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Economic Impacts of Irradiated High Assay Low-Enriched Uranium Fuel Management

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ABSTRACT

Commercial nuclear power plants typically use nuclear fuel that is enriched to less than five weight percent in the isotope ^{235}U. However, recently several vendors have proposed new nuclear power plant designs that would use fuel with ^{235}U enrichments between five weight percent and 19.75 weight percent. Nuclear fuel with this level of ^{235}U enrichment is known as "high assay low-enriched uranium." Once it has been irradiated in a nuclear reactor and becomes used (or spent) nuclear fuel, it will be stored, transported, and disposed of. However, irradiated high assay low-enriched uranium differs from typical irradiated nuclear fuel in several ways, and these differences may have economic effects on its storage, transport, and disposal, compared to typical irradiated nuclear fuel. This report describes those differences and qualitatively discusses their potential economic effects on storage, transport, and disposal.

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EXECUTIVE SUMMARY

Several vendors have proposed nuclear reactors that are fueled by high assay low-enriched uranium, which is more highly enriched in ^{235}U (5 wt% - 19.75 wt%) than the fuel typically used in current nuclear reactors, which is enriched to less than 5 wt% ^{235}U. After it has been irradiated, the characteristics of fuel will be different from that of typical irradiated spent fuel, which has the potential to affect the economics of the back end of the nuclear fuel cycle: storage, transport, and disposal. This report discusses the characteristics of this fuel and how they differ from that of typical irradiated fuel, and identifies components of the back end of the nuclear fuel cycle that could be affected economically by storing, transporting, and disposing of high assay low-enriched spent nuclear fuel.

Three different fuels that may use high assay low-enriched uranium were studied: accident tolerant fuel, tri-structural isotropic fuel, and metallic fuel. Several characteristics were identified as affecting the economics of the back end of the nuclear fuel cycle; thermal characteristics, radiation characteristics, and measures needed to ensure subcriticality.

Thermal – The higher burn-up associated with high assay low-enriched spent nuclear fuel generally results in higher decay heat than typical spent nuclear fuel on a volume basis, except for tri-structural isotropic fuel, which will likely be cooler on a volume basis than typical spent nuclear fuel because of the presence of non-fuel components associated with each fuel element. Spent fuel that is hotter on a volume basis may require longer in-pool cooling times, may be too hot to fully load existing dry storage and transportation canisters, may require new dry storage and transportation systems, may need to be repackaged into smaller canisters for disposal, or might need extended surface storage to meet repository thermal requirements. Spent fuel that is cooler on a volume basis will require more storage and transportation canisters per amount of energy produced and a larger transportation fleet, but may more easily meet thermal limits associated with deep geologic repositories intended for disposal.

Radiation – The higher burn-up associated with high assay low-enriched spent nuclear fuel results in more fission products than typical spent nuclear fuel on a volume basis, which in turn leads to more shielding to meet dose requirements. Even though tri-structural isotropic spent nuclear fuel will have high burn-up as well, the presence of additional non-fuel mass and volume associated with the fuel elements, such as the multiple layers surrounding each fuel kernel, may serve to reduce the potential dose per volume. These differences in radiation per volume will require more (or less) shielding to meet dose requirements which affects both storage and transportation costs, may result in not fully loading existing dry storage and transportation canisters, may lead to new dry storage and transportation systems, may increase radiation-related embrittlement resulting in increased mechanical degradation, may change the time at which the spent nuclear fuel is no longer considered self-protecting, and may lead to the disposal of more canisters.

Criticality – The higher initial ^{235}U enrichment of high assay low-enriched uranium spent nuclear fuel means that the fuel will likely have more fissile material at the end of the fuel cycle than typical spent nuclear fuel, resulting in the fuel being more reactive neutronically. Tri-structural isotropic spent nuclear fuel will also have more fissile material, but this fissile material will be spread over a larger volume of SNF and may not pose as much of a challenge with respect to maintaining subcritical conditions. The higher quantity of fissile material in spent nuclear fuel may affect the economics of the back end of the nuclear fuel cycle by requiring higher boron concentrations and/or increased fuel spacing in the spent fuel pools (if used), having to re-design fuel arrangements in the dry storage and transportation systems, not loading the maximum number of assemblies in existing dry storage and transportation systems, increased neutron absorbing material in canisters which increases the weight or decreases transportation payloads, more transportation trips, and more or more robust neutron absorbers in waste packages intended for disposal.

ACRONYMS AND TERMS

Acronym/Term	Definition
ATF	accident tolerant fuel
AVR	Arbeitsgemeinschaft Versuchsreaktor
DOE	U.S. Department of Energy
EBR-II	Experimental Breeder Reactor-II
FFTF	Fast Flux Test Facility
FSV	Fort St. Vrain
HALEU	high-assay low-enriched uranium
HTGR	high- temperature gas-cooled reactor
INL	Idaho National Laboratory
ISFSI	Independent spent fuel storage installation
LEU	low-enriched uranium
LWR	light-water reactor
LWT	legal-weight truck
NRC	Nuclear Regulatory Commission
RCRA	Resource Conservation and Recovery Act
SNF	spent nuclear fuel
THTR	thorium high-temperature reactor
TN-FSV	Transnuclear Fort St. Vrain
TRISO	tristructural isotropic

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1. INTRODUCTION AND BACKGROUND

In the United States (U.S.), the fuel used by most commercial nuclear power plants is low enriched uranium (LEU), which is uranium that has been enriched up to 5% by weight in the isotope ^{235}U. However, in the past few years several vendors have proposed using high assay LEU (HALEU) in their reactors. HALEU is uranium that has been enriched in the isotope ^{235}U to between 5% and 19.75% (Herczeg 2021). Compared to current practices, the use of HALEU, rather than LEU, has the potential to affect the economics of every part of the nuclear fuel cycle: uranium mining, uranium enrichment, fuel fabrication, energy production, storage, transport, used fuel treatment (if required), and disposal. This report identifies the components of the back end of the nuclear fuel cycle that are affected economically by managing irradiated HALEU rather than irradiated LEU, namely storage of spent HALEU fuel, transport of spent HALEU fuel, and disposal of spent HALEU fuel. Note that while spent nuclear fuel (SNF) is currently stored and transported safely, disposal of SNF has not yet occurred. Therefore, identifying and quantifying the economics effects of disposing of spent HALEU is more uncertain and speculative than it is for storing and transporting used HALEU.

1.1. Objectives

The objective of this report is to define those areas of spent fuel storage, transportation, and disposal that could be affected economically by using HALEU. The intention is to quantify these effects in follow-on work; thus, this report represents the first phase of the effort to quantify the economic effects of the use of HALEU on the back end of the nuclear fuel cycle.

