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Quantifying the Economic Impacts of Managing Irradiated High-Assay Low-Enriched Fuel

Laura L. Price, Cathy Ottinger Farnum, and Elena Kalinina

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

Commercial nuclear power plants typically use nuclear fuel that is enriched up to 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 fuel 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. A previous report described these differences qualitatively (Price et al., 2024); this report builds on the previous report and provides quantitative estimates of the potential economic effects on storage, transport, and disposal of high assay low-enriched uranium spent fuel.

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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 up to 5 wt% ^{235}U. After it has been irradiated, the characteristic of high assay low-enriched uranium 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. A previous report (Price et al., 2024) discussed characteristics of this fuel and how they differ from that of typical irradiated fuel, and qualitatively described the economic effects of storing, transporting, and disposing of high assay low-enriched uranium spent nuclear fuel. The results presented herein build on that previous report and provide quantitative estimates of the economic effects of storing, transporting, and disposing of high assay low-enriched uranium spent nuclear fuel.

Three different fuels that may use high assay low-enriched uranium were studied: accident tolerant fuel that can be used in a typical light-water reactor, tri-structural isotropic fuel, and metallic fuel. Three 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 (Price et al. 2024). Building on that work, costs for storing, transporting, and disposing of irradiated high assay low-enriched uranium fuel were estimated; results are summarized in Table ES-1 by comparing the costs of storing, transporting, and disposing of irradiated high assay low-enriched uranium fuel to the cost of storing, transporting and disposing of typical irradiated light-water reactor fuel.

Table ES-1. Costs of the back end of the nuclear fuel cycle for three types of high assay low-enriched spent nuclear fuel compared to those for a typical light-water reactor.

	Storage Cost		Transportation Cost		Disposal Cost	
Type of High-Assay Low-Enriched Uranium Spent Fuel	**Per metric ton of heavy metal**	**Per energy generated**	**Per metric ton of heavy metal**	**Per energy generated**	**Per metric ton of heavy metal**	**Per energy generated**
Accident tolerant	About 2 times as much	About 10% more	About 2 times as much	About 12% more	About 2 times as much	About 10% more
Tri-structural isotropic	About 20 – 50 times as much	About 5 – 12 times as much	About 25 – 42 times as much	About 5 – 10 times as much	About 5 - 25 times as much	About 1 – 5 times as much
Metallic	About 60% more	About 50% less	About 2 times as much	About 50% less	About 1.6 times as much	About 50% less

Storage – The storage cost estimate is based on a cost estimate that assumed storage of 4,000 dual-purpose canisters for 20 years. Costs were adjusted to reflect the different quantities of each type of high-assay low-enriched spent fuel that could be stored in a given size canister. The cost per metric ton of heavy metal is proportional to the mass of spent fuel that can be placed inside a canister, which is limited by the fuel form, criticality concerns, and thermal limits. The storage cost per energy generated is related to the quantity of energy that can be generated by the mass of spent fuel in a canister; generating more energy per metric ton of heavy metal is beneficial in terms of storage cost per energy generated.

The storage of cost per metric ton of heavy metal for accident-tolerant spent fuel and for metallic spent fuel is about 2 times higher than it is for typical light-water reactor spent fuel. The storage cost per metric ton of heavy metal for tri-structural isotropic spent fuel is 20 to 50 times what it is for typical light-water reactor spent fuel, depending on the type of reactor that the tri-structural isotropic fuel was used in and whether the fuel is in the form of compacts in prismatic blocks or pebbles.

For accident tolerant spent fuel, the storage cost per energy generated is 1.1 times higher than it is for typical light-water reactor spent fuel. The storage cost per energy generated for tri-structural isotropic spent fuel is about 5 – 12 times higher than it is for typical light-water reactor spent fuel, once again depending on the type of reactor that the fuel was used in and its form. The storage cost per energy generated for metallic spent fuel is about half as much as it is for typical light-water reactor spent fuel.

Much of the storage cost (~85%) is from the cost of the canisters and their overpacks. Reducing the cost of these components, particularly for tri-structural isotropic spent fuel which is not as hot and does not emit as much radiation per volume as typical light-water reactor spent fuel, has the potential to reduce storage costs.

Transport - The total transportation cost is the sum of operational costs and fleet acquisition (capital cost). The longer the transportation campaign is, the lower is the total transportation cost per energy generated and per metric ton of heavy metal because the capital costs of the fleet are spread over a longer period of time. For example, these costs are ~25% higher in a 30-year campaign compared to a 60-year campaign for all types of spent fuel. The transportation cost per metric ton of heavy metal is also proportional to the mass of heavy metal that can be placed in a canister of a given size, which is limited by the fuel form, criticality concerns, and thermal limits. The transportation cost per energy generated is related to how much energy can be generated by the quantity of waste in a canister of a given size; generating more energy per metric ton of heavy metal is beneficial in terms of transportation cost per energy generated.

The transportation cost per metric ton of heavy metal is ~2 times higher for accident-tolerant fuel and metallic spent fuel than for typical light-water reactor spent fuel. The transportation cost per metric tons of heavy metal is about 25 - 42 times higher for tri-structural isotropic spent fuel, depending on the type of reactor that the tri-structural isotropic fuel was used in and whether the fuel is in the form of compacts in prismatic blocks or pebbles.

The transportation cost per energy generated is 1.1 times higher for accident tolerant spent fuel than for typical light-water reactor spent fuel. The transportation cost per energy generated is 5.5-10.5 times higher for tri-structural isotropic spent fuel, depending on the type of reactor that the tri-structural isotropic fuel was used in and whether the fuel was in the form of compacts in a prismatic block or pebbles. The transportation cost per energy generated is about half as much for metallic spent nuclear fuel than for typical light-water reactor spent fuel.

A ~30% reduction in transportation costs for tri-structural isotropic spent fuel can be achieved if a canister that is half as heavy and half as expensive can be developed for that type of spent fuel.

Disposal – It should be noted that disposal costs were based on designs for hypothetical repositories for disposing of spent nuclear fuel that emits a lot of heat per volume, such as accident tolerant spent fuel and metallic spent fuel. Hence, the disposal cost per energy generated for each of these two types of high assay low-enriched spent fuel are not that much different than that for typical light-water reactor spent nuclear fuel. Conversely, tri-structural isotropic fuel has low heavy metal loading per volume, resulting in a disposal cost (per metric ton of heavy metal and per energy generated) that can be much higher than that for typical light-water reactor spent fuel, as shown in Table ES-1. However, low heavy metal loading per volume also results in the spent fuel not emitting much heat per volume. Taking advantage of this characteristic by disposing of this type of fuel in a repository that is designed for waste that does not emit high heat per volume could lead to disposal costs that are significantly lower than those shown in Table ES-1. For example, rather than excavating drifts and emplacing waste packages with some distance between them (e.g., 20 or 30 meters) to meet thermal requirements, low-heat waste could be disposed of in a cavern-like repository in which waste packages are placed on top of and next to each other. By doing so, a larger fraction of the volume of excavated rock could be used for waste disposal.

ACRONYMS AND TERMS

Acronym/Term	Definition
ATF	Accident-tolerant fuel
BOC	Basis of Comparison
BWR	Boiling-water reactor
DOE	U.S. Department of Energy
DPC	Dual-purpose canister
EPRI	Electric Power Research Institute
FHR	Fluoride-cooled high-temperature reactor
FLiBe	Fluoride-lithium-beryllium
GISF	Generic interim storage facility
GWd	Gigawatt-day
GWe-yr	Gigawatt-electric-year
HALEU	High-assay low-enriched uranium
HTGR	High-temperature gas-cooled reactor
LEU	Low-enriched uranium
LWR	Light-water reactor
MTHM	Metric tons of heavy metal
NGSAM	New-Generation System Analysis Model
NRC	U.S. Nuclear Regulatory Commission
PWR	Pressurized water reactor
ROM	Rough order of magnitude
SFR	Sodium-cooled fast reactor
SNF	Spent nuclear fuel
TRISO	Tri-structural isotropic
U.S.	United States

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. A previous report (Price et al. 2024) identified qualitatively how the components of the back end of the nuclear fuel cycle 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. The work reported below builds on that previous report and quantifies how the costs of the back end of the nuclear fuel cycle are affected by managing irradiated spent HALEU fuel. Note that while LEU spent nuclear fuel (SNF) is currently stored and transported safely, disposal of LEU 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 quantify the economic effects of the use of HALEU on the back end of the nuclear fuel cycle, namely storage, transportation, and disposal.

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 quantifies the economic effects on storage, transportation, and disposal associated with the use of HALEU with respect to its use in ATF, TRISO fuel, and metallic fuel. The economic effects of 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 arising because it uses HALEU, not LEU.

The following sections discuss the spent nuclear fuels considered and their characteristics that are relevant to the cost calculations, (Section 2), storage costs (Section 3), transportation costs (Section 4), and disposal costs (Section 5). A summary and conclusions are given in Section 6.

1.3. Approach

The approach to estimating costs consisted of taking costs for the various components of the back end of the nuclear fuel cycle (storage, transportation, and disposal) as applied to typical LWR SNF, adjusting those costs to account for differences between typical LWR SNF and HALEU SNF, and estimating cost per metric ton of heavy metal (MTHM) and cost per energy generated. In estimating the costs, it was assumed that the large dry storage canisters currently employed for storage and transport of typical LWR SNF would be used for HALEU SNF. This assumption provides consistency of assumptions between storage, transportation, and disposal. It is acknowledged that storage and transportation systems for some of the HALEU SNF, particularly TRISO-based HALEU SNF, would likely be different (i.e., smaller) than those currently used for typical LWR SNF. However, little to no cost information is available for such systems; thus, it was not possible to evaluate these systems in this study.

The previous study identified thermal output, radiation, and criticality as the primary characteristics affecting the economics of the back end of the nuclear fuel cycle. Accordingly, most cost adjustments are based on one or more of these characteristics. Further details are given in each section.

2. SPENT NUCLEAR FUELS CONSIDERED

As noted above, the three types of HALEU SNF considered in the previous report (Price et al., 2024) were ATF, TRISO, and metallic (no sodium) SNF. This section provides a brief description of these fuels, along with a typical LWR SNF chosen as a basis of comparison (BOC), and values of multiple parameters that are used to estimate costs for storage, transportation, and disposal of these HALEU SNFs.

2.1. Typical LWR and ATF SNF

After the Fukushima Daiichi accident in 2011, the U.S. began researching ATF for use in current reactors 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 study focuses on the ATF concepts that include the use of HALEU oxide fuel in thermal spectrum reactors.

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.

The "typical LWR" SNF chosen as a BOC for this study is pressurized water reactor (PWR) fuel enriched to 4.2% and irradiated to an average discharge burnup of 50 GWd/MTHM (Wigeland et al., 2014). Hoffman et al. (2023) analyzed the characteristics of SNF for the BOC and for two PWR ATF SNFs, one with an enrichment of 7.0% and a burnup of 84 GWd/MTHM and one with an initial enrichment of 8.3% and a burnup of 100 GWd/MTHM. For the purpose of this comparison, the only difference between the BOC and these two HALEU ATF examples is the initial enrichment and burnup; all other information about the fuel assembly remains unchanged. Relevant parameters and their values for a 17x17 PWR fuel assembly for BOC fuel and the two HALEU ATF examples, as presented in Table 2-1 of Hoffman et al. (2023) are shown in Table 2-1.

Table 2-1. BOC and HALEU ATF Fuel Assembly Parameters

	PWR – 4.2% / 50 GWd/MTHM (BOC)	PWR – 7% / 84 GWd/MTHM	PWR – 8.3% / 100 GWd/MTHM
Overall assembly length, cm	427	427	427
Assembly width, cm	21.4	21.4	21.4
Length of fuel, cm	423	423	423
Assembly volume, cc	195,458	195,458	195,458
Fuel mass, kg U	539	539	539
Assembly mass, kg	736	736	736
Average discharge burnup, GWd/MTHM	50	84	100
Initial enrichment, weight fraction	4.2%	7.0%	8.3%
Net thermal efficiency	33%	33%	33%
Electrical generation, GWe-yr/MTHM	0.045	0.076	0.090

Source: Table 2-1 of Hoffman et al. (2023)

The cost estimates presented below are normalized to MTHM and to the quantity of energy produced (GWe-yr). The analysis performed by Hoffman et al. (2023) shows that ATF SNF has a much higher decay heat per assembly than does the BOC PWR SNF (Hoffman et al., 2023, Table 4-1). For the cost estimates made below, it is assumed that waste package thermal limits associated with each facility type (storage, transportation, and disposal) remain the same. Therefore, fewer assemblies of ATF SNF can be loaded into a given canister. Table 2-2 provides the heavy metal loading per canister for each type of SNF, assuming 5 years of cooling prior to loading, that are used to estimate the ratio of the MTHM of each type of ATF SNF to the ratio of the MTHM of the BOC SNF per canister, as taken from Table 4-4 of Hoffman et al. (2023). In this calculation, a 37-PWR canister with a 37-kW heat limit is used, but the ratio can be applied to smaller canisters as well.

Table 2-2. 37-PWR Canister Loading for BOC SNF and ATF SNF (5 years cooling, 37kW heat limit)

	PWR – 4.2% / 50 GWd/MTHM (BOC)	PWR – 7% / 84 GWd/MTHM	PWR – 8.3% / 100 GWd/MTHM
Heavy metal loading in 37-PWR canister (MTHM)	12.93	7.01	5.93
Ratio of MTHM ATF per canister to MTHM BOC SNF per canister	N/A	0.54	0.46

Source: Table 4-4 of Hoffman et al. (2023)

The energy produced by the quantity of SNF (MTHM) in a given canister is also needed to calculate cost per energy generated. Table 2-3 provides the MTHM/GWe-yr for BOC SNF as well as each type of ATF SNF, as calculated from Table 2-1of Hoffman et al. (2023).

Table 2-3. MTHM per Energy Generated for BOC SNF and ATF SNF

	PWR – 4.2% / 50 GWd/MTHM (BOC)	PWR – 7% / 84 GWd/MTHM	PWR – 8.3% / 100 GWd/MTHM
MTHM/GWe-yr	22.22	13.16	11.11

Source: Table 2-1 of Hoffman et al. (2023)

2.2. TRISO SNF

TRISO fuel is different from BOC 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 2-1 (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).

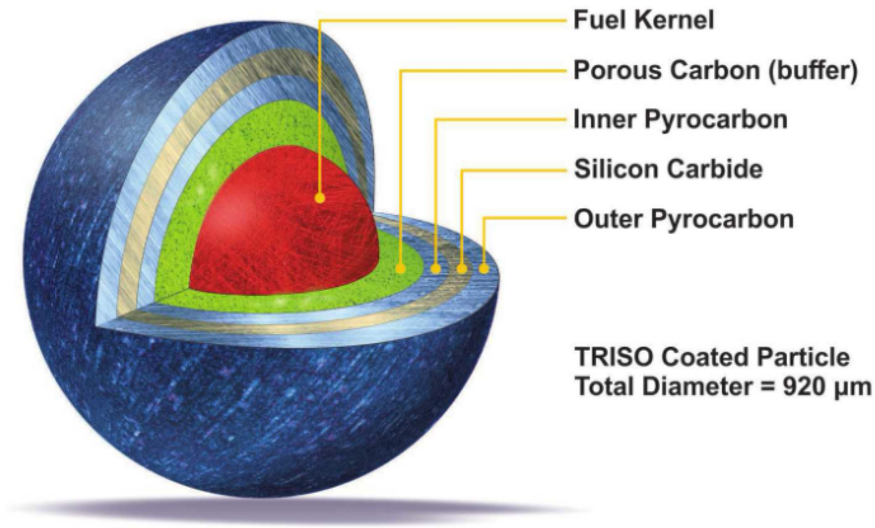

Figure 2-1. Schematic Drawing of a TRISO Fuel Particle with Four Protective Layers (Pyrocarbon - pyrolytic carbon) (Sassani et al., 2018)

TRISO fuel can be used in either a prismatic block reactor or in a pebble bed reactor. Both types of reactors use fuel with higher enrichment than BOC fuel (14 - 19.75%) and are expected to reach high burnups (>120 GWd/MTHM). 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 a pebble bed reactor, ~60 mm diameter graphite-covered spherical pebbles composed of graphite and TRISO particles move freely through the reactor. For this study, two different pebble-bed reactors were considered, a high-temperature gas cooled reactor (HTGR) and a fluoride-salt cooled high-temperature reactor (FHR).

As reported in Hoffman et al (2023), the relevant parameters for the two pebble-bed TRISO fuels are given in Table 2-4, while the relevant parameters for the prismatic block TRISO fuel are given in Table 2-5. The HTGR uses helium as a coolant and the parameters shown here were developed from publicly available information on the X-Energy's Xe-100 concept. The other pebble-bed reactor uses a fluoride-lithium-beryllium (FLiBe) salt as a coolant.

Table 2-4. TRISO Pebble Fuel Parameters

	Xe-100-like Pebble	FHR Pebble
Reactor coolant	He	FLiBe
Pebble diameter, cm	6.0	3.0
Pebble volume, cc	113	14
Fuel mass, kg U/pebble	0.0070	0.0015
Pebble mass, kg	0.13	0.02
Average discharge burnup, GWd/MTHM	165	180
Initial enrichment, weight percent	15.5%	19.9 %
Net thermal efficiency	40%	43%
Electrical generation, GWe-yr/MTHM	0.181	0.209

Source: Table 2-2 of Hoffman et al. (2023)

Table 2-5. TRISO Prismatic Block Fuel Parameters

	HTGR Prismatic Block
Overall assembly length, cm	79.3
Assembly width, cm	36.0
Length of fuel, cm	78.8
Assembly volume, cc	89,004
Fuel mass, kg U	7.8
Assembly mass, kg	83
Average discharge burnup, GWd/MTHM	120
Initial enrichment, weight percent	15.5%
Net thermal efficiency	50%
Electrical generation, GWe-yr/MTHM	0.164

Source: Table 2-3 of Hoffman et al., (2023)

The cost estimates presented below are normalized to MTHM and to the quantity of energy produced (GWe-yr). The analysis performed by Hoffman et al. (2023) shows that TRISO SNF has a much lower decay heat per volume than does the BOC SNF (Table 4-1 and Table 4-2 of Hoffman et al. (2023)). Therefore, for the disposal cost estimates made below, it is assumed that the waste package associated with each of the disposal geologies is filled with the same volume of TRISO pebbles or prismatic blocks. Table 2-6 provides the parameter values used to estimate the ratio of the MTHM of each type of TRISO SNF per canister to the ratio of the MTHM of the BOC SNF per canister, as taken from Table 4-1 and Table 4-2 of Hoffman et al. (2023). In this calculation, a 37--PWR canister is used, but the ratio can be applied to smaller canisters as well.

Table 2-6. 37-PWR Canister Loading for BOC SNF and TRISO SNF

	PWR – 4.2% / 50 GWd/MTHM (BOC)	Pebble Bed – HTGR	Prismatic Block	Pebble Bed – FHR
Heavy metal loading in 37-PWR canister (MTHM)	12.93	0.3	0.6	0.5
Ratio of MTHM TRISO per canister to MTHM BOC SNF per canister	N/A	0.02	0.05	0.04

Source: Table 4-1 and Table 4-2 of Hoffman et al. (2023).

The energy produced by the quantity of SNF (MTHM) in a given canister is also needed to calculate cost per energy generated. Table 2-7 provides the MTHM/GWe-yr for BOC SNF as well as for each type of TRISO SNF, as calculated from Table 2-1, Table 2-2, and Table 2-3 of Hoffman et al. (2023).

Table 2-7. MTHM per Energy Generated for BOC SNF and TRISO SNF

	PWR – 4.2% / 50 GWd/MTHM (BOC)	Pebble Bed – HTGR	Prismatic Block	Pebble Bed – FHR
MTHM/GWe-yr	22.22	5.52	6.10	4.78

Source: Table 2-1, Table 2-2, and Table 2-3 of Hoffman et al. (2023)

2.3. Metallic SNF

Metallic fuel consists of fuel composed of uranium or uranium alloys (e.g., uranium-molybdenum) with zirconium or non-zirconium cladding. To facilitate heat transfer 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 spent fuel is known as "sodium-bonded" spent fuel and is not considered in this report. Metallic fuels that do not have sodium interior to the fuel rod are referred to as "non-sodium bonded" spent fuel in this discussion and are the spent fuels studied in this report.

As reported by Hoffman et al. (2023), the relevant parameters for metallic SNF are given in Table 2-8. The metallic fuel chosen by Hoffman et al. (2023) is similar to the commercial version of the Natrium fuel proposed by TerraPower LLC for use in their sodium-cooled fast reactor (SFR). This concept uses sodium-free annular fuel that is in contact with the cladding to conduct heat while accommodating fuel swelling within the central void of the fuel.

Table 2-8. Metallic Fuel Assembly Parameters

	Metallic Fuel - Natrium-like SFR
Overall assembly length, cm	470
Assembly width, cm	16.1
Length of fuel, cm	120
Assembly volume, cc	106,054
Fuel mass, kg U	111
Assembly mass, kg	431
Average discharge burnup, GWd/MTHM	147.3
Initial enrichment, weight percent	17.6%
Net thermal efficiency	40%
Electrical generation, GWe-yr/MTHM	0.161

Source: Table 2-4 of Hoffman et al. (2023)

The cost estimates presented below are normalized to MTHM and to the quantity of energy produced (GWe-yr). The analysis performed by Hoffman et al., (2023) shows that SFR SNF has a slightly lower decay heat per volume than does the BOC SNF (Table 4-2 of Hoffman et al. (2023)) but that the fissile mass of discharged SFR SNF is about three times the fissile mass of discharged BOC SNF. Therefore, for the cost estimates made below, it is assumed that loading of metallic SNF into the waste package associated with each of the disposal geologies is not limited by the heat generated by the SNF but that additional neutron absorbing materials or components need to be added to maintain subcritical conditions. Table 2-9 provides the parameter values used to estimate the ratio of the MTHM of each type of metallic SNF per canister to the ratio of the MTHM of the BOC SNF per canister, as taken from Table 4-2 of Hoffman et al. (2023). In this calculation, a 37-PWR canister is used, but the ratio can be applied to smaller canisters as well.

Table 2-9. 37-PWR Canister Loading for BOC SNF and Metallic SNF

	PWR – 4.2% / 50 GWd/MTHM (BOC)	Metallic Fuel – Natrium-like SFR
Heavy metal loading in 37-PWR canister (MTHM)	12.93	8.3
Ratio of MTHM Metallic SNF per canister to MTHM BOC SNF per canister	N/A	0.64

Source: Table 4-2 of Hoffman et al. (2023).

The energy produced by the quantity of SNF (MTHM) in a given canister is also needed to calculate cost per energy generated. Table 2-10 provides the MTHM/GWe-yr for BOC SNF and metallic SFR SNF as calculated from Table 2-1 and Table 2-4 of Hoffman et al. (2023).

Table 2-10. MTHM per Energy Generated for BOC SNF and Metallic SNF

	PWR – 4.2% / 50 GWd/MTHM (BOC)	Metallic Fuel – Natrium-like SFR
MTHM/GWe-yr	22.22	6.21

Source: Table 2-1 and Table 2-4 of Hoffman et al. (2023)

3. STORAGE

Storage costs were estimated based on the report "Cost Estimate for an Away-From-Reactor Generic Interim Storage Facility (GISF) for Spent Nuclear Fuel" (EPRI, 2009). Costs were escalated from 2009$ to 2024$ by a factor of 1.46.

3.1. Approach to Storage Cost Estimates

The high burnup and high enrichment of HALEU SNF compared to BOC SNF affect the thermal, shielding, and criticality considerations of the dry storage casks. The higher decay heat and fission activity of high burnup fuels, including HALEU SNF, affect what is needed to meet thermal and shielding requirements. The higher enrichment affects what is required to meet criticality requirements. So, using existing dry storage canisters and casks for HALEU SNF will result in reduced canister capacity to meet the storage dose limits and cladding temperature limits. These canisters will then be transported as described in Section 4 and disposed as described in Section 5.

The assumptions made in Section 2 for the ratio of MTHM HALEU SNF per canister to MTHM BOC SNF per canister and the MTHM per energy generated for BOC SNF and HALEU SNF are summarized again in Table 3-1 for each HALEU type.

Table 3-1. Ratio of HALEU MTHM per Canister Compared to BOC MTHM per Canister and MTHM per Energy Generated.

Waste Type	Ratio (HALEU MTHM per canister to BOC MTHM per canister)	MTHM/GWe-yr
BOC	N/A	22.22
ATF - 7% enrichment	0.54	13.16
ATF - 8.3% enrichment	0.46	11.11
TRISO - HTGR pebble bed	0.02	5.52
TRISO - HTGR prismatic block	0.05	6.10
TRISO - FHR pebble bed	0.04	4.78
Metallic	0.64	6.21

3.2. Basis of Cost Storage Cost Calculation

Electric Power Research Institute (EPRI) prepared a cost estimate for the design, licensing, construction, and operation of a generic interim SNF storage facility (EPRI, 2009). The base case for the cost estimate assumed a 40,000 MTHM capacity generic interim storage facility (GISF) that would operate for a 40-year period. During the first 20 years, the GISF would receive SNF for storage at a rate of 2,000 MT per year and during the second 20 years, the GISF would ship the SNF offsite. Although the EPRI report also evaluated alternative capacities of 20,000 and 60,000 MTHM, the 40,000 MTHM base case was used for this report. The assumptions in the EPRI report and therefore, this report are:

- 40,000 MTHM storage capacity
- 2,000 MTHM/year
- 200 dual-purpose canisters (DPCs)/year
- 20-year period

- 4,000 DPCs stored
- 58% of the DPCs contain SNF from pressurized water reactors (PWRs), 42% of them contain SNF from boiling water reactors (BWRs)

The EPRI analysis assumed that each DPC held 10 MTHM of SNF. To be consistent with the other sections in this report, for the cost per MTHM calculations performed herein, it is assumed that each DPC holds 12.93 MTHM of SNF, as shown in Table 2-2. Therefore, instead of the storage facility storing 40,000 MTHM of SNF, in the analysis presented below, the storage facility for BOC SNF is assumed to hold 51,720 MTHM (4,000 DPCs × 12.93 MTHM/DPC)

The Fort St. Vrain Independent Spent Fuel Storage Installation was built and holds the Fort St. Vrain thorium-uranium carbide TRISO spent fuel. The fuel is micro-spherical particles comprised of thorium-uranium carbide with three carbon-based protective coatings, as shown in Figure 2-1. The fuel is highly enriched uranium (originally enriched to about 93.5% U-235). The security requirements for this highly enriched fuel drive a different and more costly dry storage facility than what is required for HALEU, so the Fort St. Vrain costs are not typical of that needed for a HALEU dry storage facility and are not useful for this report (NWTRB 2020).

The costs for each component of a dry storage flat concrete pad storage facility are shown in Table 3-2. The EPRI report used costs in 2009$. Costs were escalated from 2009$ to 2024$ by a factor of 1.46 based on the on-line Consumer Price Index.

Table 3-2. Costs of Dry Storage System for PWR and BWR per MTHM.

