Disposal of Radioactive Wastes from Advanced Reactors in Horizontal Boreholes – 21066

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ABSTRACT

Deep Isolation developed a safe, secure, and permanent deep geological disposal method for high-level waste, including spent nuclear fuel and other highly radioactive materials. The disposal method uses horizontal drilling techniques and emplaces the disposal canisters in a horizontal orientation deep underground. This approach provides additional safety factors over and above those found in deep mined repositories or deep vertical boreholes. It also provides a more economical waste management solution for advanced reactors, small modular reactors and for countries with smaller waste inventories.

During the past year, Deep Isolation participated with the Electric Power Research Institute (EPRI) examining the feasibility of co-locating a deep horizontal disposal repository with an advanced reactor. The study was a collaboration with EPRI, the Nuclear Energy Institute, Auburn University, Deep Isolation and J Kessler and Associates to assess the feasibility of onsite horizontal deep borehole disposal for the siting of advanced nuclear energy systems. The study discusses physical site characteristics, disposal operations, safety performance analysis, regulatory and licensing considerations, outlines an approach to understanding and building public support as well as a cost analysis to determine if horizontal boreholes may be a feasible solution for advanced reactors.

This approach could potentially allow the siting and development of the disposal system in parallel with reactor development. Such an approach presents the opportunity for greater system efficiencies throughout the project life-cycle as well as more productive engagement with stakeholders. This paper will address the results of the study and features of interest to advanced reactor developers and countries that are interested in starting smaller nuclear energy programs.

The cost analysis was prepared by Deep Isolation and it will be a focus of this paper. The cost analysis assumed costs for one reactor at a single site that includes a horizontal disposal system. The costs were compared to a mined repository equivalent based on a metric tons of uranium basis.

The analysis also includes review of an "ongoing disposal method" that uses the horizontal disposal system to replace above-ground storage during operations and compares that to the more traditional end-of-life disposal method that assumes disposal at the end of a reactors life and the cost impacts between the two methods.

The findings of the study are that the cost of disposal in deep horizontal drillholes will be approximately 50% of the cost of disposal within a mined repository. Other factors must be considered but the siting, safety case and technology are sufficiently developed to show that nuclear waste can be safely stored using horizontal disposal repositories while offering substantial cost savings when compared to the status quo.

INTRODUCTION

During the past year, Deep Isolation participated with the Electric Power Research Institute (EPRI) on a study about co-locating a horizontal disposal repository with an advanced reactor. The study was a collaboration with EPRI, the Nuclear Energy Institute, Auburn University, Deep Isolation and J Kessler and Associates to assess the feasibility of onsite horizontal deep borehole disposal for the siting of advanced nuclear energy systems. The study discusses physical site characteristics, disposal operations, safety performance analysis, regulatory and licensing considerations, outlines an approach to understanding and building public support as well as a cost analysis to determine if horizontal boreholes may be a feasible solution for advanced reactors.

This approach could potentially allow the siting and development of the disposal system in parallel with reactor development. Such an approach presents the opportunity for greater system efficiencies throughout the project life-cycle as well as more streamlined engagement with stakeholders. This paper will address the results of the study and features of interest to advanced reactor developers and countries that are interested in starting smaller nuclear energy programs.

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Concept of Operations

Each emplacement borehole consists of a 1,000 m vertical access hole that gradually transitions to a 1,500 m horizontal section where the waste canisters are emplaced. The deep borehole disposal facility modeled in this report (10 boreholes spaced 100 m apart with a capacity of 1,000 metric tons of waste) would occupy approximately 2.6 km^2 (640 acres) of land.

As advanced reactors will produce a variety of waste forms, this study used a standard 17 x 17 fuel assembly from a pressurized water reactor as a conservative and bounding surrogate. The disposal canister will be nominally 34 cm in diameter, 5.5 m in length and made from corrosion-resistant material such as Alloy 625.