1.2. Scope

HALEU has been proposed as a fuel in several different reactors. Potential applications include:

1. Using HALEU up to 10% ^{235}U enrichment in the current fleet of light water reactors (LWRs) as a form of accident-tolerant fuel (ATF) (NRC 2023)
2. Using HALEU between 14.5% and 19.75% ^{235}U enrichment in tristructural isotropic (TRISO) fuel for use in high temperature reactors (either gas-cooled or salt-cooled) (NAS 2022),
3. Using HALEU between 10% and 19.75% ^{235}U enrichment in metallic fuel (either sodium-bonded or non-sodium-bonded) in fast reactors (NAS 2022), and
4. Using HALEU between 12% and 19.75% ^{235}U enrichment in molten-salt fueled reactors (NAS 2022).

This report identifies the aspects of storage, transportation, and disposal that are affected economically by the use of HALEU with respect to its use in ATF, TRISO fuel, and metallic fuel. The aspects of storage, transportation, and disposal that are affected economically by the use of HALEU with respect to its use in molten-salt reactors is not discussed because the resulting spent fuel waste form (salt) is so novel that the differences in its physical and chemical properties compared to those of typical LWR spent fuel are likely to dominate any economic considerations.

The following sections discuss ATF (Section 2), TRISO fuel (Section 3), and metallic fuel (Section 4), identifying aspects of storage, transportation, and disposal that could be affected economically using HALEU in those fuels. A summary and conclusions are in Section 5.

2. ACCIDENT TOLERANT FUEL

The U.S. began researching ATF for use in current reactors after the Fukushima Daiichi accident in 2011 to reduce the likelihood that such an accident would occur in the U.S. Many different types of ATF have been proposed: new cladding materials, uranium dioxide doped with other oxide powder, HALEU, metallic fuels, uranium nitrides, uranium silicides, and TRISO fuels (Honnold et al. 2021). This section focuses on the ATF concepts that include the use of HALEU oxide fuel in thermal spectrum reactors.

As burnup increases for a given initial enrichment, the decay heat generated by an assembly increases. This is intuitive because more fissions have occurred in a high burnup fuel, creating more fission products that generate decay heat. However, as initial enrichment increases for a given burnup, the decay heat generated by an assembly decreases. This is somewhat counterintuitive and occurs because fuel that is more highly enriched in ^{235}U is, by definition, less enriched in ^{238}U. This heavier isotope of uranium creates ^{239}Pu in the reactor, which leads to the production of heat-producing higher actinides. Therefore, fuel that is more highly enriched in ^{235}U generates fewer of the higher heat-producing actinides than does fuel that is less highly enriched in ^{235}U, given the same burnup (Burns et al. 2020).

Using HALEU rather than LEU allows for a longer cycle length, increased burnup, and increased power output from the reactor (Honnold et al. 2021). This has the potential to affect which isotopes are produced, the quantities at which they are produced, the decay heat profile over time, the condition of the cladding at discharge, current methods for maintaining subcriticality, and current methods for meeting worker dose requirements.

2.1. Potential Economic Effects on Storage

This section discusses the most important factors that may affect the storage costs of spent HALEU ATF compared to the storage of current LEU LWR SNF.

With respect to wet storage, in-pool post-irradiation times prior to loading into dry storage canisters may need to be increased because of the higher decay heat. The extent to which this will be offset by the longer in-core life of the fuel is not yet known. For higher enrichments and higher burnups, there may be impacts on criticality safety and cooling times, which can be addressed via higher boron concentration in the spent fuel pool and racking configurations, for example (Banerjee 2021). Maximum spent fuel pool loadings are not yet known.

ATF is intended to be used in existing commercial nuclear reactors, so the focus has been on developing fuels with the same assembly dimensions as current LWR assemblies. This similarity will result in minimal economic impact on dry storage. Materials properties associated with new claddings or coatings, or new pellet materials may affect cladding creep and embrittlement which may affect long term dry storage. New materials will need to be reviewed against dry storage cask Certificates of Compliance (CoCs), which may need to be revised to address the new materials.

However, some of the changes associated with HALEU ATF will affect dry storage. As noted above, higher burn-up and higher enrichments for HALEU generally result in higher decay heat, resulting in higher temperatures; more fission products, resulting in more shielding to meet dose requirements; more radiation embrittlement, resulting in mechanical degradation; and more fissile material at the end of the fuel cycle, resulting in criticality issues that may affect dry storage compared to current LEU LWR SNF. All these differences may require modifications to dry storage containers and their fuel baskets, and number and location of assemblies. Changes in reactivity will need to be addressed; there are several options for doing this including fuel basket redesign, reduced number of assemblies per canister, and repositioning of assemblies in the basket (Banerjee 2021). In addition, a significantly longer time might be required until the spent HALEU ATF can meet heat and dose limits for transport. This may have implications on storage costs. Data on HALEU ATF and its long-term conditions and any degradations in dry storage will also be needed for licensing new dry storage casks or modifications to existing CoCs. (Honnold 2021)

2.2. Potential Economic Effects on Transportation

This section discusses the most important factors that may affect the transportation costs of spent HALEU ATF compared to the transportation of LEU LWR SNF.

Transportation costs will be affected by the number of packages that need to be transported and the corresponding size of the transportation fleet (number of reusable transportation casks needed to support the fleet). Two types of packages are used for transporting LWR SNF: bare fuel transportation casks or dry storage canisters in transportation overpacks. In the former case, the SNF is loaded into the cask directly from the pool and unloaded into the facility pool at the destination point (a consolidated storage facility or a geologic repository) where it is stored until it is loaded into a storage package (applicable to a consolidated storage facility) or into a disposal package (applicable to both, a consolidated storage facility and a geologic repository). However, it is anticipated that a large fraction of the LWR SNF inventory will not be transported using this method. Instead, it will be loaded into dry storage canisters that are eventually placed in transportation overpacks (casks) for delivery to the destination; the casks are then sent out to a site to be used to transport more SNF. At the delivery site, the dry storage canisters continue to store the SNF until it is loaded into a disposal overpack (or repackaged into a disposal canister and then loaded into a disposal overpack) for disposal.

The ATF dimensional and material designs are similar to the LWR ones because ATF is designed to be used in existing LWRs. Per Banerjee (2022), small changes in ATF geometry, larger pellet diameter, smaller cladding thickness, and doped fuel pellets are not expected to noticeably affect thermal, shielding, criticality, and structural requirements of the transportation system.

