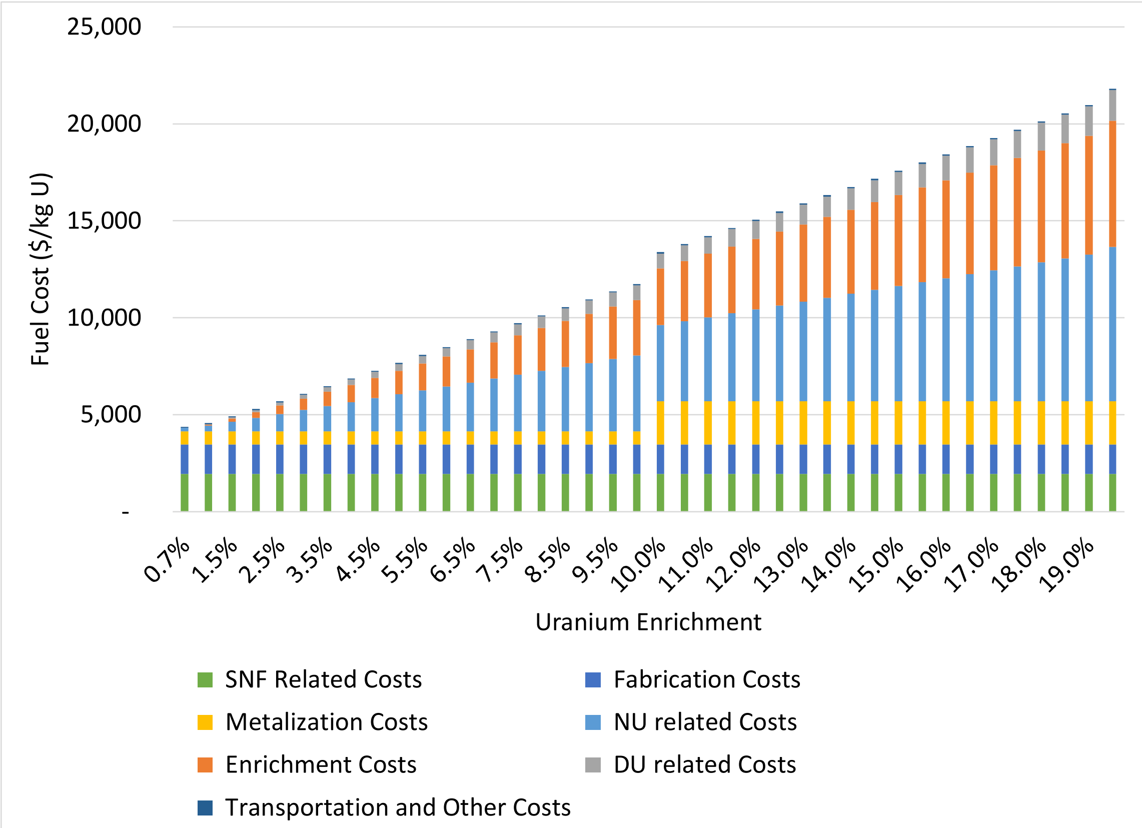


Figure 5-2 Contributions to the expected metallic fuel cost as a function of enrichment.

5.2 Fuel Cycle Cost for Refueling Cores

The levelized cost of electricity (LCOE) is a figure of merit used to compare alternatives in terms of the cost of electricity production. These costs include the reactor OCC (including fuel costs of the initial core loading), which is usually the largest component, the reactor O&M costs (including annualized decontamination and decommissioning costs), and the refueling costs. The fuel cycle costs for refueling core (often just referred to as fuel costs) are estimated by the method described in the previous section to estimate the LFCAE which is a simplified approximation of the LCOE for refueling costs. Since the LFCAE does not include the reactor cost, it is not meaningful to compare it with different reactor technologies because differences in the OCC and O&M costs are generally much greater than the differences in fuel cycle costs for the refueling core. For the same reactor technology, different fuel designs can impact reactor OCC and O&M costs. However, when there is no change in basic fuel geometry, these differences are likely to be small, making them insignificant in terms of the LFCAE indicators, which in turn are reflected in the LCOE. Fuel Cycle Cost for PWR Refueling Cores

The costs associated with higher burnup LWR fuel are represented by the LFCAE for PWR fuels. The key assumptions are that the fuel fabrication cost, in $/kgU, is independent of enrichment and final burnup. Higher enrichments may result in criticality considerations that increase cost in the fabrication process. Higher burnups or other fuel advancements could utilize additional materials that would increase fabrication costs because of more costly materials.