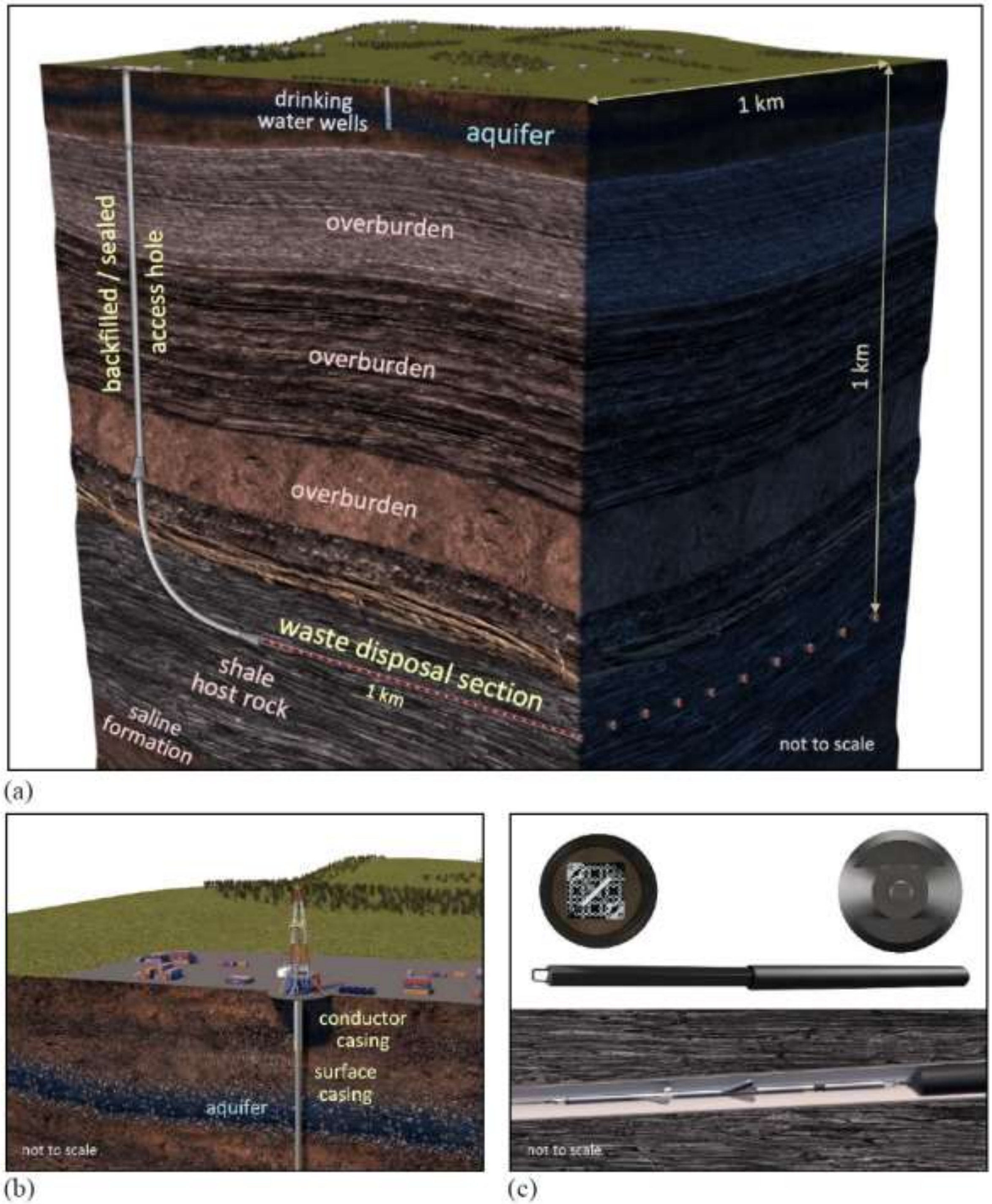

Figure 1. Schematic of a Deep Horizontal Drillhole Repository (not to scale) (Deep Isolation 2020). (a) wide-view of disposal configuration (b) close-up of surface and near-surface casing, (c) disposal canister and emplacement by wireline and tractor.

Emplacement is accomplished by lowering the canister down the vertical shaft then using a wireline tractor to push the canister along the horizontal section. Once the canister has reached its intended location, the canister is locked into place and the emplacement tool separates and returns to the surface. This emplacement process is repeated until the horizontal borehole reaches its design capacity. Following final canister emplacement and confirmation testing, the borehole is closed with ongoing system performance tracked via remote monitoring systems.