With respect to HALEU ATF, however, high burnup and high enrichment of the HALEU ATF compared to LEU LWR fuel have significant effects on thermal, shielding, and criticality considerations of the transportation system. The effects on the structural requirements are believed to be relatively small, assuming that the temperatures inside the casks do not change. High burnup affects what is required to meet thermal and shielding requirements due to the higher decay heat and fission activity of the HALEU ATF. High enrichment affects what is required to meet criticality requirements. As noted above, decay heat will be lower in HALEU ATF with high enrichment compared to the ATF with the same burnup and lower enrichment due to the reduced production of long-lived actinides. Consequently, the effects will be different in the HALEU ATF with different combinations of burnup and enrichment.

Using existing dry storage canisters for spent HALEU ATF may result in reduced canister capacity (number of spent fuel assemblies loaded) to comply with the transportation dose limits and cladding temperature limits. The same applies to the bare fuel transportation casks. Increasing spacing between assemblies or reducing the number of assemblies in the canister or the bare fuel transportation cask may also be required for ATF with high enrichment. It is estimated (Banerjee 2022) that the number of existing canisters could increase by a factor of 2 upon loading HALEU ATF in these canisters. This can be demonstrated using a dose in a simplified example. The neutron dose increases by a factor of 4 with a 30% burnup increase. Assuming that the fraction of neutron dose is 0.4, the total dose doubles with the 30% burnup increase, which requires reducing capacity by ~2. As was shown in Cumberland (2020), gamma dose tends to decrease with increasing burnup, while neutron dose tends to increase with increasing burnup. In the considered burnup range of 20 to 65 Wd/MTU, gamma dose was dominating at lower burnups and neutron dose was dominating at higher burnups. As with storage, a significantly longer time might be required until the spent HALEU ATF can meet heat and dose limits for transport. This may have indirect implications on the transportation costs.

Another option would be using canisters specifically designed for dry storage/transport of HALEU ATF. The capacity of these canisters will be lower than the capacity of the existing canisters for LWR SNF, presumably by the same factor of 2. This is because increasing shielding impacts the thermal performance of the canister and limits its decay heat capacity. Limitations are also posed by the shielding and robust structure needed to meet hypothetical accident conditions requirements. The other limitations include maximum weight and maximum diameter for transportation packages. Development and licensing of the transportation casks for these new canister designs will be required. This will result in additional costs and time.

While the number of the canisters of existing design loaded with ATF can be assumed to be comparable to the number of newly designed canisters loaded with ATF, the weight of the transportation system (fuel assemblies, canister, transportation cask, impact limiters, and cradle) might be different. The weight of a transportation system with an existing cask containing partially loaded ATF dry storage canisters will be larger than that of a transportation system with smaller new transportation casks with fully loaded ATF canisters. Even if the cask weights are similar (more shielding required for new casks), the transportation system with the new smaller cask will have smaller and lighter impact limiters and cradle. It will cost more to transport heavier packages than to transport lighter packages, assuming the same charge per ton-distance. Note that if a dedicated rail is used, the charge might be per train or per rail car. In this case the package weight may not be a factor. Developing and licensing new transportation casks will result in additional costs. However, the costs of fabrication of the lighter packages will be lower. These additional costs might be compensated by the money saved on fabricating and transporting lighter packages if the number of packages is large enough.

Transportation costs per unit energy generated will be affected by the mass of the waste required to produce that energy. Per estimates in Bragg-Sitton (2014) and NE Strategic Vision (2020), the mass of spent HALEU ATF will be approximately 30% less than the mass of LWR SNF required for the same quantity of energy generated due to the higher burnup of HALEU ATF SNF.

Finally, with respect to self-protection (10 CFR 73), HALEU ATF SNF may be self-protecting for a longer period of time than is typical LWR SNF if it has a higher burnup. On the other hand, the high enrichment of HALEU ATF SNF compared to typical LWR fuel may require it to have additional security and safeguard measures once it is no longer self-protecting (10 CFR 73). This will result in additional costs.

2.3. Potential Economic Effects on Disposal

As noted above, HALEU ATF is expected to generate more heat than typical LWR SNF on an assembly-by-assembly basis. To meet the various thermal requirements associated with different disposal geologies, thermal management strategies would have to be implemented. These include increasing surface storage time prior to disposal (potentially on the order of centuries (Hardin et al. 2015)), repackaging the HALEU SNF into smaller canisters for disposal, expanding the repository footprint, and limiting acceptable geologies to those that are better able to shed heat. These thermal management strategies would have economic effects.

Also, as noted above, HALEU ATF SNF may have a higher fissile content after removal from the reactor than typical LWR SNF, thus requiring different methods and systems for maintaining subcritical conditions over repository timescales (10^6 years), such as more robust neutron absorbers in wastes packages. Designing and fabricating waste packages for HALEU ATF SNF specifically designed to maintain subcritical conditions over repository timescales would have economic effects.

3. TRISO FUEL

TRISO fuel is different from typical LWR fuel in that it consists of very small fuel kernels surrounded by four layers, forming a particle that is approximately 1 mm in diameter, as shown in Figure 1 (Sassani et al. 2018). The layer next to the kernel is a low-density pyrolytic carbon buffer layer that absorbs fission products from the fuel and accommodates swelling of the kernel. Moving away from the kernel, the second layer is a high density inner pyrolytic carbon layer, which is resistant to fission products. The third layer is a high density, high strength ceramic layer (typically SiC) that acts as a pressure vessel and diffusion barrier, further restricting fission product release and withstanding stresses from the gas buildup within. The fourth and outer layer is the outer pyrolytic carbon layer that protects the particle from chemical attack during facility operation (Honnold et al. 2021).

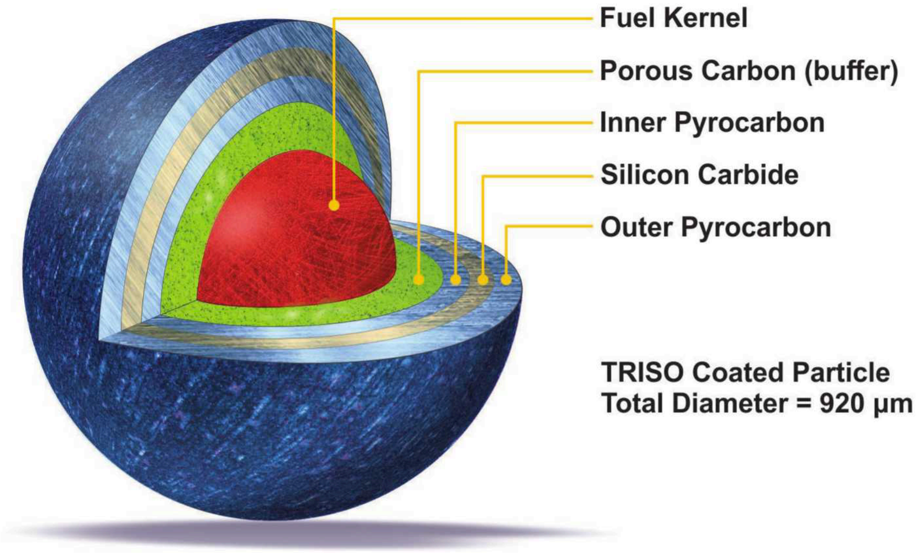


Figure 1. Schematic Drawing of a TRISO fuel particle with four protective layers (pyrocarbon = pyrolytic carbon) (Sassani et al. 2018)

