Nuclear Waste Management Organization

Integrated Strategy for Radioactive Waste
Initial Plan Development – Characterization and Options

Cost Estimate

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Executive Summary

This cost estimate report was prepared to support the initial planning of the Integrated Strategy for Radioactive Waste (ISRW), a long-term management strategy for Canada's low- and intermediate-level radioactive waste (L&ILW). This cost estimate was prepared in conjunction with the Initial Plan Development – Characterization and Options Project Report [1], which provided recommendations for long-term management options specific to Canada's L&ILW with no existing long-term management plans. The purpose of this report was to provide indicative costs per unit volume of waste for the following six (6) potential long-term management options:

- Engineered Containment Mound (ECM)
- Concrete Vault (CV)
- Shallow Rock Cavern (SRC)
- Deep Geological Repository (DGR)
- Deep Borehole (DB)
- Rolling Stewardship (RS)

The cost estimate was developed in accordance with the Association for the Advancement of Cost Engineering (AACE) cost estimating guidelines and recommended practices for a Class 5 cost estimate. A preliminary design basis and cost basis were established for each option based on publicly available information and input from Hatch subject matter experts in nuclear and non-nuclear industries. The results of this cost estimate are presented in Table ES-1 and are shown graphically in Figure ES-1. It is emphasized that this report was prepared for the relative cost comparison of different waste disposal options on a per-unit-volume basis and should not be used for the absolute cost estimate of the overall cost of individual options. Rolling Stewardship is presented as three sub-options (300, 500, and 1,000 years) for relative comparison with other options.

Table ES-1: Cost Summary of Each Long-Term Management Option

Long-Term Management Option	Cost [CAD/m^3]* Low	Average	High	Applied Accuracy Range
Engineered Containment Mound	1,900	2,700	4,200	-30% to +50%
Concrete Vault	3,500	5,000	7,500	-30% to +50%
Shallow Rock Cavern	3,300	4,700	9,500	-30% to +100%
Deep Geological Repository	18,300	26,200	39,300	-30% to +50%
Deep Borehole	123,000	247,000	493,000	-50% to +100%
Rolling Stewardship (300 years)	3,200	6,300	12,700	-50% to +100%
Rolling Stewardship (500 years)	4,400	8,900	17,800	-50% to +100%
Rolling Stewardship (1,000 years)	7,600	15,200	30,500	-50% to +100%

* Cost is reported in 2021 Canadian dollars with no future price escalation nor discounting to net present value. Cost estimate excludes transportation costs and potential cost savings due to the co-location of multiple facilities.