The results and cost breakdown are displayed in Table 5-1. The fuel cycle costs in $/kg increase with higher enrichment. But the benefits of the higher burnup (e.g., longer cycle times and more electricity generated from the fuel) overcome the higher cost, resulting in a decrease in the LFCAE for higher burnup fuels. The cost drivers are the NU and enrichment costs, and both increase with enrichment. Both costs increase faster than the benefits of burnup. However, the assumed constant costs for the fabrication and SNF costs result in a net reduction in LFCAE. To have the same LFCAE with the 7.0% enrichment and 84 MWd/kg burnup as the 4.2% enrichment and 50 MWd/kg burnup, the fuel fabrication and SNF management summed costs would have to be almost $500/kg larger to offset the benefit of higher burnup.

Figure 5-3 shows the distribution based on random sampling of the LFCAE. There are significant uncertainties in these costs, as shown in Figure 5-3. However, the difference in cost is less uncertain as the uncertainties are primarily driven by differences in requirements (e.g., NU requirements) rather than differences in unit costs. Monte Carlo sampling of the cost distributions showed that increasing burnup from 50 MWd/kg to 84 MWd/kg would reduce fuel cost 0.5-1.0 $/MWh. Further increasing from 84 MWd/kg to 100 MWd/kg would have a smaller benefit but would still reduce fuel costs by another 0.1-0.2 $/MWh.

Table 5-1 PWR LFCAE Using Mean Unit Costs.

Reactor Type	PWR	PWR	PWR
Eq. Enrichment	4.2%	7.0%	8.3%
Eq. Burnup (MWd/kg)	50	84	100
Thermal Efficiency	33%	33%	33%
Electricity Generated (MWh/kg)	400	672	800
Fuel Cost ($/kg)			
NU-related Costs	1,598	2,724	3,249
Enrichment Costs	959	1,871	2,307
DU-related Costs	288	518	625
Fabrication Costs	491	491	491
SNF-related Costs	662	662	662
Transportation and Other Costs	57	57	57
Total ($/kg)	4,055	6,322	7,391
Total LFCAE ($/MWh)	**10.1**	**9.4**	**9.2**

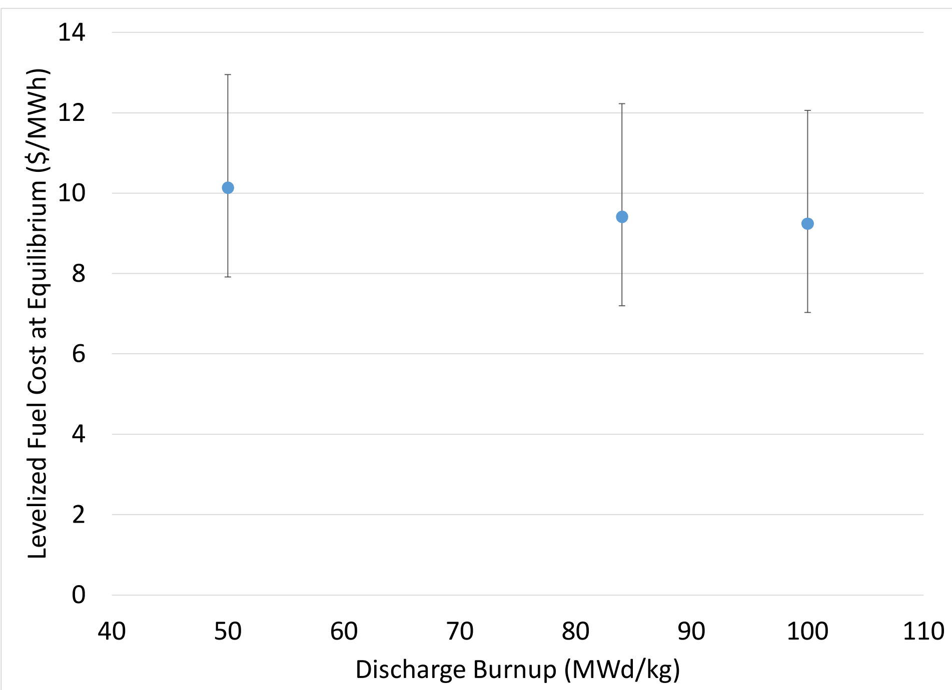


Figure 5-3 PWR LFCAE with uncertainty.