Dry Storage System Component	Fixed Costs for 40,000 MTHM (Millions2009$)	2009$/MTHM	2024$/MTHM
Design, engineering, licensing, startup professional services includes: (EPRI section 2.1)	$67.4	$1,303	$1,902
pre-license submittal: siting, design, engineering services (EPRI Table 2.1)	$18.1		
License application review: siting, design, engineering services (EPRI Table 2-2)	$40.3		
initial construction: pre-operations phase, siting, design, engineering services (EPRI Table 2-3)	$9.0		
capital costs, infrastructure includes: (EPRI Table 2-7) administrative building, security and health physics building, operations and maintenance building, canister transfer building	$40.8	$789	$1,152
fuel storage facility includes: (EPRI Table 2-8)	$87.1	$1,684	$2,459
concrete storage pads (largest cost driver, ~80%)	20 ft x 30 ft x 3 ft per cask 4,000 DPCs		

Dry Storage System Component	Fixed Costs for 40,000 MTHM (Millions2009$)	2009$/MTHM	2024$/MTHM
security fence	1500x1600 ft x 2 fences		
security system	lighting, intrusion detection, CCTV, monitoring		
Subtotal		**$3,776**	**$5,513**
annual operating costs (20-year total) includes: (EPRI Table 2-9)			
office expenses	$54.6	$1,056	$1,541
annual labor – loading/unloading (EPRI Table2-12)	$160.0	$3,093	$4,517
annual labor – caretaker periods (EPRI Table 2-13)	$74.0	$1,430	$2,089
annual labor – loading/unloading (EPRI Table 2-14)	$170.0	$3,287	$4,799
Subtotal		**$8,867**	**$12,946**
Canisters and Overpacks (20-year total) includes: (EPRI Table 2-10)			
DPCs: 116 PWR, 84 BWR DPC per year	$3,858	$74,594	$108,907
200 concrete overpacks per year	$1,040	$20,108	$29,358
Subtotal		**$94,702**	**$138,265**
Decommissioning Facility and overpacks (EPRI Section 2.5)	$225	**$4,350**	**$6,352**
Total		**$111,696**	**$163,075**

3.3. Storage Cost Calculation for ATF SNF

The costs of storing the different types of ATF are calculated by taking the storage costs shown in Table 3-2 and dividing by the appropriate ratios shown in Table 3-1. The results of this calculation are shown in Table 3-3. With the higher HALEU enrichments, the capacity of the dry storage canisters and casks are lower than for the BOC, resulting in less mass of SNF (MTHM) being stored per canister and a higher cost per MTHM. Thus, storage costs per MTHM of ATF are about double the storage cost for BOC SNF, corresponding to the lower MTHM per canister for ATF SNF

Table 3-3. Costs of Dry Storage System for BOC SNF and ATF per MTHM

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/MTHM)	ATF SNF- 7%/84 GWd/MTHM (2024$/MTHM)	ATF SNF - 8.3%/100 GWd/MTHM (2024$/MTHM)
Design, engineering, licensing, startup professional services includes: (EPRI section 2.1) pre-license submittal: siting, design, engineering services (EPRI Table 2.1) License application review: siting, design, engineering services (EPRI Table 2-2) initial construction: pre-operations phase, siting, design, engineering services (EPRI Table 2-3)	$1,902	$3,522	$4,135
capital costs, infrastructure includes: (EPRI Table 2-7) administrative building security and health physics building operations and maintenance building canister transfer building	$1,152	$2,133	$2,504
fuel storage facility includes: (EPRI Table 2-8) concrete storage pads (largest cost driver, ~80%) security fence security system	$2,459	$4,554	$5,346
Subtotal	**$5,513**	**$10,209**	**$11,985**
annual operating costs (20-year total) includes: (EPRI Table 2-9)			
office expenses	$1,541	$2,854	$3,350
annual labor – loading/unloading (EPRI Table2-12)	$4,517	$8,365	$9,820
annual labor – caretaker periods (EPRI Table 2-13)	$2,089	$3,869	$4,541
annual labor – loading/unloading (EPRI Table 2-14)	$4,799	$8,887	$10,433
Subtotal	**$12,946**	**$23,974**	**$28,144**
Canisters and Overpacks (20-year total) includes: (EPRI Table 2-10)			
DPCs: 116 PWR, 84 BWR DPC per year	$108,907	$201,679	$236,754
200 concrete overpacks per year	$29,358	$54,367	$63,822

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/MTHM)	ATF SNF- 7%/84 GWd/MTHM (2024$/MTHM)	ATF SNF - 8.3%/100 GWd/MTHM (2024$/MTHM)
Subtotal	**$138,265**	**$256,046**	**$300,576**
Decommissioning Facility and overpacks (EPRI Section 2.5)	**$6,352**	**$11,763**	**$13,808**
Total	**$163,076**	**$301,993**	**$354,513**
Ratio to BOC Cost	**1.0**	**1.85**	**2.17**

The costs per energy generated of storing the ATF are calculated by multiplying the values in Table 3-3 by MTHM per GWe-yr for each type of ATF; the results are shown in Table 3-4. These calculations indicate that, on a basis of the cost per energy generated, it is about 10% more expensive to store ATF SNF than it is to store BOC SNF.

Table 3-4. Costs of Dry Storage System for BOC SNF and ATF per Energy Generated

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/GWe-yr)	ATF SNF - 7%/84 GWd/MTHM (2024$/GWe-yr)	ATF SNF - 8.3%/100 GWd/MTHM (2024$/GWe-yr)
Design, engineering, licensing, startup professional services includes: (EPRI section 2.1) pre-license submittal: siting, design, engineering services (EPRI Table 2.1) License application review: siting, design, engineering services (EPRI Table 2-2) initial construction: pre-operations phase, siting, design, engineering services (EPRI Table 2-3)	$42,262	$46,350	$45,940
capital costs, infrastructure includes: (EPRI Table 2-7) administrative building security and health physics building operations and maintenance building canister transfer building	$25,597	$28,070	$27,819

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/GWe-yr)	ATF SNF - 7%/84 GWd/MTHM (2024$/GWe-yr)	ATF SNF - 8.3%/100 GWd/MTHM (2024$/GWe-yr)
fuel storage facility includes: (EPRI Table 2-8) concrete storage pads (largest cost driver, ~80%) security fence security system	$54,639	$59,930	$59,394
Subtotal	**$122,498**	**$134,350**	**$133,153**
annual operating costs (20-year total) includes: (EPRI Table 2-9)			
office expenses	$34,241	$37,559	$37,219
annual labor – loading/unloading (EPRI Table2-12)	$100,368	$110,083	$109,100
annual labor – caretaker periods (EPRI Table 2-13)	$46,418	$50,916	$50,451
annual labor – loading/unloading (EPRI Table 2-14)	$106,634	$116,953	$115,910
Subtotal	**$287,661**	**$315,511**	**$312,680**
Canisters and Overpacks (20-year total) includes: (EPRI Table 2-10)			
DPCs: 116 PWR, 84 BWR DPC per year	$2,419,914	$2,654,096	$2,630,337
200 concrete overpacks per year	$652,335	$715,470	$709,062
Subtotal	**$3,072,249**	**$3,369,565**	**$3,339,399**
Decommissioning Facility and overpacks (EPRI Section 2.5)	**$141,141**	**$154,801**	**$153,407**
Total	**$3,623,549**	**$3,974,228**	**$3,938,639**
Ratio to BOC Cost	**1.0**	**1.10**	**1.09**

3.4. Storage Cost Calculation for TRISO SNF

The costs per MTHM of storing the different types of TRISO spent fuel are shown in Table 3-5. These were calculated by taking the storage costs as calculated in Section 3.2 and dividing by the appropriate ratios shown in Table 3-1. Not surprisingly, costs scale directly with the MTHM loading per canister, as shown in Table 2-6.

Table 3-5. Costs per MTHM of Dry Storage for BOC SNF and Different Types of TRISO SNF

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/MTHM)	TRISO – HTGR Pebble Bed (2024$/MTHM)	TRISO – HTGR Prismatic Block (2024$/MTHM)	TRISO – FHR Pebble Bed (2024$/MTHM)
Design, engineering, licensing, startup professional services includes: (EPRI section 2.1) pre-license submittal: siting, design, engineering services (EPRI Table 2.1) License application review: siting, design, engineering services (EPRI Table 2-2) initial construction: pre-operations phase, siting, design, engineering services (EPRI Table 2-3)	$1,902	$95,100	$38,040	$47,550
capital costs, infrastructure includes: (EPRI Table 2-7) administrative building security and health physics building operations and maintenance building canister transfer building	$1,152	$57,600	$23,040	$28,800
fuel storage facility includes: (EPRI Table 2-8) concrete storage pads (largest cost driver, ~80%) security fence security system	$2,459	$122,950	$49,180	$61,475
Subtotal	**$5,513**	**$275,650**	**$110,260**	**$137,825**
annual operating costs (20-year total) includes: (EPRI Table 2-9)				
office expenses	$1,541	$77,050	$30,820	$38,525
annual labor – loading/unloading (EPRI Table2-12)	$4,517	$225,850	$90,340	$112,925
annual labor – caretaker periods (EPRI Table 2-13)	$2,089	$104,450	$41,780	$52,225
annual labor – loading/unloading (EPRI Table 2-14)	$4,799	$239,950	95,980	$119,975
Subtotal	**$12,946**	**$647,300**	**$258,920**	**$323,650**

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/MTHM)	TRISO – HTGR Pebble Bed (2024$/MTHM)	TRISO – HTGR Prismatic Block (2024$/MTHM)	TRISO – FHR Pebble Bed (2024$/MTHM)
Canisters and Overpacks (20-year total) includes: (EPRI Table 2-10)				
DPCs: 116 PWR, 84 BWR DPC per year	$108,907	$5,445,350	$2,178,140	$2,722,675
200 concrete overpacks per year	$29,358	$1,467,900	$587,160	$733,950
Subtotal	**$138,265**	**$6,913,250**	**$2,765,300**	**$3,456,625**
Decommissioning Facility and overpacks (EPRI Section 2.5)	**$6,352**	**$317,600**	**$127,040**	**$158,800**
Total	**$163,076**	**$8,153,800**	**$3,261,520**	**$4,076,900**
Ratio to BOC Cost	**1**	**50**	**20**	**25**

The costs per energy generated of storing the different types of TRISO SNF are calculated by multiplying the values in Table 3-5 by MTHM per GWe-yr for each type of ATF (from Table 2-7); the results are shown in Table 3-6. These calculations indicate that, on a basis of cost per energy generated, storage of the different types of TRISO SNF are about 5 to 12 times greater than the cost of storing BOC SNF.

Table 3-6. Costs Per Energy Generated for Dry Storage of BOC SNF and Different Types of TRISO SNF

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/GWe-yr)	TRISO – HTGR Pebble Bed (2024$/GWe-yr)	TRISO – HTGR Prismatic Block (2024$/GWe-yr)	TRISO – FHR Pebble Bed (2024$/GWe-yr)
Design, engineering, licensing, startup professional services includes: (EPRI section 2.1) pre-license submittal: siting, design, engineering services (EPRI Table 2.1) License application review: siting, design, engineering services (EPRI Table 2-2) initial construction: pre-operations phase, siting, design, engineering services (EPRI Table 2-3)	$42,262	$524,952	$232,044	$227,289

Dry Storage System Component	**BOC SNF – 4.2% /50 GWd/MTHM (2024$/GWe-yr)**	**TRISO – HTGR Pebble Bed (2024$/GWe-yr)**	**TRISO – HTGR Prismatic Block (2024$/GWe-yr)**	**TRISO – FHR Pebble Bed (2024$/GWe-yr)**
capital costs, infrastructure includes: (EPRI Table 2-7) administrative building security and health physics building operations and maintenance building canister transfer building	$25,597	$317,952	$140,544	$137,664
fuel storage facility includes: (EPRI Table 2-8) concrete storage pads (largest cost driver, ~80%) security fence security system	$54,639	$678,684	$299,998	$293,850
Subtotal	**$122,498**	**$1,521,588**	**$672,586**	**$658,803**
annual operating costs (20-year total) includes: (EPRI Table 2-9)				
office expenses	$34,241	$425,321	$188,002	$184,149
annual labor – loading/unloading (EPRI Table2-12)	$100,368	$1,246,692	$551,074	$539,781
annual labor – caretaker periods (EPRI Table 2-13)	$46,418	$576,564	$254,858	$249,635
annual labor – loading/unloading (EPRI Table 2-14)	$106,634	$1,324,524	$585,478	$573,480
Subtotal	**$287,661**	**$3,573,101**	**$1,579,412**	**$1,547,046**
Canisters and Overpacks (20-year total) includes: (EPRI Table 2-10)				
DPCs: 116 PWR, 84 BWR DPC per year	$2,419,914	$30,058,338	$13,286,654	$13,014,387
200 concrete overpacks per year	$652,335	$8,102,808	$3,581,676	$3,508,281
Subtotal	**$3,072,249**	**$38,161,140**	**$16,868,330**	**$16,522,667**

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/GWe-yr)	TRISO – HTGR Pebble Bed (2024$/GWe-yr)	TRISO – HTGR Prismatic Block (2024$/GWe-yr)	TRISO – FHR Pebble Bed (2024$/GWe-yr)
Decommissioning Facility and overpacks (EPRI Section 2.5)	**$141,141**	**$1,753,157**	**$774,944**	**$759,064**
Total	**$3,623,549**	**$45,008,986**	**$19,895,272**	**$19,487,580**
Ratio to BOC Cost	**1.0**	**12**	**5.5**	**5.4**

3.5. Storage Cost Calculation for Metallic SNF

The costs per MTHM of storing the metallic SNF fuel are calculated by taking the storage costs shown in Table 3-2 and dividing by the metallic fuel ratio shown in Table 3-1; results are shown in Table 3-7. Results indicate that it costs about 60% more, on a basis of cost per MTHM, to store metallic SNF than it costs to store BOC SNF.

Table 3-7. Costs per MTHM for Dry Storage of BOC SNF and Metallic SNF

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/MTHM)	Metallic SNF – Natrium-like SFR (2024$/MTHM)
Design, engineering, licensing, startup professional services includes: (EPRI section 2.1) pre-license submittal: siting, design, engineering services (EPRI Table 2.1) License application review: siting, design, engineering services (EPRI Table 2-2) initial construction: pre-operations phase, siting, design, engineering services (EPRI Table 2-3)	$1,902	$2,972
capital costs, infrastructure includes: (EPRI Table 2-7) administrative building security and health physics building operations and maintenance building canister transfer building	$1,152	$1,800
fuel storage facility includes: (EPRI Table 2-8) concrete storage pads (largest cost driver, ~80%) security fence security system	$2,459	$3,842
Subtotal	**$5,513**	**$8,614**
annual operating costs **(20-year total)** includes:		

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/MTHM)	Metallic SNF – Natrium-like SFR (2024$/MTHM)
(EPRI Table 2-9)		
office expenses	$1,541	$2,408
annual labor – loading/unloading (EPRI Table2-12)	$4,517	$7,058
annual labor – caretaker periods (EPRI Table 2-13)	$2,089	$3,264
annual labor – loading/unloading (EPRI Table 2-14)	$4,799	$7,498
Subtotal	**$12,946**	**$20,228**
Canisters and Overpacks (20-year total) includes: (EPRI Table 2-10)		
DPCs: 116 PWR, 84 BWR DPC per year	$108,907	$170,167
200 concrete overpacks per year	$29,358	$45,872
Subtotal	**$138,265**	**$216,039**
Decommissioning Facility and overpacks (EPRI Section 2.5)	**$6,352**	**$9,925**
Total	**$163,076**	**$254,806**
Ratio to BOC Cost	**1.0**	**1.6**

The cost per energy generated of storing metallic SNF are calculated by multiplying the values in Table 3-7 by the MTHM per GWe-yr for metallic SNF, as shown in Table 3-1. Results are shown in Table 3-8 and indicate that, on a basis of cost per energy generated, storage of metallic SNF costs about half as much as storage of BOC SNF.

Table 3-8. Costs per Energy Generated of Dry Storage for BOC and Metallic SNF

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/GWe-yr)	Metallic SNF – Natrium-like SFR (2024$/GWe-yr)
Design, engineering, licensing, startup professional services includes: (EPRI section 2.1) pre-license submittal: siting, design, engineering services (EPRI Table 2.1) License application review: siting, design, engineering services (EPRI Table 2-2) initial construction: pre-operations phase, siting, design, engineering services (EPRI Table 2-3)	$42,262	$18,456
capital costs, infrastructure includes: (EPRI Table 2-7) administrative building	$25,597	$11,178

Dry Storage System Component	BOC SNF – 4.2% /50 GWd/MTHM (2024$/GWe-yr)	Metallic SNF – Natrium-like SFR (2024$/GWe-yr)
security and health physics building operations and maintenance building canister transfer building		
fuel storage facility includes: (EPRI Table 2-8) concrete storage pads (largest cost driver, ~80%) security fence security system	$54,639	$23,859
Subtotal	**$122,498**	**$53,493**
annual operating costs **(20-year total)** includes: (EPRI Table 2-9)		
office expenses	$34,241	$14,954
annual labor – loading/unloading (EPRI Table2-12)	$100,368	$43,830
annual labor – caretaker periods (EPRI Table 2-13)	$46,418	$20,269
annual labor – loading/unloading (EPRI Table 2-14)	$106,634	$46,563
Subtotal	**$287,661**	**$125,616**
Canisters and Overpacks **(20-year total)** includes: (EPRI Table 2-10)		
DPCs: 116 PWR, 84 BWR DPC per year	$2,419,914	$1,056,737
200 concrete overpacks per year	$652,335	$284,865
Subtotal	**$3,072,249**	**$1,341,602**
Decommissioning Facility and overpacks (EPRI Section 2.5)	**$141,141**	**$61,634**
Total	**$3,623,549**	**$1,582,345**
Ratio to BOC Cost	**1.0**	**0.44**

4. TRANSPORTATION

A simplified approach was developed to estimate the potential differences in transportation costs of HALEU SNF compared to BOC SNF. This approach is described in Section 4.1. Sections 4.2 – 4.4 provide transportation cost estimates for ATF, TRISO, and Metallic SNF respectively.

4.1. Approach to Estimating Transportation Costs

The high burnup and high enrichment of HALEU SNF compared to BOC SNF have significant effects on thermal, shielding, and criticality considerations associated with the transportation system. High burnup affects what is required to meet thermal and shielding requirements due to the higher decay heat and fission activity of the HALEU SNF. High enrichment affects what is required to meet criticality requirements. Consequently, using existing dry storage canisters for HALEU SNF will result in reduced canister capacity (MTHM loaded per canister) to comply with the transportation dose limits and cladding temperature limits in case of ATF. HALEU.

The assumptions made in Section 2 regarding the ratio of MTHM HALEU SNF per canister to MTHM BOC SNF per canister are summarized in Table 4-1 for different types of HALEU SNF. Also summarized in Table 4-1 are the MTHM per energy generated for BOC SNF and HALEU SNF.

Table 4-1. MTHM per Canister, MTHM per Canister Ratio, MTHM per Energy Generated, and MTHM per Energy Generated Ratio

Waste Type	MTHM per Canister	MTHM per Canister Ratio	MTHM per GWe-yr	MTHM per GWe-yr Ratio
BOC	13.0	N/A	22.22	N/A
ATF – 7% enrichment	7.01	0.54	13.16	0.592
ATF – 8.3% enrichment	5.93	0.46	11.11	0.500
TRISO – HTGR Pebble Bed	0.30	0.02	5.52	0.248
TRISO - HTGR Prismatic Block	0.60	0.05	6.10	0.275
TRISO – FHR Pebble Bed	0.50	0.04	4.78	0.215
Metallic	8.3	0.64	6.21	0.280

It is commonly assumed that a geologic repository acceptance rate would be 3,000 MTHM per year of LWR SNF, consistent with what was planned for the proposed repository at Yucca Mountain (DOE 2008b, Section 1.2.1.1.2). To be consistent with this assumption, the annual transportation rate is assumed to be 3,000 MTHM for BOC SNF. This quantity of BPC SNF produces 135 GWe-yr of energy. The HALEU SNF annual transportation rates in MTHM transported per year (Table 4-2) were calculated as the BOC annual transportation rate times the corresponding MTHM/GWe-yr ratio from Table 4-1.

The number of canisters to be transported each year was calculated by dividing the MTHM transported per year by the MTHM per canister for each type of HALEU SNF (found in Table 4-1).In the calculations, it was assumed that the same type of canister will be used for LWR and for HALEU SNF. The annual MTHM transportation rates and number of canisters transported annually are provided in Table 4-2 for the different types of SNF.

Table 4-2. Annual Transportation Rate and Number of Canisters of Different SNF Types

Waste Type	Annual MTHM Transported	Canisters/yr
BOC	3,000	231
ATF - 7% enrichment	1,777	254
ATF - 8.3% enrichment	1,500	253
TRISO - HTGR pebble bed	745	2,497
TRISO - HTGR prismatic block	824	1,373
TRISO - FHR pebble bed	645	1,291
Metallic	838	102

The following costs were estimated for BOC SNF and HALEU SNF:
-Total capital costs of acquisition of transportation fleet
- Annual operational cost of transportation

Note that the total transportation cost is the total fleet cost plus the annual operational costs times the duration of transportation campaign. The duration of transportation campaign depends on the total anticipated inventory of HALEU SNF that is not known. A convenient metric is cost per energy generated. Consequently, the effects on transportation costs of HALEU SNF can be expressed in terms of increase or decrease (delta) in cost per energy generated with HALEU fuel compared to the cost of energy generated with LWF fuel.

4.2. Transportation Cost Calculation

The following assumptions were made about the transportation campaign:

- The canisters are loaded in type B transportation casks for transport. The transportation casks are equipped with 2 impact limiters. The casks and impact limiters are reusable.
- The transportation casks are loaded either into Atlas or Fortis railcars meeting S-2043 requirements for transport of SNF (AAR, 2023)
- A dedicated train is used for transport. The train has 2 buffer railcars and one escort railcar.
- The transportation fleet (transportation casks, impact limiters, cask railcars, buffer railcars, and escort railcars) is sufficient to maintain the annual transportation rate of BOC and HALEU SNF (Table 4-2).
- The SNF is transported from the reactor sites to a hypothetical location set in the center of the U.S.
- The costs of the heavy haul and barge transport from some reactor sites to a near rail are not considered. However, the average duration of a roundtrip considers the additional time required for this transport.
- The transportation roundtrip cycle consists of time of travel of a dedicated train from destination site to the reactor site, time needed to transfer the transportation casks from the reactor site (by heavy haul or barge, if needed) to the rail node, time needed to load the cask

on the railcars, time of travel to the destination, and time of unloading the casks at destination.

- The fleet/cask maintenance facility is co-located with the destination site.
- The rail transport is assumed to be by main line rail. The short line and regional railroad segments are significantly shorter, and the transportation cost are small compared to main line rail.
- The costs of escort services are not included.

4.2.1. Fleet Acquisition Capital Costs

The transportation fleet consists of cask railcars, buffer railcars, escort railcars, transportation casks, and impact limiters. The transportation fleet is acquired before the beginning of the transportation campaign and represents capital costs of transportation. The transportation fleet must have sufficient rolling stock for maintaining the specified annual transportation rate. The fleet size is a function of the duration of transportation cycle (number of trips that one train can perform per year), the number of cask railcars in one train, and the annual number of casks to be transported (Table 4-2).

The average transportation cycle in terms of the number of trips per year that a train can perform was estimated from the scenario considered in (Peterson et al., 2023). This scenario assumed an annual transportation rate of 3,000 MTHM, meaning that 231 canisters with BOC SNF were transported annually from the reactor sites to a central U.S. location. The calculated fleet included 32 cask railcars, 12 buffer cars, and 6 escort cars. In this scenario, six trains with an average of 4.8 casks per train each made eight trips per year. The average duration of the transportation cycle (and corresponding number of trips per train per year) depends on the average duration of the roundtrip from a reactor site to a repository and average handling time (loading and unloading transportation casks and other handling operations). It is not a function of the annual transportation rate and should be similar for the other transportation rates. The average duration of the roundtrip may be affected by the geographic location of a geologic repository and may result in a different average duration of the transportation cycle (number of trips per train per year). The number of trips per train per year assumed in this analysis and used in calculating BOC and HALEU SNF transportation fleet was eight trips per train per year as estimated above.

For each type of SNF the number of trips per year was calculated as the annual number of canisters divided by the number of casks per train (assumed to be five). The number of trains was calculated as the number of trips divided by the number of trips per train (eight trips per train per year). The number of escort cars is equal to the number of trains. The number of buffer cars is two times the number of trains. The number of transportation casks is equal to the number of casks per train times number of trains.

The transportation fleet costs were calculated using the 2016 unit-costs in the New Generation System Analysis Model (NGSAM) database. The unit costs in 2016$ were converted to the costs in 2024$ using an escalation factor of 1.32 from the Consumer Price Index for goods (https://www.bls.gov/ppi/). These costs are summarized in Table 4-3.

Table 4-3. Transportation Fleet Unit Costs

Fleet Element	2016$ Unit Cost	2024$ Unit Costs
Railcar	$1,500,000	$ 1,980,000
Buffer car	$350,000	$462,000
Escort car	$7,700,000	$10,164,000
Transportation cask	$11,200,000	$ 14,784,000
Impact limiters (set of two)	$1,100,000	$ 1,452,000
Cask Decommissioning per cask	$600,000	$792,000

4.2.2. Operational Costs

The shipment operational cost is the cost of the roundtrip rail transport and the handling cost (transfer and loading and unloading).

The annual operational cost is the shipment operational cost times number of shipments per year.

Main Line Rail Transportation Costs

The Union Pacific Railroad, BNSF Railway Company, and Norfolk Southern railroad companies have entered into settlement agreements with the U.S. Department of Energy (DOE) that prescribe a rate methodology to estimate the maximum reasonable rates associated with the cost of transporting SNF. These settlement agreements prescribe the rate methodology and the maximum revenue-to-variable cost (R/VC) ratios pertaining to the commodities and rail services involved. It was assumed that the rate methodology contained in the settlement agreements would be used for all mainline railroads.

The total main line cost is calculated as described by Equation 4-1 through Equation 4-9. The sum of the cars handled cost, cars originated or terminated cost, and switch engine minute cost (Eq. 4-2) is about 5% of the total shipment cost. These cost elements (shown in purple font in Eq. 4-2) were not calculated because of their small contribution to the total cost. However, the main line cost was increased by 1.05 to account for these cost elements.

The **mainline cost** is calculated as:

Mainline Cost=3.51*Shipment Cost **Eq. 4-1**

The coefficient **3.51** in Equation 4-1 comes from the settlement agreement.

The **shipment cost** is calculated as:

Shipment cost = gross ton mile cost + train mile cost + locomotive unit mile cost + **cars handled cost** + **cars originated or terminated cost** + **switch engine minute cost** + dedicated train mile cost **Eq. 4-2**

The **gross ton mile cost** is calculated as:

gross ton mile cost = shipment gross ton miles * cost per gross ton mile **Eq. 4-3**

The **train mile cost** is calculated as:

train mile cost =shipment train miles * cost per train mile. **Eq. 4-4**

The **locomotive unit mile cost** is calculated as:

locomotive unit mile cost = shipment locomotive unit miles * cost per locomotive unit mile

Eq. 4-5

The **dedicated train mile cost** is calculated as:

dedicated train mile cost = dedicated train miles * cost per dedicated train mile **Eq. 4-6**

The **shipment gross ton miles** are calculated as:

shipment gross ton miles = weight * shipment miles **Eq. 4-7**

The **shipment train miles** are calculated as:

shipment train miles = weight / trailing weight regular train * shipment miles **Eq. 4-8**

The **shipment locomotive unit miles** are calculated as:

shipment locomotive unit miles = weight / trailing weight regular train * shipment miles * average locomotives regular train **Eq. 4-9**

The parameters in Equations 4-1 – 4-9 are color coded. The parameters shown in red font are from the settlement agreements, the parameters shown in blue font are shipment related, and the parameters shown in green font are route related. The settlement agreement parameters used in the main line cost calculations represent the average values of the parameters specified for three main line railroad companies.