Scenarios and Assumptions

The base case for this feasibility assessment is a dedicated borehole facility co-located with a 1 MW advanced nuclear reactor. The reactor operates for 20-years and produces 1,000 metric tons of waste. From a regulatory and geographic perspective, the facility is assumed to operate in the southeastern United States.

REGULATORY FRAMEWORK

In the United States, there is no functioning program for the disposal of commercial SNF. The intended disposal site (Yuca Mountain in Nevada) has proven to be politically unworkable due, in part, to the federal government's failure to follow the facility siting best practices; however, it is still the legally required option in the United States.

In this context, a proposed new regulatory pathway has been developed for the disposal of spent nuclear fuel from advanced reactors. The approach deemed "Borehole Storage with Intent to Confirm Disposal" is a phased and adaptive approach, supported by the existing US regulatory framework and consisting of four key steps as illustrated below.

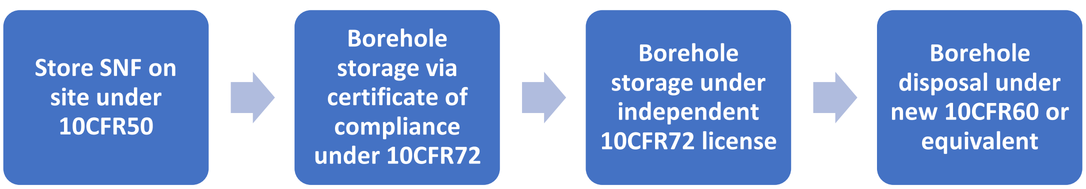

Figure 3 - Regulatory Pathway for "Borehole Storage with Intent to Confirm Disposal"

Initially, SNF would be stored on site under the reactor's 10CFR50 license. In parallel, the construction and operation of borehole disposal would proceed, and the operator would apply for a Certificate of Compliance (CoC) under 10CFR72. This CoC would then be used to allow for storage of SNF in boreholes at the reactor site in a manner which is the performance equivalent of the current above-ground dry storage systems. While the SNF is being stored, a new independent storage license would then be applied for under 10CFR72. A key feature of the new license application is that the Environmental Impact Statement would be prepared assuming a 1 million year performance period.[a] A successful license application under 10CFR72 would result in a finding that SNF placed in deep boreholes is a safe and effective over a 1 million year period and is the functional equivalent of disposal. Upon receipt of this finding, then a formal determination of disposal would be accomplished through new federal legislation replacing the current and outdated 10CFR60. This flexible approach also includes a series of decision points that, at each subsequent step, would allow for one of three potential outcomes:

i. Agreement on a regulatory framework to license the borehole for permanent disposal

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[a] The preliminary safety assessment concluded that deep borehole disposal yields a radiation dose at 1 million years of less than $1/1000^{th}$ of the 10mrem/year standard.

ii. A decision to extend the period of storage while permanent disposal is further considered (with actions to enable the renewal of the 10CFR72 storage license)

iii. A decision to retrieve spent fuel from the boreholes and transport to an alternate off-site disposal location.

Maintaining retrievability of spent fuel in the boreholes would be an important necessity throughout this process. Even though the intent of this endeavor would be to ultimately confirm – both from a scientific and public acceptance perspective – permanent disposal at the reactor site, the reactor operators would still enter into a contract for offsite disposal with DOE. This contract would serve as a "stop loss" provision should the project fail to reach this ultimate goal.