5.2.1 Fuel Cycle Cost for SFR Refueling Cores

The same key assumptions used in the PWR fuel costs apply to SFR fuel costs. The additional assumption associated with the SFR is that changes in fuel design (higher fuel volume fraction and taller assemblies) and an increased core diameter do not impact reactor costs. The reactor costs (OCC and O&M) are the largest parts of the LCOE, so any impact on those costs can exceed any changes in fuel costs. These impacts can potentially go in either direction, meaning that if the larger core diameter allows for an increase in power that exceeds the increase in reactor costs, it could reduce the LCOE. However, if the larger diameter core does not lead to an increase in power, then the LCOE will increase because of increases in the fuel costs. The potential change in LCOE is beyond the scope of this report.

The costs associated with advanced SFR fuel (increased fuel residence time, higher fuel volume fraction, longer fuel assemblies) are represented by the LFCAE. The results and cost breakdown for 6 examples are shown in Table 5-2, with the cases matching those discussed in Table 4-2. The first three examples (REF_12months, REF_18months, REF_24months) are for the reference 12-ring compact core design and represent changes in fuel residence time modeled by variation in cycle length. The next 13-ring example (MOD_13rings) is an increase in core size (taller and larger diameter core). The last two 14-ring examples represent a further increase in core diameter (MOD_14rings_0.266v) and additionally a large increase in fuel volume fraction (MOD_14rings_0.33v).

The estimated LFCAE shows the potential fuel cycle cost benefits of both increased fuel residence time and improved neutronics (reduced neutron leakage). Across the 6 SFR examples, the estimated LFCAE for fuel representative of the current limits (REF_12months) is reduced significantly by advances in fuel residence time made possible in larger cores. If the fuel residence time can be doubled in the compact core, the LFCAE would be reduced by approximately 40%. If increases in core size can be achieved for the range of examples, the LFCAE would be reduced by 66%. The combined effects of higher burnup and lower enrichment result in the most dramatic reductions.

Figure 5-4 shows the LFCAE with uncertainties. There are significant uncertainties in these costs. However, the difference in cost is less uncertain, as these differences are primarily driven by benefits in reduced material requirements (e.g., less NU per unit energy). Monte Carlo sampling confirmed that costs decline, as shown in Figure 5-4, when uncertainties are considered. For example, in the compact core when going from the 7-year fuel residence time (REF_12months) to the 10-year fuel residence time (REF_18months), the cost reduction ranges from 4-6 $/MWh. With more advanced fuels, the cost reduction increases relative to the REF_12months core, and the uncertainty remains about 20% of the mean cost reduction. This result clearly shows that deep burnup fuels in SFRs can result in significant cost reductions. Unlike thermal reactors, in which increased burnup requires increased enrichment, the SFR has a much more complex relationship with advanced fuels: increase burnup is associated with a small increase or a decrease in enrichment, resulting in large reductions in the LFCAE.

Table 5-2 SFR LFCAE Using Mean Unit Costs.

Label	REF_ 12months	REF_ 18months	REF_ 24months	MOD_ 13rings	MOD_14ri ngs_0.266v	MOD_14ri ngs_0.33v
Core Size	Compact	Compact	Compact	Increased Core	Larger Core	Larger Core
Fuel Residence Time (EFPY)	7	10	14	24	32	32
Fuel Volume Fraction	0.266	0.266	0.266	0.266	0.266	0.330
Eq. Enrichment	15.8%	17.7%	20.3%	15.3%	14.8%	9.8%
Eq. Burnup (MWd/kg)	98	147	196	188	200	161
Thermal Efficiency	41%	41%	41%	41%	41%	41%
Electricity Generated (MWh/kg)	968	1,450	1,933	1,846	1,966	1,583
Fuel Cost ($/kg)						
NU-related Costs	6,287	7,038	8,089	6,082	5,863	3,855
Enrichment Costs	4,992	5,662	6,603	4,811	4,616	2,817
DU-related Costs	1,245	1,398	1,613	1,203	1,159	749
Cat II Conversion Costs	2,220	2,220	2,220	2,220	2,220	-
Fabrication Costs	1,520	1,520	1,520	1,520	1,520	743
SNF-related Costs	1,947	1,947	1,947	1,947	1,947	1,947
Transportation and Other Costs	70	70	70	70	70	56
Total ($/kg)	18,282	19,856	22,063	17,854	17,396	10,168
Total LFCAE ($/MWh)	**18.9**	**13.7**	**11.4**	**9.7**	**8.8**	**6.4**

