Economic Case for Universal Canister System (UCS) in Dry Storage, Transportation, and Disposal – 25274

Matt Waples[1], Vaibhav Sharma[1], Chris Parker[1], Jesse Sloane[1]
[1]Deep Isolation, Inc.

ABSTRACT

A key impediment to augmenting nuclear power generation, through extended operation of existing reactors and deployment of advanced reactors, is a lack of accepted disposal solutions for spent nuclear fuel (SNF) and high-level radioactive waste (HLW). The lack of clear and cost-effective disposal pathways in most countries means that SNF and HLW continue to be stored on a long-term basis in interim above-ground storage facilities, and the owners of these hazardous materials need to make investment decisions based on significant uncertainty about future pathways. Inevitably, decisions therefore focus on minimizing short-term storage costs, not optimizing total lifecycle costs across storage, transport, and eventual disposal.

There have been increasing calls for a triple-purpose canister, capable of storing, transporting, and disposing of SNF and HLW without the costs and radiological dose risks of repackaging between different stages. Exploring how such an innovation could optimize lifecycle costs for the back end of new nuclear reactors is a core goal of Joint Project on Waste Integration for Small and Advanced Reactor Designs (WISARD) being launched by the Organization for Economic Co-Operation and Development (OECD) Nuclear Energy Agency in 2025 [1].

This paper supports that work by examining the economic case for such a triple-purpose canister. It does so by studying the economics of the Universal Canister System (UCS) using a model developed through the Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E) Converting UNF[1] Radioisotopes Into Energy (CURIE) program. This model was developed to optimize waste disposal costs considering use of the UCS in a deep borehole repository. Deep Isolation, through collaboration with the United States (US) government and industry stakeholders, has developed the UCS to manage a wide range of SNF and HLW for dry storage, transportation, and eventual disposal in either a borehole or mined geologic repository. The UCS has been designed for compatibility with existing dry storage and transportation licensed cask systems as well as multiple forms of standard oil and gas lifting equipment.

This paper presents economic analysis results for three strategic options facing a hypothetical waste owner:

- **Option 1:** Use standard interim storage technologies to store SNF or HLW for an indefinite period, with an eventual need to incur additional costs and radiological dose risks by repackaging the material for eventual disposal.
- **Option 2:** Encapsulate the material in UCS canisters, then store indefinitely pending eventual disposal (with no need for further repackaging).
- **Option 3:** Encapsulate the material in UCS canisters, then dispose at a co-located deep borehole repository.

The analysis is informed by deep borehole disposal cost studies undertaken by Deep Isolation for a variety of countries with light-water reactor (LWR) inventories that have been reported in previous conference

---

[1] UNF: Used Nuclear Fuel.

papers (including typical cost savings on the order of 60% relative to mined geologic repository disposal [2]). This paper builds upon the reference disposal estimates by 1) factoring in storage and transportation costs involving the UCS relative to current practices; 2) exploring disposal costs for advanced reactor waste forms; and 3) updating elements of the cost model based upon recent manufacturability reviews and canister prototyping through projects with the US and United Kingdom (UK) governments.

Storage and transportation costs are benchmarked against those for bare pressurized water reactor assemblies packaged into high-capacity casks which can accommodate up to 37 assemblies. This cost information was derived from both a top-down and bottom-up basis through studies undertaken by the US Government Accountability Office and validated through discussion with experts in the SNF dry storage and transportation industry. Deep Isolation then determined storage and transportation costs with early use of the UCS. Given that fewer UCS canisters can fit into a given cask relative to bare SNF assemblies, near term storage and transportation costs are higher for UCS canisters containing SNF and HLW. However, upfront packaging into canisters results in significant system-wide cost savings due to an eliminated need for later repackaging for disposal preparations. Additionally, up-front packaging for disposal may enable further cost savings through co-locating a borehole repository with the waste generation and storage site.

This paper presents strategic cost analysis results for the most important use case in the US today: disposal of the large and growing inventory of SNF from our existing fleet of LWRs. For this use case, Option 3 (co-located deep borehole disposal) is significantly the lowest cost option – saving two-thirds of the lifecycle costs for SNF management compared with the status quo at Option 1. And in cases where such an option is not available at the time interim storage decisions need to be made, use of the UCS triple-purpose canister rather than traditional interim storage technologies still offers lower lifecycle costs across storage, transport, and disposal – whether the future disposal route is in a deep borehole repository or a mined disposal facility.