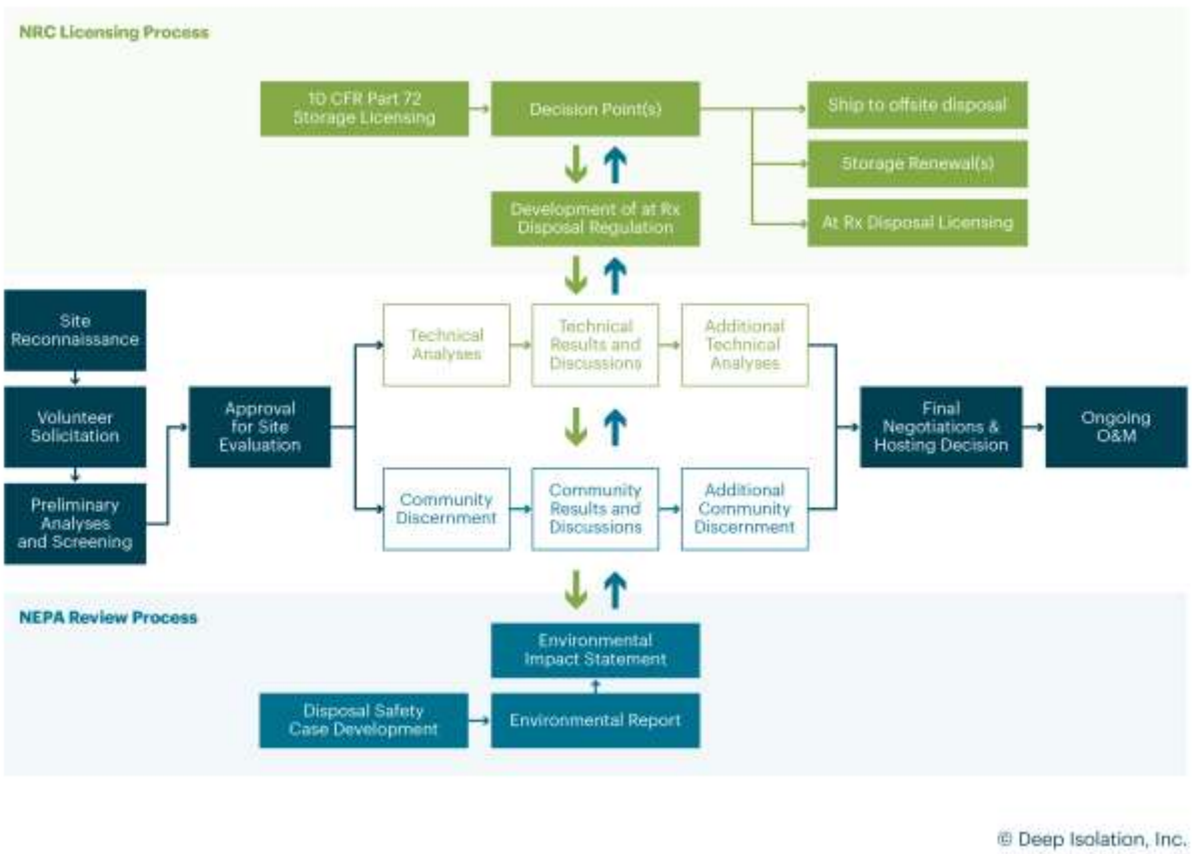

Figure 4 – Roadmap for Regulatory Approvals

A conceptual roadmap for federal regulatory approvals combined with host community discernment is shown above and would be further refined to incorporate local and state requirements as these become known.

COST AND SCHEDULE

Schedule and Budget Background for Disposal Aspects

This report modeled two scenarios for the disposal of SNF from an advanced reactor – an "ongoing disposal" disposal method and an "end-of-life disposal" method. The actual disposal operations are the same in each method, but the timing of when the disposal operations occur and storage costs for each method is different. This results in either greater storage costs or greater mobilization/demobilization costs for disposal.

Baseline Assumptions

Several baseline assumptions are used across all of the specific cost and schedule sections for the two scenarios modeled. Unless otherwise discussed, the following assumptions apply to all of the cost and schedule scenarios.