TRISO fuel can be used in either a prismatic block reactor or in a pebble bed reactor. Both types of reactors use fuel with high enrichment (14 - 19.75%) and are expected to reach high burnups (160 GWD/MTU). In a prismatic block reactor, the TRISO particles are distributed in graphitic cylindrical fuel compacts that are ~1 cm in diameter and ~5 cm in length, which in turn are placed in hexagonal nuclear-grade graphite fuel blocks by stacking them in fuel holes drilled into the blocks. In the US, two such reactors were operated - Peach Bottom Unit 1 and Fort St. Vrain (FSV), the latter of which operated commercially in Colorado between 1979 and 1989 and used fuel enriched to 93.5% (Bahr et al. 2017). Experience with FSV provides a good baseline for understanding the waste requirements of high temperature gas reactors (HTGRs) (Lotts 1992). A significant difference between FSV fuel and proposed HTGR spent fuel is the significantly higher burnup of the new fuel (Framatome steam-cycle HTGR) compared to FSV. The Framatome steam-cycle HTGR is a modular, graphite-moderated, helium-cooled, high-temperature reactor (IAEA 2020).

In a pebble bed reactor, ~60 mm diameter graphite-covered spherical pebbles composed of graphite and TRISO particles move freely through the reactor. There were no pebble bed TRISO reactors in the US, but there was one in Germany that operated from 1967 to 1988, the Arbeitsgemeinschaft Versuchsreaktor (AVR) (NAS 2022).

3.1. Potential Economic Effects on Storage

This section discusses experience with storing TRISO SNF as well as the most important factors that may affect the costs of storing spent TRISO compared to the costs of storing LWR SNF.

When the AVR shut down, ~ 290,000 spent fuel elements with TRISO and bi-structural isotropic (BISO)-coated particles in graphite pebbles were discharged from the AVR and stored in approximately 153 CASTOR Thorium High Temperature Reactor (THTR)/AVR casks at the AVR interim storage facility (Hall 2019a). The CASTOR THTR/AVR cask is certified in Germany for both storage and transportation. The cask accommodates 2 canisters with a total canister volume of 0.49 m^3.

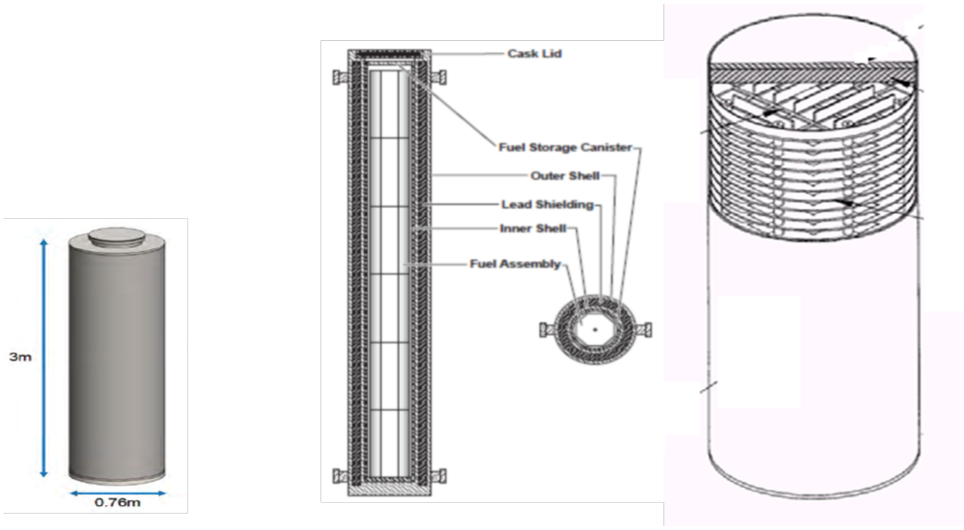
Operation of FSV generated ~ 23.35 MTHM of SNF; ~ 15 MTHM of that SNF is currently stored in sealed carbon steel containers in an air-cooled DOE-owned and NRC-licensed Independent Spent Fuel Storage Installation (ISFSI) in Colorado while the remaining ~8 MTHM is stored at Idaho National Laboratory (INL) in carbon steel canisters at storage area CPP-603. Each fuel storage container at the ISFSI holds as many as six graphite fuel blocks. TRISO fuel from operation of the Peach Bottom Unit 1 is currently stored at INL in carbon steel-lined, double O-ring sealed aluminum canisters at storage area CPP-749. (Bahr et al. 2017; NWTRB 2020).

The mass of spent fuel per quantity of energy generated is inversely proportional to burnup and thermal efficiency. The spent fuel volume also depends on reactor-specific design features. For example, the TRISO fuel designed to be used in X-energy's proposed Xe-100 reactor, with an expected average discharge burnup up 165 GWd/MTU and a thermal efficiency of 40%, generates 0.181 GWe-yr per metric ton of uranium (Hoffman et al, 2023). In contrast, typical PWR fuel with an average discharge burnup of 50 GWd/MTU and a thermal efficiency of 33% generates 0.045 GWe-yr per metric ton of uranium (Hoffman et al. 2023.) Therefore, this TRISO fuel generates about four times as much energy per metric ton of uranium as does typical PWR fuel. However, because a TRISO pebble contains a significant amount of non-fuel components, the volume of spent pebble bed TRISO fuel is estimated to be 12 times the volume of typical LWR SNF per energy generated (Hoffman et al. 2023, Petersen 2023). The volume of spent prismatic TRISO fuel will be greater than the volume of pebble bed TRISO fuel because the pebble bed contains the fuel and the moderator and does not have the large graphite fuel elements of prismatic fuel.

X-energy's proposed Xe-100 reactor, which is a pebble-bed reactor, has a closed fuel handling system. After six nominal cycles, pebbles will be removed and placed in dry storage canisters. The Xe-100 plant design incorporates a Spent Fuel Intermediate Storage Facility (SFISF). The SFISF includes 32x20 canister storage rack. The proposed storage canister is a 3 m long cylinder with diameter of 0.76 m, Figure 2 (a), which is significantly smaller than typical canisters used to store LWR SNF. The cylinder volume is 1.36 m^3 (X-Energy 2023). The inner cavity has a smaller volume.