Finally, the paper presents an initial and more qualitative analysis of these options in two other use cases:

- The lifetime spent fuel from an advanced reactor using tri-structural isotropic (TRISO) SNF, and
- HLW processed from LWR SNF.

The paper's preliminary conclusion is that the same result (i.e., that disposition of material in the UCS is the lowest cost option even when the disposal path is uncertain) – is highly likely to apply for these advanced reactor SNF and processed HLW cases. Deep Isolation is now working to validate this conclusion through current projects with advanced reactor and reprocessing companies.

INTRODUCTION

Back-end management of the nuclear fuel cycle continues to be one of the greatest impediments to the large-scale adoption of nuclear energy. While nuclear energy can be a key solution in achieving net-zero carbon emissions by 2050 [3], the hazardous waste generated by nuclear energy poses a still unresolved problem.

The current methodology for handling spent nuclear fuel (SNF) and high-level radioactive waste (HLW), that is widely adopted across utilities, is to contain the waste in dry storage systems indefinitely until the corresponding government agency with jurisdiction determines its disposal solution. The most widely proposed disposal solution being considered is a mined geological repository (MGR) concept. However, very few countries are near completion of an MGR for disposal of their national SNF/HLW inventory. Only Finland's Onkalo repository [4] and Sweden's planned repository [5] have made significant strides toward constructing and opening an MGR. The large upfront costs, lengthy implementation times, and siting and operational complexities can make the adoption of this proposed solution difficult for countries with relatively small and/or undetermined waste inventories (including those planning to implement small modular reactors (SMRs)).

A new disposal solution and integrated waste management strategy has been proposed to responsibly handle the fate of SNF and HLW – especially for new advanced reactors and SMRs. Through the Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E) Optimizing Nuclear Waste and Advanced Reactor Disposal Systems (ONWARDS) program, Deep Isolation is developing the Universal Canister System (UCS). The UCS is a triple-purpose canister designed to safely store, transport, and dispose of SNF and HLW from advanced reactors (ARs), that is designed to be compatible with both mined and deep borehole repositories. The UCS comprises a family of canisters of varying diameters and shell thicknesses to accommodate a variety of waste forms, including pressurized water reactor (PWR) spent fuel assemblies. Currently, three different canister sizes have been designed, tailored around the dimensions of particular waste forms. Waste forms which can be sized to any of these designs require economic optimization to determine which size is most practicable to a customer, and these studies can result in additional canister designs as necessary. The UCS provides utilities and waste management organizations with a fresh opportunity to contain their SNF and HLW in a canister design that provides a disposal-ready path forward, as opposed to the status quo of necessitating repackaging at least once prior to final disposition. While the UCS is intended to be compatible with the MGR concept, pairing the UCS with the deep borehole disposal (DBD) solution provides the greatest benefits with respect to cost, schedule, and siting flexibility [6].

A cost comparison study [2] conducted by Amentum Technical Services LLC (Amentum), a global engineering services supplier, calculates a normalized 2024 average cost for DBD of \$0.45M per metric ton of heavy metal (MTHM) across three potential inventories, which vary in size and location. For comparison, the study calculates a normalized 2024 average cost for a mined repository of \$1.07M per MTHM across 6 similar potential inventories. This comparison signifies that ~ 60% cost savings could be achieved through DBD for the disposal of SNF and HLW.

Moreover, the timeline of deployment for a mined repository can be highly cumbersome. Construction alone for the Onkalo repository, for example, (not accounting for community engagement, administrative planning, designing, and site investigations) has spanned over 2 decades [7]. This extended construction time results in additional expenditure required for maintaining SNF and HLW in dry storage systems in independent spent fuel storage installations (ISFSIs) either onsite or offsite[2]. In turn, even larger costs for the lifecycle management of SNF and HLW can be incurred. Therefore, an alternative, cost-efficient solution is needed to solve the nuclear waste issue.

This paper seeks to address the nuclear fuel cycle back-end economic case for a triple-purpose canister, specifically the UCS, when paired with the DBD solution. As it currently stands, US utilities have no other option than to store their waste in above-ground storage systems. These costs will be incurred indefinitely until a final disposal solution is agreed upon by the host country, which could take many decades as seen by the case of Onkalo. Moreover, when the SNF/HLW inventory is in fact ready to be emplaced in a repository environment, that inventory will require repackaging from the dry storage system to a disposal system. This can result in unforeseen and considerable expenses.