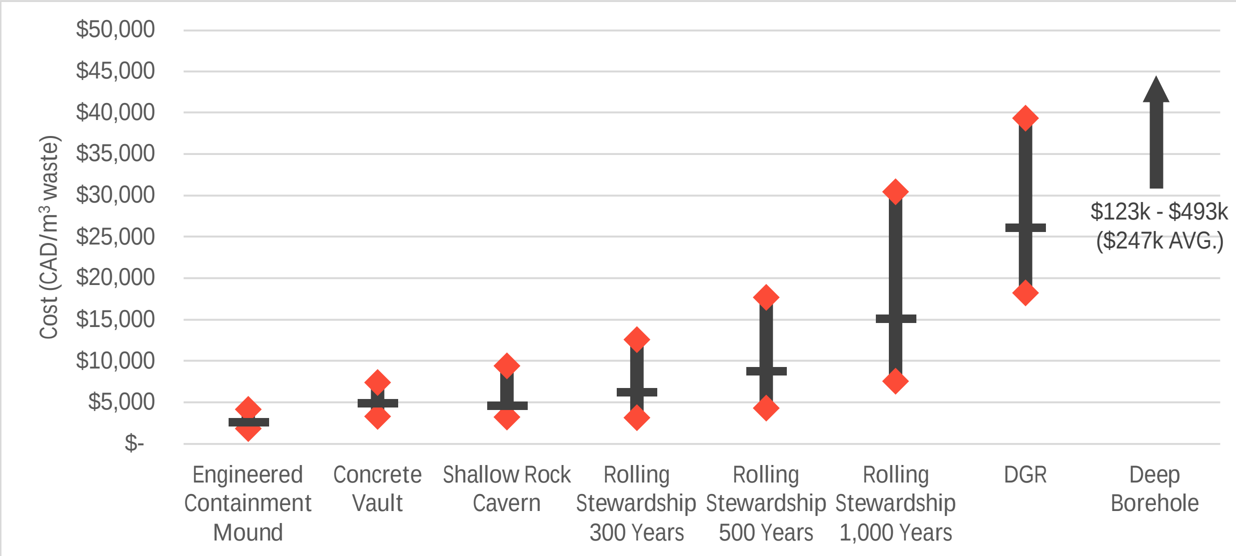

Figure ES-1: Cost Summary Graph of Each Long-Term Management Option, Including Accuracy Range

The basis of the estimates for DGR and Deep Borehole (waste quantity and length of the operational period) are different from other options as explained in sections 2.2.1 and 2.2.3. The cost estimate assumed the reference management scenarios and facility sizes for each option based on the recommendations made in the technical report [1]. It should be noted that the per-unit-volume cost of each long-term management facility benefits from economies of scale, and the results shown in this report can vary if the reference waste volume changes. The influence of economies of scale is shown, approximately, in Figure ES-2.

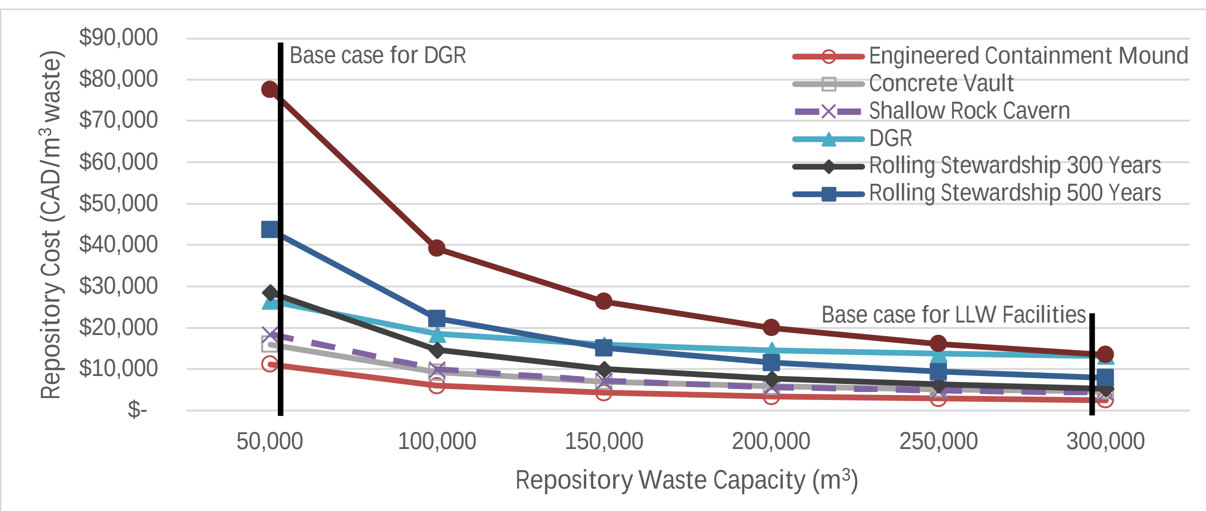

Figure ES-2: Indicative Effect of Changing Facility Size on Per-Unit-Cost. Accuracy Range and Deep Borehole Not Shown for Clarity

The four low-cost options (ECM, Concrete Vault, Shallow Rock Cavern, and 300-yr Rolling Stewardship) are only considered suitable for Low-Level Waste (LLW) and the first three may not meet the requirements for Intermediate-Level Waste (ILW) in the current Canadian regulatory framework.[1] The ECM was found to be the least expensive option, on average. However, the accuracy ranges of all four options overlap, so further investigation and definition are recommended to confirm the most economical option as one of several option evaluation criteria.

For ILW disposal via a DGR or Deep Borehole, the Deep Borehole was found to be approximately 10 times more expensive than the DGR per unit volume of waste. Furthermore, the Deep Borehole is only capable of disposing of part of the ISRW ILW inventory [1]. A DGR would be required to dispose of the remaining ILW. Thus, the additional high cost of a Deep Borehole may not be suitable for ILW under the ISRW scope.