The dimensions of both the Peach Bottom and FSV fuel elements are different than LWR fuel assemblies. TRISO reactor designs may also have different dimensions that may impact dry storage canister designs. TRISO fuels may have higher burn-up, but lower decay heat per volume due to the larger mass associated with the fuel elements, such as graphite blocks. Another proposed concept using TRISO fuel in a pebble-bed molten-salt-cooled reactor (Hoffman et al 2023) would introduce additional factors to consider in designing storage canisters.

With larger element dimensions, the number of dry storage casks for TRISO fuels will be larger (see below) and the dose rates lower than those for LWRs.



Note: The casks dimensions are approximately in the same scale.

Figure 2. (a) X-Energy Dry Storage Canister (X-Energy, 2023); (b) TN-FSV Cask (Figure G-2 in DOE, 2000); and (c) NAC-MPC Transportable Dry Storage Canister

3.2. Potential Economic Effects on Transportation

This section discusses experience with transporting TRISO SNF as well as the most important factors that may affect the cost of transporting spent TRISO compared to the cost of transporting LWR SNF.

With respect to the AVR, special rail cars were built for transportation of the CASTOR THTR/AVR casks from the THTR reactor to the interim storage facility. A total of 305 CASTOR casks were transported in 57 shipments (IAEA 2012) and (Laug 1997). Consequently, about 5 casks were transported by one train.

The FSV reactor, shut down in 1989, generated 2,208 spent fuel elements (24 MTHM of SNF) in the form of TRISO-coated particles in graphite prismatic blocks. The first 726 spent fuel elements, discharged prior to 1989, were shipped to INL and stored in a dry storage facility at the Idaho Chemical Processing Plant. DOE used the Transnuclear Fort St. Vrain (TN-FSV) cask, Figure 2 (b), to transport the FSV spent fuel elements to INL by truck with one fuel storage canister fitting in one TN-FSV (Clark 1994). The dimensions of the internal cask cylinder were 5.05 m in length and 0.46 m in diameter. The internal volume was then 0.84 m^3. There was a total of 43 shipments. Also shown in Figure 2 (c) is the NAC-MPC transportable dry storage canister for LWR SNF. The canister is similar in height to FSV cask, but larger in diameter and has a volume of ~ 10 m^3. The geometry of NAC-MPC canister allows for accommodating 9 or 10 FSV casks. If the design of the canister is demonstrated to be acceptable for transporting FSV casks, it would increase the transportation efficiency.

The transportation configuration of the FSV cask is shown in Figure 3.

Figure 3. Transportation Configuration of the TN-FSV Cask (Turner and Lynn, 2004).

The study summarized in Kim (2023) compared the activity and decay heat at 10 years after discharge of the TRISO spent fuel and LWR SNF per energy generated (GWe-yr). The TRISO spent fuel activity and decay heat at 10 years were 0.79 of the LWR SNF activity and decay heat at that time. Because the activity and decay heat are lower, no issues related to thermal output and radiation dose of the TRISO dry storage canisters and transportation casks were identified.

No significant issues related to the structural performance of dry storage systems or transportation packages were identified as well (Petersen 2023). Furthermore, it was concluded that subcriticality of a single canister can be maintained in both dry storage and transportation conditions (Petersen 2023]) although a smaller canister diameter might be required.

With respect to safeguards and security, the TRISO particles have higher proliferation resistance compared to LWR fuel due to the small quantity of ^{235}U within each pebble and the difficulty of extracting it from the matrix.

In X-Energy's concept of how an Xe-100 fuel cycle would operate, as outlined above, the spent TRISO fuel is placed in dry storage as it is removed from the reactor and remains there until the end of the reactor life, which is 60 years (X-Energy 2023). The transportation campaign would then start after the reactor shutdown. Transportation costs will be affected by the combination of the significantly smaller spent TRISO mass and substantially larger volume compared to LWR SNF.

3.3. Potential Economic Effects on Disposal

As noted above, spent TRISO produces about an order of magnitude less heat and emits less radiation per volume as does typical LWR SNF. Thus, canisters of spent TRISO are not likely to present a challenge to disposal with respect to repository thermal limits and it would not be necessary to implement thermal management strategies with respect to disposal. On the other hand, for a given quantity of energy generated, it will take more waste packages and more emplacement operations to dispose of spent TRISO than it will take to dispose of typical LWR SNF. If the spent TRISO has been stored and transported in canisters that remain subcritical under all analyzed conditions, and if these canisters are also used to dispose of the spent TRISO, then no additional effort would be needed to address postclosure criticality concerns and repackaging would not be necessary. All of these would affect the economics of disposal.

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4. METALLIC FUEL

This section discusses the economic effects of storing, transporting, and disposing of metallic fuel. Metallic fuel consists of fuel composed of uranium or uranium alloys (e.g., uranium-molybdenum) with zirconium or non-zirconium cladding. To facilitate heat transport between the fuel and the coolant, some metallic fuels have sodium between the fuel and the cladding. When this fuel is used as a driver fuel, over time and with exposure to the reactor environment, the sodium becomes bonded to the fuel and becomes difficult to remove. This fuel is known as "sodium-bonded" fuel. Metallic fuels that do not have sodium interior to the fuel rod are referred to as "non-sodium bonded" fuel in this discussion.

4.1. Potential Economic Effects on Storage

This section discusses previous experience with storing metallic fuel as well as the most important factors that may affect the cost of storing of spent metallic fuel compared to the cost of storing LWR SNF.

Metallic fuels, both those that are non-sodium bonded and those that are sodium-bonded, have been used in several reactors in the past, have had their fuels discharged, shipped, and stored for many years. These reactor fuels are in non-NRC licensed dry storage at INL, including blanket fuel from Fermi-1, fuel from the Hanford Fast Flux Test Facility (FFTF), fuel from Experimental Breeder Reactor-II (EBR-II) and fuel from the Hanford N-reactor. (Petersen, 2023; Bahr et al., 2017). The first three of these fuels are sodium-bonded metallic fuel while the last one is non-sodium bonded metallic fuel.

For one proposed metallic fuel reactor design, the Natrium reactor proposed by TerraPower, the length of the metallic fuel assemblies may be longer than PWR assemblies which, if this is the final design, would require longer or taller dry storage canisters than are currently being used for typical LWR SNF. This proposed fuel cycle uses sodium-bonded fuel initially, later switching to non-sodium bonded fuels. Metallic fuels may have smaller masses, different isotopic compositions upon discharge, different temperature limits and different heat transfer characteristics, so rates of decay heat generation as well as decay heat limits may be different from those for typical LWR SNF. This may result in shorter in-pool cooling times before transferring to dry storage, so spent fuel pools may not have to be as large (Hoffman et al. 2023).