---

[2] Offsite dry storage facilities may provide storage from a single or multiple reactor site. For this paper, offsite facilities are assumed to be sourced from a single reactor site. While a waste owner may favor dry storage at the reactor site, two options in this study assume offsite storage, largely for illustrative purposes.

DESCRIPTION

The UCS presents an opportunity for policymakers, regulators, and utilities to reconsider how SNF and HLW are handled upon discharge from a reactor. This paper first focuses solely on the management of PWR SNF assemblies and discusses the economic impact of three strategic options facing a hypothetical waste owner as detailed below:

- **Option 1 (Reference Case):** This case looks at using standard technology to package SNF at the reactor site, then transport and store SNF for a reference time period at an off-site dry storage facility, with an eventual need to incur additional costs and increased radiological dose risks by repackaging the material for disposal. The assumed disposal configuration will be a mined repository. Therefore, the assumed canister for disposal will be the transportation, aging, and disposal (TAD) canister system developed by the DOE originally designed for Yucca Mountain but assumed to be compatible with a general mined repository site[3].

- **Option 2:** This case involves encapsulating SNF in UCS canisters at the reactor site, then transporting and storing the SNF for a reference time period at an off-site dry storage facility pending eventual disposal (with no need for repackaging at that point). The assumed disposal configuration will be in a deep borehole repository.

- **Option 3:** This case considers encapsulating SNF in UCS canisters, storing, and then disposing of the SNF at a co-located deep borehole repository. Transportation will not be required, and operations will be optimized to reduce the on-site lag storage footprint.

This paper then analyzes how these scenarios are impacted when oriented toward HLW emerging from advanced reactor (AR) and reprocessing technology. The goal of this paper is to provide a long-term vantage point of the cumulative costs required to manage and dispose of SNF and HLW, thereby allowing key stakeholders to optimize their waste management strategies. Such analysis will be informative, especially for new reactors applying for operational licensing, as back-end design considerations can be incorporated in front-end critical decision making.

DISCUSSION

Option 1: Standard Dry Storage Costs for SNF

The cost analysis for traditional dry storage (as well as for the other dry storage scenarios) utilizes a -bottom up approach for calculating dry storage costs based on a 2014 US Government Accountability Office (GAO) report on SNF management [8]. For this analysis, the assumed initial input of heavy metal content requiring disposal is based on an approximation of the discharge quantity from a single reactor for a 40-year operational period. A reference 20-year dry storage period is assumed following reactor shutdown. This reference time frame offers a buffer period for potential regulatory changes to be made in the national stance on deep geological disposal of SNF and HLW. Discharge rates and timelines from the GAO report result in approximately 2,065 SNF assemblies per reactor requiring dry storage, requiring roughly 65 dry storage casks. This analysis assumes that the dry storage facility has the capacity to store a lifetime inventory of SNF assemblies, which is comparable to larger existing ISFSI sites (i.e., Zion with 2,226 assemblies). These dry storage assumptions are tabulated in Table 1 below.

---

[3] The UCS is also designed for compatibility with the mined repository concept, but Option 1 incorporates the TAD canister design as it is considered the benchmark multipurpose canister for a mined repository.

Table 1. Option 1 Dry Storage Assumptions.

Assumptions	
Parameter	**Value**
Reactor Lifetime (Years)	40
Typical Core Size (# Assemblies)	193 [8]
Typical Discharge Quantity per Discharge Period (# Assemblies)	72 [8]
Typical Discharge Timeline (Months)	18
Dry Storage Time Period (Years)	20
Total Number of Assemblies Discharged per Reactor	2,065
MTHM per Assembly	0.45 [8]
Total MTHM Discharged per Reactor	929
Dry Storage Cask Capacity (# of Assemblies/Cask)	32 [8][4]
Number of Dry Storage Casks	65
Number of Transportable Storage Canisters (TSC) Required[5]	33

The costs of dry storage for this reference case are also based primarily on the GAO report, which provides a range of values for each cost category. This analysis assumes the average value within this cost range throughout this economic analysis. Furthermore, the dry storage cost estimate accounts for annual operating costs (this cost category increases dramatically once a reactor has shut down at a site), initial start-up costs for design, licensing, and initial construction, labor costs, and the cost to procure dry storage systems. This cost analysis assumes that the SNF will be in wet storage in cooling pools during half the duration of reactor operations. During the second half of reactor operations, the quantity of SNF that needs to be accommodated will exceed the capacity and therefore dry storage will be required. Therefore, the annual operating costs of dry storage during reactor operations would only need to be applied for 20 years vice the full lifetime of 40 years. An additional 20 years of annual operating costs will need to be accounted for in the 20-year post-reactor operational period. This cost category increases dramatically post-reactor operations for a shut-down facility.