Transportation costs and the implementation of a decentralized approach (i.e., multiple spread-out facilities) or a co-located approach (i.e., a single facility with one or more long-term management options) were not considered in this cost estimate. These considerations require further development and optimization as the project progresses.

Overall, the comparative cost estimate presented in this report is provided with observations and recommendations for further investigation as part of the ISRW. Given the preliminary design and cost bases produced for this initial plan, there is an opportunity to further define each long-term management option and investigate the implementation of a decentralized or co-located approach.

[1] As discussed in the technical report [1], there is international experience in disposing short-lived ILW in Shallow Rock Caverns. In Canada, there is no classification for short-lived ILW, so further investigation would be required.

Revision History

Rev #	Description of Change	Date Revised
0	Issued for Use	30-Nov-2021

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Nomenclature

Abbreviation/Term	Definition
AACE	Association for the Advancement of Cost Engineering
AECL	Atomic Energy of Canada Limited
APM	Adaptive Phased Management – Canada's long-term management plan for used nuclear fuel.
CANDU	Canada Deuterium Uranium – A Canadian heavy water reactor that is currently the only type of power reactor operating in Canada.
CNL	Canadian Nuclear Laboratories
CNSC	Canadian Nuclear Safety Commission
CV	Concrete Vault
DGR	Deep Geological Repository
Disposal	The emplacement of radioactive waste without the intention of retrieval.
ECM	Engineered Containment Mound
ILW	Intermediate-Level Radioactive Waste, as defined in [2]
LLW	Low-Level Radioactive Waste, as defined in [2]
Long-term Management	The long-term management of radioactive nuclear waste by means of storage or disposal.
L&ILW	Low- and Intermediate-Level Waste, as defined in [2]
NWMO	Nuclear Waste Management Organization
OPG	Ontario Power Generation
RS	Rolling Stewardship
SRC	Shallow Rock Cavern
Waste	In the context of this report, *waste* is assumed to be radioactive waste unless specified otherwise (e.g., *non-nuclear waste*).
Waste Owner	The *waste owner* is the organization currently responsible for the radioactive waste.
WWMF	Western Waste Management Facility, owned and operated by OPG located at the Bruce Nuclear Generating Station site.

1. Introduction

The Nuclear Waste Management Organization (NWMO) was tasked by Canada's Minister of Natural Resources to develop the strategy to manage Canada's low- and intermediate-level radioactive waste (L&ILW). The NWMO identified six (6) potential options that can be considered for the long-term management of Canada's L&ILW. They are:

- Engineered Containment Mound (ECM)
- Concrete Vault (CV)
- Shallow Rock Cavern (SRC)
- Deep Geological Repository (DGR)
- Deep Borehole (DB)
- Rolling Stewardship (RS)

The details of these options are presented in further detail on the Integrated Strategy for Radioactive Waste (ISRW) website.[2] The high-level details of these options are also provided in Appendix A.

The NWMO retained Hatch to analyze the technical suitability of these six long-term waste management options against Canada's L&ILW inventory and characteristics. The assessment report was published in the ISRW Project Report [1].

In addition to their technical suitability, the cost of long-term waste management options should be considered in developing the ISRW. Hatch was further retained by the NWMO to estimate the comparative cost of the six identified long-term management options.

This report presents the result of the cost estimating effort for the L&ILW management options based on reference scenarios. Along with the technical report [1], this cost estimate report will be used to support the public and stakeholder discussions in developing the ISRW.

[2] Website URL: https://radwasteplanning.ca/content/learn-more

2. Cost Estimating

2.1 Methodology

The cost estimate presented in this report is based on input from actual cost estimates for similar facilities performed by Hatch in the past. The cost estimate also draws from parallel industry experience (e.g., nuclear, mining, oil and gas, and industrial construction) and input from Hatch subject matter experts. Where available, the provided cost estimate was compared to international benchmarks.

For each option, the lifecycle cost was determined through a bottom-up approach to cost estimating for each development phase (siting, regulatory approvals, design & construction, operation, decommissioning & closure, and monitoring). Common infrastructure and facilities were identified for each long-term management option (e.g., offices, utilities, security, etcetera) and were estimated on a general basis. Facilities-specific costs are also identified and estimated for each long-term management option.