4.2. Potential Economic Effects on Transportation

This section discusses previous experience with transporting metallic fuel as well as the most important factors that may affect the cost of transporting spent metallic fuel compared to the cost of transporting typical LWR SNF.

There is experience with storing and transporting spent sodium-bonded metallic fuel. The spent fuel generated from FFTF and Fermi-1 was transported from Washington and Michigan, respectively, to Idaho and placed in storage at several locations at INL, along with the spent fuel from EBR-II (Hall et al. 2019b). Storing and transporting non-sodium-bonded metallic fuel should pose fewer challenges compared to storing and transporting sodium-bonded metallic fuel.

The NLI-1/2, T-3, and NAC-LWT casks were certified by NRC to transport certain types of spent metal fuels with different radiation levels (Hall et al. 2020). The specifications and use of these casks are discussed below.

The NLI-1/2 cask (Figure 4) was used to transport Fermi-1 and EBR-II blanket fuel. The cask containment cavity is 0.32 m in inner diameter and 4.52 m long (NLI-1/2 SAR 1996). The internal cavity volume is 0.37 m^3.

The T-3 (Figure 5) cask was used to transport spent fuel from FFTF (Ross 2014). T-3 containment cavity is 0.20 m in inner diameter and 4.50 m long. The internal cavity volume is 0.14 m^3.

The NAC-LWT cask (Figure 6) was used to transport metallic fuel rods. The containment cavity is 0.34 m in inner diameter and 4.52 m long (DOE 2000). The internal cavity volume is 0.41 m^3.

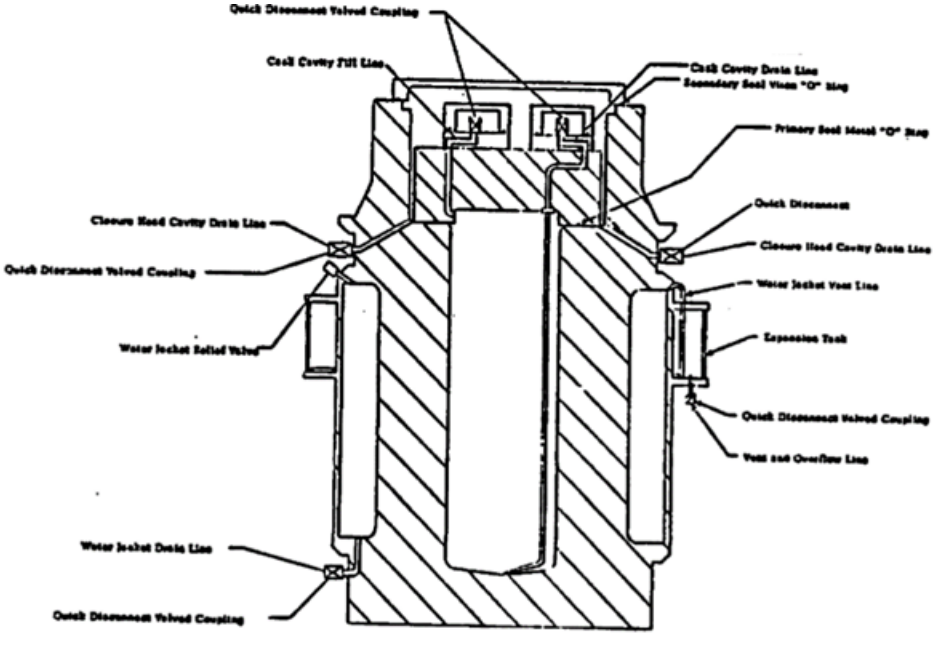

Figure 4. NLI-1/2 cask (NLI-1/2 SAR 1996).

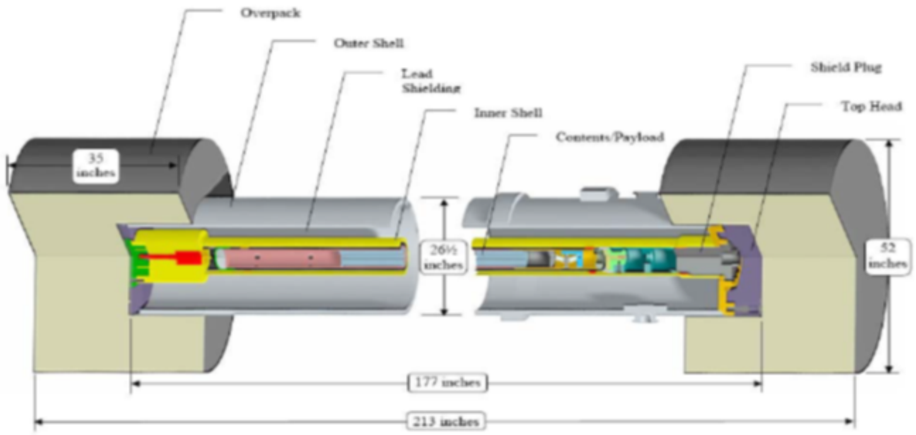

Figure 5. T-3 cask used to transport sodium-bonded spent FFTF metal fuel from Hanford to INL (Ross 2014)

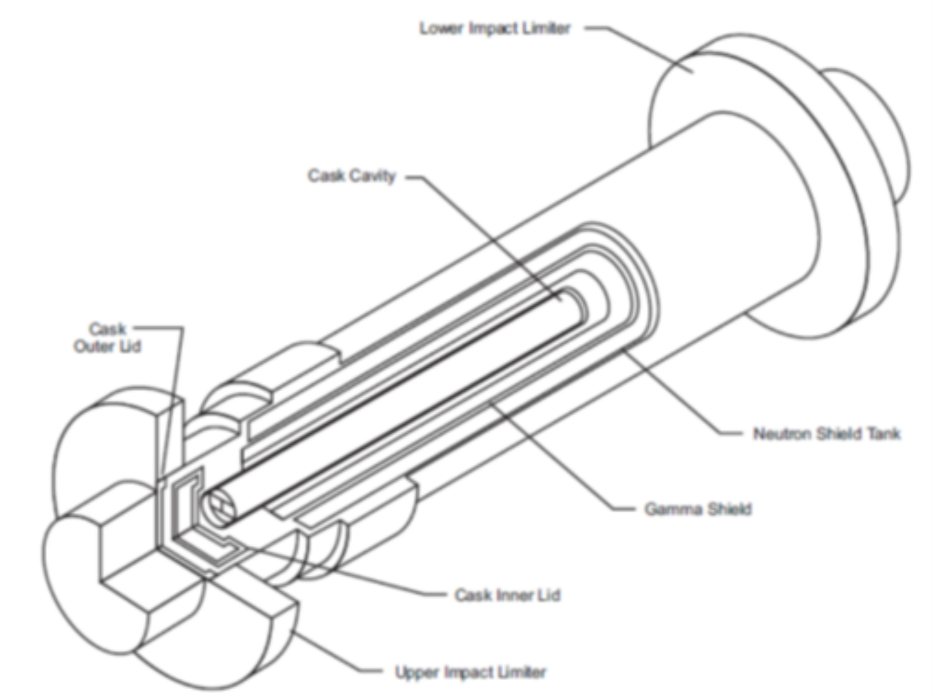

Figure 6. Simplified drawing of a NAC-LWT (legal weight truck) shipping cask (Figure G-3 in DOE 2000).