Moreover, the transportation cost from the reactor site to the off-site dry storage facility is based on transportation costs to Yucca Mountain from the Amentum cost comparison study [2], which amounts to \$257k/MTHM after converting to 2024 USD. These are not final costs, however, since waste that has been packaged for dry storage requires repackaging for eventual disposal following the reference period of dry storage. The cost for unloading from conventional dry storage systems followed by loading into the TAD canister are sourced from a comparative cost analysis conducted by Sandia National Laboratories (SNL) [9]. The combined repackaging cost results in \$130k in 2024 USD.

Also, since repackaging of SNF will take place after the waste is transported from the reactor site to an off-site dry storage facility, additional costs will be required to construct, operated, and decommission a repackaging facility[6]. The additional cost to repackage SNF from dry storage into the UCS is interpolated

---

[4] For consistency in methodology, the paper cites average values from the GAO report, though high-capacity casks capable of storing 37 PWR assemblies are becoming increasingly popular. Use of these systems would yield approximately 16% in packaging efficiency savings, though such casks may prove more expensive per unit than the "average" cask from the GAO report.

[5] TSCs may be reused. Therefore, instead of having a 1:1 ratio of TSCs per cask, half the cask quantity is assumed (2:1 ratio).

[6] No applicable existing infrastructure at the reactor site is assumed in this option.

from an average encapsulation facility cost triangulated from Finland's Posiva [10], Sweden's SKB [11], and SNL [12] encapsulation facility costs. After normalizing to 2024 USD, the average cost for SNF repackaging operations and maintenance (O&M) amounts to $100k/MTHM. An additional $60k/MTHM is required for encapsulation facility capital infrastructure (capital expenditure and decommissioning costs), assuming existing infrastructure cannot be leveraged in this option.

Finally, the cost for disposal needs to be factored into the final cost estimate. The Amentum cost comparison study [2] shows that the average cost of disposal for a mined repository equates to $1.11M/MTHM as of 2024. The total cost therefore results in **$2.09M/MTHM in 2024 USD** for the lifecycle management of SNF after discharge from reactor operations.

These individual cost categories, as well as the total cost for dry storage and normalized cost per MTHM, are summarized in Table 2 below.

Table 2. Option 1 Dry Storage and Lifecycle Costs.

Option 1 Cost Analysis (Costs in 2024 USD)	
Dry Storage Cost Breakdown [8]	
Annual Operating Cost (Operating Reactor Site)	$264k
Annual Cost (Permanently Shut-Down Reactor Site)	$5.9M
Design, Licensing, and Construction Cost	$31.35M
Dry Storage Canister Cost	$1.45M
Dry Storage Cask Cost	$396k
Transfer Cask Cost	$2.97M
Labor Cost for Transfer/Repackage	$462k
Total Dry Storage Costs	$403.59M
Total Lifecycle Management Cost Breakdown	
Dry Storage Costs per MTHM	$434k
Repacking for Disposal Costs per MTHM	$290k
Transportation Costs per MTHM[7]	$257k
Disposal Costs (Mined Repository) per MTHM	$1.11M
Total Costs per MTHM	**$2.09M**

Option 2: Waste Loading in UCS and Subsequent Dry Storage

This scenario analyzes the cost of directly loading discharged SNF from cooling pools into UCS canisters, which will then be placed into dry storage preceding eventual disposal. With the preliminary design of Deep Isolation's triple-purpose canister now complete, it provides a suitable alternative solution to utilities from the conventional method of storing SNF in existing dry storage systems without planning for disposal. The main assumptions that differ from those listed in Table 1 are shown in ***bold italics*** within Table 3 and are summarized below:

---

[7] Discussions with key stakeholders suggest that transportation costs may be higher once all fixed costs are factored in. More data is required to better quantity this preliminary estimate.

- SNF assemblies will first be loaded into UCS canisters before loading into a dry storage cask. Thus, pre-existing infrastructure at the reactor site can be utilized for UCS loading operations, thereby lowering the overall cost of loading operations.
- Based on strategic partner engagement, a typical dry storage system is expected to be able to contain roughly 19 UCS Class 0 canisters. This will result in an overall increase in the number of casks required to contain a given SNF inventory during dry storage and, if necessary, transportation.
- A UCS-centric disposal approach is optimally suited for a deep borehole repository, and therefore the total lifecycle management costs will be analyzed for DBD.