Costs that depend on facility size (i.e., total waste volume) were separated to identify variable costs. Fixed and variable costs were separately estimated to determine the economy of scale each facility type if the facility design inventory changes from the reference scenario.

2.2 Estimate Basis and Assumptions

2.2.1 Reference Facility Size

The waste volumes under the ISRW scope include current and future Canadian L&ILW that have no current long-term management plans, totalling approximately 294,000 m^3 of LLW and 51,000 m^3 of ILW [1]. The technical study showed that rolling stewardship (RS), engineered containment mound (ECM), concrete vault (CV), and shallow rock cavern (SRC) are not suitable for the long-term management of ILW. It is therefore assumed that the reference facilities for RS, ECM, CV and SRC are sized to host the LLW inventory, and the reference facilities for a deep geological repository (DGR) and deep boreholes (DB) are sized to host the ILW inventory. The reference facility sizes that were used in estimating the costs in this report are shown in Table 2-1.

Table 2-1: Assumed Waste Contents and Reference Facility Sizes for Each Long-Term Management Option

Facility Type	Assumed Waste Contents	Reference Facility Size
Rolling Stewardship Engineered Containment Mound Concrete Vault Shallow Rock Cavern	LLW, Bulk LLW, Other	294,000 m^3
Deep Geological Repository	ILW, General ILW, Small	51,000 m^3
Deep Borehole	ILW, Small (site-specific)	7,600 m^3

The assumed waste contents for each management option are described as follow:

- LLW, Bulk Material – Includes contaminated soil, concrete, and construction materials.
- LLW, Other – Includes containerized/drummed waste, metallic components, and large objects.
- ILW, General – Includes packaged/drummed waste, bulky metallic components, large objects that are too large to fit in a Deep Borehole.
- ILW, Small - Includes small, malleable objects such as spent IX resins and solidified liquids that are possible for potential Deep Borehole disposal. Existing ILW in this category will likely require repackaging for Deep Borehole disposal.

2.2.2 Waste Inventory Assumptions

All liquid waste is assumed to be solidified via incineration, vitrification, grouting, solidification agent, etcetera, as required. This additional processing cost was not included in this cost estimate.

Unless quantified by the waste owner, additional decontamination and volume reduction practices were not assumed in this study.

2.2.3 Project Assumptions

The study assumes that new waste management facilities will be built. For all facility types except for the Deep Borehole, the cost estimate assumed the site development would occur in a new greenfield environment, in an unspecified general location with good access to infrastructure and trades personnel, and at a reasonable distance from developed urban areas. Since Deep Boreholes were assumed to be built on existing waste management sites with existing infrastructure, utilities, and support amenities, the site development costs are excluded from the Deep Borehole estimates.

Cost savings due to the potential co-location of multiple types of facilities was not considered in this study. However, co-location of multiple waste types and/or facility types could provide an opportunity to combine common facilities (offices, administration, utilities, security, etcetera), reducing fixed infrastructure costs. Additionally, co-location may reduce costs for siting, licensing, and long-term monitoring.

Radioactive waste transportation costs are excluded as the location(s) of the ISRW facility (or facilities) has not been selected yet. As a result, costs associated with transportation cannot be estimated at this time. Instead, transportation cost considerations are discussed qualitatively in the discussion section of this report.

The cost associated with radioactive waste processing and/or conditioning is not considered as part of this estimate. However, a Deep Borehole repackaging plant is considered as part of this estimate since repackaging is necessary for the Deep Borehole to be feasible with the current ISRW waste inventory [1]. Note that some waste owners presently conduct waste processing and/or conditioning, but these costs are out of ISRW scope.

The operations phase covers the period when waste is received and emplaced in the facility. This period is assumed to be about 50 years, based on the current refurbishment and decommissioning schedules of Canada's existing CANDU nuclear fleet. The 50-year duration of this phase may need to be revisited should there be new nuclear development in Canada. For the Deep Borehole, the operational period depends on the number of boreholes in the facility. For example, the operational period for a 100-borehole facility is about 25 years. The cost could be reduced if the facility operation period was shortened, but generally, the operational costs are expected to fall within the accuracy range provided.

2.2.4 Financial Assumptions

The cost estimate does not include any cost related to the price of borrowing, interest rates or other costs related to the financial management of the program.