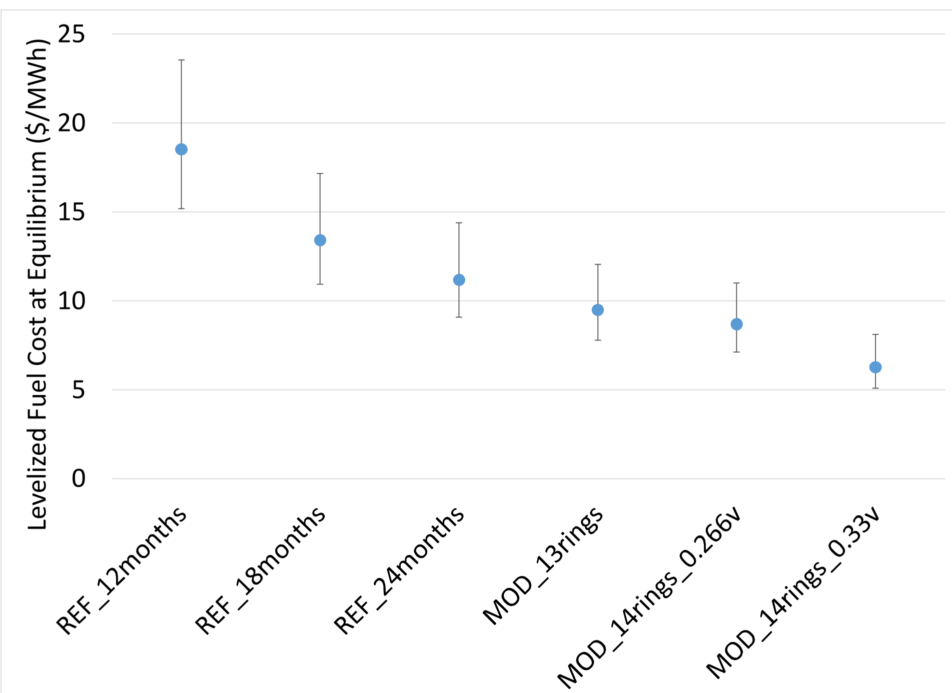


Figure 5-4 SFR LFCAE with uncertainty.

5.3 Fuel Cycle Cost for Initial Core Cores

Table 5-3 provides a summary of the estimated fuel cycle cost of initial cores considered in this work. The average enrichment for the example PWR was estimated to be about 3%, which would result in an upfront fuel cycle cost for the initial core of $275/kWe.

For the SFR, the initial enrichments are much higher, while the specific power and thermal efficiency are only a little higher than the reference PWR. For the compact core, the initial enrichments are in the 14-15% range. While the larger cores have initial enrichments of about 12%. For the 12-ring compact core, the upfront fuel cycle cost exceeds $1,000/kWe. Assuming a 60-year lifetime, 5% real weighted average cost of capital and a 90% capacity factor, this initial core cost represents a contribution of about $7/MWh to the LCOE. For PWRs, the initial core contributes approximately $2/MWh to the LCOE.

For the larger SFR cores (MOD-14rings), without an increase in power level there will be a large increase in the fuel cycle cost for the initial core in terms of $/kWe that will need to be paid upfront to fill the start-up core. For the largest core, the fuel cycle cost for the initial core is almost double that of the compact core for the same power level. This cost increase is driven by a lower specific power in the larger core. Assuming no increase in power, this fuel cycle cost contributes approximately $14/MWh to the LCOE. This increase in initial core cost is more than the reduction in refueling core costs that results from increasing the core size.

For the benefits in the fuel cycle cost for the refueling core not to be offset by higher fuel cycle cost for the initial core, significant increases in power level will be required. The 14-ring example was reevaluated assuming that the power level was increased to have the same specific power as the 12-ring compact core. This power change would reduce the fuel cycle cost for the initial core contribution to the LCOE to $6/MWh and the combined fuel cycle cost to below what is achievable in the 12-ring core. This design change represents a challenge in producing a passively safe SFR design with more than a doubling of the power level, but it is necessary to achieve the benefits of an increased core size.