The shipment and route parameters are:

- Shipment weight (ton) – includes the weight of buffer, escort, and cask cars and the weight of transportation cask (either loaded or empty)
- Number of casks

- Shipment miles, which are equal to dedicated train miles

The combined weight of the Atlas car, buffer rail car, and escort rail car was assumed to be 132 tons (NGSAM). The weight of the loaded transportation cask was assumed to be 120 tons (with BOC SNF). The loaded weight of the HALEU SNF was calculated based on MTHM of HALEU per canister. The average route (one way) was assumed to be 2,000 mi.

Handling Costs

The cost of loading and unloading per cask (~$10,000) used in calculations is based on information in Module O1 (INL, 2021).

4.3. Transportation Cost Results

The results of the calculations of the transportation costs of BOC and HALEU SNF are summarized in Table 4-4. **Error! Reference source not found.**The cost elements include total fleet costs and annual operational costs as well as the ratios of the corresponding HALEU and BOC SNF transportation costs.

Table 4-4. BOC and HALEU SNF Transportation Costs

Waste Type	Fleet Cost 2024 $Million	Ratio (HALEU Fleet Cost/BOC Fleet Cost)	Annual Operational Costs 2024 $Million	Ratio (HALEU Operational Cost/BOC Operational Cost)
BOC	636.8	N/A	22.6	N/A
ATF - 7% enrichment	742.9	1.17	24.3	1.08
ATF - 8.3% enrichment	742.9	1.17	24.3	1.07
TRISO - HTGR pebble bed	3,714.5	10.50	236.3	10.46
TRISO - HTGR prismatic block	3,502.2	5.83	130.0	5.75
TRISO - FHR pebble bed	318.4	5.50	122.4	5.42
Metallic	6,686.1	0.50	10.0	0.44

Figure 4-1 compares the total fleet costs of the different types of SNF. The total fleet costs of ATF with 7% enrichment and 84 GWd/MTHM burnup and ATF with 8.3% enrichment 100 GWd/MTHM burnup SNF are only slightly higher (x 1.17) than BOC SNF fleet cost. The total fleet cost of the metallic SNF is half as much as the fleet cost of BOC SNF. The highest total fleet cost is associated with TRISO pebble HTGR SNF, and that is 10.5 times the BOC SNF fleet cost. The total fleet cost of TRISO SNF is 5.8 times (prismatic) and 5.5 times (pebble FHR) higher than the fleet cost of BOC SNF. The main factor affecting the fleet cost is the annual number of canisters that need to be transported. The more canisters that need to be transported, the larger the transportation fleet is.

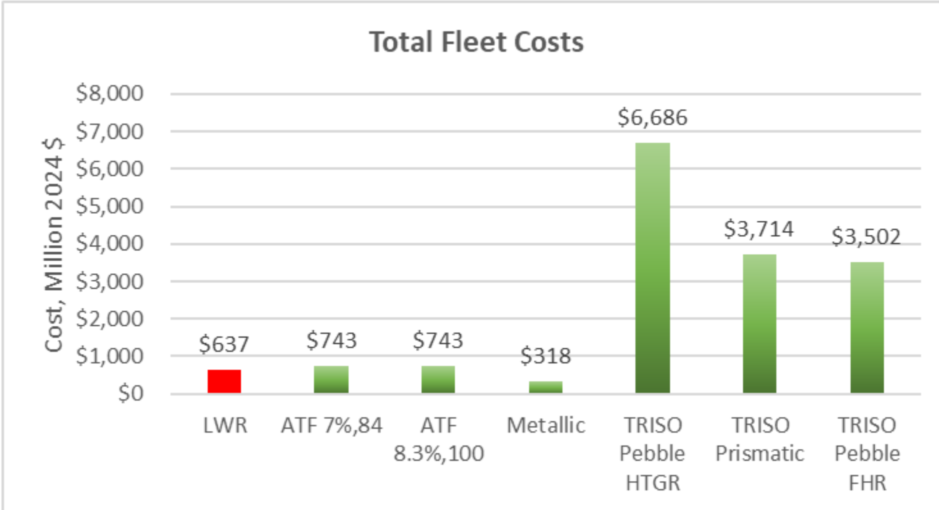

Figure 4-1. Total Fleet Costs of LWR (BOC) and HALEU SNF

Figure 4-2 compares the annual operational costs of the different types of SNF. The annual operational costs of transporting ATF with 7% enrichment and 84 GWd/MTHM burnup and ATF with 8.3 % enrichment and 100 GWd/MTHM burnup SNF are only slightly higher (x 1.08) than annual operational cost of transporting BOC SNF. The annual operational cost of transporting the metallic SNF is half as much as the annual operational cost of transporting BOC SNF. The highest annual operational cost is associated with TRISO pebble HTGR SNF, and that is 10.5 times the BOC SNF annual operational cost. The annual operational cost of transporting TRISO SNF is 5.8 times (prismatic) and 5.4 times (pebble FHR) higher than the annual operating cost of transporting BOC SNF. The main factor affecting the annual operational cost is the number of trips per year. The more trips that need to be performed, the higher the operational cost is.

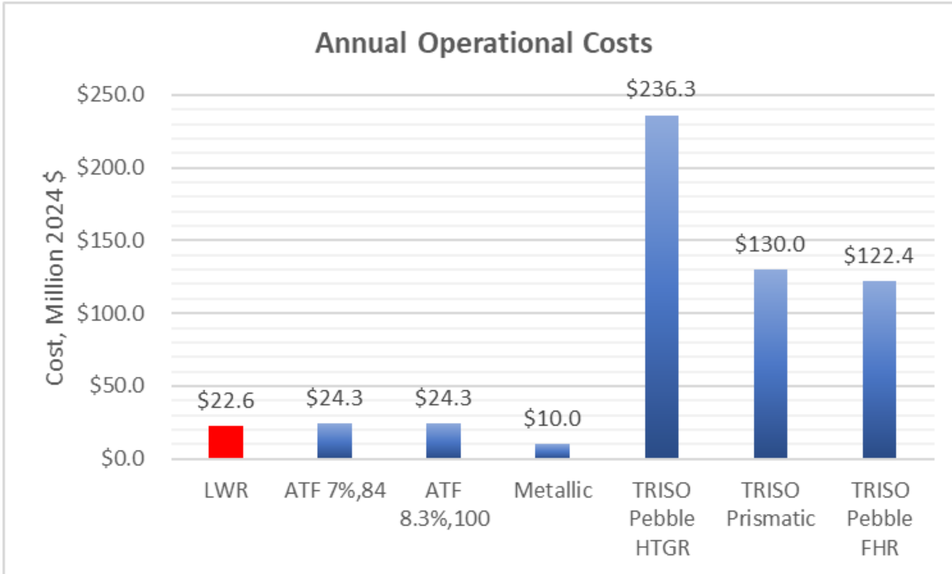

Figure 4-2. Annual Operational Costs of Transporting LWR (BOC) and HALEU SNF

The transportation costs of LWR SNF were given in Module O1 of INL (2021). The shipment consisted of one HI STAR transportation cask containing one dry storage canister with LWR SNF. It was assumed that each canister carried 10 MTHM of LWR SNF. The approach taken in INL (2021) was to rent the transportation fleet instead of acquiring it. The cost of a dry storage canister (~$600,000) was included in the transportation cost. The calculated median cost per shipment without the cost of the canister was $365,512. The per-shipment cost in this analysis was calculated as the sum of operational cost to transport one cask with BOC SNF and annual fleet cost per cask. The per shipment cost was $336,942 (30-year campaign) and $428,828 (15-year campaign). The estimate in Module O1 of INL (2021) falls within this range.

Figure 4-3 shows the total transportation cost per energy generated with the different types of fuel as a function of transportation campaign duration. The total transportation cost was calculated as the total fleet cost plus the annual operational costs times the duration of the transportation campaign in years. The cost per energy generated is the total transportation cost divided by the energy associated with the MTHM of SNF transported during the transportation campaign. The longer the transportation campaign is, the lower is the cost per energy generated because the capital costs of fleet are applied to a longer period of time. The costs of energy generated with BOC SNF and with ATF SNF are very similar. The costs per energy generated with metallic SNF are lower than those associated with BOC SNF. The highest costs per energy generated are associated with TRISO pebble bed HTGR. The cost per energy generated with TRISO prismatic and pebble bed FHR are higher than that for BOC and ATF SNF and lower than that for pebble bed HTGR.

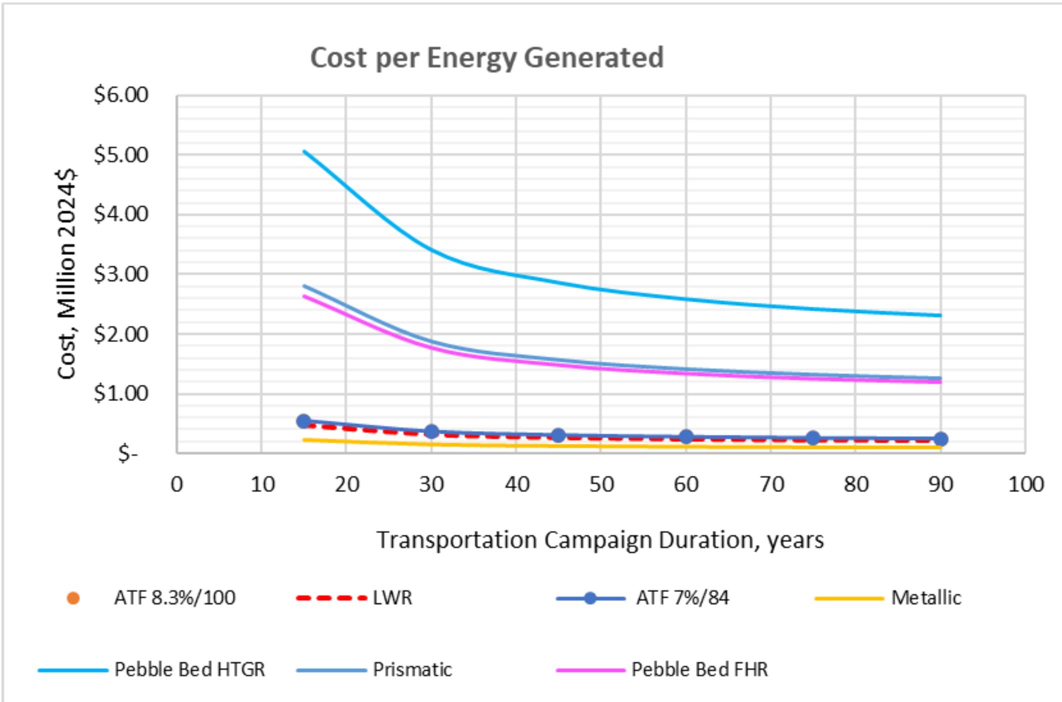

Figure 4-3. Cost of Transportation per Energy Generated for LWR (BOC) and HALEU Fuel as a Function of the Transportation Campaign Duration

Table 4-5 summarizes the cost per energy generated with BOC and HALEU fuel. These two campaigns provide a possible range for the duration of the future transportation campaign of SNF. The inventory of BOC SNF transported during these campaigns is 90,000 MTHM (30-year campaign) and 180,000 MTHM (60-year campaign). The cost increases by ~25% in a 30-year campaign compared to a 60-year campaign for ATF and HALEU SNF. The cost per energy generated is 1.1 times higher for ATF SNF than for BOC SNF. The cost per energy generated is 2 times lower for metallic SNF than for BOC SNF. The cost per energy generated is 5.5-5.8 times higher for prismatic and TRISO pebble FHR SNF than for BOC SNF. The cost per energy generated is 10.5 times higher for TRISO pebble HTGR SNF than for BOC SNF.

Table 4-5. Cost of Transportation per Energy Generated for Different Waste Types for 30-Year and 60-Year Transportation Campaigns

Waste Type	30-year Campaign (2024 $Million per GWe-yr)	60-year Campaign (2024 $Million per GWe-yr)	Ratio (HALEU Cost/BOC Cost)
BOC	$ 0.32	$0.25	N/A
ATF – 7% enrichment	$0.36	$0.27	1.1
ATF – 8.3% enrichment	$0.36	$0.27	1.1
TRISO – HTGR Pebble Bed	$3.40	$2.58	10.5
TRISO – HTGR Prismatic Block	$1.88	$1.42	5.8
TRISO – FHR Pebble Bed	$1.77	$1.34	5.5
Metallic	$0.15	$0.11	0.5

Table 4-6 summarizes the transportation cost per MTHM for BOC and HALEU SNF. The cost increases by ~25% in a 30-year campaign compared to a 60-year campaign for BOC and HALEU SNF. The cost per MTHM is ~2 times higher for ATF and metallic SNF than for BOC SNF. The cost per MTHM is about 25 times higher for TRISO prismatic and TRISO pebble FHR SNF than for BOC SNF. The cost per MTHM is about 42 times higher for TRISO pebble HTGR SNF than for BOC SNF.

Table 4-6. Cost of Transportation per MTHM for Different Waste Types for 30-Year and 60-Year Transportation Campaigns

Waste Type	30-year Campaign (Thousand 2024$ per MTHM)	60-year Campaign (Thousand 2024$ per MTHM)	Ratio (HALEU Cost/BOC Cost)
BOC	$14.61	$11.07	N/A
ATF - 7% enrichment	$27.64	$20.67	1.9
ATF - 8.3% enrichment	$32.70	$24.44	2.2
TRISO - HTGR pebble bed	$616.04	$466.52	42.2
TRISO - HTGR prismatic block	$308.18	$233.01	21.1
TRISO - FHR pebble bed	$370.51	$280.07	25.4
Metallic	$0.02	$18.25	1.7

Figure 4-4 compares the differences in the transportation cost (cost delta) per energy generated for 30-year and 60-year transportation campaigns for HALEU SNF compared to the transportation cost per energy generated for a 30-year and 60-year transportation campaign for BOC SNF.

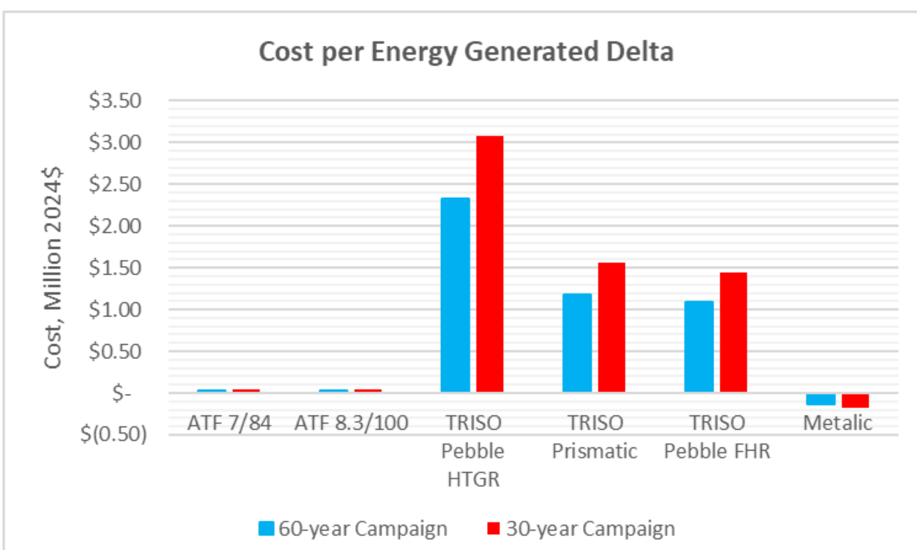

Figure 4-4. Cost per Energy Generated Difference for 30-year and 60-year Transportation Campaigns

Because the transportation cost per energy generated with TRISO fuel is significantly higher compared to BOC fuel, using a new canister specifically designed for TRISO might be more cost effective. To estimate how a smaller in size and less expensive in manufacturing canister may affect the cost per energy generated the following scenarios for a 30-year transportation campaign were considered:

- Base case scenario in which a BOC SNF cask is used to transport TRISO SNF
- Scenario 1 in which TRISO SNF is transported in a new cask that is half as heavy as a BOC SNF cask
- Scenario 2 in which TRISO SNF is transported in a new cask that is half as expensive as a BOC SNF cask
- Scenario 3 in which TRISO SNF is transported in a new cask that is half as expensive and half as heavy as a BOC SNF cask

The base case assumes the cost and the weight of the transportation cask used for BOC SNF. In scenarios 1-3, it is assumed that a new transportation cask can be developed for TRISO SNF and that the weight or/and cost of a new cask could be lower compared to BOC SNF cask. The costs of developing the new cask design and the costs of licensing the new cask were not included.

Figure 4-5 shows the cost per energy generated for the base case and the three scenarios. The cask cost has a larger impact compared to the cask weight. The maximum reduction in the total cost that can be achieved with a lighter and less expensive cask is 24% to 27%.

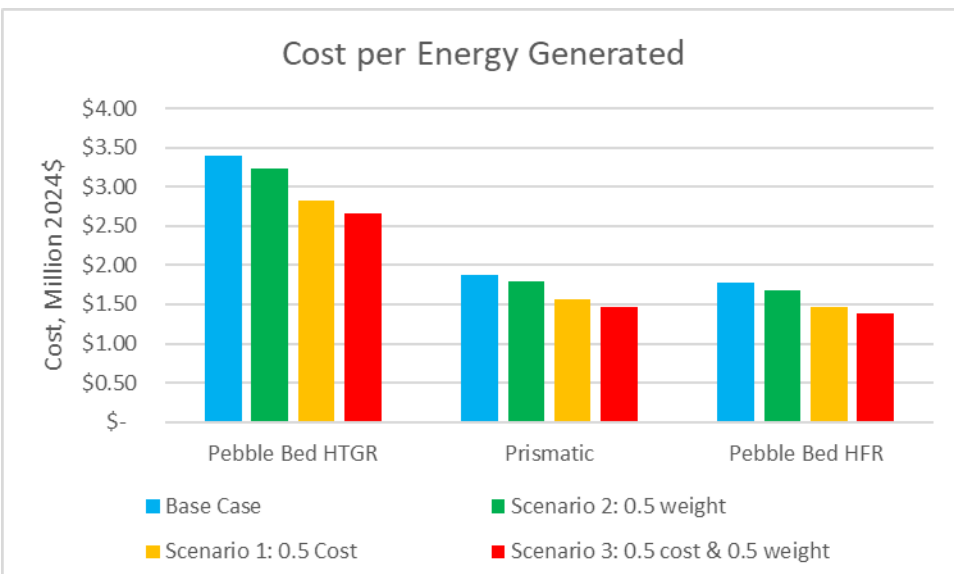

Figure 4-5. TRISO Transportation Cost Delta for 0.5 Lighter or/and 0.5 Less Expensive Cask

5. DISPOSAL

As noted above, the primary characteristics of irradiated HALEU affecting the cost of disposal are its thermal output, radiation, and fissile content. To obtain a rough order of magnitude (ROM) of the cost to dispose of the three types of HALEU SNF discussed in this report, the cost to dispose of BOC SNF in six different types of repositories were studied. To provide a common basis for the calculations across the three types of HALEU SNF, repository costs are presented in terms of cost per mass of that waste disposed of (2024 $ million per MTHM) and cost per quantity of energy generated by that SNF (2024 $ million per GWe-yr).

The cost estimate for each of the six different types of repositories was based on a particular design that was used as the basis for estimating the cost. For the purposes of this study, each design was "adjusted" to account for the SNF characteristic(s) (thermal, radiation, fissile content) that would affect repository design. For example, TRISO SNF emits much less heat per volume than does BOC SNF, so the waste packages could be closer together in a repository containing TRISO SNF than in a repository containing BOC SNF.

For the analyses described below, it is assumed that the entire repository is filled with the particular waste under consideration; that is, no other waste types are included. Other assumptions that were made for each repository type and each HALEU SNF type are discussed individually below.

Costs were escalated from either 2007$ or from 2012$ to 2024$. The escalation factor for escalating costs from 2007 to 2024 is 1.52 while the escalation factor for escalating costs from 2012 to 2024 is 1.36, based on the on-line Consumer Price Index, using January as the month in the calculator for each year.

The first repository for which economic impacts of disposal of HALEU SNF are estimated is a repository similar to the one proposed at Yucca Mountain. The source of cost data for that repository is DOE (2008a). The other five repositories considered are crystalline, salt (enclosed), clay/shale (enclosed), shale (unbackfilled), and sedimentary backfilled (open). The source of repository design and cost data for these five is Hardin et al. (2012). Each of these repositories, its design, and how it was "adjusted" for each type of waste is described below.

5.1. Cost of Disposal in a Repository Similar to Yucca Mountain

The cost of disposing of irradiated HALEU in a repository similar to the one proposed at Yucca Mountain was taken from Analysis of the Total System Lifecycle Cost of the Civilian Radioactive Waste Program, Fiscal Year 2007 (DOE 2008a), sometimes referred to below as the TSLCC. Repository costs are broken down by phase of the project:

- Repository Development and Evaluation
- Repository Engineering, Procurement, and Construction Costs
- Repository Operations Costs
- Repository Monitoring costs
- Repository Closure Costs
- Balance of Program Costs

These costs do not include transportation costs. Also, estimates of costs for repositories located in different geologies (Sections 5.2 – 5.6) do not include the equivalent of "Repository Development and Evaluation" costs so these costs were omitted in the costs for disposing of HALEU SNF in a repository similar to that planned at Yucca Mountain.

The proposed Yucca Mountain repository was to be located on federal land in Nye County in southern Nevada, about 90 miles northwest of Las Vegas (DOE 2008b). This location is within the Basin and Range Geological Province of the western U.S. The repository horizon was to be located in the unsaturated zone a minimum of 690 feet above the water table. Waste packages were to be emplaced in 5.5 m diameter emplacement drifts that were 81 meters apart. Nominal spacing between adjacent waste packages was to be 10 cm and waste packages were to be covered by drip shields that were to be installed during closure activities. The repository was to be ventilated for 50 years prior to closure to remove decay heat. There was no backfill material.

Detailed costs were not available, so only a ROM estimate was possible. These ROM estimates were obtained as described above, by adjusting TSLCC costs as needed to accommodate the HALEU SNF. How the costs were adjusted for each type of HALEU SNF is described in each section below, after first presenting the cost for disposing of BOC SNF in a repository similar to the one proposed at Yucca Mountain to provide a baseline.

Table 5-1 shows the cost of disposing of BOC SNF in a repository similar to Yucca Mountain, as taken from multiple tables in Section 2 of the TSLCC. Costs in the TSLCC are in 2007$; Table 5-1 shows these costs as well as the same costs escalated to 2024$ by multiplying by an escalation factor of 1.52, which was obtained from the U.S. Consumer Price Index calculator, comparing costs between January 2007 and January 2024.

Table 5-1. Cost of Disposing of BOC SNF in a Repository Similar to the One Proposed at Yucca Mountain (Excluding Transportation and Repository Development and Evaluation Costs)

Cost Component and Subcomponents	Cost (2007 $Million)	Cost (2024 $Million)
Licensing	2,340	3,557
Surface & Subsurface Facilities	15,550	23,636
Waste Package & Drip Shield Fabrication	240	365
Performance Confirmation	0	0
Regulatory, Infrastructure, & Management Support	0	0
Repository Engineering, Procurement, and Construction Costs	**18,130**	**27,558**
Licensing	0	0
Surface & Subsurface Facilities	9,580	14,562
Waste Package & Drip Shield Fabrication	12,580	19,122
Performance Confirmation	1,680	2,554
Regulatory, Infrastructure, and Management Support	2,890	4,393
Repository Operations Costs	**26,730**	**40,630**

Cost Component and Subcomponents	Cost (2007 $Million)	Cost (2024 $Million)
Licensing	0	0
Surface & Subsurface Facilities	1,030	1,566
Waste Package & Drip Shield Fabrication	7,630	11,598
Performance Confirmation	1,040	1,581
Regulatory, Infrastructure, and Management Support	440	669
Repository Monitoring Costs	**10,150**	**15,428**
Licensing	0	
Surface & Subsurface Facilities	970	1,474
Waste Package & Drip Shield Fabrication	0	0
Performance Confirmation	300	456
Regulatory, Infrastructure, and Management Support	120	182
Repository Closure Costs	**1,390**	**2,113**
Development and Evaluation	2,300	3,496
Quality Assurance	730	1,110
Waste Management	360	547
Program Management	3,280	4,986
Benefits, PETT, Outreach and Institutional	3,150	4,788
Other Agencies	1,370	2,082
Balance of Program Costs	**11,200**	**17,024**
Total	**67,600**	**102,752**

5.1.1. Normalized Cost to Dispose of BOC SNF in a Repository Similar to Yucca Mountain

The repository described in the TSLCC was intended to hold 122,100 MTHM of SNF and HLW in about 17,450 waste packages. Of that 122,100 MTHM, 109,300 MTHM was commercial SNF from BOCs. This commercial SNF was to be disposed of in 12,983 waste packages; thus the average heavy metal loading per waste package for BOC SNF was 8.42 MTHM/waste package. Assuming all 17,450 waste packages contained BOC SNF leads to a total of 146,929 MTHM of BOC SNF in the repository. As noted above, the mass of SNF required to generate a GWe-yr of energy was calculated to be 22.22 MTHM/GWe-yr. Table 5-2 summarizes the cost of disposing of BOC SNF in a repository similar to the one planned for Yucca Mountain in terms of 2024 $ Million/MTHM and 2024 $Million/GWe-yr.

Table 5-2. Normalized Cost of Disposing of BOC SNF in a Repository Similar to Yucca Mountain

Waste Type	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	103,000	146,929	0.70	16

5.1.2. *Normalized Cost to Dispose of ATF in a Repository Similar to Yucca Mountain*

Estimates of the normalized cost to dispose of ATF in a repository similar to that proposed at Yucca Mountain are based on the following assumptions and are shown in Table 5-3, along with the cost to dispose of BOC SNF to facilitate cost comparisons. For each of the two types of ATF SNF, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-3. Detailed calculations of total repository cost are shown in Appendix A.1.

<u>Assumptions</u>

- The limiting characteristic for ATF SNF is its thermal output.
- Each ATF waste package can hold about half as many assemblies as a waste package for BOC SNF, based on how many assemblies can be loaded in a canister at 5 years cooling and with a canister decay heat limit of 37 kW: 24 for BOC SNF, 13 for 7% enriched, and 11 for 8.3% enriched (Table 4-4 of Hoffman et al., 2023).
- Because waste packages for ATF SNF will have about half the capacity (i.e., between 46% and 54%) as waste packages for BOC SNF, the waste package cost for ATF SNF is 75% of what it is for BOC SNF because of this size reduction (see Table A-1).
- Repository capacity was not adjusted in terms of number of waste packages (17,450) but was adjusted to account for the lower mass of SNF that could be disposed of in the same number of waste packages. The mass per waste package was taken from Table 4-4 of Hoffman (see assumption #1).

Table 5-3. Normalized Cost of Disposing of BOC and ATF SNF in a Repository Similar to Yucca Mountain

Waste Type	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	103,000	146,929	0.70	16
ATF - 7% enrichment	95,000	79,658	1.2	16
ATF - 8.3% enrichment	95,000	67,385	1.4	16

5.1.3. *Normalized Cost to Dispose of TRISO SNF in a Repository Similar to Yucca Mountain*

Estimates of the normalized cost to dispose of TRISO SNF in a repository similar to that proposed at Yucca Mountain are based on the following assumptions and are shown in Table 5-4, along with the cost to dispose of BOC SNF to facilitate cost comparisons. For each of the three types of TRISO SNF, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-7. Detailed calculations of total repository cost are shown in Appendix A.1.