Long-term escalations due to inflation, commodity, and labour market changes over the next several hundred years were not considered reasonable to estimate for this study. This assumption produces estimating uncertainty when estimating Rolling Stewardship costs, which have a significant percentage of costs spread over the full facility design life (i.e., several hundred years). Other long-term management options have the bulk of the facility cost front-loaded during several decades for design, construction, and operations which reduces (but does not eliminate) this uncertainty.

2.2.5 Estimating Accuracy

The cost estimate was developed in accordance with AACE cost estimating guides and recommended practices for a Class 5 cost estimate. The order-of-magnitude costs are provided for each option with an accuracy range of -20% to -50% (low) and +30% to +100% (high).

2.2.6 Currency

The cost estimate is presented in 2021 Canadian Dollars. No forward escalation and discounting of the future cash flow has been applied.

2.3 Common Cost Factors

The estimated costs for each waste management option included the costs associated with the project lifecycle and those associated with the site infrastructures and services for each facility.

2.3.1 Project Lifecycle Costs

The lifecycle for each long-term management option has been divided into the following distinct phases:

- Site Selection
- Regulatory Approvals
- Facility Design and Construction
- Facility Operation
- Decommissioning and Closure

- Long-term Monitoring

Table 2-2 provides a breakdown of fixed and variable costs by development phase. Only the cost associated directly with the size of the long-term management facility and land size is considered variable. All other costs are considered fixed. Operational cost may appear to be variable (i.e., dependent on facility size and throughput). However, the dependency of the operational cost on the facility size was found to be minimal due to minimum staff levels and long durations. The main cost impact influencing the operations phase is the duration of the operating phase, which is considered to be fixed for this study.

Table 2-2: Fixed vs. Variable Cost per Project Phase

Life Cycle Project Phase	Cost Type	
	Fixed	Variable
Site Selection	✓	
Regulatory Approvals	✓	
Design And Construction:		
- Site Development		✓
- Onsite/Offsite Utility Connections	✓	
- Common Infrastructure/Services	✓	
- Facility Development		✓
Operational Cost	✓	
Decommissioning and Closure	✓	
Monitoring	✓	

The costs for each phase for each management option were separately estimated. The activities that incur significant costs in each phase are described in the following subsections.

2.3.1.1 *Site Selection*

Site selection includes the work associated with establishing a siting process, initial screening of potential communities, the detailed evaluation of shortlisted communities, and negotiating hosting agreements leading to a final site selection. For the purpose of this study, it is assumed that process would be open to any willing host community, with one or more sites selected to proceed with detailed site evaluations.

Public engagement for the ISRW is already underway to ensure the strategy aligns with the expectations of Canadians and Indigenous peoples. More information on the ongoing community engagement is available on the ISRW website.[3] In addition to general public acceptance of the ISRW, it is anticipated that each long-term management facility pursued will require community engagement including public outreach, Indigenous relations, engagement, and education.

[3] https://radwasteplanning.ca/engagement-initiatives/public-engagement-integrated-strategy-radioactive-waste-isrw

Community engagement is expected to be a significant fixed cost for all types of long-term waste management facilities. Other significant costs in this phase include facility development studies, design optimization efforts and conceptual design development, as well as initial interaction with regulators.

Site selection is expected to have a similar cost for all near-surface long-term management options, with the exception of the Shallow Rock Cavern. The Shallow Rock Cavern and DGR are expected to cost more in order to complete the geological studies necessary to find a suitable rock environment. The Deep Borehole is expected to cost less since the facility is assumed to be constructed on a brownfield nuclear site.

2.3.1.2 Regulatory Approvals

The costs associated with the regulatory approvals work include all activities required for preparing and obtaining site preparation and construction licences. The scope of this phase covers all supporting activities required for construction licence application, such as geoscientific and hydrogeologic site investigations, a safety assessment, and an environmental impact assessment. The engineering studies, calculations and models required for Preliminary Safety Analysis Report and Environmental Impact Assessment Report are included.

Regulatory approvals are expected to have a similar cost for all long-term management options.

2.3.1.3 Design and Construction

The costs associated with this phase include all direct and indirect costs associated with the design and construction of each facility option. The facility design development includes site surveys and the development of the facility's detailed design package.