Table 3. Option 2 Dry Storage Assumptions.

Assumptions	
Parameter	**Value**
Reactor Lifetime	40
Typical Core Size (# Assemblies)	193 [8]
Typical Discharge Quantity (# Assemblies)	72 [8]
Typical Discharge Timeline (Months)	18
Dry Storage Time Period (Years)	20
Total Number of Assemblies Discharged from Reactor	2,065
MTHM per assembly	0.45 [8]
Total MTHM Discharged per Reactor	929
Number of UCS Canisters	***2,065***
Dry Storage Cask Capacity (# UCS)	***19***
Number of Dry Storage Casks	***109***
Number of TSCs Required [8]	***37***

Additionally, the cost for loading the SNF into the UCS and welding the UCS lid will be based on an average triangulated encapsulation cost from SNL, Posiva, and SKB, which amounts to $53k/MTHM [13]. This only accounts for encapsulation facility O&M costs, as it is assumed a portion of the cooling pool will serve as the encapsulation facility for the UCS. Therefore, fixed costs for setting up and decommissioning will already be accounted for. Labor and equipment costs associated with repacking the dry storage containers are not required. This cost is therefore considerably less than for the in the preceding scenario.

Moreover, cost synergies can be achieved for certain equipment shared between initial UCS loading and eventual disposal operations (e.g., analogous systems to the TSC will be required for disposal emplacement operations). The overall equipment demands are therefore reduced, and the overall cost is assumed to be at the lower end of the cost range. Transportation costs are nearly 30% higher than for the preceding scenario as internal stakeholder engagement shows that transportation costs do not scale linearly, and fixed costs will need to be factored in for a greater cask inventory.

Finally, per the Amentum cost comparison study [2], an average of borehole disposal costs within the US amounts to $468k/MTHM as of 2024. Thus, the total cost results in **$1.31M/MTHM in 2024 USD** for

---

[8] This analysis assumes one-third the cask quantity is already present (3:1 ratio) since the procurement of analogous systems is accounted for in disposal costs. This assumption results in a required TSC reduction from 55 to 37.

the lifecycle management of SNF after discharge from reactor operations. The cost categories and resulting total and normalized cost per heavy metal content are displayed in Table 4 below.

Table 4. Option 2 Dry Storage and Lifecycle Costs.

Option 2 Cost Analysis (Costs in 2024 USD)	
Dry Storage Cost Breakdown [8]	
Annual Operating Cost (Operating Reactor Site)	$264k
Annual Cost (Permanently Shut-Down Reactor Site)	$5.9M
Design, licensing, and Construction Cost	$31.35M
Dry Storage Canister Cost	$1.45M
Dry Storage Cask Cost	$396k
Transfer Cask Cost [9]	***$1.98M***
Labor Cost for Transfer	***$0***
Total Dry Storage Costs	***$430.12M***
Total Lifecycle Management Cost Breakdown	
Dry Storage Costs per MTHM	$463k
Repacking for Disposal Costs per MTHM	$53k
Transportation Costs per MTHM	$330k
Disposal Costs (Borehole Repository) per MTHM	$468k
Total Costs per MTHM	**$1.31M**

Option 3: Waste Loading in UCS Followed by Disposal

This scenario analyzes the cost of loading SNF into the UCS, which will then be subsequently disposed of in a co-located deep borehole repository. The main difference between this scenario and previous scenarios is the amount of time the dry storage facility will need to be operational. While the other scenarios assume that disposal will occur at some point in the distant future after completion of reactor operations, this scenario does have a disposal path incorporated into the near future following reactor operations. This means that the number of years the dry storage facility will need to be in operation can be greatly reduced below the reference nominal timeline of 20 years after reactor shutdown. At the end of the reactor lifetime, emplacement operations can begin for the entire inventory of SNF assemblies. Assuming an average of three canister emplacements per day and 250 operational days per year, it will take approximately three years to emplace the total inventory of 2,065 SNF assemblies into a borehole repository. Lag dry storage (dry storage systems serving an interim purpose such as storing while awaiting transporting to a repository or disposal while at the repository surface site) during this emplacement period is assumed for the 3 years of emplacement operations. It is assumed that some of the dry storage containers and TSCs can be reused as some of the SNF will still be in the wet cooling pool during emplacement operations. Table 5 below details the assumptions for this scenario, with the major differences from the preceding scenario shown in ***bold italics***.