The discussion below is based on the non-sodium-bonded metallic fuel proposed in the Natrium-U concept. This fuel was identified as representative (Petersen, 2023) because the Natrium project is currently the most mature and is the most likely to be built in the near term. The Natrium-U fuel is a uranium-metal annular fuel with helium in the central core arranged in hexagonal fuel assemblies.

Instead of sodium bond, the fuel will have a "fuel-cladding chemical interaction barrier" (Neider 2021). The fuel is clad with HT9 ferritic-martensitic steel. The first Natrium deployment is expected to use fuel with 16.5% enrichment and 150 GWd/t burnup. The enrichment in later Natrium units is expected to be below 10%. The projected refueling cycle is 18-22 months. After discharge, the spent fuel assemblies will be kept 10 years in a pool and then placed in dry storage.

The mass of spent metallic fuel is estimated to be 0.27 of the LWR SNF per same energy generated (Petersen 2023). The volume is estimated to be 0.55 of the volume of the LWR SNF per same energy generated (Petersen 2023). However, if future transportation casks are similar to those that have been used in the past, canisters will be smaller than those used for storing and transporting LWR SNF. Using information in Petersen (2023), existing transportation cask internal volume, and average capacity of the LWR SNF canister indicates that the number of spent metallic fuel canisters will be about seven times larger compared to the number of LWR SNF dry storage canisters. However, a new package design specific to metallic fuel may have larger internal volume resulting in a smaller number of packages.

The study summarized in Kim (2022) compared the activity and decay heat at 10 years after discharge of the metallic spent fuel and LWR SNF per energy generated (GWe-yr). The metallic spent fuel activity and decay heat at 10 years were 0.63 and 0.60 of the LWR SNF activity and decay heat respectively at that time per energy generated. The volume of the metallic spent fuel was estimated to be 0.58 of the LWR spent fuel per energy generated. However, as previously discussed, the volumes of the canisters used to transport the existing metallic fuel were significantly lower than the volumes of canisters used to transport LWR fuel.

No significant issues related to the structural performance of dry storage systems or transportation packages were identified (Petersen 2023). It was concluded that subcriticality of a single canister can be maintained in both dry storage and transportation conditions (Petersen 2023). No significant issues related to shielding and radiation dose control are expected due to criticality loading constraints (Petersen 2023).

In Natrium's concept, the spent metallic fuel is expected to be removed from the reactor vessel and placed in a pool for 10 years before being moved to dry storage. The fuel will be discharged every 18-22 months. The transportation campaign can begin 10 years after the reactor deployment. Alternatively, the transportation campaign can start after reactor shutdown.

The costs will be affected by the combination of the significantly smaller spent metallic fuel mass and somewhat smaller volume compared to LWR SNF.

4.3. Potential Economic Effects on Disposal

The chemical characteristics of sodium-bonded metallic SNF make it unsuitable for disposal without further treatment. The sodium that will remain inside the fuel rods is ignitable and reactive and carries the Resource Conservation and Recovery Act (RCRA) hazardous waste codes D001 and D003 as defined in 40 CFR Part 261.21 through Part 261.24. In the 1990's, the DOE began a study to determine which of its SNF was subject to RCRA requirements (DOE 1997). The study concluded that "All metallic sodium-bonded or sodium-containing SNF types are currently considered suspect of exhibiting the RCRA characteristics of reactivity" (DOE 1997). In 2000, the DOE studied the question of disposal of its sodium-bonded SNF in the proposed Yucca Mountain repository and concluded that, even though there were no final waste acceptance criteria for disposal, including sodium-bonded spent fuel in the proposed repository would complicate modeling the long-term performance of the repository and therefore that "stabilization of the sodium-bonded spent nuclear fuel and/or removal of the metallic sodium would provide greater protection for human health and the environment" (DOE 2000). Therefore, the DOE decided to treat all its driver sodium-bonded spent fuel using electrometallurgical treatment.

Once sodium-bonded SNF is designated as waste, it would be subject to RCRA requirements, which make it subject to the Land Disposal Restrictions (40 CFR 268) imposed by RCRA. These prohibit land disposal of hazardous (and mixed radioactive and hazardous) waste unless it is treated to certain standards or receives a variance, extension, or exemption (EPA 2001). The EPA identifies treatment standards that make hazardous wastes acceptable for land disposal (40 CFR 268.40, Table 1). The EPA lists "Vitrification of high level mixed radioactive wastes in units in compliance with all applicable radioactive protection requirements under control of the Nuclear Regulatory Commission." Thus, waste produced by reprocessing or treating spent fuel that would otherwise be subject to RCRA can be disposed of without being subject to regulation as hazardous waste under RCRA by vitrifying it. Reprocessing or treating sodium-bonded spent fuel would have enormous economic effects.

In addition, uranium metal itself is pyrophoric, meaning that it spontaneously ignites in air below 55°C; it also reacts with water. Uranium hydride, which is also chemically reactive and pyrophoric, forms when uranium metal reacts with hydrogen (Bahr et al. 2017). With respect to the planned disposal of non-sodium bonded metallic uranium and uranium alloy fuels in Yucca Mountain, the DOE decided that the limited quantity of (non-sodium bonded) uranium metal and uranium alloy SNF was acceptable for disposal (DOE 2008a, Section 1.5) but that sodium-bonded metallic fuel was not to be disposed of directly (DOE 2000). The DOE analyzed the consequences of a pyrophoric event caused by spontaneous ignition of uranium metal fuel at the proposed repository and determined that the temperature rise of the waste package would be negligible, the pyrophoric event would not increase the fuel degradation rate because the model already assumed a bounding instantaneous degradation rate, and the pyrophoric event would not lead to significant pressurization of the waste package (DOE 2008b), thereby meeting the waste acceptance criteria for Yucca Mountain (DOE 2008c). However, this analysis was for an unsaturated repository (i.e., one above the water table); a similar analysis of the consequences of a pyrophoric event involving uranium metal waste that was disposed of in a saturated repository (i.e., below the water table) might yield different results. If it were determined that metallic fuel could not be disposed of safely, it would have to be treated, which would increase costs significantly.