Assumptions

- No Wet Handling Facility will be needed because no repackaging will be needed. (p. 9 of TSLCC)
- No Initial Handling Facility will be needed as there will be no Naval SNF or HLW. (p. 9 of TSLCC)
- No Aging Pad will be necessary because waste packages containing TRISO SNF are cool enough that thermal management won't be necessary.
- The subsurface emplacement area can hold 17,450 TAD-bearing waste packages. (p. 11 of TSLCC)
- The cost split between surface facilities and subsurface facilities is 50/50.
- Surface facilities cost half as much because of not needing the Wet Handling Facility, the Initial Handling Facility, and the Aging Pad
- Subsurface facilities cost the same.
- The cost multiplier for Surface and Subsurface Facilities in every phase of development is then 0.5*1 + 0.5 *0.5 = 0.75 (See Table A-2)

Table 5-4. Normalized Cost of Disposing of BOC and TRISO SNF in a Repository Similar to Yucca Mountain

Waste Type	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	103,000	146,929	0.70	16
TRISO - HTGR pebble bed	92,000	3,409	27	150
TRISO - HTGR prismatic block	92,000	6,818	14	82
TRISO - FHR pebble bed	92,000	5,682	16	78

5.1.4. Normalized Cost to Dispose of SFR SNF in a Repository Similar to Yucca Mountain

Estimates of the cost to dispose of SFR SNF in a repository similar to that proposed at Yucca Mountain were based on the following assumptions and are shown in Table 5-5, along with the cost to dispose of BOC SNF to facilitate cost comparisons. For the SFR SNF discussed herein, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-10. Detailed calculations of total repository cost are shown in Appendix A.1.

Assumptions

- For a canister that has been optimized for SFR loading (hexagonal array), the heat generated by that SNF is similar to that generated by BOC SNF placed in the same canister volume (Table 4-2 of Hoffman et al., 2023). However, the fissile mass of the discharged fuel is about three times higher per canister and thus represents the limiting characteristic.

- Additional neutron absorbing capability or other treatment will be needed for the canister because of the ~3x higher fissile content in the canister.
- The "waste package and drip shield fabrication" cost increases by 10% because of this additional material or treatment (See Table A-3).

Table 5-5 Normalized Cost of Disposing of BOC and Metallic SNF in a Repository Similar to Yucca Mountain

Waste Type	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	103,000	146,929	0.70	16
Metallic	106,000	94,316	1.1	7.0

5.1.5. *Summary and Discussion – Repository Similar to Yucca Mountain*

To facilitate comparison, the ratios of the repository capacity (MTHM) and costs for disposal of the different types of HALEU SNF in a repository similar to Yucca Mountain to the repository capacity and cost for disposal of BOC SNF in a repository similar to Yucca Mountain were calculated and are given in Table 5-6.

Table 5-6. Ratios of Repository Capacity (MTHM) and Costs for Disposal of HALEU SNF in a Crystalline Repository to Repository Capacity and Costs for Disposal of BOC SNF in a Repository Similar to Yucca Mountain

Waste Type	Cost Ratio	MTHM Ratio	Cost per MTHM Ratio	Cost per Energy Generated Ratio
BOC	1.0	1.0	1.0	1.0
ATF - 7% enrichment	0.92	0.54	1.7	1.0
ATF - 8.3% enrichment	0.92	0.46	2.0	1.0
TRISO - HTGR pebble bed	0.90	0.02	39	10
TRISO - HTGR prismatic block	0.90	0.05	19	5.3
TRISO - FHR pebble bed	0.90	0.04	23	5.0
Metallic	1.0	0.64	1.6	0.45

These results indicate that, for ATF SNF, the repository cost is somewhat less because the waste packages are smaller and are slightly less expensive. The waste packages are smaller so that thermal limits can be met, which also means that the repository capacity (MTHM) is less, about half as much. Accordingly, the cost to dispose of it is roughly double that to dispose of BOC SNF when measured on a basis of MTHM. However, because ATF produces more energy per MTHM than does BOC SNF, the cost to dispose of it is about the same as BOC SNF when measured on a basis of energy generated.

For TRISO SNF, the repository itself is about 90% of the cost of the same repository for BOC SNF. This is primarily because TRISO SNF is so much cooler than BOC SNF that an aging pad, which was intended to store waste packages above ground until they were cool enough to emplace in the repository, and other surface facilities are not needed. As noted above, in the proposed Yucca Mountain repository waste packages were emplaced in drifts about 10 cm apart, with the drifts being 81 m apart. Given that configuration, it is not possible to reduce waste package spacing, but it is possible to decrease drift spacing to take advantage of the lower heat generating TRISO SNF. However, the necessary information was not available to estimate how repository costs might change by decreasing drift spacing, so such a calculation was not performed.

Repository design is driven by thermal considerations. The Yucca Mountain repository was designed to accept high heat generating waste, planning on 50 years of ventilation after waste emplacement and spacing drifts far apart (81 m, DOE 2008b). For a low heat generating waste such as TRISO SNF, these measures would not be necessary, and the repository would be designed differently.

For metallic SNF, the cost of a repository is slightly higher (on the order of 3%, which is sometimes hidden by rounding) because of the assumed need to increase the neutron-absorbing capability of the canisters, resulting in a 10% increase in the cost of waste packages. The heavy metal loading of each waste package is about 64% of what is in a BOC SNF waste package, resulting in the emplacement of less MTHM of metallic SNF than of BOC SNF in the same size repository. Accordingly, the cost to dispose of metallic SNF is about 2.5 times the cost to dispose of BOC SNF when measured on a basis of MTHM. However, because metallic SNF generates about 3.5 times the energy per MTHM than does BOC SNF (see Table 2-10), the cost of disposal per energy generated is less than that for BOC SNF.

5.2. Cost of Disposal in a Hypothetical Crystalline Repository

The cost of disposing of irradiated HALEU in a crystalline repository was taken from Hardin et al. (2012). The enclosed crystalline concept consists of copper-coated stainless-steel waste packages containing 4-PWR/9-BWR assemblies emplaced in vertical boreholes surrounded by a clay buffer. A diagram of the repository used by Hardin et al. (2012) for cost estimation is shown in Figure 5-1 The repository is assumed to be 500 m below the ground surface in a hydrologically saturated, low-permeability granitic host rock. As shown in Figure 5-1, the repository consists of 12 1000-ft long access drifts that are backfilled. The drifts are 6.5 m in diameter and are spaced 20 m apart (center-to-center). Waste packages are emplaced in vertical boreholes that are 1.66 m in diameter and that are spaced 10 m apart. The total capacity of the repository is 140,000 MTHM. The waste packages are surrounded by bentonite clay backfill and the access drifts are backfilled with a mixture of 30% bentonite clay and 70% crushed rock.

In the Hardin et al. (2012) cost study, a range of costs was calculated, low and high, for eight different elements (note that site selection or characterization, at-reactor packaging, centralized storage, re-packaging to meet disposal requirements, and waste transport to the repository are not included):

- Facility design, construction, startup
- Operations and maintenance
- Closure
- Waste packages
- Regulatory and licensing
- Monitoring

- Performance confirmation
- Program integration

These costs, in both 2012$ and 2024$, are shown in Table 5-7.

Table 5-7. Cost to Dispose of BOC SNF in a Crystalline Repository

	Costs for BOC SNF (2012$Millions)		Costs for BOC SNF (2024$Millions)	
Element	**Low**	**High**	**Low**	**High**
Facility Design Construction, Startup	3,754	5,495	5,105	7,473
Operations and Maintenance	17,545	22,475	23,861	30,566
Closure	9,563	13,704	13,006	18,637
Waste Packages	17,489	21,647	23,785	29,440
Regulatory & Licensing	424	441	577	600
Monitoring	10,685	14,571	14,532	19,817
Performance Confirmation	411	561	559	763
Program Integration	1,575	2,136	2,142	2,905
Total	**61,446**	**81,030**	**83,567**	**110,201**

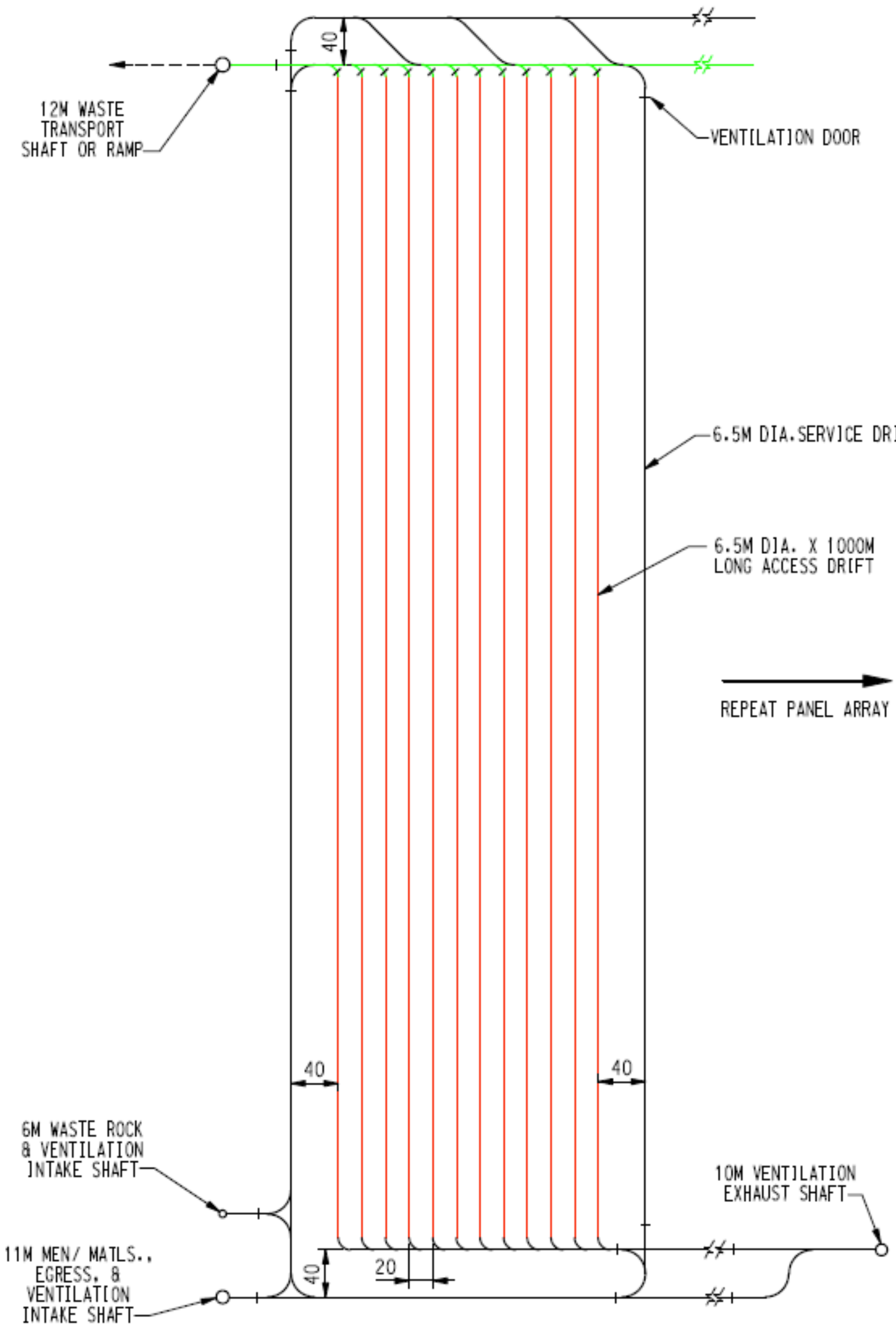

Figure 5-1. Crystalline (Enclosed) Concept Repository Panel Schematic for Cost Estimation (from Hardin et al., 2012, Figure 4.1-1)

5.2.1. Normalized Cost to Dispose of BOC SNF in a Crystalline Repository

The crystalline repository described above was designed to hold 140,000 MTHM of SNF, and the MTHM required per energy generated for the BOC fuel is given in Table 2-3. Using these values, the cost of disposing of BOC SNF in a crystalline repository in terms of 2024 $Million/MTHM and 2024$Million/GWe-yr were calculated and are shown in Table 5-8.

Table 5-8. Normalized Cost of Disposing of BOC SNF in a Crystalline Repository

Low or High	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
Low	84,000	140,000	0.60	13
High	110,000		0.79	17

5.2.2. Normalized Cost to Dispose of ATF in a Crystalline Repository

Estimates of the normalized cost to dispose of ATF in a crystalline repository are based on the following assumptions and are summarized in Table 5-9, along with the cost to dispose of BOC SNF to facilitate comparison. For each of the two types of ATF SNF, the mass of SNF used to generate 1 GWe-yr of energy was taken from Table 2-3. Detailed calculations of total repository cost are shown in Appendix A.2.

<u>**Assumptions:**</u>

- Because spent ATF has higher decay heat than BOC SNF at any given time (Table 4-1 of Hoffman et al., 2023), it is assumed that waste packages used to dispose of spent ATF are smaller than those used to dispose of BOC SNF so that repository thermal limits can be met. Table 4-4 of Hoffman et al. (2023) indicates that roughly half as many assemblies of spent ATF can be loaded in a given canister to meet thermal limits, as compared to BOC SNF. Therefore, waste package costs for ATF are assumed to be 75% of the cost of those of waste packages for BOC SNF. The number of waste packages does not change but each one is assumed to be smaller.
- The layout of the repository does not change.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 7% enrichment and 84 GWd/MTHM burnup in that canister is about 0.54 times that of BOC SNF (7.01/12.93). Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of spent ATF with 7% enrichment and 84 GWd/MTHM (kg HM) in this repository is calculated as ~140,000 MTHM *0.54.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 8.3% enrichment and 100 GWd/MTHM burnup in that canister is about 0.46 times that of BOC SNF (5.93/12.93). Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of spent ATF with 8.3% enrichment and 100 GWd/MTHM (kg HM) in this repository is calculated as ~140,000 MTHM *0.46.

Table 5-9. Normalized Cost of Disposing of BOC and ATF SNF in a Crystalline Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	84,000	140,000	0.60	13
	High	110,000		0.79	17
ATF - 7% enrichment	Low	78,000	75,901	1.0	13
	High	103,000		1.4	18
ATF – 8.3% enrichment	Low	78.000	64,207	1.2	13
	High	103,000		1.6	18

5.2.3. Normalized Cost to Dispose of TRISO SNF in a Crystalline Repository

Estimates of the normalized cost to dispose of TRISO SNF in a hypothetical crystalline repository are based on the following assumptions and are summarized in

Table 5-10, along with the cost to dispose of BOC SNF to facilitate cost comparisons. For each of the three types of TRISO SNF, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-7. Detailed calculations of total repository cost are shown in Appendix A.2.

Assumptions:

- The 4-PWR/9-BWR waste package is 0.82 m in diameter and 5 m long (Hardin et al., 2012, Table 1.4-1), and each is placed in a borehole (either horizontally or vertically) which is drilled from a drift approximately 500 m below the ground surface (Hardin et al., 2012, Figure 1.1-4).
- The reference repository used for the cost analyses assumes the drifts are 20 m apart (center to center) and the waste packages are 10 m apart (Hardin et al., 2012, Section 4.1). Because a canister of TRISO SNF is so much cooler than a similarly sized canister of SNF, for the purposes of this analysis, it is assumed that the drifts are 10 m apart (rather than 20 m apart) and that two waste packages can be placed in each borehole (which is 10 m deep). This results in having four times as many waste packages in the same footprint. The number of waste packages per panel is 4,800 (instead of 1,200 per panel as shown in Table 4.1-1 of Hardin et al. (2012)) because the number of access drifts per panel is 24 (instead of 12 per panel as shown in Table 4.1-1 of Hardin et al, (2012)) and the number of waste packages per drift is 200 per 1,000 m segment (rather than 100 per 1,000 m segment as shown in Table 4.1-2 of Hardin et al. (2012)).
- The length of material per panel that needs to be mined for access drifts (Hardin et al., 2012, Table 4.1-1) increases from 12,000 to 24,000.
- The volume that needs to be backfilled increases by 2.7E7 m^3 for the access drifts (Hardin et al., 2012, Table 4-2) (doubles the value of 2.7E7 m^3).
- The Adjustment Factor for "Operations and Maintenance" is adjusted by for increased mining costs by multiplying 12,000 m by $2,353/ft (Hardin et al., 2012, Table 5.1-3) and 3.28

ft/m and 69 panels (82,583 WP/1200 WPs per panel). The adjustment for additional costs for backfill and muck disposal is calculated as 2.7E7 m^3 multiplied by the sum of (150 + 111 $/cubic yard) * (1.3 yd^3/m^3). These two adjustments are added together and divided by 1E6 to convert to millions of dollars, resulting in an adjustment factor of 2012$ Million 15,551.

- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO pebble bed SNF is about 0.3 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR and with a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *4*0.3/12.93.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO prismatic block SNF is 0.6 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR and with a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of prismatic block TRISO in this repository is calculated as 140,000 MTHM *4*0.6/12.93.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of FHR TRISO pebble bed SNF 0.5 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR and with a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *4*0.5/12.93.

Table 5-10. Normalized Cost to Dispose of BOC and TRISO SNF in a Crystalline Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	84,000	140,000	0.60	13
	High	110,000		0.79	17
TRISO - HTGR pebble bed	Low	180,000	12,993	14	75
	High	220,000		17	93
TRISO - HTGR Prismatic block	Low	180,000	25,986	6.8	41
	High	220,000		8.5	52
TRISO - FHR pebble bed	Low	180,000	21,655	8.1	39
	High	220,000		10	49

5.2.4. Normalized Cost to Dispose of Metallic SNF in a Crystalline Repository

Estimates of the normalized cost to dispose of Metallic SNF in a crystalline repository are based on the following assumptions and are summarized in Table 5-11, along with the cost to dispose of BOC SNF to facilitate cost comparisons. For the SFR SNF discussed herein, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-10. Detailed calculations of total repository cost are shown in Appendix A.2.

Assumptions:

- For a canister that has been optimized for SFR loading (hexagonal array), the heat generated by that SNF is similar to that generated by BOC SNF placed in the same canister volume (Table 4-2 of Hoffman et al. 2023). Thus, the layout of the repository is unchanged.
- However, the fissile mass of the discharged fuel is about three times higher for the same volume. Thus, additional neutron absorbing capability or other treatment will be needed for the canister.
- The waste package cost is assumed to increase by 10% to account for the increased neutron absorber capability.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size and with optimized loading of SFR SNF, the heavy metal loading of spent SFR is about 0.64 times that of BOC SNF (8.3/12.93). Therefore, for the purpose of calculating disposal cost per MTHM of SFR SNF in this repository, the MTHM is calculated as 140,000 MTHM*0.64.

Table 5-11. Normalized Cost to Dispose of BOC and Metallic SNF in a Crystalline Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	84,000	140,000	0.60	13
	High	110,000		0.79	17
Metallic	Low	86,000	89,869	0.96	5.9
	High	110,000		1.3	7.8

5.2.5. *Summary and Discussion – Crystalline Repository*

To facilitate comparison, the ratios of the repository capacity (MTHM) and costs for disposal of the different types of HALEU SNF in a hypothetical crystalline repository to the repository capacity and cost for disposal of BOC SNF in a crystalline repository were calculated and are given in Table 5-12.

Table 5-12. Ratios of Repository Capacity (MTHM) and Costs for Disposal of HALEU SNF in a Crystalline Repository to Repository Capacity and Costs for Disposal of BOC SNF in a Crystalline Repository

Waste Type	Low or High End of Range	Cost Ratio	MTHM Ratio	Cost per MTHM Ratio	Cost per Energy Generated Ratio
BOC	Low	1.0	1.0	1.0	1.0
	High	1.0		1.0	1.0
ATF - 7% enrichment	Low	0.93	0.54	1.7	1.0
	High	0.93		1.7	1.0
ATF - 8.3% enrichment	Low	0.93	0.46	2.0	1.0
	High	0.93		2.0	1.0
TRISO - HTGR pebble bed	Low	2.1	0.09	23	5.6
	High	2.0		21	5.3
TRISO - HTGR prismatic block	Low	2.1	0.19	11	3.1
	High	2.0		11	3.0
TRISO - FHR pebble bed	Low	2.1	0.15	14	2.9
	High	2.0		13	2.8
Metallic	Low	1.0	0.64	1.6	0.45
	High	1.0		1.6	0.45

These results indicate that, for ATF SNF, the repository cost is somewhat less because the waste packages are smaller and are slightly less expensive. The waste packages are smaller so that thermal limits can be met, which also means that the repository capacity (MTHM) is less, about half as much. Accordingly, the cost to dispose of it is roughly double that to dispose of BOC SNF when measured on a basis of MTHM. However, because ATF produces more energy per MTHM than does BOC SNF, the cost to dispose of it is about the same as the BOC SNF when measured on a basis of energy generated.

For TRISO SNF, the repository itself is roughly twice the cost of a repository for BOC SNF. This is primarily because TRISO SNF is so much cooler than BOC SNF that more TRISO SNF can be emplaced in the same repository area by emplacing two waste packages in a single borehole instead of one and doubling the number of drifts by reducing their spacing. Thus, as described in Section 5.2.3, it was assumed that there are four times as many waste packages, increasing the waste package cost by a factor of four. In addition, costs were higher because more rock needs to be mined and backfilled to create additional access drifts and to backfill them after repository closure. As shown in Appendix A.2, this roughly doubles the Operations and Maintenance Cost for this type of repository. As noted above, for a given volume, TRISO SNF contains far less MTHM than does BOC SNF. Even though the hypothetical repository is assumed to contain four times as many similar-sized waste packages, the quantity of TRISO MTHM it can contain is only ~ 10% - 20% of the quantity of BOC SNF. This results in disposal costs that are about 10 to 25 times higher than costs for disposal of BOC SNF, when measured on a basis of MTHM. When measured on a basis of energy generated, disposing of TRISO SNF is about three to six times as expensive as disposing of BOC SNF in a crystalline repository.

However, this repository, like the repository similar to Yucca Mountain, is designed for high heat generating waste. To meet thermal limits, waste packages are small (4-PWR/9-BWR), access drifts are 20 m apart and disposal boreholes are 10 m apart. Because TRISO SNF is not a high heat generating waste, a repository dedicated to this waste could be designed differently. For example, a cavern-type disposal concept could be adopted, in which a large cavern is excavated, and waste packages are emplaced next to and on top of each other in that cavern. Such a concept in crystalline rock has been proposed by Canada (NWMO 2017). This would reduce the cost of disposal significantly.

For metallic SNF, the cost of a repository is slightly higher (on the order of 3%, which is sometimes hidden by rounding) because of the assumed need to increase the neutron-absorbing capability of the canisters, resulting in a 10% increase in the cost of waste packages. The heavy metal loading of each waste package is about 64% of what is in a waste package containing BOC SNF, resulting in the emplacement of fewer MTHM of metallic SNF than of BOC SNF in the same size repository. Accordingly, the cost to dispose of metallic SNF is about 1.6 times the cost to dispose of BOC SNF when measured on a basis of MTHM. However, because metallic SNF generates about 3.5 times the energy per MTHM than does BOC SNF (see Table 2-10), the cost of disposal per energy generated is about half that for BOC SNF.

5.3. Cost of Disposal in a Hypothetical Salt Repository

The cost of disposing of irradiated HALEU in a salt repository was taken from Hardin et al, (2012). The concept consists of thin-walled stainless-steel canisters containing 12 PWR or 24 BWR assemblies in a carbon steel overpack. The packages would be placed on the floor and covered immediately with crushed salt from excavation operations. The waste is emplaced in mined alcoves that are 3 m high, 6 m wide, and 12 m deep, oriented 45 degrees to the access drifts that are 6 m high and 9 m wide. The alcoves are 11.25 m apart and are located on each side of the access drift. The repository is assumed to be 500 m below the surface in bedded salt. The repository would consist of about 100 panels spread out over 30 square kilometers. A layout of one of the panels in the salt repository concept is shown in Figure 5-2.

As with the crystalline repository, both low and high costs were calculated for the same eight elements. These costs, in both 2012$ and 2024$, as shown in Table 5-13.

Table 5-13. Cost to Dispose of BOC SNF in a Salt Repository

	Costs for BOC SNF (2012$Millions)		Costs for BOC SNF (2024$Millions)	
Element	**Low**	**High**	**Low**	**High**
Facility Design Construction, Startup	3,896	5,595	5,299	7,609
Operations and Maintenance	7,947	10,259	10,808	13,952
Closure	832	1,363	1,132	1,854
Waste Packages	3,998	4,950	5,437	6,732
Regulatory & Licensing	368	379	500	515
Monitoring	4,580	6,246	6,229	8,495
Performance Confirmation	567	773	771	1,051

	Costs for BOC SNF (2012$Millions)		Costs for BOC SNF (2024$Millions)	
Program Integration	2,136	2,907	2,905	3,954
Total	**24,324**	**32,472**	**33,081**	**44,162**

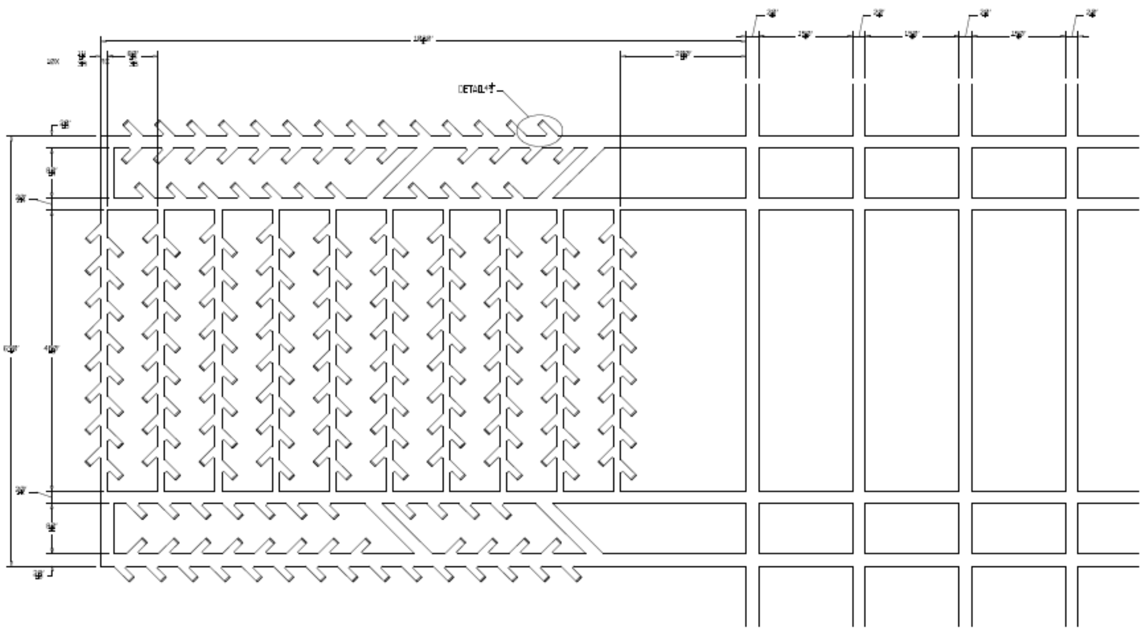

Figure 5-2. Salt Repository Panel Concept Layout (From Hardin et al., 2012, Figure 4.2-1)

5.3.1. Normalized Cost to Dispose of Typical SNF in a Salt Repository

The salt repository described above was designed to hold 140,000 MTHM of SNF, and the MTHM required per energy generated for the BOC fuel is given in Table 2-3. Using these values, the cost of disposing of BOC SNF in a salt repository in terms of 2024$/MTHM and 2024$/GWe-yr are calculated and are shown in Table 5-14.