Table 5-3 Initial Core Requirements.

	PWR	REF-12months	REF-18months	REF-24months	MOD-14rings	
Core Power (MWe)	1,000	345	345	345	345	775*
Specific Power (kWth / kg HM)	34	39	39	39	17	39
Average Initial Core Enrichment	3%	14.3%	14.7%	15.3%	12.0%	12.0%
Fuel cycle cost for initial core, $/kWe	275	1,060	1,082	1,115	2,114	941
LCOE contribution of initial core $/MWh	1.8	7.1	7.2	7.5	14.2	6.3
LCOE contribution of both initial and refueling cores, $/MWh	12.0	26.0	20.9	18.9	23.0	15.1

* Power level artificially raised to have the same specific power as the 12-ring compact core

6. Summary

This report explores advancements in nuclear fuel technology, focusing on once-through HALEU fuels. It examines the potential for increased fuel residence time in reactors and the fuel cost implications. The study highlights the differences between fast and thermal reactors in terms of fuel enrichment and burnup, emphasizing the complex relationship in fast reactors where increased core size and fuel density can lead to lower enrichment requirements. Various advances in fuel technologies for (LWR and SFR are presented in this report.

A literature review was conducted to summarize recent progress in advanced nuclear fuel and cladding technologies aimed at improving burnup, safety, and efficiency in LWRs. Among fuel options, doped or large-grain UO_2 fuels, such as Westinghouse's ADOPT®, have the highest technology readiness level and are already in commercial use. MOX fuel also shows high maturity globally, although it remains unlicensed in the U.S. For cladding, chromium-coated zirconium alloys and HT9 steel are the most developed options, providing enhanced oxidation resistance and high burnup capability. While longer-term solutions like ceramic fuels with SiC cladding offer promising benefits, they still require additional testing and regulatory approval before deployment.

Three examples of PWRs fuel options were evaluated to represent current technology and advancement using HALEU for LWRs. The impact of using HALEU to increase fuel burnup from 50 MWD/kg to 100 MWd/kg will result in a 309 MT increase in demand for NU per year, per 100 GWe-y. To double the burnup, approximately a 20% increase in SWU would be required. The quantity of fabricated fuel and SNF will decrease, because it is inversely proportional to the burnup. If the technology can be developed and deployed commercially without a large increase in the cost of fabrication, the analysis in this report shows a cost benefit of HALEU to achieve higher burnups on the order of 2-4 cents/MWh, per MWd/kg increase in burnup. Over the entire fleet of ~100 GWe, with assumed capacity of 90%, this would be $15-30M/yr per, MWd/kg increase in burnup.

Achieving the large increases in burnup will add additional challenges that will require significant development and testing. The different claddings, coatings, etc. discussed here will require further analysis to evaluate their impact on neutron economy (enrichment requirement to achieve a target burnup) and any impact on reactor performance (e.g., higher operating temperatures). There will be a need to estimate how the fuel fabrication costs change, compared with the standard zircalloy fuel cladding. Further study of how the higher burnup and different materials will impact SNF management and the costs associated with SNF management.

TRISO fuel has been developed that can utilized for the full range of HALEU enrichments and resulting burnups. Three different TRISO fuel examples were considered including helium-cooled pebbles and blocks, and molten-salt cooled pebbles. There were important differences between designs, but overall, the fuel cycle requirements are similar to those of the PWR on a per unit electricity generated basis. There is a difference in the volume of SNF produced, with TRISO fuel producing on the order of 10 times more volume per unit electricity generated than the PWRs.

Fast reactors have different behavior than thermal reactors for increased fuel irradiation, which is driven by important differences in their physics. The high neutron leakage rate results in fast reactors being sensitive to the physical size of the reactor (larger reactors means reduced neutron leakage). In thermal reactors, sufficient moderator is needed, which drives the geometry of the fuel, which is reflected in the large amount of graphite in TRISO-fueled designs. Fast reactors want to minimize all other components in the fuel (e.g., reflectors) because they reduce the reactivity. This desire to minimize components leads to a need to maximize the fuel volume fraction. These desiresmake evaluation of the HALEU fuel in fast reactors sensitive to the design of the fuel assembly and the size of the reactor core. Detailed design and safety analysis are needed to ensure all safety and other criteria are met. This level of analysis is beyond the scope of this work.