According to TerraPower, the decay heat per active spent fuel volume of their proposed Natrium fuel is higher than that of typical PWR SNF (Neider 2021). With respect to disposal, depending on the geology and design of the disposal site that is eventually selected, if large storage and transportation canisters are used to store and transport Natrium SNF, the higher thermal output of the Natrium SNF may present a challenge for disposing of that SNF directly in those canisters, assuming the repository waste acceptance criteria regarding pyrophoric and reactive material can be met. If the host rock and design of the eventual repository require the waste packages to have a relatively low thermal output (e.g., a few kilowatts) at the time of emplacement, thermal management strategies will likely need to be invoked, which would affect the economics of disposal.

TerraPower also notes that, while they plan on using dry storage and transportation casks similar to those used for LWR SNF, the licenses for these casks will have to be revised for a different fissile content (Neider 2021). Presumably this means a higher fissile content, which could mean that, compared to LWR SNF, additional measures might have to be taken to address postclosure criticality. This would also affect the economics of disposal.

5. SUMMARY AND CONCLUSIONS

Several vendors have proposed using HALEU in their reactors. The production of HALEU SNF has the potential to affect the economics of the back end of the nuclear fuel cycle: storage, transport, disposal. This report identified components of the back end of the nuclear fuel cycle that could be affected economically by storing, transporting, and disposing of HALEU SNF.

Three different fuels that may use HALEU were used in this study: HALEU in ATF, HALEU in TRISO fuel, and HALEU in metallic fuel. HALEU proposed to be used in molten salt fuel was not used in this study because it is likely that other factors (e.g., the novel salt waste form) are likely to dominate economic concerns. It should be noted that sodium-bonded metallic fuel is not suitable for disposal as-is and requires treatment or reprocessing prior to disposal, which will dominate economic concerns for that type of SNF as well.

Several characteristics of HALEU SNF were identified as affecting the economics of the back end of the nuclear fuel cycle. The one area where no economic effects were identified is with respect to structural concerns regarding storage and transportation canisters and casks. The characteristics that could affect the economics of the back end of the nuclear fuel cycle and how the economics are affected are as follows.

Thermal – Higher burn-up in HALEU SNF generally results in higher decay heat than LEU SNF on a volume basis, except for TRISO SNF. In contrast, TRISO SNF will be much cooler on a volume basis than LEU SNF because of the presence of non-fuel components associated with each fuel element. Thus, TRISO SNF will require significantly more canisters for storage, transportation, and disposal for the same amount of energy produced. The implications of these differences that may affect economics include:

- Storage
  - Longer in-pool cooling times prior to moving to dry storage
  - Not loading the maximum number of assemblies in existing DPCs to meet heat limits, leading to the use of more DPCs
  - Designing and licensing canisters smaller than DPCs specifically for HALEU SNF
  - For TRISO SNF, about 12 times the volume of SNF per quantity of energy produced
- Transport
  - Lower transport costs per mass transported per energy generated, assuming the same charge per ton-distance, when less fuel mass is required to generate a given quantity of energy
  - For TRISO SNF, more canisters can be shipped per trip because of lower thermal output
  - More transport trips or larger transportation fleet because there are more canisters to move (particularly TRISO SNF)
    - More components needed in the transportation fleet
    - Increased fleet maintenance costs
    - Increased cask handling costs at the destination and the origin
- Disposal

  - Longer surface storage prior to disposal to meet repository thermal requirements
  - Repackaging to meet repository thermal requirements
  - Limiting the types of geologies to those that are better at rejecting heat
  - For TRISO SNF, about 12 times the volume of SNF to emplace per quantity of energy generated
  - For TRISO SNF, canisters can be emplaced closer together because of lower thermal output
  - If repackaging is needed to meet thermal limits, TRISO SNF might be cool enough to meet thermal requirements without repackaging

Radiation – HALEU SNF will have higher burn-up, resulting in more fission products, which in turn leads to more shielding to meet dose requirements. Even though TRISO SNF will have high burn-up as well, the presence of additional non-fuel mass and volume associated with the fuel elements, such as the multiple layers surrounding each fuel kernel, may serve to reduce the potential dose per volume. The implications of this that may affect economics include:

- Storage
  - More shielding to meet dose requirements (except TRISO SNF)
  - Less shielding to meet dose requirements for TRISO SNF
  - Not loading the maximum number of assemblies in existing DPCs to meet dose limits, leading to the use of more DPCs per energy generated
  - Designing and licensing canisters smaller than DPCs specifically for HALEU SNF
  - More radiation embrittlement, resulting in increased mechanical degradation
  - Potential costs associated with safeguards and security once the SNF is no longer self-protecting
- Transport
  - Increased shielding requirements (except for TRISO SNF) which increases weight or decreases payload, or both
  - For TRISO SNF, more canisters can be shipped per trip because of lower radiation hazard and decreased shielding requirements
  - More transport trips or larger transportation fleet because there are more canisters to move (particularly TRISO SNF)
    - More components needed in the transportation fleet
    - Increased fleet maintenance costs
    - Increased cask handling costs at the destination and the origin
  - Potential costs associated with safeguards and security once the SNF is no longer self-protecting
- Disposal
  - More canisters (particularly TRISO SNF canisters) to emplace, assuming more, smaller, specifically designed canisters or short-loaded DPCs

Criticality – HALEU SNF (except for TRISO SNF) will likely have more fissile material at the end of the fuel cycle than LEU SNF, resulting in the fuel being more reactive neutronically. TRISO SNF will also have more fissile material, but this fissile material will be spread over a larger volume of

SNF and may not pose as much of a challenge with respect to maintaining subcritical conditions. This may affect the economics of the back end of the nuclear fuel cycle in the following ways:

- Storage
    - Higher boron concentration in the spent fuel pools
    - Increased fuel spacing in the spent fuel pools
    - Fuel basket redesign in the dry storage canisters
    - Not loading the maximum number of assemblies in existing DPCs to ensure subcriticality, leading to the use of more canisters per energy generated
    - Designing and licensing canisters capable of maintaining subcritical conditions when loaded with the more reactive HALEU SNF
- Transport
    - Increased neutron absorbing material in canisters, which increases weight or decreases payload, or both
    - More transport trips or larger transportation fleet because there are more canisters to move
        - More components needed in the transportation fleet
        - Increased fleet maintenance costs
        - Increased cask handling costs at the destination and the origin
- Disposal
    - More or more robust neutron absorbers in the waste package to maintain subcritical conditions over repository timescales

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