- The base case is one reactor per site with each site having its own dedicated waste disposal facility.
- SNF is assumed to be similar in size and characteristics to PWR SNF from a traditional reactor. Most advanced reactor fuel will be smaller sized and more compact, so this assumption represents an upper bound to the drilling and emplacement costs for disposal from an advanced reactor.
- SNF is produced ratably over 20-years resulting in the production of 2,100 assemblies with 1,000 metric tons of heavy metal at a single advanced reactor.
- The cost models for end of life disposal and a mined repository also include procurement of 100 multipurpose canisters (MPCs) with 21 PWR SNF assemblies based on an EPRI Cost Report.[1]
- Advanced reactor facilities will have small temporary storage facilities for the SNF between major outages, if needed. These may vary in size and utility but for purposes of this report, it was assumed for the Ongoing Disposal scenario (see below) that the advanced reactor either transfers SNF to dry storage (traditional MPCs) or disposes of SNF every other year.
- Disposal is assumed to be in a horizontal borehole 1 km deep and 1.5 km in horizontal length in a sedimentary rock such as shale.
- The borehole is 44 cm in diameter in the disposal section to accommodate a 34 cm disposal canister sized for PWR fuel. One SNF assembly is placed in a disposal canister and each borehole holds 210 disposal canisters. This results in a total of 10 boreholes for disposal of all of the SNF from each reactor.
- Emplacement assumes that one disposal borehole is operational at any time and three canisters per day are emplaced, five days per week, 50 weeks per year, until all of the canisters are emplaced for disposal.
- The EPRI Cost Report detailed costs for a consolidated storage facility. Those costs were used but modified to exclude transportation and related unloading/loading operations to develop at-reactor ISFSI costs. The size was also reduced.
- The EPRI Cost Report assumed 21 SNF assemblies per MPC which provided a total of 2,100 assemblies, 100 MPCs and 1,000 MTU for this report.
- For a mined repository, the average time in years between a grant of regulatory approval and the start of disposal operations is approximately 9.3 years (see Table 1 below).
- The U.S. DOE Office of Inspector General audit report dated November 2019 noted that DOE estimated $36.5 billion of liabilities for storage of SNF prior to the availability of a repository, of which $8.0 billion has already been paid. This leaves $28.5 billion of liabilities to be incurred for storage or $20,682/MTU.

Mined Repository Cost

There is global consensus across governments, regulators, scientists and the nuclear industry that the only safe solution for the long-term disposal of this high-level nuclear waste (HLW) is through deep geological disposal. To date, every country that has identified a complete disposal solution has included deep geological disposal based on a traditional mined repository. To that end, this report used the costs for a mined repository for comparison to a deep horizontal borehole repository.

A number of leading nuclear nations have published their budgets and plans for delivering a mined geologic repository for their high-level waste. Table 1 below gives the costs for deep geological disposal that have been published by the Canadian, Swedish, UK and US government authorities. This gives a basis to compare the average cost of a mined repository with the cost of a deep, horizontal borehole solution.

TABLE 1: Example costs of mined repositories for deep geological disposal

Cost of a mined repository[b]	• Canada [2]:	$19.8 billion
(in 2020 US dollar prices)	• Sweden [3]:	$6.2 billion
	• UK [4]:	$23.9 billion
	• US [5]:	$122.2 billion
Average cost per tonne in a mined repository	• $1.24 million	
Typical time to market	• 1 year from regulatory approval to start of construction	
	• 8.3 years for construction	
	• 10 years for emplacement	

Based on an average of $1.24M per MTU for the four referenced countries above, the model calculated a cost of $1.24B for disposal of the reference reactor's 1,000 MTU of waste in a traditional mined repository.

Next, the price of storage for a mined repository was considered. The storage period was split into two segments – storage during the operating life of the reactor and storage from shutdown until the mined repository takes the stored waste.

For a mined repository, it was assumed that the storage costs during the operational life of the reactor were based on the EPRI Cost report. The ISFSI storage facility base buildings and transport cask cost was $6.1M; MPCs including concrete overpacks cost $1.2M each and decommissioning for each overpack costs $56K in this model resulting in a cost of $130M during the 20-year operating life of the reactor.

[b] Note that the budget estimates for the four countries date from different years. Canadian, UK and Swedish figures have been converted to US dollars using average exchange rates for the relevant year from ofx.com, and all figures have been updated to 2020 values using inflation calculators published by the relevant national monetary authorities.

The model also assumed a 9.3-year storage period after the reactor shutdown. Based on the assumed cost of $20,682/MTU for storage each year, this results in a cost of $192M for 1,000 MTU of SNF for a mined GDF after shutdown. Thus, the total storage cost for a mined repository is $322M.