Table 5-14. Normalized Cost of Disposing of BOC SNF in a Salt Repository

Low or High	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
Low	33,000	140,000	0.24	5.3
High	44,000		0.32	7.0

5.3.2. Normalized Cost to Dispose of ATF SNF in a Salt Repository

Estimates of the normalized cost to dispose of ATF in a hypothetical salt repository are based on the following assumptions and are summarized in Table 5-15, along with the cost to dispose of BOC SNF to facilitate comparison. For each of the two types of ATF SNF, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-3. Detailed calculations are shown in Appendix A.3.

Assumptions:

- The cost analysis for this case assumed 4-PWR/9-BWR waste packages were used to dispose of BOC SNF. Because spent ATF has higher decay heat than BOC SNF at any given time (Table 4-1 of Hoffman et al., 2023), it is assumed that waste packages used to dispose of spent ATF are smaller. Table 4-4 (Hoffman et al. 2023) indicates that roughly half as many assemblies of spent ATF can be loaded in a given canister to meet thermal limits, as compared to BOC SNF.
- Accordingly, waste package costs are assumed to be 75% of the cost of those of BOC SNF. The number of waste packages used to dispose of ATF SNF does not change but each one is assumed to be smaller.
- The layout of the repository does not change.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 7% enrichment and 84 GWd/MTHM burnup in that canister is about 0.54 times that of BOC SNF (7.01/12.93). Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of spent ATF with 7% enrichment and 84 GWd/MTHM in this repository is calculated as 140,000 MTHM *0.54.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 8.3% enrichment and 100 GWd/MTHM burnup in that canister is about 0.46 times that of BOC SNF (5.93/12.93). Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of spent ATF with 8.3% enrichment and 100 GWd/MTHM in this repository is calculated as 140,000 MTHM *0.46.

Table 5-15. Normalized Cost to Dispose of BOC and ATF SNF in a Salt Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	33,000	140,000	0.24	5.3
	High	44,000		0.32	7.0
ATF - 7% enrichment	Low	32,000	75,901	0.42	5.5
	High	42,000		0.56	7.4
ATF – 8.3% enrichment	Low	32,000	64,207	0.49	5.5
	High	42,000		0.66	7.4

5.3.3. *Normalized Cost to Dispose of TRISO SNF in a Salt Repository*

Estimates of the normalized cost to dispose of TRISO SNF in a hypothetical salt repository are based on the following assumptions and are summarized in Table 5-16, along with the cost to dispose of BOC SNF to facilitate cost comparisons. For each of the three types of TRISO SNF, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-7. Detailed calculations are shown in Appendix A.3.

Assumptions:

- In the cost analysis for the salt repository (Section 1.4.5.2), the waste package was a 12-PWR/24-BWR waste package, which is 1.29 m in diameter and 5 m long (Table 1.4-1) of Hardin et al. (2012).
- The reference repository used for the cost analyses assumes the alcoves are 3 m high, 6 m wide, and 12 m deep (Section 4.2). Because a canister of TRISO SNF is so much cooler than a similarly sized canister of SNF, for the purposes of this analysis, it is assumed that each alcove can accommodate six waste packages containing TRISO SNF. These would be placed parallel to each other in a single layer and would result in having six times as many waste packages emplaced within the same footprint. The number of waste packages per panel is thus 1,416 (instead of 236 per panel as shown in Table 4.2-1).
- Excavation costs remain the same for the TRISO case as they are for the BOC case.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO pebble bed SNF is about 0.3 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *6*0.3/12.93. The repository was designed for 140,000 MTHM of BOC SNF Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO prismatic block SNF is 0.6 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of prismatic block TRISO in this repository is calculated as 140,000 MTHM *6*0.6/12.93.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of FHR TRISO pebble bed SNF 0.5 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *6*0.5/12.93.

Table 5-16. Normalized Cost to Dispose of BOC and TRISO SNF in a Salt Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	33,000	140,000	0.24	5.3
	High	44,000		0.32	7.0
TRISO - HTGR pebble bed	Low	60,000	19,490	3.1	17
	High	78,000		4.0	22
TRISO - HTGR Prismatic block	Low	60,000	38,979	1.5	9.4
	High	78,000		2.0	12
TRISO - FHR pebble bed	Low	60,000	32,483	1.9	8.9
	High	78,000		2.4	11

5.3.4. *Normalized Cost to Dispose of Metallic SNF in a Salt Repository*

Estimates of the normalized cost to dispose of metallic SNF in a hypothetical salt repository are based on the following assumptions and are summarized in Table 5-17, along with the cost to dispose of BOC SNF to facilitate cost comparisons. For the SFR SNF discussed herein the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-10. Detailed calculations are shown in Appendix A.3.

<u>Assumptions:</u>

- For a canister that has been optimized for SFR loading (hexagonal array), the heat generated by that SNF is similar to that generated by BOC SNF placed in the same canister volume (Table 4-2 of Hoffman et al. 2023). Thus, the layout of the repository is unchanged.
- However, the fissile mass of the discharged fuel is about three times higher for the same volume. Thus, additional neutron absorbing capability or other treatment will be needed for the canister to meet storage and transport subcriticality requirements.
- The waste package cost is assumed to increase by 10% to account for the increased neutron absorber capability.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size and with optimized loading of SFR SNF, the heavy metal loading of spent SFR is about 0.64 times that of BOC SNF (8.3/12.93). Therefore, for the purpose of calculating disposal cost per MTHM of SFR SNF in this repository, the MTHM is calculated as 140,000 MTHM*0.64

Table 5-17. Normalized Cost to Dispose of BOC and Metallic SNF in a Salt Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	33,000	140,000	0.24	5.3
	High	44,000		0.32	7.0
Metallic	Low	34,000	89,869	0.37	2.3
	High	45,000		0.50	3,1

5.3.5. *Summary and Discussion – Salt Repository*

To facilitate comparison, the ratios of the repository capacity (MTHM) and costs for disposal of the different types of HALEU SNF in a hypothetical salt repository to the repository capacity and cost for disposal of BOC SNF in a hypothetical salt repository were calculated and are given in Table 5-18.

Table 5-18. Ratios of Repository Capacity (MTHM) and Costs for Disposal of HALEU SNF in a Salt Repository to Repository Capacity and Costs for Disposal of BOC SNF in a Salt Repository

Waste Type	Low or High End of Range	Cost Ratio	MTHM Ratio	Cost per MTHM Ratio	Cost per Energy Generated Ratio
BOC	Low	1.0	1.0	1.0	1.0
	High	1.0		1.0	1.0
ATF - 7% enrichment	Low	0.96	0.54	1.8	1.1
	High	0.96		1.8	1.1
ATF – 8.3% enrichment	Low	0.96	0.46	2.1	1.1
	High	0.96		2.1	1.1
TRISO - HTGR pebble bed	Low	1.8	0.14	13	3.3
	High	1.8		13	3.2
TRISO - HTGR prismatic block	Low	1.8	0.28	6.5	1.8
	High	1.8		6.3	1.7
TRISO - FHR pebble bed	Low	1.8	0.23	7.9	1.7
	High	1.8		7.6	1.6
Metallic	Low	1.0	0.64	1.6	0.44
	High	1.0		1.6	0.44

These results indicate that, for ATF SNF, the repository cost is somewhat less because the waste packages are smaller and are slightly less expensive. The waste packages are smaller so that thermal limits can be met, which also means that the repository capacity (MTHM) is less, about half as much. Accordingly, the cost to dispose of it is roughly double that to dispose of BOC SNF when measured on a basis of MTHM. However, because ATF produces more energy per MTHM than does BOC SNF, the cost to dispose of it is about the same as the cost to dispose of BOC SNF when measured on a basis of energy generated.

For TRISO SNF, the repository itself is roughly twice the cost of a repository for BOC SNF. This is primarily because TRISO SNF is so much cooler than BOC SNF that six TRISO SNF waste packages can be emplaced in a single alcove instead of one. Thus, as described in Section 5.3.3, it was assumed that there are six times as many waste packages, increasing the waste package cost by a factor of six. As noted above, for a given volume, TRISO SNF contains far less MTHM than does BOC SNF. Even though the hypothetical salt repository is assumed to contain six times as many similar-sized waste packages, the quantity of TRISO MTHM it can contain is only ~ 15% - 30% of the quantity of BOC SNF. This results in disposal costs that are about five to 15 times higher than costs for disposal of BOC SNF, when measured on a basis of MTHM. When measured on a basis of energy generated, disposing of TRISO SNF is about two to three times as expensive as disposing of BOC SNF in a salt repository.

However, this repository, like the repository similar to Yucca Mountain, is designed for high heat generating waste. To meet thermal limits, a single waste package is emplaced in each alcove and the alcoves as 11.25 m apart. Because TRISO SNF is not a high heat generating waste, a repository dedicated to this waste could be designed differently. For example, a system similar to that employed at WIPP, in which waste packages are emplaced in large panels, stacked on top of each other and side by side (DOE, 2004). This could reduce the cost of disposal significantly.

For metallic SNF, the cost of a repository is slightly higher (on the order of 2%) because of the assumed need to increase the neutron-absorbing capability of the canisters while they are being stored and transported, resulting in a 10% increase in the cost of waste packages. The heavy metal loading of each waste package is about 64% of what is in a waste package containing BOC SNF, resulting in the emplacement of less MTHM of metallic SNF than of BOC SNF in the same size repository. Accordingly, the cost to dispose of metallic SNF is about 1.5 times the cost to dispose of BOC SNF when measured on a basis of MTHM. However, because metallic SNF generates about 3.5 times the energy per MTHM than does BOC SNF (see Table 2-10), the cost of disposal per energy generated is about half that for BOC SNF.

5.4. Cost of Disposal in a Clay/Shale (enclosed) Repository

The cost for disposing of irradiated HALEU in a clay/shale enclosed repository is taken from Hardin et al., (2012), as shown in Table 5-19. The concept consists of 4-PWR/9-BWR canisters in carbon steel overpacks emplaced in horizontal, steel-lined tunnels with a diameter of 2.64 m and surrounded by clay-based buffer material. Surrounding each waste package with bentonite makes it "enclosed." Each horizontal steel-lined tunnel can hold four waste packages. The horizontal emplacement holes are located on either side of the access drifts. The waste package spacing is 5 m and the drift spacing is 30 m. Approximately 100 panels of four 630-m long access drifts will be needed to dispose of 140,000 MTHM of BOC SNF. The repository is assumed to be 500 m below the ground surface in clay/shale. A typical panel is depicted in Figure 5-3.

Table 5-19. Cost to Dispose of BOC SNF in a Clay/Shale (enclosed) Repository

	Costs for BOC SNF (2012$Millions)		Costs for BOC SNF (2024$Millions)	
Element	**Low**	**High**	**Low**	**High**
Facility Design Construction, Startup	6,872	10,064	9,346	13,687
Operations and Maintenance	26,884	34,525	36,562	46,954
Closure	5,556	8,334	7,556	11,334
Waste Packages	7,542	9,337	10,257	12,698
Regulatory & Licensing	414	429	563	583
Monitoring	9,021	12,302	12,269	16,731
Performance Confirmation	758	1,034	1,031	1,406
Program Integration	2,914	3,965	3,963	5,392
Total	**59,961**	**79,990**	**81,547**	**108,786**

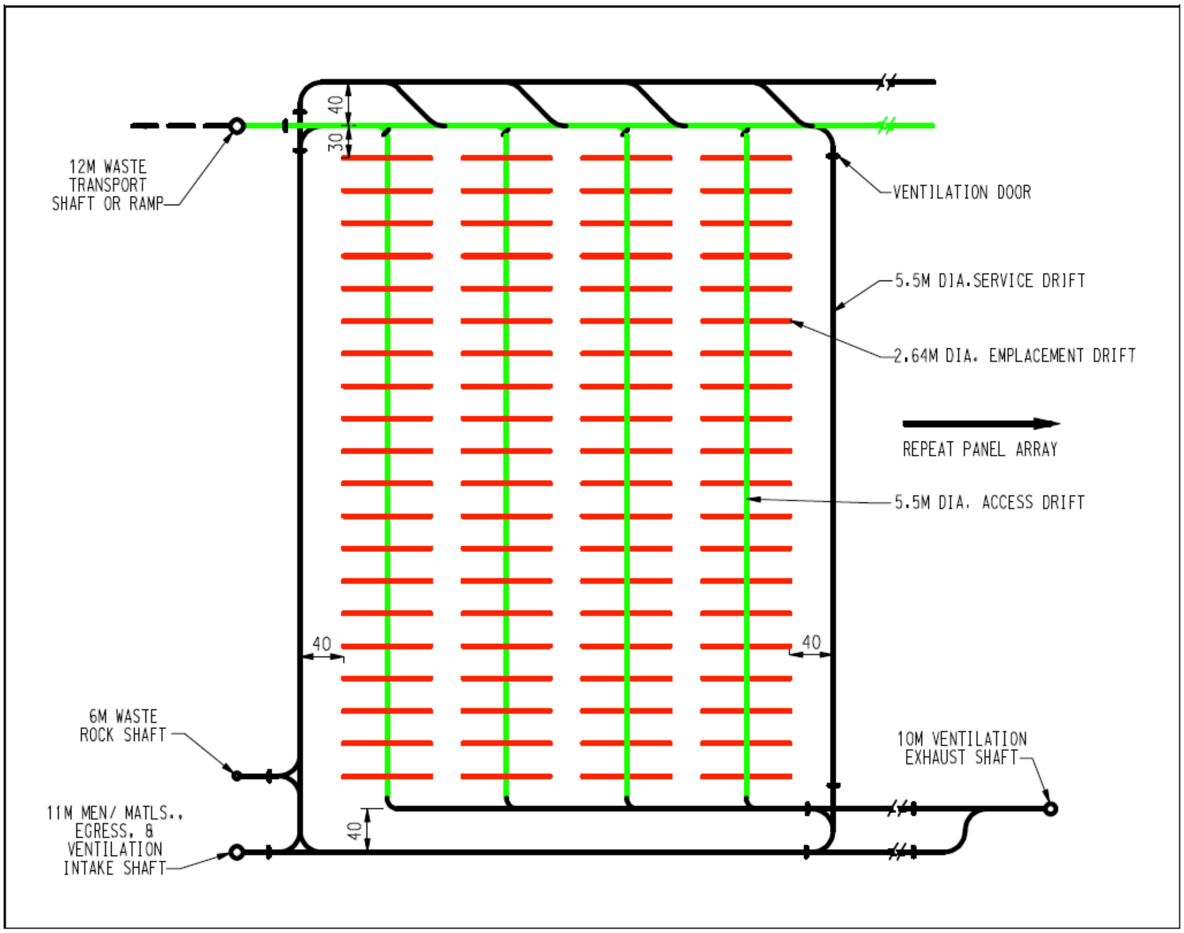

Figure 5-3. Clay/Shale (enclosed) Concept Panel Layout (From Hardin et al., Figure 4.3-1)

5.4.1. Normalized Cost to Dispose of Typical SNF in an Enclosed Clay/Shale Repository

The enclosed clay/shale repository described above was designed to hold 140,000 MTHM of SNF, and the MTHM required per energy generated for BOC fuel is given in Table 2-3. Using these values, the cost of disposing of BOC SNF in an enclosed clay/shale repository in terms of 2024$/MTHM and 2024$/GWe-yr are calculated and are shown in Table 5-20.

Table 5-20. Normalized Cost of Disposing of BOC SNF in a Clay/Shale (enclosed) Repository

Low or High	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
Low	82,000	140,000	0.58	13
High	110,000		0.78	17

5.4.2. Normalized Cost to Dispose of ATF SNF in an Enclosed Clay/Shale Repository

Estimates of the normalized cost to dispose of ATF in a hypothetical enclosed clay/shale repository are based on the following assumptions and are summarized in Table 5-21, along with the cost to dispose of BOC SNF to facilitate comparison. For each of the two types of ATF SNF, the mass of SNF generated by the production of 1 GWe-yr of energy as taken from Table 2-3. Detailed calculations are shown in Appendix A.4.

Assumptions:

- Because spent ATF has higher decay heat than BOC SNF at any given time (Table 4-1 of Hoffman et al., 2023), it is assumed that waste packages used to dispose of spent ATF are smaller. Table 4-4 (Hoffman et al. 2023) indicates that roughly half as many assemblies of spent ATF can be loaded in a given canister to meet thermal limits, as compared to BOC SNF. Therefore, for estimating the cost of waste packages, it assumed that spent ATF waste packages have half the capacity of BOC SNF waste packages.
- Accordingly, waste package costs are assumed to be 75% of the cost of those of BOC SNF. The number of waste packages does not change but each one is assumed to be smaller.
- The layout of the repository does not change.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 7% enrichment and 84 GWd/MTHM burnup in that canister is about 0.54 times that of BOC SNF (7.01/12.93). Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of spent ATF with 7% enrichment and 84 GWd/MTHM in this repository is calculated as 140,000 MTHM *0.54.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 8.3% enrichment and 100 GWd/MTHM burnup in that canister is about 0.46 times that of BOC SNF (5.93/12.93). Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of spent ATF with 8.3% enrichment and 100 GWd/MTHM in this repository is calculated as 140,000 MTHM *0.46.

Table 5-21. Normalized Cost to Dispose of BOC and ATF SNF in an Enclosed Clay/Shale Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	82,000	140,000	0.58	13
	High	110,000		0.78	17
ATF - 7% enrichment	Low	79,000	75,901	1.0	14
	High	110,000		1.4	18
ATF – 8.3% enrichment	Low	79,000	64,207	1.2	14
	High	110,000		1.6	18

5.4.3. Normalized Cost to Dispose of TRISO SNF in an Enclosed Clay/Shale Repository

Estimates of the normalized cost to dispose of TRISO SNF in a hypothetical enclosed clay/shale repository are based on the following assumptions and are summarized in Table 5-22, along with the cost to dispose of BOC SNF to facilitate cost comparison. For each of the three types of TRISO

SNF, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-7. Detailed calculations are shown in Appendix A.4.

Assumptions:

- The reference repository used for the cost analyses assumes the emplacement drifts are 30 m apart (center to center) and the waste packages are 10 m apart (center to center) (Section 4.3 of Hardin et al., 2012). Because a canister of TRISO SNF is so much cooler than a similarly sized canister of SNF, for the purposes of this analysis, it is assumed that the emplacement boreholes are 10 m apart (rather than 30 m apart) and that eight waste packages can be placed in each horizontal borehole (which is 40 m long), rather than four waste packages. This results in having six times as many waste packages in the same footprint. The number of waste packages per panel is thus 3,840 (instead of 640 per panel as shown in Table 4.3-2 of Hardin et al., 2012).
- Because the number of emplacement drifts increases by a factor of three, the length of material per panel that needs to be mined for emplacement drifts (Table 4.3-1 of Hardin et al., 2012) increases from 6,400 m to 19,200 m, a difference of 12,800 m.
- The volume that needs to be mined and backfilled increases by from 4.6E6 to 1.4E7 m^3 for the emplacement drifts (Table 4-2 of Hardin et al., 2012) (triples the value of 4.6E6), a difference of 9.2E6 m^3.
- The cost for "Operations and Maintenance" is adjusted for increased mining costs by multiplying 12,800 m by $2,384/ft (Table 5.1-3 of Hardin et al., 2012) and 3.28 ft/m and 130 panels (Table 4.6-2 of Hardin et al., 2012). The adjustment for additional steel liner is calculated by multiplying 12,800 m by $8,308/ft and 3.28 ft/m and 130 panels. The adjustment for additional costs for backfill and muck disposal is calculated as 9.2E6 m^3 multiplied by the sum of (150 + 111 $/cubic yard) * (1.3 yd^3/m^3) (Table 5.1-4 of Hardin et al., 2012). These adjustments are added together and divided by 1E6 to convert to millions of dollars.
- The repository was designed for 140,000 MTHM of BOC SNF.
- Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO pebble bed SNF is about 0.3 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *6*0.3/12.93.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO prismatic block SNF is 0.6 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of prismatic block TRISO in this repository is calculated as 140,000 MTHM *6*0.6/12.93.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of FHR TRISO pebble bed SNF 0.5 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy

metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *6*0.5/12.93.

Table 5-22. Normalized Cost to Dispose of TRISO SNF in an Enclosed Clay/Shale Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	82,000	140,000	0.58	13
	High	110,000		0.78	17
TRISO - HTGR pebble bed	Low	220,000	19,490	11	61
	High	260,000		13	73
TRISO - HTGR Prismatic block	Low	220,000	38,979	5.6	34
	High	260,000		6.6	40
TRISO - FHR pebble bed	Low	220,000	32,483	6.7	32
	High	260,000		7.9	38

5.4.4. Normalized Cost to Dispose of Metallic SNF in a Clay/Shale Repository

Estimates of the normalized cost to dispose of metallic SNF in a hypothetical enclosed clay/shale repository are based on the following assumptions and are summarized in Table 5-23, along with the cost to dispose of BOC SNF to facilitate cost comparisons. For the SFR SNF discussed herein, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-10. Detailed calculations are shown in Appendix A.4.

Assumptions:

- For a canister that has been optimized for SFR loading (hexagonal array), the heat generated by that SNF is similar to that generated by BOC SNF placed in the same canister volume (Table 4-2 of Hoffman et al. 2023). Thus, the layout of the repository is unchanged.
- The fissile mass of the discharged fuel is about three times higher for the same volume. Thus, additional neutron absorbing capability or other treatment will be needed for the canister.
- The waste package cost is assumed to increase by 10% to account for the increased neutron absorber capability.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size and with optimized loading of SFR SNF, the heavy metal loading of spent SFR is about 0.64 times that of BOC SNF (8.3/12.93). Therefore, for the purpose of calculating disposal cost per MTHM of SFR SNF in this repository, the MTHM is calculated as 140,000 MTHM*0.64.

Table 5-23. Normalized Cost to Dispose of BOC and Metallic SNF in an Enclosed Clay/Shale Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	82,000	140,000	0.58	13
	High	110,000		0.78	17
Metallic	Low	83,000	89,869	0.92	5.7
	High	110,000		1.2	7.6

5.4.5. *Summary and Discussion – Enclosed Clay/Shale Repository*

To facilitate comparison, the ratios of the repository capacity (MTHM) and costs for disposal of the different types of HALEU SNF in a hypothetical enclosed clay/shale repository to the repository capacity and cost for disposal of BOC SNF in a hypothetical enclosed clay/shale repository were calculated and are given in Table 5-24.

Table 5-24. Ratios of Repository Capacity (MTHM) and Costs for Disposal of HALEU SNF in an Enclosed Clay/Shale Repository to Repository Capacity and Costs for Disposal of BOC SNF in an Enclosed Clay/Shale Repository

Waste Type	Low or High End of Range	Cost Ratio	MTHM Ratio	Cost per MTHM Ratio	Cost per Energy Generated Ratio
BOC	Low	1.0	1.0	1.0	1.0
	High	1.0		1.0	1.0
ATF - 7% enrichment	Low	0.97	0.54	1.8	1.1
	High	0.97		1.8	1.1
ATF - 8.3% enrichment	Low	0.97	0.46	2.1	1.1
	High	0.97		2.1	1.1
TRISO - HTGR pebble bed	Low	2.7	0.14	19	4.7
	High	2.4		17	4.2
TRISO - HTGR prismatic block	Low	2.7	0.28	9.5	2.6
	High	2.4		8.5	2.3
TRISO - FHR pebble bed	Low	2.7	0.23	11	2.5
	High	2.4		10	2.2
Metallic	Low	1.0	0.64	1.6	0.44
	High	1.0		1.6	0.44

These results indicate that, for ATF SNF, the repository cost is somewhat less because the waste packages are smaller and are slightly less expensive. The waste packages are smaller so that thermal limits can be met, which also means that the repository capacity (MTHM) is less, about half as much. Accordingly, the cost to dispose of it is roughly double that to dispose of BOC SNF when measured on a basis of MTHM. However, because ATF produces more energy per MTHM than does BOC SNF, the cost to dispose of it is about ten percent more than the cost to dispose of BOC SNF when measured on a basis of energy generated.

For TRISO SNF, the repository itself is roughly two and a half times the cost of a repository for BOC SNF. This is primarily because TRISO SNF is so much cooler than BOC SNF that more waste packages can be emplaced in the same footprint. Thus, as described in Section 5.4.3, it was assumed that there are six times as many waste packages, increasing the waste package cost by a factor of six. As noted above, for a given volume, TRISO SNF contains far less MTHM than does BOC SNF. Even though the hypothetical enclosed clay/shale repository is assumed to contain six times as many similar-sized waste packages, the quantity of TRISO MTHM it can contain is only ~ 15% - 25% of the quantity of BOC SNF. This results in disposal costs that are about five to 20 times higher than costs for disposal of BOC SNF, when measured on a basis of MTHM. When measured on a basis of energy generated, disposing of TRISO SNF is about two to five times as expensive as disposing of BOC SNF in an enclosed clay/shale repository.

However, this repository, like the repositories discussed above, is designed for high heat generating waste. To meet thermal limits, waste packages are 10 m apart in each horizontal emplacement borehole and the emplacement boreholes are 30 m apart. Because TRISO SNF is not a high heat generating waste, it is not necessary to have as much space between waste packages, and, as discussed above, it would be possible to design a repository for this waste that would be significantly less expensive.

For metallic SNF, the cost of a repository is negligibly higher (on the order of 1%) because of the assumed need to increase the neutron-absorbing capability of the canisters, resulting in a 10% increase in the cost of waste packages. The heavy metal loading of each waste package is about 64% of what is in a waste package containing BOC SNF, resulting in the emplacement of less MTHM of metallic SNF than of BOC SNF in the same size repository. Accordingly, the cost to dispose of metallic SNF is about 1.6 times the cost to dispose of BOC SNF when measured on a basis of MTHM. However, because metallic SNF generates about 3.5 times the energy per MTHM than does BOC SNF (see Table 2-10), the cost of disposal per energy generated is about half that for BOC SNF.

5.5. Cost of Disposal in a Clay/Shale Unbackfilled (Open)

The cost for disposing of irradiated HALEU in a clay/shale unbackfilled (open) repository is taken from Hardin et al., (2012), as shown in Table 5-25. As described in Hardin et al. (2012), the unbackfilled, open emplacement mode concept for SNF disposal in shale is similar to the clay/shale (enclosed) mode, but with important differences. In-drift emplacement would be used for potentially much larger waste packages, and forced ventilation would remove heat for decades prior to closure. At closure, emplacement drift segments containing approximately 10 waste packages would be isolated from one another by seals. Low permeability backfill with swelling properties would be installed in the service and access drifts only. Ventilation would be adjusted during seals installation and backfilling operations to provide a fresh-air, temperature-controlled working environment. Backfilling of cross-drifts would serve to seal off adjacent emplacement drift segments from each other. No backfill would be installed within the drift segments where waste packages are emplaced. As stated previously, backfilling of these emplacement drift segments remains an option until repository closure, if determined to be necessary to assure waste isolation

Table 5-25. Cost to Dispose of BOC SNF in Clay/Shale (open) Repository

	Costs for BOC SNF (2012$Millions)		Costs for BOC SNF (2024$Millions)	
Element	**Low**	**High**	**Low**	**High**
Facility Design Construction, Startup	3,303	4,711	4,492	6,407
Operations and Maintenance	9,702	12,408	13,195	16,875
Closure	1,622	2,515	2,206	3,420
Waste Packages	2,882	3,569	3,920	4,854
Regulatory & Licensing	417	421	567	573
Monitoring	3,395	4,629	4,617	6,295
Performance Confirmation	423	576	575	783
Program Integration	3,732	5,084	5,076	6,914
Total	**25,476**	**33,913**	**34,647**	**46,122**

The concept consists of 21-PWR/44-BWR canisters in carbon steel overpacks emplaced in 90-m long emplacement segments, each holding about 10 waste packages spaced 10 m apart. There would be eight emplacement segments per 700-m long emplacement drift and the repository would consist of 16 panels of 12 emplacement drifts. A typical panel is depicted in Figure 5-4.