A total of 84 design variations of an SFR model representative of current SFR technology were characterized to evaluate the relationship between fuel enrichment and residence time of a HALEU-fueled SFR core. Three SFR design variations were studied in more detail: a compact core with 12 fuel assembly rings and a core height of 1.3 m, a larger 13-ring core with a core height of 1.8 m, and a large 14-ring core with a core height of 1.8 m. For the first configuration, the equilibrium enrichment increases as the fuel residence time increases, with increasing fuel residence time, reaching a maximum of about 13 years when the fuel remains under the 20% LEU limit. The larger 13-ring core size reduces the required fuel enrichment for the same burnup. The enrichment continued to rise with increased fuel residence time in the 13-ring core. The 20% limit was not reached at a fuel residence time of 30 years. The larger core size of the third configuration further reduced the enrichment, which increased with burnup, resulting in a 1% reduction in enrichment at a burnup of 150 MWd/kg compared with the 13-ring core. For all three configurations, increasing the fuel volume fraction could extend the fuel residence time that could be achieved while staying under 20% enrichment. With sufficient increase in the fuel volume fraction the equilibrium enrichment would be less than 10% and very long residence times (>30 years) are possible.

For SFRs based on current technology, the NU and SWU requirements are larger than for thermal reactors. With advanced fuel and core designs, it is possible to reduce these requirements to less than the thermal reactor requirements. For all cases (thermal and fast reactors), the amount of SNF generated is reduced proportionally as the burnup increases for the same fuel design. PWRs and SFRs produce similar volumes of SNF at the same burnup.

The impacts of deep-burn fuels in SFR were compared using the LFCAE. The LFCAE includes the entire fuel cycle costs, which include all fuel-related costs from mining to disposal, but does not include the reactor OCC and O&M costs. For the SFR, there is a reduction in refueling LFCAE that results from increased fuel residence time. Larger LFCAE reductions are enabled through better neutron economy (larger core size and increased fuel volume fraction). The refueling LFCAE was evaluated for 6 examples that cover the range of fuel residence time and core designs studied: one of each SFR core configuration with the base volume fraction, and one for each configuration with an increased volume fraction. The refueling LFCAE based on current technology was estimated to be between 15-24 $/MWh. For the most advanced concept (largest core size and longest fuel residence time) evaluated, the refueling LFCAE was reduced to between 5-8 $/MWh. This cost is approximately 63% of the current technology PWR, which ranges between 8-13 $/MWh.

The fuel cycle costs of initial core costs were also estimated for the SFR. The initial core requires lower enriched fuels but a larger amount of fuel than the reload fuel. For the 12-ring reference core, the initial core fuel cycle costs are about $1,000/kWe, which represents a contribution to the LCOE of about $7/MWh. For the PWR, the initial core cost would be about $275/kWe, which represents a contribution to the LCOE of about $1.8/MWh. For the larger SFR core sizes considered, the cost of the fuel will roughly double for the largest core, compared with the 12-ring reference core. If the power level is not increased, this would be around $2,100/kWe and an LCOE contribution of $14.2/MWh, offsetting most of the benefit of reduced refueling costs. It is anticipated that power levels would increase which would reduce the initial core cost in $/kWe, but this was beyond the scope of this study.

Increasing the fuel residence time with deep burn fuels requires overcoming many challenges, but if achieved, then the impact can increase or decrease the measures of interest (required amount of NU, SWU, fuel fabrication, disposal SNF volume, etc.). The LFCAE for refueling SFR cores can be reduced with increased fuel residence time. If that increase in fuel residence time is achieved by a physically larger core, this could drive up the reactor OCC because of larger vessels and other effects, as well as a substantial increase in the fuel cycle cost of the initial core. However, potential increases in the power level from advanced fuels may overcome the increased costs. The potential range of impacts on LFCAE and OCC is from negligible impacts on some measures to very dramatic reductions in quantities for others. Cost impacts can also be quite large for SFRs, as noted by the large increase in initial core loading with increased core size. These impacts were not evaluated beyond showing the benefits for an assumed increase in power level. The impacts of a longer fuel residence time using HALEU are likely lesser for PWRs, as there will be no overall change in geometry.