---

[9] Internal stakeholder engagement shows that the cost of similar systems that would be used for borehole emplacement operations is lower than that assumed in the GAO report [8].

Table 5. Option 3 Dry Storage Assumptions.

Assumptions	
Parameter	**Value**
Reactor Lifetime	40
Typical Core Size (# Assemblies)	193 [8]
Typical Discharge Quantity (# Assemblies)	72 [8]
Typical Discharge Timeline (Months)	12
Dry Storage Time Period (Years)	***0***
Total Number of Assemblies Discharged from Reactor	2,065
MTHM per assembly	0.45 [8]
Total MTHM Discharged per Reactor	929
Number of UCS Canisters	2,065
Dry Storage Cask Capacity (# UCS)	19
Number of Dry Storage Casks	***55***
Number of TSCs Required [10]	***19***

This scenario assumes there will be no transportation to a dry storage facility required as lag storage operations can occur at the borehole repository site. Borehole disposal costs and UCS packaging costs are identical to those of Option 2. Thus, the total cost results in **$694k/MTHM in 2024 USD** for the lifecycle management of SNF following reactor shutdown, as can be seen in Table 6 below.

Table 6. Option 3 Dry Storage and Lifecycle Costs.

Option 3 Cost Analysis (Costs in 2024 USD)	
Dry Storage Cost Breakdown [8]	
Annual Operating Cost (Operating Reactor Site)	$264k
Annual Cost (Permanently Shut-Down Reactor Site)	$5.9M
Design, licensing, and Construction Cost	$31.35M
Dry Storage Canister Cost	$1.45M
Dry Storage Cask Cost	$396k
Transfer Cask Cost[11]	$1.98M
Labor Cost for Transfer	$0
Total Dry Storage Costs	***$160.22M***
Total Lifecycle Management Cost Breakdown	
Dry Storage Costs per MTHM	172k
Packing for Disposal Costs per MTHM	$53k
Transportation Costs per MTHM	$0k
Disposal Costs (Borehole Repository) per MTHM	$468k
Total Costs per MTHM	**$694k**

---

[10] Per Footnote 8, a reuse assumption reduces equipment quantity by about 33%.

[11] Per Footnote 9, internal data indicate lower costs than asserted in GAO report.

Application to Alternative SNF and Waste Forms

While the previous cases primarily analyzed the cost implications of dry storage for traditional PWR SNF, this section considers the implications for AR fuel types and reprocessed waste forms. The primary candidates under consideration for this study are TRI-structural ISOtropic (TRISO) pebbles, ceramic waste form (CWF), and alloy waste form (AWF). TRISO is currently being considered as a suitable AR SNF form for the UCS through a Deep Isolation-led project under ARPA-E's ONWARDS program. CWF and AWF are types of HLW emerging from pyroprocessing techniques and are being considered for disposal in the UCS through an Argonne National Laboratory-led, Deep Isolation-supported project under ARPA-E's Converting UNF[12] Radioisotopes Into Energy (CURIE) program.

The main impact on the three dry storage scenarios for these alternative waste forms is the **amount of heavy metal content** that will be produced over the reactor/reprocessing facility lifetime and the **loading capacity** of the waste forms in the UCS. For the reference PWR SNF, approximately 929 MTHM is expected to be produced over a reactor's operating lifetime; the loading capacity of a single PWR SNF assembly per Class 0 UCS is approximately 0.45 MTHM.

Alternatively, new commercial TRISO-based reactor designs are expected to contain on average 6.5 g of uranium per pebble [14], which results in 0.023 MTHM per UCS based on geometric constraints (**volume limited**). With an average burnup of around 174 GWd/MTHM and thermal power generation of 218 MW_t between these two commercial TRISO-based reactor designs [15], the total MTHM required over the course of a reactor lifetime is approximately 17 MTHM. With regards to the CWF and AWF, data from ongoing project work shows that the loading capacities of these waste forms into the UCS will likely be **mass limited**. Therefore, the amount of heavy metal content per UCS will be based on the UCS maximum mass limit, which translates to no more than 0.907 metric tons of CWF or AWF (proportion of heavy metal may vary) per UCS. The CURIE project also provides data in order to determine the total lifecycle heavy metal content for these two waste forms. These assumption differences from the traditional PWR SNF case are tabulated in Table 7 below.

Table 7. Loading Differences between Traditional PWR SNF and Alternative SNF/Waste Forms.