This results in a disposal price of $1.24B plus storage of $322M for a total cost for storage and disposal of $1.56B for a mined repository.

Disposal Using "Ongoing Disposal" Cost

The "ongoing disposal" method is where a disposal provider regularly disposes of fuel that has accumulated in a small, temporary fuel pool or storage facility. No additional storage costs are incurred in the ongoing disposal scenario, but it includes mobilization/demobilization (mob/demob) costs for each disposal borehole. The mob/demob cost covers the drilling rig and disposal crew. The drilling rig and disposal crew are assumed to be mobile and can move from plant to plant similar to how temporary outage workers move from plant to plant.

The workflow is illustrated in Figure 5 below. The SNF originates in the reactor building, goes to a temporary storage facility such as a spent fuel pool, is placed into a disposal canister, is transferred to the disposal site and emplaced for disposal. The drilling rig would drill the hole prior to the arrival of the fuel and would be used for emplacement activities.

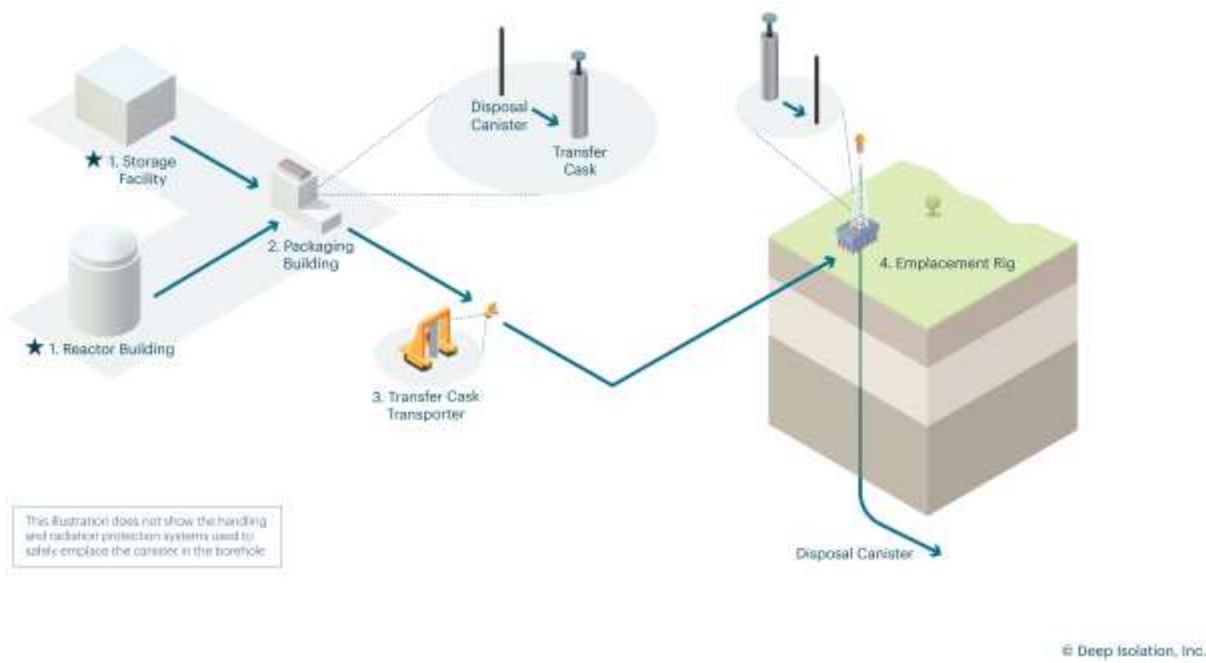

Figure 5 – Ongoing Disposal Process

The cost of deploying Deep Isolation's deep borehole technology is estimated to be approximately $469M (or $469K/MTU) plus mob/demob costs of $9M for a total of $478M. Site specific conditions and license requirements may impact the cost estimate and timeline.

Comparing the reference reactor's waste disposal and storage costs of $1.56B for a mined repository to the disposal and mob/demob costs of $478M for a deep, horizontal ongoing disposal repository, results in expected cost savings of $1.09B (approximately 69%).