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Appendix A

Cost Information

A-1. Unit Cost Estimates and Assumptions

This appendix provides all the unit costs and their basis. They are organized into four tables. Table A-1 provides the front-end unit costs for NU, SWU, and conversion and deconversion of materials. Some of these quantities are divided between low assay low enriched uranium (LALEU, 0.7-5%) and HALEU (5-20%) Table A-2 provides the fabrication costs for different fuel types. Table A-3 provides the cost of transporting the various materials. Table A-4 provides the disposal costs of the various materials.

Table A-1 Front End Unit Costs.

ID	Units	Low	Mean	High	Dist. Type	CBR Module
NU	$/kgU	41.5	168.5	360	TRI	A1
NU Conversion	$/kgU	7	13.8	20.8	UNI	B
LALEU SWU	$/kgU	119	153	188	TRI	C1
HALEU SWU	Percent SWU premium above LEU SWU prices in C1 above	3	15	27	UNI	C3b
Cat III Metal	$/kgU as U-metal shards	220	670	1110	UNI	C3d
Cat III UO2	$/kgU as clean UO2	110	610	1110	UNI	C3e
Cat II Metal	$/kgU as U-metal shards	1110	2220	3330	UNI	C3f
Cat II UO2	$/kgU as clean UO2	550	1390	2220	UNI	C3g
DU Deconversion	$/kgDU	5	8	11	TRI	K1-1

Table A-2 Fabrication Costs.

ID	Units	Low	Mean	High	Dist. Type	Module
PWR UOX	$/kgU	281	491	702	TRI	D1-1a
TRISO	$/kgU	1160	5416	10443	TRI	D1-3
Cat III Metal	$/kgU	469	743	1172	TRI	D1-6A.6
Cat II Metal	$/kgU	1290	1520	1760	TRI	D1-6A.8

Table A-3 Transportation Costs.

ID	Units	Low	Mean	High	Dist. Type	CBR Module, Assumption or Ref.
NU Transport	$/kg U	2.4	3.4	4.4	TRI	O2
LALEU UF6 Transport	$/kg U	1.4	1.5	1.7	TRI	O2
HALEU UF6 Transport	$/kg U	14	15	17	TRI	Assumed 10x LALEU
DU Transport	$/kg U	1.4	1.5	1.7	TRI	O2
DU U3O8 Transport	$/kg U	2.4	3.4	4.4	TRI	O2
Fresh PWR UOX Transport	$/kg U	53	55	57	TRI	O2
Fresh TRISO Transport	$/kg U	265	275	285	TRI	Assumed 5x PWR UOX
Fresh Cat III Metal Transport	$/kg U	53	55	57	TRI	Assumed PWR UOX
Fresh Cat II Metal Transport	$/kg U	53	55	57	TRI	Assumed PWR UOX
PWR UOX SNF Transport	$/kg iHM	182	201	226	TRI	[41]
He-cooled TRISO Pebble SNF Transport	$/kg iHM	5,307	5,856	6,588	TRI	[41]
MS-cooled TRISO Pebble SNF Transport	$/kg iHM	3,395	3,746	4,214	TRI	[41]
TRISO Block SNF Transport	$/kg iHM	2,675	2,952	3,321	TRI	[41]
Cat III SNF Metal Transport	$/kg iHM	747	825	928	TRI	[41]
Cat II SNF Metal Transport	$/kg iHM	747	825	928	TRI	[41]
HLW Transport	$/kg FP	1,075	1,186	1,334	TRI	[41]

Table A-4 Disposal Costs.

ID	Units	Low	Mean	High	Dist. Type	CBR Module, Assumption or Ref.
DU Disposal	$/kgDU	5	25	53	TRI	K1-2
PWR UOX SNF Disposal	$/kg iHM	236	461	787	TRI	[41]
He-cooled TRISO Pebble SNF Disposal	$/kg iHM	3,119	10,971	25,890	TRI	[41]
MS-cooled TRISO Pebble SNF Disposal	$/kg iHM	1,890	6,649	15,691	TRI	[41]
TRISO Block SNF Disposal	$/kg iHM	1,559	5,486	12,945	TRI	[41]
Cat III SNF Metal Disposal	$/kg iHM	576	1123	1938	TRI	[41]
Cat II SNF Metal Disposal	$/kg iHM	576	1123	1938	TRI	[41]
HLW Disposal	$/kg FP	1,811	6,032	9,050	TRI	L1