	Total MTHM Produced over a 40-Year Operational Period	MTHM per UCS
Reference PWR SNF	929	0.45
TRISO[13]	17	0.023
CWF	*	*
AWF	*	*
* Data from project work is still in progress and undergoing final analysis		

The total lifecycle management cost for each scenario can be calculated for each of these alternative SNF and waste forms based on these updated parameters. The results of these updated parameters on the dry storage calculations for each option will be summarized in the subsequent section.

---

[12] Per Footnote 1, UNF: Used Nuclear Fuel.

[13] The TRISO values in this report are based on those from companies with whom Deep Isolation are exploring disposal solutions for their TRISO SNF.

CONCLUSIONS

The three potential loading cases discussed in this paper shed light on the economic consequences of pursuing the traditional path for management of SNF and HLW versus adopting a holistic, lifecycle approach. In regard to the management of traditional PWR SNF, Table 8 and Figure 1 below summarize the cost for each case and the relative cost savings from the reference case. Considering all long-term costs for the back-end management of SNF, the third option that involves a deep borehole repository co-located with the reactor facility provides the greatest cost savings of the three options presented to a waste generator.

Table 8. Cost Comparison for Traditional SNF Loading Options.

Scenario	Cost ($/MTHM)	Savings from Reference Case (%)
Option 1 (Reference Case)	$2,094,539	N/A
Option 2	$1,314,138	37.26%
Option 3	$693,650	66.88%

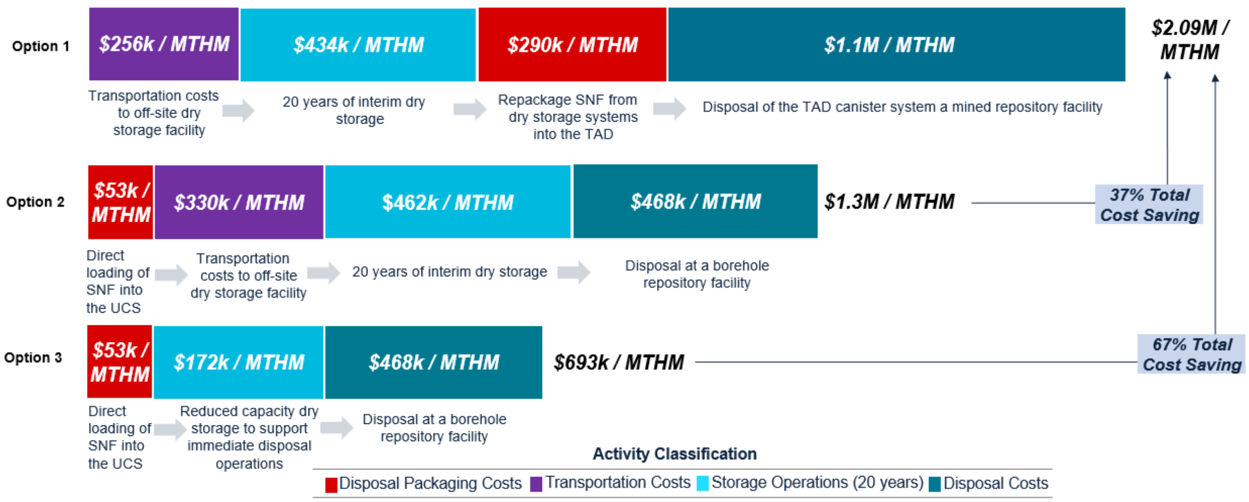

Figure 1. SNF Dry Storage Scenario Cost Comparison.

In regard to the management of HLW, the cost per MTHM across each waste form varies dramatically. This is due to the large difference in the amount of heavy metal content involved with these alternate waste forms. Due to higher enrichment in TRISO fuel compared with current PWR fuel assemblies, a significantly lower amount of uranium content is required to fuel a TRISO-based reactor core than for a PWR. For the AWF, the higher density and concentration of fission products within the waste immobilization matrix results in a relatively lower amount MTHM produced than for traditional PWR SNF. On the contrary, the lower density and immobilization matrix fission product concentration for CWF results in a higher amount of MTHM produced than for traditional PWR SNF. Nevertheless, both CWF and AWF are projected to fall within a bounding range of the PWR SNF cost estimates in each of these scenarios. All three specified HLW forms are expected to follow the pattern as seen in the traditional SNF scenarios, where greater cost savings can be achieved by first packing the waste in UCS canisters before pursuing dry storage and subsequent disposal. The total lifecycle cost across these waste forms is being actively investigated through collaboration with project partners and will inform follow-on economic evaluation.