Disposal Using "End of Life Disposal" Cost

The "end of life disposal" method is when traditional above-ground, dry-cask storage is used until all of the SNF is produced and then a single disposal campaign is performed during the decommissioning of the advanced reactor.

The workflow is illustrated in Figure 6 below. The SNF originates in the reactor building, goes to a temporary storage facility such as a spent fuel pool, is placed into a storage canister (which could also be the ultimate disposal canister), is transferred to the long-term storage facility, eventually repackaged into a disposal canister or the disposal canister is removed from the long-term storage case, the disposal canister is transferred to the disposal site and emplaced for disposal. The drilling rig would drill the hole prior to the arrival of the fuel and would be used for emplacement activities.

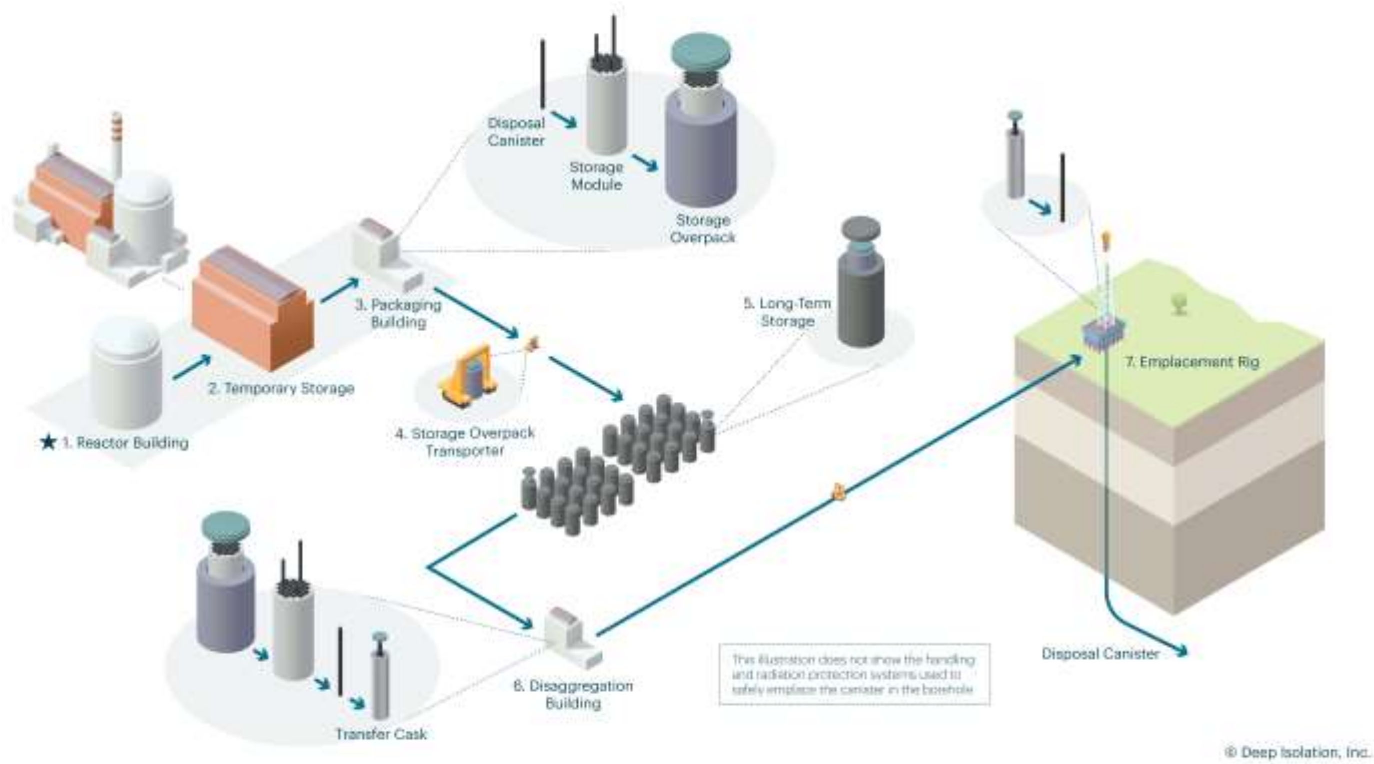

Figure 6 – End of Life Disposal Process

The cost of deploying Deep Isolation's deep borehole technology is estimated to be approximately $469M (or $469K/MTU) plus storage of $130M for a total of $599M. Site specific conditions and license requirements may impact the cost estimate and timeline.