Construction costs include all the direct costs required for the development of offsite infrastructure (access roads, utility connections and communications), onsite infrastructure (roads, utilities, services, normal and emergency power, mechanical, electrical, control and monitoring systems and distribution networks), surface facilities (site clearing and earthworks, construction of all surface buildings, site security fencing), and construction of the specific long-term waste management facility.

All construction indirect costs are also included and cover the costs of procurement, construction management, construction indirects (temporary trailers, contractor facilities), first fills, freight for materials and equipment, commissioning costs and project management costs. The construction, equipment and material costs are based on Hatch internal cost databases that have been developed using actual historic project costs and estimates received from vendors.

Each long-term management option involves a unique facility to manage the waste. As a result, the design and construction cost of each management facility varies significantly among the management options. The most significant cost factors between each management option are discussed in further detail in Section 2.4.

2.3.1.4 *Operations*

The cost of facility operations covers all the staffing, materials/equipment, and other services required to run the facility for the operational phase. Mobile equipment and utility costs are included under operational costs. Operational costs also cover all activities required to prepare the operating licence application, obtain the licence and periodic licence renewals.

The operating cost of all facilities is similar, with minor variations due to the number of personnel and types of equipment needed to support placement operations. The main factor that affects operating cost is the length of the operating phase due to the annual cost of labour and maintenance. For this reason, the 25-year operating period of the Deep Borehole facility is less expensive than the 50-year operating period of other management options.

2.3.1.5 *Decommissioning and Closure*

The decommissioning and closure phase includes the effort required for final repository closure and sealing, removal of site surface facilities and site infrastructure, and site rehabilitation. This task also covers the preparation of the Decommissioning and Sealing Plan, the preparation of the Final Safety Assessment Report in support of the decommissioning licence, and the CNSC application for the decommissioning licence. All the effort to prepare the licence application, liaise with regulators, and the CNSC fees were included in the cost.

Decommissioning and closure take place at different times depending on the option, as shown in Table 2-3.

Table 2-3: Scheduled Time of the Decommissioning and Closure Phase

Long-Term Management Option	Scheduled Time of Decommissioning/Closure Phase	Description
Concrete Vault	After the operations phase, before the monitoring phase.	Seal repository and remove all site facilities except for those needed for monitoring.
Shallow Rock Cavern		
Engineered Containment Mound		
Deep Geological Repository	After the monitoring phase.	Seal repository and remove all site facilities.
Deep Borehole		Seal borehole(s) and remove all site facilities.
Rolling Stewardship		Remove waste for conventional disposal and remove all site facilities.

For the Concrete Vault, the Shallow Rock Cavern, and the Engineered Containment Mound options, the facility is monitored after the repository is closed and sealed. For this reason, some buildings and infrastructure remain onsite after the decommissioning and closure phase to support monitoring efforts. These buildings and infrastructure include the security fence, radiological and environmental monitoring station(s), and the site passive drainage system. These remaining buildings and infrastructure would be decommissioned at the end of the monitoring phase. Although the method of sealing the repositories varies, the decommissioning and closure cost of these facilities are similar.

For the DGR and Deep Borehole options, a monitoring phase would take place prior to decommissioning and closure. Closure of the repository is delayed allowing for access to the underground repository during the monitoring period; this is discussed further in the next section. After the monitoring period, the repository would be closed and sealed, all surface buildings and infrastructure would be removed, and the site rehabilitated to greenfield conditions. The DGR has a high sealing cost attributed to sealing the DGR shafts bottom-to-top. The Deep Borehole has a relatively low sealing cost due to the relatively small volume of backfill (e.g., concrete) needed to seal each borehole bottom-to-top.

For the Rolling Stewardship option, site decommissioning and closure would not take place until the radioactive waste has decayed to a level that is no longer considered radioactive (i.e., no higher than natural background radiation levels). This decay period would coincide with the monitoring phase discussed in the next section. Once the decay period is over, it is assumed that the waste would be suitable for disposal in a conventional landfill. Note that LLW may contain some trace amounts of radioactive elements that remain hazardous after several hundred years. For the purpose of this study, it is assumed that these radionuclides would be present in levels allowing site release from CNSC licensing or waste disposal in conventional landfill, but this would be the subject of future waste characterization and facility acceptance criteria. The decommissioning and closure cost includes the removal of all site buildings and infrastructure and rehabilitating the site to greenfield conditions. The decommissioning and closure cost is expected to be significantly higher than other management options due to the cost of waste transportation and landfill disposal.