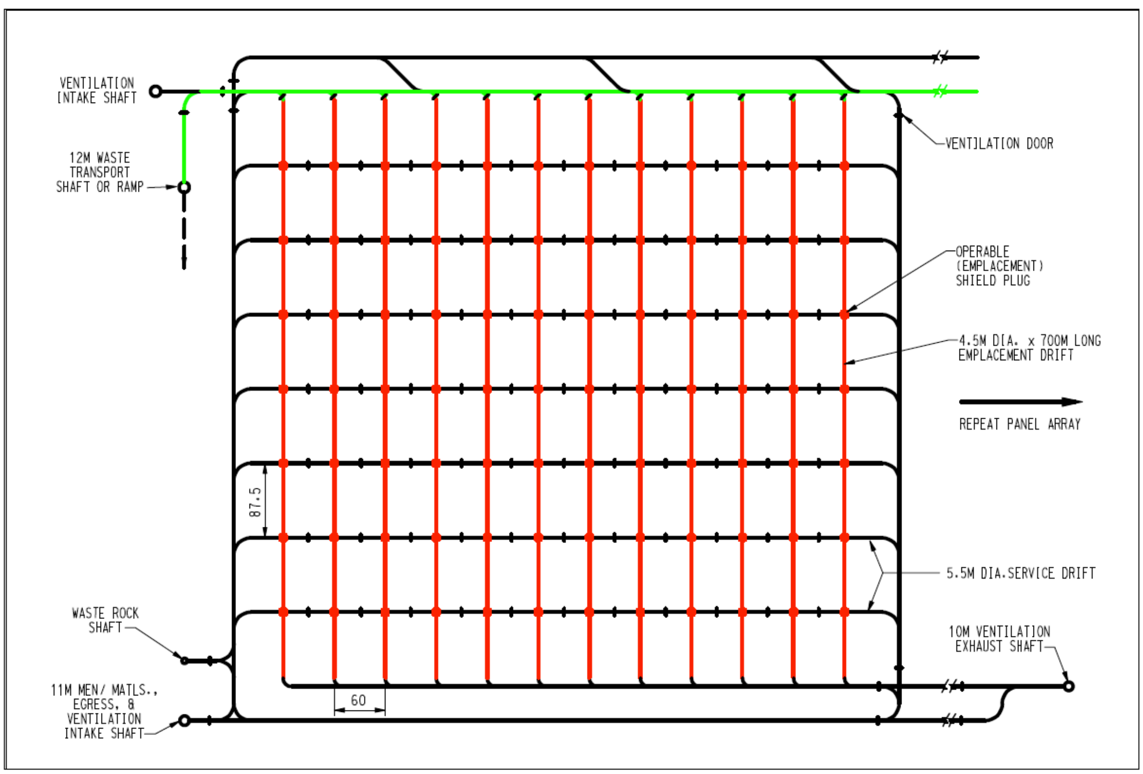

Figure 5-4. Shale Unbackfilled Open Concept Repository Panel Layout (from Hardin et al., 2012 Figure 4.4-1)

5.5.1. Normalized Cost to Dispose of Typical SNF in a Clay/Shale Unbackfilled (Open) Repository

The open clay/shale repository described above was designed to hold 140,000 MTHM of SNF, and the MTHM required per energy generated for BOC fuel is given in Table 2-3. Using these values, the cost of disposing of BOC SNF in an open clay/shale repository in terms of 2024$/MTHM and 2024$/GWe-yr are calculated and are shown in Table 5-26.

Table 5-26. Normalized Cost of Disposing of BOC SNF in an Unbackfilled Clay/Shale (Open) Repository

Low or High	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
Low	35,000	140,000	0.25	5.5
High	46,000		0.33	7.3

5.5.2. Normalized Cost to Dispose of ATF SNF in a Clay/Shale Unbackfilled (Open) Repository

Estimates of the normalized cost to dispose of ATF in a hypothetical open clay/shale repository are based on the following assumptions and are summarized in Table 5-27 , along with the cost to dispose of BOC SNF to facilitate comparison. For each of the two types of ATF SNF, the mass of SNF generated by the production of 1 GWe-yr of energy as taken from Table 2-3. Detailed calculations are shown in Appendix A.5.

<u>**Assumptions:**</u>

- Because spent ATF has higher decay heat than BOC SNF at any given time (Table 4-1 of Hoffman et al., 2023), it is assumed that waste packages used to dispose of spent ATF are smaller. Table 4-4 (Hoffman et al. 2023) indicates that roughly half as many assemblies of spent ATF can be loaded in a given canister to meet thermal limits, as compared to BOC SNF. Therefore, for estimating the cost of waste packages, it assumed that spent ATF waste packages have half the capacity of BOC SNF waste packages.
- Accordingly, waste package costs are assumed to be 75% of the cost of those of BOC SNF. The number of waste packages does not change but each one is assumed to be smaller.
- The layout of the repository does not change.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 7% enrichment and 84 GWd/MTHM burnup in that canister is about 0.54 times that of BOC SNF (7.01/12.93). Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of spent ATF with 7% enrichment and 84 GWd/MTHM in this repository is calculated as 140,000 MTHM *0.54.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 8.3% enrichment and 100 GWd/MTHM burnup in that canister is about 0.46 times that of BOC SNF (5.93/12.93). Therefore, for the purpose of calculating cost per MTHM

SNF, the MTHM of spent ATF with 8.3% enrichment and 100 GWd/MTHM in this repository is calculated as 140,000 MTHM *0.46.

Table 5-27. Normalized Cost to Dispose of BOC and ATF SNF in an Unbackfilled (Open) Clay/Shale Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	35,000	140,000	0.25	5.5
	High	46,000		0.33	7.3
ATF - 7% enrichment	Low	34,000	75,901	0.44	5.8
	High	45,000		0.59	7.8
ATF – 8.3% enrichment	Low	34,000	64,207	0.52	5.8
	High	45,000		0.70	7.8

5.5.3. *Normalized Cost to Dispose of TRISO SNF in an Unbackfilled (Open) Clay/Shale Repository*

Estimates of the normalized cost to dispose of TRISO SNF in a hypothetical open clay/shale repository are based on the following assumptions and are summarized in Table 5-28, along with the cost to dispose of BOC SNF to facilitate cost comparison. For each of the three types of TRISO SNF, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-7. Detailed calculations are shown in Appendix A.5.

Assumptions:

- The 21-PWR/44-BWR waste package used in the repository is 1.6 m in diameter and 5 m long (Table 1.4-1 of Hardin et al., (2012)), and 10 of them are placed along the axis of a 700-m long emplacement drift that is approximately 500 m below the ground surface (Figure 4.4-1, Table 4.4-1, Table 4.4-2 of Hardin et al. (2012)). The emplacement drift consists of eight 90-m long segments.
- The reference repository used for the cost analyses assumes the drifts are 60 m apart (center to center) and the waste packages are 10 m apart (Section 4.4 of Hardin et al. (2012)). Because a canister of TRISO SNF is so much cooler than a similarly sized canister of SNF, for the purposes of this analysis, it is assumed that the drifts are 10 m apart (rather than 60 m apart) and that 18 waste packages can be placed in each of the eight 90-m long drift segments, rather than 10 (Table 4.4-2). This results in having 14.4 times as many waste packages in the same footprint (6 x 1.8). Thus, the number of waste packages per panel is 10,368 (instead of 960 per panel as shown in Table 4.4-2 of Hardin et al. (2012)).
- The length of material per panel that needs to be mined for emplacement drifts (Table 4.4-1 of Hardin et al. (2012)) increases by 42,000 m from 8,400 m to 50,400 m.
- The volume that needs to be backfilled does not change because only the access drifts are backfilled; the emplacement drifts are not backfilled.
- "Operations and Maintenance" is adjusted for increased mining costs by multiplying 42,000 m by $2,540/ft (Table 5.1-3 of Hardin et al., (2012)) and 3.28 ft/m and 17 panels (Table 4.6-2 of Hardin et al. (2012)). This adjustment is then divided by 1E6 to convert to millions of dollars.

- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO pebble bed SNF is about 0.3 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *14.4*0.3/12.93.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO prismatic block SNF is 0.6 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of prismatic block TRISO in this repository is calculated as 140,000 MTHM *14.4*0.6/12.93.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of FHR TRISO pebble bed SNF 0.5 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *14.4*0.5/12.93.

Table 5-28. Normalized Cost to Dispose of BOC and TRISO SNF in an Unbackfilled (Open) Clay/Shale Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	35,000	140,000	0.25	5.5
	High	46,000		0.33	7.3
TRISO - HTGR pebble bed	Low	95,000	46,775	2.0	11
	High	120,000		2.5	14
TRISO - HTGR Prismatic block	Low	95,000	93,550	1.0	6.2
	High	120,000		1.3	7.8
TRISO- FHR pebble bed	Low	95,000	77,958	1.2	5.8
	High	120,000		1.5	7.3

5.5.4. Normalized Cost to Dispose of Metallic SNF in an Unbackfilled (Open) Clay/Shale Repository

Estimates of the normalized cost to dispose of metallic SNF in a hypothetical open clay/shale repository are based on the following assumptions and are summarized in Table 5-29 , along with the cost to dispose of BOC SNF to facilitate cost comparisons. For the SFR SNF discussed herein, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-10. Detailed calculations are shown in Appendix A.5.

Assumptions:

- For a canister that has been optimized for SFR loading (hexagonal array), the heat generated by that SNF is similar to that generated by BOC SNF placed in the same canister volume (Table 4-2 of Hoffman et al. 2023). Thus, the layout of the repository is unchanged.
- However, the fissile mass of the discharged fuel is about three times higher for the same volume. Thus, additional neutron absorbing capability or other treatment will be needed for the canister.
- The waste package cost is assumed to increase by 10% to account for the increased neutron absorber capability.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size and with optimized loading of SFR SNF, the heavy metal loading of spent SFR is about 0.64 times that of BOC SNF (8.3/12.93). Therefore, for the purpose of calculating disposal cost per MTHM of SFR SNF in this repository, the MTHM is calculated as 140,000 MTHM*0.64.

Table 5-29. Normalized Cost to Dispose of BOC and Metallic SNF in an Unbackfilled (Open) Clay/Shale Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	35,000	140,000	0.25	5.5
	High	47,000		0.33	7.3
Metallic	Low	35,000	58,392	0.39	2.4
	High	47,000		0.52	3.2

5.5.5. *Summary and Discussion – Open Clay/Shale Repository*

To facilitate comparison, the ratios of the repository capacity (MTHM) and costs for disposal of the different types of HALEU SNF in a hypothetical enclosed clay/shale repository to the repository capacity and cost for disposal of BOC SNF in a hypothetical enclosed clay/shale repository were calculated and are given in Table 5-30.

Table 5-30. Ratios of Repository Capacity (MTHM) and Costs for Disposal of HALEU SNF in an Unbackfilled (Open) Clay/Shale Repository to Repository Capacity and Costs for Disposal of BOC SNF in an Unbackfilled (Open) Clay/Shale Repository

Waste Type	Low or High End of Range	Cost Ratio	MTHM Ratio	Cost per MTHM Ratio	Cost per Energy Generated Ratio
BOC	Low	1.0	1.0	1.0	1.0
	High	1.0		1.0	1.0
ATF - 7% enrichment	Low	0.97	0.54	1.8	1.1
	High	0.97		1.8	1.1
ATF - 8.3% enrichment	Low	0.97	0.46	2.1	1.1
	High	0.97		2.1	1.1

Waste Type	Low or High End of Range	Cost Ratio	MTHM Ratio	Cost per MTHM Ratio	Cost per Energy Generated Ratio
TRISO - HTGR pebble bed	Low	2.8	0.33	8.2	2.1
	High	2.6		7.7	1.9
TRISO - HTGR prismatic block	Low	2.8	0.67	4.1	1.1
	High	2.6		3.9	1.1
TRISO - FHR pebble bed	Low	2.8	0.56	4.9	1.1
	High	2.6		4.6	1.0
Metallic	Low	1.0	0.64	1.6	0.44
	High	1.0		1.6	0.44

These results indicate that, for ATF SNF, the repository cost is somewhat less because the waste packages are smaller and are slightly less expensive. The waste packages are smaller so that thermal limits can be met, which also means that the repository capacity (MTHM) is less, about half as much. Accordingly, the cost to dispose of it is roughly double that to dispose of BOC SNF when measured on a basis of MTHM. However, because ATF produces more energy per MTHM than does BOC SNF, the cost to dispose of it is about ten percent more than the cost to dispose of BOC SNF when measured on a basis of energy generated.

For TRISO SNF, the repository itself is almost three times the cost of a repository for BOC SNF. This is primarily because TRISO SNF is so much cooler than BOC SNF that more waste packages can be emplaced in the same footprint. Thus, as described in Section 5.5.3, it was assumed that there are 14.4 times as many waste packages, increasing the waste package cost by a factor of 14.4. As noted above, for a given volume, TRISO SNF contains far less MTHM than does BOC SNF. Even though the hypothetical open clay/shale repository is assumed to contain 14.4 times as many similar-sized waste packages, the quantity of TRISO MTHM it can contain is ~ 30% - 70% of the quantity of BOC SNF. This results in disposal costs that are about four to eight times higher than costs for disposal of BOC SNF, when measured on a basis of MTHM. When measured on a basis of energy generated, disposing of TRISO SNF is about one to two times as expensive as disposing of BOC SNF in an open clay/shale repository.

For metallic SNF, the cost of a repository is negligibly higher (on the order of 1%) because of the assumed need to increase the neutron-absorbing capability of the canisters, resulting in a 10% increase in the cost of waste packages. The heavy metal loading of each waste package is about 64% of what is in a waste package containing BOC SNF, resulting in the emplacement of less MTHM of metallic SNF than of BOC SNF in the same size repository. Accordingly, the cost to dispose of metallic SNF is about 1.5 times the cost to dispose of BOC SNF when measured on a basis of MTHM. However, because metallic SNF generates about 3.5 times the energy per MTHM than does BOC SNF (see Table 2-10), the cost of disposal per energy generated is about half that for BOC SNF.

5.6. Cost of Disposal in a Sedimentary Backfilled (Open)

The cost for disposing of irradiated HALEU SNF in a sedimentary backfilled (open) repository is taken from Hardin et al. (2012), as shown in Table 5-31. The concept consists of 21-PWR/44-BWR canisters in carbon-steel overpacks emplaced in twelve 4-segment emplacement panels. Each segment would be 200 m long and would contain 15 waste packages spaced 10 m apart (center-to-center). The emplacement drifts would be 60 m apart. Approximately 20 panels of 48 emplacement drift segments would be needed to dispose of 140,000 MTHM of BOC SNF. The repository would be located in a sedimentary rock 500 m below the ground surface, and repository opening would remain open until closure, at which point access drifts and emplacement drifts would be backfilled. A typical panel is depicted in Figure 5-5.

Table 5-31. Cost to Dispose of BOC SNF in a Sedimentary Backfilled (open) Repository

	Costs for BOC SNF (2012$Millions)		Costs for BOC SNF (2024$Millions)	
Element	**Low**	**High**	**Low**	**High**
Facility Design Construction, Startup	5,410	7,599	7,358	10,335
Operations and Maintenance	9,614	12,264	13,075	16,679
Closure	2,263	3,558	3,078	4,839
Waste Packages	2,882	3,569	3,920	4,854
Regulatory & Licensing	668	679	908	923
Monitoring	3,775	5,148	5,134	7,001
Performance Confirmation	798	1,088	1,085	1,480
Program Integration	6,878	9,370	9,354	12,743
Total	**32,288**	**43,275**	**43,912**	**58,854**

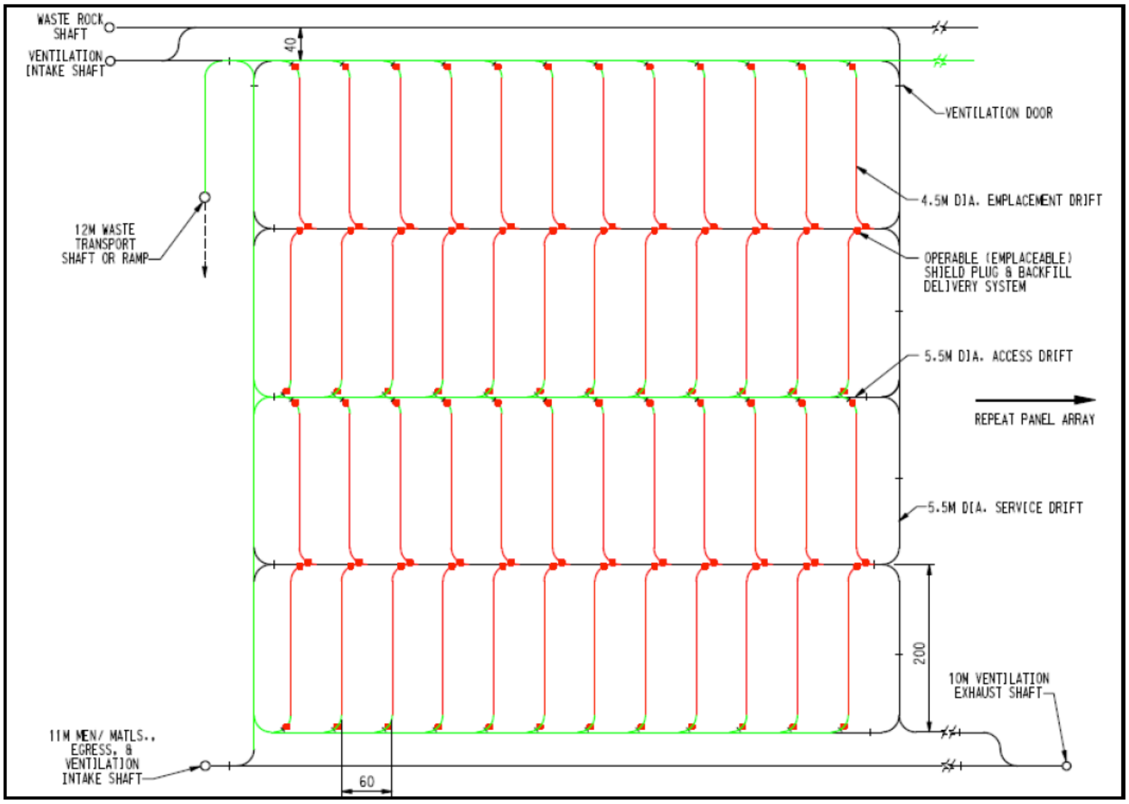

Figure 5-5. Sedimentary Backfilled Open Concept Repository Panel Layout (From Figure 4.5-1 of Hardin et al., 2012)

5.6.1. Normalized Cost to Dispose of Typical SNF in a Sedimentary Backfilled (Open) Repository

The open backfilled sedimentary repository described above was designed to hold 140,000 MTHM of SNF, and the MTHM required per energy generated for BOC fuel is given in Table 2-3. Using these values, the cost of disposing of BOC SNF in an open clay/shale repository in terms of 2024$/MTHM and 2024$/GWe-yr are calculated and are shown in Table 5-32.

Table 5-32. Normalized Cost of Disposing of BOC SNF in a Sedimentary Backfilled (open) Repository

Low or High	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
Low	44,000	140,000	0.31	7.0
High	59,000		0.42	9.3

5.6.2. Normalized Cost to Dispose of ATF SNF in a Sedimentary Backfilled (Open) Repository

Estimates of the normalized cost to dispose of ATF in a hypothetical sedimentary backfilled (open) repository are based on the following assumptions and are summarized in Table 5-33, along with the cost to dispose of BOC SNF to facilitate comparison. For each of the two types of ATF SNF, the mass of SNF generated by the production of 1 GWe-yr of energy as taken from Table 2-3. Detailed calculations are shown in Appendix A.6.

Assumptions:

- Because spent ATF has higher decay heat than BOC SNF at any given time (Table 4-1 of Hoffman et al., 2023), it is assumed that waste packages used to dispose of spent ATF are smaller. Table 4-4 (Hoffman et al. 2023) indicates that roughly half as many assemblies of spent ATF can be loaded in a given canister to meet thermal limits, as compared to BOC SNF. Therefore, for estimating the cost of waste packages, it assumed that spent ATF waste packages have half the capacity of BOC SNF waste packages.
- Accordingly, waste package costs are assumed to be 75% of the cost of those of BOC SNF. The number of waste packages does not change but each one is assumed to be smaller.
- The layout of the repository does not change.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 7% enrichment and 84 GWd/MTHM burnup in that canister is about 0.54 times that of BOC SNF (7.01/12.93). Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of spent ATF with 7% enrichment and 84 GWd/MTHM in this repository is calculated as 140,000 MTHM *0.54.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-4 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of spent ATF SNF with 8.3% enrichment and 100 GWd/MTHM burnup in that canister is about 0.46 times that of BOC SNF (5.93/12.93). Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of spent ATF with 8.3% enrichment and 100 GWd/MTHM in this repository is calculated as 140,000 MTHM *0.46.

Table 5-33. Normalized Cost to Dispose of BOC and ATF SNF in a Sedimentary Backfilled (Open) Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	44,000	140,000	0.31	7.0
	High	59,000		0.42	9.3
ATF - 7% enrichment	Low	43,000	75,901	0.57	7.4
	High	58,000		0.76	10
ATF – 8.3% enrichment	Low	43,000	64,207	0.67	7.4
	High	58,000		0.90	10

5.6.3. *Normalized Cost to Dispose of TRISO SNF in a Sedimentary Backfilled (Open) Repository*

Estimates of the normalized cost to dispose of TRISO SNF in a hypothetical sedimentary backfilled (open) repository are based on the following assumptions and are summarized in Table 5-34, along with the cost to dispose of BOC SNF to facilitate cost comparison. For each of the three types of

TRISO SNF, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-7. Detailed calculations are shown in Appendix A.6.

- A 21-PWR/44-BWR waste package is the waste package used in the cost analyses for the sedimentary 69backfilled (open) repository concept (Table 4.5-2 of Hardin et al. 2012). The 21-PWR/44-BWR waste package is 1.6 m in diameter and 5 m long (Table 1.4-1 of Hardin et al. 2012), and 15 of them are placed along the axis of a 200-m long emplacement drift that is approximately 500 m below the ground surface (Figure 4.5-1, Table 4.5-1, Table 4.5-2 of Hardin et al, 2012). Each of the 12 emplacement drifts consists of four 200-m long segments.
- The reference repository used for the cost analyses assumes the drifts are 60 m apart (center to center) and the waste packages are 10 m apart (Section 4.5 of Hardin et al. 2012). Because a canister of TRISO SNF is so much cooler than a similarly sized canister of SNF, for the purposes of this analysis, it is assumed that the number of drifts increases by a factor of six such that they are 10 m apart (rather than 60 m apart) and that 40 waste packages can be placed in each of the 200-m long drift segments, rather than 15 (Table 4.5-2). This results in having 16 times as many waste packages in the same footprint (6 x 40/15). Thus, the number of waste packages per panel is 11,520 (instead of 720 per panel as shown in Table 4.5-2 of Hardin et al. 2012).
- The length of material per panel that needs to be mined for emplacement drifts (Table 4.5-1 of Hardin et al. 2012) increases by 48,000 m from 9,600 m to 57,600 m.
- The volume that needs to be backfilled increases by 1.8E7 m^3, from 3.5E6 m^3 to 2.1E7 m^3 (Table 4-2 of Hardin et al. 2012).
- "Operations and Maintenance" is adjusted for increased mining costs by multiplying 48,000 m by $2,384/ft (Table 5.1-3 of Hardin et al. 2012) and 3.28 ft/m and 23 panels (Table 4.6-2 of Hardin et al. 2012). The adjustment for additional costs for backfill and muck disposal is calculated as 1.8E7 m^3 multiplied by the sum of (150 + 111 $/cubic yard) * (1.3 yd^3/m^3) (Table 5.1-4 of Hardin et al. 2012). These adjustments are added together and then divided by 1E6 to convert to millions of dollars.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO pebble bed SNF is about 0.3 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM SNF, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *16*0.3/12.93..
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of TRISO prismatic block SNF is 0.6 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of prismatic block TRISO in this repository is calculated as 140,000 MTHM *16*0.6/12.93.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-1 of Hoffman et al. (2023) indicates that, for a given canister size, the heavy metal loading of FHR TRISO pebble bed SNF 0.5 MTHM. Table 4-4 of Hoffman et al. (2023) indicates that the heavy

metal loading of BOC SNF 5 years OOR in a canister with a thermal limit of 37 kW is 12.93 MTHM. Therefore, for the purpose of calculating cost per MTHM, the MTHM of pebble bed TRISO SNF in this repository is calculated as 140,000 MTHM *16*0.5/12.93.

Table 5-34. Normalized Cost to Dispose of BOC and TRISO SNF in a Sedimentary Backfilled (Open) Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	44,000	140,000	0.31	7.0
	High	59,000		0.42	9.3
TRISO - HTGR pebble bed	Low	120,000	51,972	2.4	13
	High	150,000		2.9	16
TRISO - HTGR Prismatic block	Low	120,000	103,944	1.2	7.2
	High	150,000		1.5	8.9
TRISO - FHR pebble bed	Low	120,000	86,620	1.4	6.8
	High	150,000		1.8	8.4

5.6.4. Normalized Cost to Dispose of Metallic SNF in a Sedimentary Backfilled (Open) Repository

Estimates of the normalized cost to dispose of metallic SNF in a hypothetical sedimentary backfilled (open) sedimentary repository are based on the following assumptions and are summarized in Table 5-35, along with the cost to dispose of BOC SNF to facilitate cost comparisons. For the SFR SNF discussed herein, the mass of SNF generated by the production of 1 GWe-yr of energy was taken from Table 2-10. Detailed calculations are shown in Appendix A.6.

Assumptions:

- For a canister that has been optimized for SFR loading (hexagonal array), the heat generated by that SNF is similar to that generated by BOC SNF placed in the same canister volume (Table 4-2 of Hoffman et al. 2023). Thus, the layout of the repository is unchanged.
- However, the fissile mass of the discharged fuel is about three times higher for the same volume. Thus, additional neutron absorbing capability or other treatment will be needed for the canister.
- The waste package cost is assumed to increase by 10% to account for the increased neutron absorber capability.
- The repository was designed for 140,000 MTHM of BOC SNF. Table 4-2 of Hoffman et al. (2023) indicates that, for a given canister size and with optimized loading of SFR SNF, the heavy metal loading of spent SFR is about 0.64 times that of BOC SNF (8.3/12.93). Therefore, for the purpose of calculating disposal cost per MTHM of SFR SNF in this repository, the MTHM is calculated as 140,000 MTHM*0.64.

Table 5-35. Normalized Cost to Dispose of BOC and Metallic SNF in a Sedimentary Backfilled (Open) Repository

Waste Type	Low or High End of Range	Cost (2024 $Million)	MTHM	Cost/MTHM (2024 $Million /MTHM)	Cost per Energy Generated (2024 $Million /GWe-yr)
BOC	Low	44,000	140,000	0.31	7.0
	High	59,000		0.42	9.3
Metallic	Low	44,000	89,869	0.49	3.1
	High	59,000		0.66	4.1

5.6.5. *Summary and Discussion – Sedimentary Backfilled (Open) Repository*

To facilitate comparison, the ratios of the repository capacity (MTHM) and costs for disposal of the different types of HALEU SNF in a hypothetical backfilled (open) sedimentary repository to the repository capacity and cost for disposal of BOC SNF in a hypothetical backfilled (open) sedimentary repository were calculated and are given in Table 5-36.