As a whole, this study provides valuable insight into how the triple-purpose capability of the UCS presents waste generators and policy makers with a new perspective on the economics of SNF and HLW management. The spectrum of dry storage options across the various waste forms considered in this study shows that planning reactor and reprocessing operations with disposal in mind will result in net positive cost savings as compared to the status quo of interim dry storage without plans for eventual disposal.

REFERENCES

[1] “Nuclear Energy Agency (NEA) - Joint Project on Waste Integration for Small and Advanced Reactor Designs (WISARD).” [Online]. Available: https://www.oecd-nea.org/jcms/pl_86832/joint-project-on-waste-integration-for-small-and-advanced-reactor-designs-wisard)

[2] W. Duggan and E. Knox, “Cost Comparison for Deep Borehole Disposal as Alternative to Mined Repository,” presented at the Waste Management Symposia 2024, Phoneix, Arizona, Mar. 2024.

[3] DOE, “At COP28, Countries Launch Declaration to Triple Nuclear Energy Capacity by 2050, Recognizing the Key Role of Nuclear Energy in Reaching Net Zero.” [Online]. Available: https://www.energy.gov/articles/cop28-countries-launch-declaration-triple-nuclear-energy-capacity-2050-recognizing-key

[4] “Finland Begins Trial Run of Onkalo Repository,” *Nuclear Newswire*, vol. Waste Management, no. Radwaste Solutions, Sep. 03, 2024. [Online]. Available: https://www.ans.org/news/article-6349/finland-begins-trial-run-of-onkalo-repository/

[5] “Sweden’s SKB Approved to Begin Construction of Spent Fuel Repository,” *Nuclear Newswire*, vol. Waste Management, no. Radwaste Solutions, Oct. 29, 2024. [Online]. Available: https://www.ans.org/news/article-6520/swedens-skb-approved-to-begin-construction-of-spent-fuel-repository/

[6] M. Waples, V. Sharma, E. Bates, and J. Sloane, “Economic Model Development for Deep Borehole Repositories,” presented at the ANS Annual Conference, Las Vegas, NV, Jun. 2024.

[7] E. Johansson, T. Siren, M. Hakala, and P. Kantia, “ONKALO POSE Experiment - Phase 1&2: Execution and Monitoring,” Posiva, Working Report 2012–60, Feb. 2014. [Online]. Available: https://inis.iaea.org/collection/NCLCollectionStore/_Public/46/094/46094985.pdf

[8] “Spent nuclear fuel management: Outreach needed to help gain public acceptance for federal activities that address liability,” United States Government Accountability Office, GAO-15-141, Oct. 2014.

[9] E. Hardin and A. Alsaed, “Comparative Cost Analysis for Disposal of DPCs vs. Repackaging,” presented at the ANS Winter Meeting & Expo 2019, Nov. 2019.

[10] T. Kukkola, “Final disposal plant for spent nuclear fuel cost estimate of above ground facilities,” Posiva, Helsinki, Finland, Working Report 99-66.

[11] SKB, “Plan 2019 - costs from and including 2021 for radioactive residual products from nuclear power,” Sweden, TR-19-26, Dec. 2019. [Online]. Available: https://www.skb.com/publication/2494604/TR-19-26.pdf

[12] G. Freeze, E. J. Bonano, E. Kalinina, J. Meacham, L. Price, and P. Swift, “Comparative Cost Analysis of Spent Nuclear Fuel Management Alternatives,” Sandia National Laboratories, SAND2019-6999, Jun. 2019.

[13] M. Waples, V. Sharma, and J. Sloane, “Cost Model Overview,” Deep Isolation, 2024.

[14] C. Forsberg and A. C. Kadak, “Safeguards and Security for High-Burnup TRISO Pebble BedSpent Fuel and Reactors,” MIT, 2024. [Online]. Available: https://www.tandfonline.com/doi/epdf/10.1080/00295450.2023.2298157?needAccess=true

[15] S. Brinton, “UPWARDS: Universal Performance Criteria and Canister for Advanced Reactor Waste Form Acceptance in Borehole and Mined Repositories Considering Design Safety,” Deep Isolation, Technical Volume DE-FOA-0002531, Apr. 2022.

ACKNOWLEDGEMENTS

The analysis within this document was funded under ARPA-E grant DE-AR0001696.