Comparing our reference reactor's waste disposal and storage costs of $1.56B for a mined repository to the disposal and storage costs of $599M for a deep, horizontal ongoing disposal repository, results in expected cost savings of $963M (approximately 62%).

Schedule

Deep Isolation expects that siting of the horizontal borehole disposal facility with an advanced reactor is a two-year effort followed by a three-year licensing effort for the disposal facility. Note that some licensing activities such as the general safety case can be started in advance of the siting effort. In the fifth year, operations could begin to emplace the storage/disposal canisters at the disposal facility. Thus, for an advanced reactor that is operational in 2027, siting could begin in 2022 and licensing in 2024 so the disposal facility is ready for operations in 2027 – the same time as the reactor.

This study assumed that 2,100 assemblies are produced over the lifetime of one advanced reactor. The disposal operations, given the aforementioned work schedule and inventory, would take less than three years. Closure and post-closure could begin as soon as disposal operations are complete, depending on the license requirements and needs for retrieval.

Thus, for an end of life disposal approach the disposal operations could be complete within three years of the end of the life of the plant depending on the thermal properties and other aspects of the SNF.

For an ongoing disposal approach, disposal operations could be complete within a year of the end of the life of the plant depending on the thermal properties and other aspects of the SNF.

CONCLUSION

As illustrated below, the cost savings from implementation of a deep, horizontal storage/disposal solution compared to a mined repository are significant.

TABLE 2: Costs in Millions for Disposal by Scenario

($M)	End of Life Disposal	Ongoing Disposal	Mined Repository
Base disposal	$ 469	$ 469	$ 1,240
Mob/Demob	$ -	$ 9	$ -
Storage during ARx life	$ 130	$ -	$ 130
Storage after ARx life	$ -	$ -	$ 192
Total costs	$ 599	$ 478	$ 1,562
Savings from Mined ($M)	$ 963	$ 1,085	
Savings as % of Mined	62%	69%	

TABLE 3: Costs per MTU for Disposal by Scenario

($K/MTU)	End of Life Disposal	Ongoing Disposal	Mined Repository
Base disposal	$ 469	$ 469	$ 1,290

Mob/Demob	$ -	$ 9	$ -
Storage during ARx life	$ 130	$ -	$ 130
Storage after ARx life	$ -	$ -	$ 192
Total costs	$ 599	$ 478	$ 1,562
Savings from Mined ($K/MTU)	$ 963	$ 1,084	
Savings as % of Mined	62%	69%	

Note that the table values for cost and MTU look similar due to the use of 1,000 MTU as the base factor in Table 3.

Using an on-site, horizontal borehole approach, the entire waste inventory for a single advanced reactor can be disposed of in an ongoing disposal or end of life disposal method at a savings of over 60% or more when compared to the cost of a mined repository.

While it is acknowledged that the cost values are estimates, the significant potential cost and schedule savings and reduction in the uncertainty of disposal for advanced reactors (when compared to a mined repository) warrants serious consideration of the horizontal borehole solution at advanced reactor sites.[7]

Including a deep, horizontal disposal facility with an advanced reactor allows flexibility in the chosen disposal method (e.g. end of life disposal or ongoing disposal) and results in the disposal SNF more cost effectively, earlier and with greater operational certainty.

REFERENCES

1 EPRI report number 1018722 "*Cost Estimate for an Away-From-Reactor Generic Interim Storage Facility (GISF) for Spent Nuclear Fuel*" dated May 2009

2 Implementing Adaptive Phased Management 2020 to 2024, Nuclear Waste Management Organization, March 2020.

3 Plan 2019: Costs from and including 2021 for the radioactive residual products from nuclear power, SKB, December 2019

4 Geological Disposal: Steps towards implementation, NDA Report no. NDA/RWMD/013, March 2012.

5 Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program DOE/RW-0591 Fiscal Year 2007, Department of Energy, July 2008