Table 5-36. Ratios of Repository Capacity (MTHM) and Costs for Disposal of HALEU SNF in a Backfilled (Open) Sedimentary Repository to Repository Capacity and Costs for Disposal of BOC SNF in a Backfilled (Open) Sedimentary Repository

Waste Type	Low or High End of Range	Cost Ratio	MTHM Ratio	Cost per MTHM Ratio	Cost per Energy Generated Ratio
BOC	Low	1.0	1.0	1.0	1.0
	High	1.0		1.0	1.0
ATF - 7% enrichment	Low	0.98	0.54	1.8	1.1
	High	0.98		1.8	1.1
ATF - 8.3% enrichment	Low	0.98	0.46	2.1	1.1
	High	0.98		2.1	1.1
TRISO - HTGR pebble bed	Low	2.8	0.37	7.5	1.9
	High	2.6		6.9	1.7
TRISO - HTGR prismatic block	Low	2.8	0.74	3.8	1.0
	High	2.6		3.5	0.95
TRISO - FHR pebble bed	Low	2.8	0.62	4.5	0.97
	High	2.6		4.2	0.90
Metallic	Low	1.0	0.64	1.6	0.44
	High	1.0		1.6	0.44

These results indicate that, for ATF SNF, the repository cost is somewhat less because the waste packages are smaller and are slightly less expensive. The waste packages are smaller so that thermal limits can be met, which also means that the repository capacity (MTHM) is less, about half as much. Accordingly, the cost to dispose of it is roughly double that to dispose of BOC SNF when measured on a basis of MTHM. However, because ATF produces more energy per MTHM than does BOC SNF, the cost to dispose of it is about ten percent more than the cost to dispose of BOC SNF when measured on a basis of energy generated.

For TRISO SNF, the repository itself is almost three times the cost of a repository for BOC SNF. This is primarily because TRISO SNF is so much cooler than BOC SNF that more waste packages can be emplaced in the same footprint. Thus, as described in Section 5.6.3, it was assumed that there are 16 times as many waste packages, increasing the waste package cost by a factor of 16. As noted above, for a given volume, TRISO SNF contains far less MTHM than does BOC SNF. Even though the hypothetical open clay/shale repository is assumed to contain 16 times as many similar-sized waste packages, the quantity of TRISO MTHM it can contain is ~ 35% - 75% of the quantity of BOC SNF. This results in disposal costs that are about three to eight times higher than costs for disposal of BOC SNF, when measured on a basis of MTHM. When measured on a basis of energy generated, disposing of TRISO SNF is about one to two times as expensive as disposing of BOC SNF in an open clay/shale repository.

For metallic SNF, the cost of a repository is negligibly higher (on the order of 1%) because of the assumed need to increase the neutron-absorbing capability of the canisters, resulting in a 10% increase in the cost of waste packages. The heavy metal loading of each waste package is about 64% of what is in a waste package containing BOC SNF, resulting in the emplacement of less MTHM of metallic SNF than of BOC SNF in the same size repository. Accordingly, the cost to dispose of metallic SNF is about 1.6 times the cost to dispose of BOC SNF when measured on a basis of MTHM. However, because metallic SNF generates about 3.5 times the energy per MTHM than does BOC SNF (see Table 2-10), the cost of disposal per energy generated is about half that for BOC SNF.

6. SUMMARY AND CONCLUSIONS

In the U.S., the fuel used by most commercial nuclear power plants is 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 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. After it has been irradiated, the characteristic of high assay low-enriched uranium 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. A previous report (Price et al. 2024) identified qualitatively how the components of the back end of the nuclear fuel cycle 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. The work reported herein builds on that previous report and quantifies how the costs of the back end of the nuclear fuel cycle are affected by managing irradiated spent HALEU fuel. Note that while LEU SNF is currently stored and transported safely, disposal of LEU 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.

Three different fuels that may use high assay low-enriched uranium were studied: ATF that can be used in a typical light-water reactor, TRISO fuel, and metallic fuel. Three 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 (Price et al. 2024). Building on that work, costs for storing, transporting, and disposing of irradiated HALEU fuel were estimated. The approach to estimating costs consisted of taking costs for the various components of the back end of the nuclear fuel cycle (storage, transportation, and disposal) as applied to typical LWR SNF, adjusting those costs to account for differences between typical LWR SNF and HALEU SNF, and estimating cost per MTHM and cost per energy generated. In estimating the costs, it was assumed that the large dry storage canisters currently employed for storage and transport of typical LWR SNF would be used for HALEU SNF. This assumption provides consistency of assumptions between storage, transportation, and disposal. It is acknowledged that storage and transportation systems for some of the HALEU SNF, particularly TRISO-based HALEU SNF, would likely be different (i.e., smaller) than those currently used for typical LWR SNF. However, little to no cost information is available for such systems; thus, it was not possible to evaluate these systems in this study.

The results are summarized in Table 6-1 by comparing the costs of storing, transporting, and disposing of irradiated HALEU fuel to the cost of storing, transporting and disposing of typical irradiated LWR SNF.

Table 6-1. Costs of the back end of the nuclear fuel cycle for three types of irradiated HALEU compared to those for typical LWR SNF

	Storage		Transportation Cost		Disposal Cost	
Type of High-Assay Low-Enriched Uranium Spent Fuel	**Per MTHM**	**Per energy generated**	**Per MTHM**	**Per energy generated**	**Per MTHM**	**Per energy generated**
ATF	About 2 times as much	About 10% more	About 2 times as much	About 12% more	About 2 times as much	About 10% more
TRISO	About 20 – 50 times as much	About 5 – 12 times as much	About 25 – 42 times as much	About 5 – 10 times as much	About 5 - 25 times as much	About 1 – 5 times as much
Metallic	About 60% more	About 50% less	About 2 times as much	About 50% less	About 1.6 times as much	About 50% less

Storage – The storage cost estimate is based on a cost estimate that assumed storage of 4,000 DPCs for 20 years. Costs were adjusted to reflect the different quantities of each type of HALEU SNF that could be stored in a given size canister. The cost per MTHM is proportional to the mass of spent fuel that can be placed inside a canister, which is limited by the fuel form, criticality concerns, and thermal limits. The storage cost per energy generated is related to the quantity of energy that can be generated by the mass of spent fuel in a canister; generating more energy per metric ton of heavy metal is beneficial in terms of storage cost per energy generated.

The storage of cost per MTHM for ATF SNF and for metallic SNF about 2 times higher than it is for typical LWR SNF. The storage cost per MTHM for TRISO SNF is 20 to 50 times what it is for typical LWR SNF, depending on the type of reactor that the TRISO SNF was used in and whether the fuel is in the form of compacts in prismatic blocks or pebbles.

For ATF, the storage cost per energy generated is 1.1 times higher than it is for typical LWR SNF. The storage cost per energy generated for TRISO SNF is about 5 – 12 times higher than it is for typical LWR SNF, once again depending on the type of reactor that the fuel was used in and its form. The storage cost per energy generated for metallic spent fuel is about half as much as it is for typical LWR SNF.

Much of the storage cost (~85%) is from the cost of the canisters and their overpacks. Reducing the cost of these components, particularly for TRISO SNF which is not as hot and does not emit as much radiation per volume as typical light-water reactor spent fuel, has the potential to reduce storage costs.

Transport - The total transportation cost is the sum of operational costs and fleet acquisition (capital cost). The longer the transportation campaign is, the lower is the total transportation cost per energy generated and per MTHM because the capital costs of the fleet are spread over a longer period of time. For example, these costs are ~25% higher in a 30-year campaign compared to a 60-year campaign for all types of spent fuel. The transportation cost per MTHM is also proportional to the mass of heavy metal that can be placed in a canister of a given size, which is limited by the fuel form, criticality concerns, and thermal limits. The transportation cost per energy generated is related to how much energy can be generated by the quantity of waste in a canister of a given size; generating more energy per MTHM is beneficial in terms of transportation cost per energy generated.

The transportation cost per MTHM is ~2 times higher for ATF and metallic spent fuel than for typical LWR SNF. The transportation cost per metric tons of heavy metal is about 25 - 42 times higher for TRISO SNF, depending on the type of reactor that the TRISO fuel was used in and whether the fuel is in the form of compacts in prismatic blocks or pebbles.

The transportation cost per energy generated is 1.1 times higher for ATF SNF than for typical LWR SNF. The transportation cost per energy generated is 5.5-10.5 times higher for TRISO SNF, depending on the type of reactor that the TRISO fuel was used in and whether the fuel was in the form of compacts in a prismatic block or pebbles. The transportation cost per energy generated is about half as much for metallic spent nuclear fuel than for typical light-water reactor spent fuel.

A ~30% reduction in transportation costs for TRISO SNF can be achieved if a canister that is half as heavy and half as expensive can be developed for that type of spent fuel.

Disposal – It should be noted that disposal costs were based on designs for hypothetical repositories for disposing of spent nuclear fuel that emits a lot of heat per volume, such as ATF SNF and metallic SNF. Hence, the disposal cost per energy generated for each of these two types of HALEU spent fuel are not that much different than that for typical light-water reactor spent nuclear fuel. Conversely, TRISO fuel has low heavy metal loading per volume, resulting in a disposal cost (per MTHM and per energy generated) that can be much higher than that for typical light-water reactor spent fuel, as shown in Table 6-1. However, low heavy metal loading per volume also results in the spent fuel not emitting much heat per volume. Taking advantage of this characteristic by disposing of this type of fuel in a repository that is designed for waste that does not emit high heat per volume could lead to disposal costs that are significantly lower than those shown in Table 6-1. For example, rather than excavating drifts and emplacing waste packages with some distance between them (e.g., 20 or 30 meters) to meet thermal requirements, low-heat waste could be disposed of in a cavern-like repository in which waste packages are placed on top of and next to each other. By doing so, a larger fraction of the volume of excavated rock could be used for waste disposal.

REFERENCES

Association of American Railroads (AAR), 2023. "Manual of Standards and Recommended Practices", AAR, Washington D.C., 2023.

DOE (Department of Energy) 2004. "2004 WIPP Compliance Recertification Application" DOE/WIPP 04-3231, U.S. Department of Energy, Office of Environmental Management

DOE (Department of Energy). 2008a. "Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007." DOE/RW-0591. U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Washington D.C.

DOE (Department of Energy), 2008b. "Yucca Mountain Repository License Application," DOE/RW-0573, Update No. 1. U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Washington, D.C.

EPRI, 2009. "Cost Estimate for an Away-From-Reactor Generic Interim Storage Facility (GISF) for Spent Nuclear Fuel," #1018722, Palo Alto, CA: Electric Power Research Institute

Hardin, E., Hadgu, T., Clayton, D., Howard, R., Greenberg, H., Blink, J., Sharma, M., Sutton, M., Carter, J., Dupont, M., and Rodwell, P. (2012). "Repository Reference Disposal Concepts and Thermal Load Management Analysis." SAND2012-9737 P. November 2012. Sandia National Laboratories. Albuquerque, NM.

Herczeg, J. 2021. "High-Assay Low Enriched Uranium (HALEU)," presentation at Nuclear Energy Advisory Committee Meeting, March 28, 2019. *https://www.energy.gov/sites/prod/files/2019/04/f61/HALEU%20Report%20to%20NEAC%20Committee%203-28-19%20%28FINAL%29.pdf*

Hoffman, E., Kim, T.K., and Price, L. (2023). "HALEU Fuel Impacts on Spent Nuclear Fuel Management," July 31, 2023, ANL/NSE-23/41.

Honnold, P, Montgomery, R., Billone, M., Hanson, B., and Saltzstein, S. (2021). "High Level Gap Analysis for Accident tolerant and Advanced Fuels for Storage and Transportation," SAND2021-4732, April 15, 2021

INL, 2021. "Advanced Fuel Cycle Cost Basis Report: O Modules Transportation Processes," INL/EXT-21-64453 Rev. 0, Idaho Falls, ID: Idaho National Laboratory

NAS, 2022. "Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors." Washington, DC: The National Academies Press. https://doi.org/10.17226/26500.

NRC, 2023. "Accident Tolerant Fuel Regulatory Activities," U.S. Nuclear Regulatory Commission, https://www.nrc.gov/reactors/power/atf/enrichment.html, accessed August 1, 2023.

NWMO, 2017. "Postclosure Safety Assessment of a Used Fuel Repository in Crystalline Rock," NWMO-TR-2017-02, Toronto, Canada: Nuclear Waste Management Organization.

NWTRB, 2020 "Department of Energy-Managed Spent Nuclear Fuel at Fort St. Vrain, Revision 1," Washington, DC: Nuclear Waste Technical Review Board (NWTRB).

Peterson, G., Joseph, R., Ramey, K., Blachowicz, D., Rudolph, J., Hoffman, E., Blomquist, R., Vander Wal, L., Cumberland, R., Reed, L., Karriem, V., Mondal, K., Whan Bae, J., Gadey, H., McGee, K., Kalinina, E., and Lujan, L. 2023. “System Analysis Scenario Summary Report FY-23", Spent Fuel and Waste Science and Technology, August 2023.

Price, L., Kalinina, E., and Farnum, C., 2024. “Economic Impacts of Irradiated High Assay Low-Enriched Uranium Fuel Management,” SAND2024-01681. Albuquerque, NM: Sandia National Laboratories.

Sassani, D., Brady, P., Gelbard, F., Price, L., Prouty, J., Rechard, R., Rigali, M., Rogers, R., Sanchez, A., Walkow, W. and Weck, P. (2018). "Inventory and Waste Characterization Status Report and OWL Update," SAND2018-12352R. Albuquerque, NM: Sandia National Laboratories

Wigeland, R., Taiwo, T., Ludewig, H., Todosow, M., Halsey, W., Gehin, J., Jubin, R., Buelt, J., Stockinger, S., Jenni, K., and Oakley, B., 2014. “Nuclear Fuel Cycle Evaluation and Screening – Final Report,” Prepared for the U.S. Department of Energy, February 28, 2014.

APPENDIX A. DETAILED COST CALCULATIONS

A.1. Cost of Disposal in a Repository Similar to Yucca Mountain – Detailed Calculations

The following tables present the detailed calculations for estimating the cost of disposing of the three different types of HALEU SNF in a repository similar to the one proposed at Yucca Mountain. Detailed calculations of the cost to dispose of ATF SNF in a repository similar to Yucca Mountain are presented first, followed by detailed calculations of the cost to dispose of TRISO and SFR SNF in such a repository. Costs to dispose of BOC SNF are taken from DOE (2008) and are in 2007$. The multiplier to escalate from 2007$ to 2024$ was 1.52, as obtained from the U.S. Consumer Price Index calculator, using January as the representative months for each of the years.

Table A- 1 shows how the cost to dispose of BOC SNF in a repository similar to Yucca Mountain was adjusted to dispose of ATF, as described in the assumptions outlined in Section 5.1.2, and escalated to 2024$.

Table A- 2 shows how the cost to dispose of BOC SNF in a repository similar to Yucca Mountain was adjusted to dispose of TRISO SNF, as described in the assumptions outlined in Section 5.1.3, and escalated to 2024$.

Table A- 3 shows how the cost to dispose of BOC SNF in a repository similar to Yucca Mountain was adjusted to dispose of SFR SNF, as described in the assumptions outlined in Section 5.1.4, and escalated to 2024$.

Table A- 1. Detailed Cost Calculations to Dispose of ATF SNF in a Repository Similar to Yucca Mountain

Cost Component and Subcomponents	Cost to Dispose of BOC SNF (2007 $Million)	Multiplier	Cost to Dispose of ATF SNF (2007 $Million)	Cost to Dispose of ATF SNF (2024 $Million)
Licensing	2,340	1	2,340	3,557
Surface & Subsurface Facilities	15,550	1	15,550	23,636
Waste Package & Drip Shield Fabrication	240	0.75	180	274
Performance Confirmation	0	1	0	0
Regulatory, Infrastructure, & Management Support	0	1	0	0
Repository Engineering, Procurement, and Construction Costs	**18,130**		**18,070**	**27,466**
Licensing	0	1	0	0
Surface & Subsurface Facilities	9,580	1	9,580	14,562
Waste Package & Drip Shield Fabrication	12,580	0.75	9,435	14,341
Performance Confirmation	1,680	1	1,680	2,554
Regulatory, Infrastructure, and Management Support	2,890	1	2,890	4,393
Repository Operations Costs	**26,730**		**23,585**	**35,849**
Licensing	0	1	0	0
Surface & Subsurface Facilities	1,030	1	1,030	1,566
Waste Package & Drip Shield Fabrication	7,630	0.75	5,723	8,698
Performance Confirmation	1,040	1	1,040	1,581
Regulatory, Infrastructure, and Management Support	440	1	440	669
Repository Monitoring Costs	**10,150**		**8,233**	**12,513**
Licensing	0	1	0	0
Surface & Subsurface Facilities	970	1	970	1,474
Waste Package & Drip Shield Fabrication	0	1	0	0
Performance Confirmation	300	1	300	456
Regulatory, Infrastructure, and Management Support	120	1	120	182
Repository Closure Costs	**1,390**		**1,390**	**2,113**

Cost Component and Subcomponents	Cost to Dispose of BOC SNF (2007 $Million)	Multiplier	Cost to Dispose of ATF SNF (2007 $Million)	Cost to Dispose of ATF SNF (2024 $Million)
Development and Evaluation	2,300	1	2,300	3,496
Quality Assurance	730	1	730	1,110
Waste Management	360	1	360	547
Program Management	3,280	1	3,280	4,986
Benefits, PETT, Outreach and Institutional	3,150	1	3,150	4,788
Other Agencies	1,370	1	1,370	2,082
Balance of Program Costs	**11,190**		**11,190**	**17,009**
Total	**75,920**		**62,468**	**94,951**

Table A- 2. Detailed Cost Calculations to Dispose of TRISO SNF in a Repository Similar to Yucca Mountain

Cost Component and Subcomponents	Cost to Dispose of BOC SNF (2007 $Million)	Multiplier	Cost to Dispose of TRISO SNF (2007 $Million)	Cost to Dispose of TRISO SNF (2024 $Million)
Licensing	2,340	1	2,340	3,557
Surface & Subsurface Facilities	15,550	0.75	11,663	17,727
Waste Package & Drip Shield Fabrication	240	1	240	365
Performance Confirmation	0	1	0	0
Regulatory, Infrastructure, & Management Support	0	1	0	0
Repository Engineering, Procurement, and Construction Costs	**18,130**		**14,243**	**21,649**
				0
Licensing	0	1	0	0
Surface & Subsurface Facilities	9,580	0.75	7,185	10,921
Waste Package & Drip Shield Fabrication	12,580	1	12,580	19,122
Performance Confirmation	1,680	1	1,680	2,554
Regulatory, Infrastructure, and Management Support	2,890	1	2,890	4,393
Repository Operations Costs	**26,730**		**24,335**	**36,989**

Cost Component and Subcomponents	Cost to Dispose of BOC SNF (2007 $Million)	Multiplier	Cost to Dispose of TRISO SNF (2007 $Million)	Cost to Dispose of TRISO SNF (2024 $Million)
				0
Licensing	0	1	0	0
Surface & Subsurface Facilities	1,030	0.75	773	1,174
Waste Package & Drip Shield Fabrication	7,630	1	7,630	11,598
Performance Confirmation	1,040	1	1,040	1,581
Regulatory, Infrastructure, and Management Support	440	1	440	669
Repository Monitoring Costs	**10,150**		**9,883**	**15,021**
				0
Licensing	0	1	0	0
Surface & Subsurface Facilities	970	0.75	728	1,106
Waste Package & Drip Shield Fabrication	0	1	0	0
Performance Confirmation	300	1	300	456
Regulatory, Infrastructure, and Management Support	120	1	120	182
Repository Closure Costs	**1,390**		**1,148**	**1,744**
				0
Development and Evaluation	2,300	1	2,300	3,496
Quality Assurance	730	1	730	1,110
Waste Management	360	1	360	547
Program Management	3,280	1	3,280	4,986
Benefits, PETT, Outreach and Institutional	3,150	1	3,150	4,788
Other Agencies	1,370	1	1,370	2,082
Balance of Program Costs	**11,190**		**11,190**	**17,009**
				0
Total	**75,920**		**60,798**	**92,412**

Table A- 3. Detailed Cost Calculations to Dispose of SFR SNF in a Repository Similar to Yucca Mountain

Cost Component and Subcomponents	Cost to Dispose of BOC SNF (2007 $Million)	Multiplier	Cost to Dispose of SFR SNF (2007 $Million)	Cost to Dispose of SFR SNF (2024 $Million)
Licensing	2,340	1	2,340	3,557
Surface & Subsurface Facilities	15,550	1	15,550	23,636
Waste Package & Drip Shield Fabrication	240	1.1	264	401
Performance Confirmation	0	1	0	0
Regulatory, Infrastructure, & Management Support	0	1	0	0
Repository Engineering, Procurement, and Construction Costs	**18,130**		**18,154**	**27,594**
Licensing	0	1	0	0
Surface & Subsurface Facilities	9,580	1	9,580	14,562
Waste Package & Drip Shield Fabrication	12,580	1.1	13,838	21,034
Performance Confirmation	1,680	1	1,680	2,554
Regulatory, Infrastructure, and Management Support	2,890	1	2,890	4,393
Repository Operations Costs	**26,730**		**27,988**	**42,542**
Licensing	0	1	0	0
Surface & Subsurface Facilities	1,030	1	1,030	1,566
Waste Package & Drip Shield Fabrication	7,630	1.1	8,393	12,757
Performance Confirmation	1,040	1	1,040	1,581
Regulatory, Infrastructure, and Management Support	440	1	440	669
Repository Monitoring Costs	**10,150**		**10,903**	**16,573**
Licensing	0	1	0	0
Surface & Subsurface Facilities	970	1	970	1,474
Waste Package & Drip Shield Fabrication	0	1	0	0
Performance Confirmation	300	1	300	456

Cost Component and Subcomponents	Cost to Dispose of BOC SNF (2007 $Million)	Multiplier	Cost to Dispose of SFR SNF (2007 $Million)	Cost to Dispose of SFR SNF (2024 $Million)
Regulatory, Infrastructure, and Management Support	120	1	120	182
Repository Closure Costs	**1,390**		**1,390**	**2,113**
Development and Evaluation	2,300	1	2,300	3,496
Quality Assurance	730	1	730	1,110
Waste Management	360	1	360	547
Program Management	3,280	1	3,280	4,986
Benefits, PETT, Outreach and Institutional	3,150	1	3,150	4,788
Other Agencies	1,370	1	1,370	2,082
Balance of Program Costs	**11,190**		**11,190**	**17,009**
				0
Total	**75,920**		**69,625**	**105,830**

A.2. Cost of Disposal in a Hypothetical Crystalline Repository – Detailed Calculations

The following tables present the detailed calculations for estimating the cost of disposing of the three different types of HALEU SNF in a hypothetical crystalline repository. Detailed calculations of the cost to dispose of ATF SNF in a hypothetical crystalline repository are presented first, followed by detailed calculations of the cost to dispose of TRISO and SFR SNF in such a repository. Costs to dispose of BOC SNF in the hypothetical crystalline repository are taken from Hardin et al. (2012). The multiplier to escalate from 2012$ to 2024$ was 1.36, as obtained from the U.S. Consumer Price Index calculator, using January as the representative month for each of the years.

Table A- 4 shows how the cost to dispose of BOC SNF in a hypothetical crystalline repository was adjusted to dispose of ATF, as described in the assumptions outlined in Section 5.2.2. Table A- 5 shows the same costs escalated to 2024$.

Table A- 6 shows how the cost to dispose of BOC SNF in a hypothetical crystalline repository was adjusted to dispose of TRISO SNF, as described in the assumptions outlined in Section 5.2.3. Table A- 7 shows the same costs escalated to 2024$.

Table A- 8 shows how the cost to dispose of BOC SNF in a hypothetical crystalline repository was adjusted to dispose of SFR SNF, as described in the assumptions outlined in Section 5.2.4. Table A- 9 shows the same costs escalated to 2024$.

Table A- 4. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Crystalline Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2012$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2012$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	3,754	5,495	1	3,754	5,495	3,754	5,495
Operations and Maintenance	17,545	22,475	1	17,545	22,475	17,545	22,475
Closure	9,563	13,704	1	9,563	13,704	9,563	13,704
Waste Packages	17,489	21,647	0.75	13,117	16,235	13,117	16,235
Regulatory & Licensing	424	441	1	424	441	424	441
Monitoring	10,685	14,571	1	10,685	14,571	10,685	14,571
Performance Confirmation	411	561	1	411	561	411	561
Program Integration	1,575	2,136	1	1,575	2,136	1,575	2,136
Total	**61,446**	**81,030**		**57,074**	**75,618**	**57,074**	**75,618**

Table A- 5. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Crystalline Repository in 2024$.

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2024$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2024$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	5,105	7,473	1	5,105	7,473	5,105	7,473
Operations and Maintenance	23,861	30,566	1	23,861	30,566	23,861	30,566
Closure	13,006	18,637	1	13,006	18,637	13,006	18,637
Waste Packages	23,785	29,440	0.75	17,839	22,080	17,839	22,080
Regulatory & Licensing	577	600	1	577	600	577	600
Monitoring	14,532	19,817	1	14,532	19,817	14,532	19,817
Performance Confirmation	559	763	1	559	763	559	763

Program Integration	2,142	2,905	1	2,142	2,905	2,142	2,905
Total	**83,567**	**110,201**		**77,620**	**102,841**	**77,620**	**102,841**

Table A- 6. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Crystalline Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		**Adjustment Factor**	**Adjusted Costs for HTGR Pebble Bed (2012$Million)**		**Adjusted Costs for Prismatic Block(2012$Millions)**		**Adjusted Costs for FHR Pebble Bed (2012$Millions)**	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	3,754	5,495	1	3,754	5,495	3754	5495	3754	5495
Operations and Maintenance	17,545	22,475	15,551	33,096	38,026	33,096	38,026	33,096	38,026
Closure	9,563	13,704	1	9,563	13,704	9563	13704	9563	13704
Waste Packages	17,489	21,647	4	69,956	86,588	69956	86588	69956	86588
Regulatory & Licensing	424	441	1	424	441	424	441	424	441
Monitoring	10,685	14,571	1	10,685	14,571	10685	14571	10685	14571
Performance Confirmation	411	561	1	411	561	411	561	411	561
Program Integration	1,575	2,136	1	1,575	2,136	1575	2136	1575	2136
Total	**61,446**	**81,030**		**129,464**	**161,522**	**129,464**	**161,522**	**129,464**	**161,522**

Table A- 7. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Crystalline Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for HTGR Pebble Bed (2024$Million)		Adjusted Costs for Prismatic Block (2024$Millions)		Adjusted Costs for FHR Pebble Bed (2024$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	5,105	7,473	1	5,105	7,473	5,105	7,473	5,105	7,473
Operations and Maintenance	23,861	30,566	21,150	45,011	51,716	45,011	51,716	45,011	51,716
Closure	13,006	18,637	1	13,006	18,637	13,006	18,637	13,006	18,637
Waste Packages	23,785	29,440	4	95,140	117,760	95,140	117,760	95,140	117,760
Regulatory & Licensing	577	600	1	577	600	577	600	577	600
Monitoring	14,532	19,817	1	14,532	19,817	14,532	19,817	14,532	19,817
Performance Confirmation	559	763	1	559	763	559	763	559	763
Program Integration	2,142	2,905	1	2,142	2,905	2,142	2,905	2,142	2,905
Total	**83,567**	**110,201**		**176,072**	**219,671**	**176,072**	**219,671**	**176,072**	**219,671**

Table A- 8. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Crystalline Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2012$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**
Facility Design Construction, Startup	3,754	5,495	1	3,754	5,495
Operations and Maintenance	17,545	22,475	1	17,545	22,475
Closure	9,563	13,704	1	9,563	13,704
Waste Packages	17,489	21,647	1.1	19,238	23,812
Regulatory & Licensing	424	441	1	424	441
Monitoring	10,685	14,571	1	10,685	14,571
Performance Confirmation	411	561	1	411	561
Program Integration	1,575	2,136	1	1,575	2,136
DCSOCMC	**61,446**	**81,030**		**63,195**	**83,195**

Table A- 9. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Crystalline Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2024$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**
Facility Design Construction, Startup	5,105	7,473	1	5,105	7,473
Operations and Maintenance	23,861	30,566	1	23,861	30,566
Closure	13,006	18,637	1	13,006	18,637
Waste Packages	23,785	29,440	1.1	26,164	32,384
Regulatory & Licensing	577	600	1	577	600
Monitoring	14,532	19,817	1	14,532	19,817
Performance Confirmation	559	763	1	559	763
Program Integration	2,142	2,905	1	2,142	2,905
DCSOCMC	**83,567**	**110,201**		**85,945**	**113,145**

A.3. Cost of Disposal in a Hypothetical Salt Repository – Detailed Calculations

The following tables present the detailed calculations for estimating the cost of disposing of the three different types of HALEU SNF in a hypothetical salt repository. Detailed calculations of the cost to dispose of ATF SNF in a hypothetical salt repository are presented first, followed by detailed calculations of the cost to dispose of TRISO and SFR SNF in such a repository. Costs to dispose of BOC SNF in the hypothetical salt repository are taken from Hardin et al. (2012). The multiplier to escalate from 2012$ to 2024$ was 1.36, as obtained from the U.S. Consumer Price Index calculator, using January as the representative month for each of the years.

Table A- 10 shows how the cost to dispose of BOC SNF in a hypothetical salt repository was adjusted to dispose of ATF, as described in the assumptions outlined in Section 5.3.2. Table A- 11 shows the same costs escalated to 2024$.

Table A- 12 shows how the cost to dispose of BOC SNF in a hypothetical salt repository was adjusted to dispose of TRISO SNF, as described in the assumptions outlined in Section 5.3.3. Table A- 13 shows the same costs escalated to 2024$.

Table A- 14 shows how the cost to dispose of BOC SNF in a hypothetical salt repository was adjusted to dispose of SFR SNF, as described in the assumptions outlined in Section 5.3.4. Table A- 15 shows the same costs escalated to 2024$.

Table A- 10. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Salt Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2012$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2012$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	3,896	5,595	1	3,896	5,595	3,896	5,595
Operations and Maintenance	7,947	10,259	1	7,947	10,259	7,947	10,259
Closure	832	1,363	1	832	1,363	832	1,363
Waste Packages	3,998	4,950	0.75	2,999	3,713	2,999	3,713
Regulatory & Licensing	368	379	1	368	379	368	379
Monitoring	4,580	6,246	1	4,580	6,246	4,580	6,246
Performance Confirmation	567	773	1	567	773	567	773
Program Integration	2,136	2,907	1	2,136	2,907	2,136	2,907
Total	**24,324**	**32,472**		**23,325**	**31,235**	**23,325**	**31,235**

Table A- 11. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Salt Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2024$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2024$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	5,299	7,609	1	5,299	7,609	5,299	7,609
Operations and Maintenance	10,808	13,952	1	10,808	13,952	10,808	13,952
Closure	1,132	1,854	1	1,132	1,854	1,132	1,854
Waste Packages	5,437	6,732	0.75	4,078	5,049	4,078	5,049
Regulatory & Licensing	500	515	1	500	515	500	515
Monitoring	6,229	8,495	1	6,229	8,495	6,229	8,495
Performance Confirmation	771	1,051	1	771	1,051	771	1,051
Program Integration	2,905	3,954	1	2,905	3,954	2,905	3,954
Total	**33,081**	**44,162**		**31,721**	**42,479**	**31,721**	**42,479**

Table A- 12. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Salt Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for HTGR Pebble Bed (2012$Million)		Adjusted Costs for Prismatic Block(2012$Millions)		Adjusted Costs for FHR Pebble Bed (2012$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	3,896	5,595	1	3,896	5,595	3,896	5,595	3896	5595
Operations and Maintenance	7,947	10,259	1	7,947	10,259	7,947	10,259	7947	10259
Closure	832	1,363	1	832	1,363	832	1,363	832	1363
Waste Packages	3,998	4,950	6	23,988	29,700	23,988	29,700	23988	29700
Regulatory & Licensing	368	379	1	368	379	368	379	368	379
Monitoring	4,580	6,246	1	4,580	6,246	4,580	6,246	4580	6246
Performance Confirmation	567	773	1	567	773	567	773	567	773
Program Integration	2,136	2,907	1	2,136	2,907	2,136	2,907	2136	2907
Total	**24,324**	**32,472**		**44,314**	**57,222**	**44,314**	**57,222**	**44,314**	**57,222**

Table A- 13. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Salt Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for HTGR Pebble Bed (2024$Million)		Adjusted Costs for Prismatic Block (2024$Millions)		Adjusted Costs for FHR Pebble Bed (2024$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	5,299	7,609	1	5,299	7,609	5,299	7,609	5,299	7,609
Operations and Maintenance	10,808	13,952	1	10,808	13,952	10,808	13,952	10,808	13,952
Closure	1,132	1,854	1	1,132	1,854	1,132	1,854	1,132	1,854
Waste Packages	5,437	6,732	6	32,624	40,392	32,624	40,392	32,624	40,392
Regulatory & Licensing	500	515	1	500	515	500	515	500	515
Monitoring	6,229	8,495	1	6,229	8,495	6,229	8,495	6,229	8,495
Performance Confirmation	771	1,051	1	771	1,051	771	1,051	771	1,051
Program Integration	2,905	3,954	1	2,905	3,954	2,905	3,954	2,905	3,954
Total	**33,081**	**44,162**		**60,267**	**77,822**	**60,267**	**77,822**	**60,267**	**77,822**

Table A- 14. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Salt Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2012$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**
Facility Design Construction, Startup	3,896	5,595	1	3,896	5,595
Operations and Maintenance	7,947	10,259	1	7,947	10,259
Closure	832	1,363	1	832	1,363
Waste Packages	3,998	4,950	1.1	4,398	5,445
Regulatory & Licensing	368	379	1	368	379
Monitoring	4,580	6,246	1	4,580	6,246
Performance Confirmation	567	773	1	567	773
Program Integration	2,136	2,907	1	2,136	2,907
Total	**24,324**	**32,472**		**24,724**	**32,967**

Table A- 15. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Salt Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2024$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**
Facility Design Construction, Startup	5,299	7,609	1	5,299	7,609
Operations and Maintenance	10,808	13,952	1	10,808	13,952
Closure	1,132	1,854	1	1,132	1,854
Waste Packages	5,437	6,732	1.1	5,981	7,405
Regulatory & Licensing	500	515	1	500	515
Monitoring	6,229	8,495	1	6,229	8,495
Performance Confirmation	771	1,051	1	771	1,051
Program Integration	2,905	3,954	1	2,905	3,954
Total	**33,081**	**44,162**		**33,624**	**44,835**

A.4. Cost of Disposal in a Hypothetical Clay/Shale (enclosed) Repository – Detailed Calculations

The following tables present the detailed calculations for estimating the cost of disposing of the three different types of HALEU SNF in a hypothetical clay/shale (enclosed) repository. Detailed calculations of the cost to dispose of ATF SNF in a hypothetical clay/shale (enclosed) repository are presented first, followed by detailed calculations of the cost to dispose of TRISO and SFR SNF in such a repository. Costs to dispose of BOC SNF in the hypothetical clay/shale (enclosed) repository are taken from Hardin et al. (2012). The multiplier to escalate from 2012$ to 2024$ was 1.36, as obtained from the U.S. Consumer Price Index calculator, using January as the representative month for each of the years.

Table A- 16 shows how the cost to dispose of BOC SNF in a hypothetical clay/shale (enclosed) repository was adjusted to dispose of ATF, as described in the assumptions outlined in Section 5.4.2. Table A- 17 shows the same costs escalated to 2024$.

Table A- 18 shows how the cost to dispose of BOC SNF in a hypothetical clay/shale (enclosed) repository was adjusted to dispose of TRISO SNF, as described in the assumptions outlined in Section 5.4.3. Table A- 19 shows the same costs escalated to 2024$.

Table A- 20 shows how the cost to dispose of BOC SNF in a hypothetical clay /shale (enclosed) repository was adjusted to dispose of SFR SNF, as described in the assumptions outlined in Section 5.4.4. Table A- 21 shows the same costs escalated to 2024$.

Table A- 16. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Clay/Shale (enclosed) Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2012$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2012$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	6,872	10,064	1	6,872	10,064	6,872	10,064
Operations and Maintenance	26,884	34,525	1	26,884	34,525	26,884	34,525
Closure	5,556	8,334	1	5,556	8,334	5,556	8,334
Waste Packages	7,542	9,337	0.75	5,657	7,003	5,657	7,003
Regulatory & Licensing	414	429	1	414	429	414	429
Monitoring	9,021	12,302	1	9,021	12,302	9,021	12,302
Performance Confirmation	758	1,034	1	758	1,034	758	1,034
Program Integration	2,914	3,965	1	2,914	3,965	2,914	3,965
Total	**59,961**	**79,990**		**58,076**	**77,656**	**58,076**	**77,656**

Table A- 17. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Clay/Shale (enclosed) Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2024$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2024$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	9,346	13,687	1	9,346	13,687	9,346	13,687
Operations and Maintenance	36,562	46,954	1	36,562	46,954	36,562	46,954
Closure	7,556	11,334	1	7,556	11,334	7,556	11,334
Waste Packages	10,257	12,698	0.75	7,693	9,524	7,693	9,524
Regulatory & Licensing	563	583	1	563	583	563	583
Monitoring	12,269	16,731	1	12,269	16,731	12,269	16,731
Performance Confirmation	1,031	1,406	1	1,031	1,406	1,031	1,406
Program Integration	3,963	5,392	1	3,963	5,392	3,963	5,392
Total	**81,547**	**108,786**		**78,983**	**105,612**	**78,983**	**105,612**

Table A- 18. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Clay/Shale (enclosed) Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for HTGR Pebble Bed (2012$Million)		Adjusted Costs for Prismatic Block(2012$Millions)		Adjusted Costs for FHR Pebble Bed (2012$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	6,872	10,064	1	6,872	10,064	6,872	10064	6872	10064
Operations and Maintenance	26,884	34,525	61,478	88,362	96,003	88,362	96,003	88,362	96,003
Closure	5,556	8,334	1	5,556	8,334	5,556	8334	5556	8334
Waste Packages	7,542	9,337	6	45,252	56,022	45,252	56022	45252	56022
Regulatory & Licensing	414	429	1	414	429	414	429	414	429
Monitoring	9,021	12,302	1	9,021	12,302	9,021	12302	9021	12302
Performance Confirmation	758	1,034	1	758	1,034	758	1034	758	1034
Program Integration	2,914	3,965	1	2,914	3,965	2,914	3965	2914	3965
Total	**59,961**	**79,990**		**159,149**	**188,153**	**159,149**	**188,153**	**159,149**	**188,153**

Table A- 19. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Clay/Shale (enclosed) Repository in 2024$

Element	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for HTGR Pebble Bed (2024$Million)		Adjusted Costs for Prismatic Block (2024$Millions)		Adjusted Costs for FHR Pebble Bed (2024$Millions)	
	Low Range	High Range		Low Range	High Range	Low Range	High Range	Low Range	High Range
Facility Design Construction, Startup	9,346	13,687	1	9,346	13,687	9,346	13,687	9,346	13,687
Operations and Maintenance	36,562	46,954	83,610	120,172	130,564	120,172	130,564	120,172	130,564
Closure	7,556	11,334	1	7,556	11,334	7,556	11,334	7,556	11,334
Waste Packages	10,257	12,698	6	61,543	76,190	61,543	76,190	61,543	76,190
Regulatory & Licensing	563	583	1	563	583	563	583	563	583
Monitoring	12,269	16,731	1	12,269	16,731	12,269	16,731	12,269	16,731
Performance Confirmation	1,031	1,406	1	1,031	1,406	1,031	1,406	1,031	1,406
Program Integration	3,963	5,392	1	3,963	5,392	3,963	5,392	3,963	5,392
Total	**81,547**	**108,786**		**216,442**	**255,888**	**216,442**	**255,888**	**216,442**	**255,888**

Table A- 20. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Clay/Shale (enclosed) Repository in 2012$

Element	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2012$Millions)	
	Low Range	High Range		Low Range	High Range
Facility Design Construction, Startup	6,872	10,064	1	6,872	10,064
Operations and Maintenance	26,884	34,525	1	26,884	34,525
Closure	5,556	8,334	1	5,556	8,334
Waste Packages	7,542	9,337	1.1	8,296	10,271
Regulatory & Licensing	414	429	1	414	429
Monitoring	9,021	12,302	1	9,021	12,302
Performance Confirmation	758	1,034	1	758	1,034
Program Integration	2,914	3,965	1	2,914	3,965
Total	**59,961**	**79,990**		**60,715**	**80,924**

Table A- 21. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Clay/Shale (enclosed) Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2024$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**
Facility Design Construction, Startup	9,346	13,687	1	9,346	13,687
Operations and Maintenance	36,562	46,954	1	36,562	46,954
Closure	7,556	11,334	1	7,556	11,334
Waste Packages	10,257	12,698	1.1	11,283	13,968
Regulatory & Licensing	563	583	1	563	583
Monitoring	12,269	16,731	1	12,269	16,731
Performance Confirmation	1,031	1,406	1	1,031	1,406
Program Integration	3,963	5,392	1	3,963	5,392
Total	**81,547**	**108,786**		**82,573**	**110,056**

A.5. Cost of Disposal in a Hypothetical Shale Unbackfilled (Open) Repository – Detailed Calculations

The following tables present the detailed calculations for estimating the cost of disposing of the three different types of HALEU SNF in a hypothetical shale unbackfilled (open) repository. Detailed calculations of the cost to dispose of ATF SNF in a hypothetical shale unbackfilled (open) repository are presented first, followed by detailed calculations of the cost to dispose of TRISO and SFR SNF in such a repository. Costs to dispose of BOC SNF in the hypothetical shale unbackfilled (open) repository are taken from Hardin et al. (2012). The multiplier to escalate from 2012$ to 2024$ was 1.36, as obtained from the U.S. Consumer Price Index calculator, using January as the representative month for each of the years.

Table A- 22 shows how the cost to dispose of BOC SNF in a hypothetical shale unbackfilled (open) repository was adjusted to dispose of ATF, as described in the assumptions outlined in Section 5.5.2. Table A- 23 shows the same costs escalated to 2024$.

Table A- 24 shows how the cost to dispose of BOC SNF in a hypothetical shale unbackfilled (open) repository was adjusted to dispose of TRISO SNF, as described in the assumptions outlined in Section 5.5.3. Table A- 25 shows the same costs escalated to 2024$.

Table A- 26 shows how the cost to dispose of BOC SNF in a hypothetical shale unbackfilled (open) repository was adjusted to dispose of SFR SNF, as described in the assumptions outlined in Section 5.5.4. Table A- 27 shows the same costs escalated to 2024$.

Table A- 22. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Shale Unbackfilled (Open) Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2012$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2012$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	3,303	4,711	1	3,303	4,711	3,303	4,711
Operations and Maintenance	9,702	12,408	1	9,702	12,408	9,702	12,408
Closure	1,622	2,515	1	1,622	2,515	1,622	2,515
Waste Packages	2,882	3,569	0.75	2,162	2,677	2,162	2,677
Regulatory & Licensing	417	421	1	417	421	417	421
Monitoring	3,395	4,629	1	3,395	4,629	3,395	4,629
Performance Confirmation	423	576	1	423	576	423	576
Program Integration	3,732	5,084	1	3,732	5,084	3,732	5,084
Total	**25,476**	**33,913**		**24,756**	**33,021**	**24,756**	**33,021**

Table A- 23. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Shale Unbackfilled (Open) Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2024$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2024$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	4,492	6,407	1	4,492	6,407	4,492	6,407
Operations and Maintenance	13,195	16,875	1	13,195	16,875	13,195	16,875
Closure	2,206	3,420	1	2,206	3,420	2,206	3,420
Waste Packages	3,920	4,854	0.75	2,940	3,640	2,940	3,640
Regulatory & Licensing	567	573	1	567	573	567	573
Monitoring	4,617	6,295	1	4,617	6,295	4,617	6,295
Performance Confirmation	575	783	1	575	783	575	783
Program Integration	5,076	6,914	1	5,076	6,914	5,076	6,914
Total	**34,647**	**46,122**		**33,667**	**44,908**	**33,667**	**44,908**

Table A- 24. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Shale Unbackfilled (Open) Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for HTGR Pebble Bed (2012$Million)		Adjusted Costs for Prismatic Block(2012$Millions)		Adjusted Costs for FHR Pebble Bed (2012$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	3,303	4,711	1	3,303	4,711	3303	4711	3303	4711
Operations and Maintenance	9,702	12,408	5,948	15,650	18,356	15,650	18,356	15,650	18,356
Closure	1,622	2,515	1	1,622	2,515	1622	2515	1622	2515
Waste Packages	2,882	3,569	14.4	41,501	51,394	41500.8	51393.6	41500.8	51393.6
Regulatory & Licensing	417	421	1	417	421	417	421	417	421
Monitoring	3,395	4,629	1	3,395	4,629	3395	4629	3395	4629
Performance Confirmation	423	576	1	423	576	423	576	423	576
Program Integration	3,732	5,084	1	3,732	5,084	3732	5084	3732	5084
Total	**25,476**	**33,913**		**70,043**	**87,686**	**70,043**	**87,686**	**70,043**	**87,686**

Table A- 25. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Shale Unbackfilled (Open) Repository in 2024$

Element	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for HTGR Pebble Bed (2024$Million)		Adjusted Costs for Prismatic Block (2024$Millions)		Adjusted Costs for FHR Pebble Bed (2024$Millions)	
	Low Range	High Range		Low Range	High Range	Low Range	High Range	Low Range	High Range
Facility Design Construction, Startup	4,492	6,407	1	4,492	6,407	4,492	6,407	4,492	6,407
Operations and Maintenance	13,195	16,875	8,090	21,285	24,965	21,285	24,965	21,285	24,965
Closure	2,206	3,420	1	2,206	3,420	2,206	3,420	2,206	3,420
Waste Packages	3,920	4,854	14.4	56,441	69,895	56,441	69,895	56,441	69,895
Regulatory & Licensing	567	573	1	567	573	567	573	567	573
Monitoring	4,617	6,295	1	4,617	6,295	4,617	6,295	4,617	6,295
Performance Confirmation	575	783	1	575	783	575	783	575	783
Program Integration	5,076	6,914	1	5,076	6,914	5,076	6,914	5,076	6,914
Total	**34,647**	**46,122**		**95,259**	**119,253**	**95,259**	**119,253**	**95,259**	**119,253**

Table A- 26. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Shale Unbackfilled (Open) Repository in 2012$

Element	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2012$Millions)	
	Low Range	High Range		Low Range	High Range
Facility Design Construction, Startup	3,303	4,711	1	3,303	4,711
Operations and Maintenance	9,702	12,408	1	9,702	12,408
Closure	1,622	2,515	1	1,622	2,515
Waste Packages	2,882	3,569	1.1	3,170	3,926
Regulatory & Licensing	417	421	1	417	421
Monitoring	3,395	4,629	1	3,395	4,629
Performance Confirmation	423	576	1	423	576
Program Integration	3,732	5,084	1	3,732	5,084
Total	**25,476**	**33,913**		**25,764**	**34,270**

Table A- 27. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Shale Unbackfilled (Open) Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2024$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**
Facility Design Construction, Startup	4,492	6,407	1	4,492	6,407
Operations and Maintenance	13,195	16,875	1	13,195	16,875
Closure	2,206	3,420	1	2,206	3,420
Waste Packages	3,920	4,854	1.1	4,311	5,339
Regulatory & Licensing	567	573	1	567	573
Monitoring	4,617	6,295	1	4,617	6,295
Performance Confirmation	575	783	1	575	783
Program Integration	5,076	6,914	1	5,076	6,914
Total	**34,647**	**46,122**		**35,039**	**46,607**

A.6. Cost of Disposal in a Hypothetical Sedimentary Backfilled (Open) Repository – Detailed Calculations

The following tables present the detailed calculations for estimating the cost of disposing of the three different types of HALEU SNF in a hypothetical sedimentary backfilled (open) repository. Detailed calculations of the cost to dispose of ATF SNF in a hypothetical sedimentary backfilled (open) repository are presented first, followed by detailed calculations of the cost to dispose of TRISO and SFR SNF in such a repository. Costs to dispose of BOC SNF in the hypothetical sedimentary backfilled (open) repository are taken from Hardin et al. (2012). The multiplier to escalate from 2012$ to 2024$ was 1.36, as obtained from the U.S. Consumer Price Index calculator, using January as the representative month for each of the years.

Table A- 28 shows how the cost to dispose of BOC SNF in a hypothetical sedimentary backfilled (open) repository was adjusted to dispose of ATF, as described in the assumptions outlined in Section 5.6.2. Table A- 29 shows the same costs escalated to 2024$.

Table A- 30 shows how the cost to dispose of BOC SNF in a hypothetical sedimentary backfilled (open) repository was adjusted to dispose of TRISO SNF, as described in the assumptions outlined in Section 5.6.3. Table A- 31 shows the same costs escalated to 2024$.

Table A- 32 shows how the cost to dispose of BOC SNF in a hypothetical sedimentary backfilled (open) repository was adjusted to dispose of SFR SNF, as described in the assumptions outlined in Section 5.6.4. Table A- 33 shows the same costs escalated to 2024$.

Table A- 28. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Sedimentary Backfilled (Open) Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2012$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2012$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	5,410	7,599	1	5,410	7,599	5,410	7,599
Operations and Maintenance	9,614	12,264	1	9,614	12,264	9,614	12,264
Closure	2,263	3,558	1	2,263	3,558	2,263	3,558
Waste Packages	2,882	3,569	0.75	2,162	2,677	2,162	2,677
Regulatory & Licensing	668	679	1	668	679	668	679
Monitoring	3,775	5,148	1	3,775	5,148	3,775	5,148
Performance Confirmation	798	1,088	1	798	1,088	798	1,088
Program Integration	6,878	9,370	1	6,878	9,370	6,878	9,370
Total	**32,288**	**43,275**		**31,568**	**42,383**	**31,568**	**42,383**

Table A- 29. Detailed Cost Calculations to Dispose of ATF SNF in a Hypothetical Sedimentary Backfilled (Open) Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for 7%/84 GWd/MTHM ATF (2024$Millions)		Adjusted Costs for 8.3%/100 GWd/MTHM ATF (2024$Millions)	
Cost Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	7,358	10,335	1	7,358	10,335	7,358	10,335
Operations and Maintenance	13,075	16,679	1	13,075	16,679	13,075	16,679
Closure	3,078	4,839	1	3,078	4,839	3,078	4,839
Waste Packages	3,920	4,854	0.75	2,940	3,640	2,940	3,640
Regulatory & Licensing	908	923	1	908	923	908	923
Monitoring	5,134	7,001	1	5,134	7,001	5,134	7,001
Performance Confirmation	1,085	1,480	1	1,085	1,480	1,085	1,480
Program Integration	9,354	12,743	1	9,354	12,743	9,354	12,743
Total	**43,912**	**58,854**		**42,932**	**57,641**	**42,932**	**57,641**

Table A- 30. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Sedimentary Backfilled (Open) Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for HTGR Pebble Bed (2012$Million)		Adjusted Costs for Prismatic Block(2012$Millions)		Adjusted Costs for FHR Pebble Bed (2012$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	5,410	7,599	1	5,410	7,599	5410	7599	5410	7599
Operations and Maintenance	9,614	12,264	14,740	24,354	27,004	24,354	27,004	24,354	27,004
Closure	2,263	3,558	1	2,263	3,558	2263	3558	2263	3558
Waste Packages	2,882	3,569	16	46,112	57,104	46112	57104	46112	57104
Regulatory & Licensing	668	679	1	668	679	668	679	668	679
Monitoring	3,775	5,148	1	3,775	5,148	3775	5148	3775	5148
Performance Confirmation	798	1,088	1	798	1,088	798	1088	798	1088
Program Integration	6,878	9,370	1	6,878	9,370	6878	9370	6878	9370
Total	**32,288**	**43,275**		**90,258**	**111,550**	**90,258**	**111,550**	**90,258**	**111,550**

Table A- 31. Detailed Cost Calculations to Dispose of TRISO SNF in a Hypothetical Sedimentary Backfilled (Open) Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for HTGR Pebble Bed (2024$Million)		Adjusted Costs for Prismatic Block (2024$Millions)		Adjusted Costs for FHR Pebble Bed (2024$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design Construction, Startup	7,358	10,335	1	7,358	10,335	7,358	10,335	7,358	10,335
Operations and Maintenance	13,075	16,679	20,047	33,122	36,726	33,122	36,726	33,122	36,726
Closure	3,078	4,839	1	3,078	4,839	3,078	4,839	3,078	4,839
Waste Packages	3,920	4,854	16	62,712	77,661	62,712	77,661	62,712	77,661
Regulatory & Licensing	908	923	1	908	923	908	923	908	923
Monitoring	5,134	7,001	1	5,134	7,001	5,134	7,001	5,134	7,001
Performance Confirmation	1,085	1,480	1	1,085	1,480	1,085	1,480	1,085	1,480
Program Integration	9,354	12,743	1	9,354	12,743	9,354	12,743	9,354	12,743
Total	**43,912**	**58,854**		**122,751**	**151,708**	**122,751**	**151,708**	**122,751**	**151,708**

Table A- 32. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Sedimentary Backfilled (Open) Repository in 2012$

	Original Costs for BOC SNF (2012$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2012$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**
Facility Design Construction, Startup	5,410	7,599	1	5,410	7,599
Operations and Maintenance	9,614	12,264	1	9,614	12,264
Closure	2,263	3,558	1	2,263	3,558
Waste Packages	2,882	3,569	1.1	3,170	3,926
Regulatory & Licensing	668	679	1	668	679
Monitoring	3,775	5,148	1	3,775	5,148
Performance Confirmation	798	1,088	1	798	1,088
Program Integration	6,878	9,370	1	6,878	9,370
Total	**32,288**	**43,275**		**32,576**	**43,632**

Table A- 33. Detailed Cost Calculations to Dispose of SFR SNF in a Hypothetical Sedimentary Backfilled (Open) Repository in 2024$

	Original Costs for BOC SNF (2024$Millions)		Adjustment Factor	Adjusted Costs for SFR SMF (2024$Millions)	
Element	**Low Range**	**High Range**		**Low Range**	**High Range**
Facility Design Construction, Startup	7,358	10,335	1	7,358	10,335
Operations and Maintenance	13,075	16,679	1	13,075	16,679
Closure	3,078	4,839	1	3,078	4,839
Waste Packages	3,920	4,854	1.1	4,311	5,339
Regulatory & Licensing	908	923	1	908	923
Monitoring	5,134	7,001	1	5,134	7,001
Performance Confirmation	1,085	1,480	1	1,085	1,480
Program Integration	9,354	12,743	1	9,354	12,743
Total	**43,912**	**58,854**		**44,304**	**59,339**

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