2.3.1.6 Monitoring

All options for long-term management facilities include a period of extended monitoring. The extent and duration of monitoring depend on the type of long-term management facility, as shown in Table 2-4. Thus, the monitoring cost varies significantly among the management options.

Table 2-4: Scheduled Time of the Monitoring Phase.

Long-Term Management Option	Scheduled Time	Monitoring Duration	Description
Concrete Vault	After the decommissioning and closure phase.	300 years	Periodic monitoring of the surface environment. Passive water management program.
Shallow Rock Cavern			
Engineered Containment Mound			
Deep Geological Repository	After the operations phase, before decommissioning and closure phase.	70 years	Active monitoring of surface and underground environments. Active water management program.
Deep Borehole		70 years	
Rolling Stewardship		As required by waste.	Active monitoring of the surface environment. Periodic inspection and maintenance of facilities and waste containers. Active water management program. This cost estimate assumed 300, 500, and 1,000 years of the monitoring period for a cost comparison.

For near-surface facilities, the monitoring period is assumed to take place for the full duration that the waste remains hazardous (approximately 300 years). This monitoring period includes periodic radiological and environmental monitoring, site inspections, and landscaping work to keep the repository seal and passive drainage systems free of excess vegetation and shrubs. Apart from Rolling Stewardship, the cost of the monitoring phase is expected to be minimal in the project lifecycle. For the Rolling Stewardship option, the monitoring period also includes ongoing site security (using a security fence and an offsite security response team), facility maintenance costs, and minimum supervisory staff to maintain the facility. The monitoring period is expected to be the most expensive lifecycle phase for the Rolling Stewardship option.

The Deep Geological Repository and Deep Borehole facilities include a period of extended monitoring that takes place between the end of facility operations and the start of decommissioning and closure. This period allows for repository access underground to monitor and potentially retrieve the disposed waste. This monitoring period is conservatively assumed to be 70 years. Given the reduced length of the monitoring period compared to near-surface facilities, the monitoring periods for the DGR and Deep Borehole options are expected to cost less than other management options.

For all options, the cost associated with monitoring also includes the development of periodic update reports for CNSC (e.g., every 10 years) until release from licensing. There may be some ongoing monitoring program for groundwater conditions after the final closure and release from licensing period, but these costs are negligible compared to earlier project phases.

2.3.2 Common Infrastructure & Services Costs

All long-term management options require supporting infrastructure and services, and these are significant cost components. It is assumed that all long-term waste management options except for the Deep Borehole option are built in a greenfield (i.e., previously undeveloped) environment and would therefore require new infrastructure, utility connections, and support buildings.

There are technical and operational differences between the options. For instance, an ECM does not require a concrete batch plant since it does not require any significant amount of concrete for its construction or operation. However, a concrete batch plant is a recommended onsite support facility for a CV option. Table 2-5 provides a matrix of the supporting infrastructure that was accounted for in the cost estimate of each long-term management option.

Table 2-5: Matrix of Common Infrastructure and Services

	ECM	Concrete Vault	Shallow Rock Cavern	DGR	Deep Borehole	Rolling Stewardship
New Road Connection or Railway	✓	✓	✓	✓	✗	✓
Utility Connections (Electrical, Water, Sewage, etcetera)	✓	✓	✓	✓	✗	✓
Onsite Petrol/LPG Storage	✓	✓	✓	✓	✗	✓
Security Fence	✓	✓	✓	✓	✓	✓
Fire Buffer Zone	✓	✓	✓	✓	✓	✓
Guardhouse/Office Building	✓	✓	✓	✓	✗	✓
Truck Inspection/Wash Station	✓	✓	✓	✓	✓	✓
Material Reception/Transfer Building	✓	✓	✓	✓	✓	✗
Maintenance Building w/ Warehouse Storage	✓	✓	✓	✓	✓	✓
Water Run-Off Pond	✓	✓	✓	✓	✓	✓
Emergency Generator	✗	✓	✓	✓	✓	✗
Environmental Monitoring Station	✓	✓	✓	✓	✓	✓
Leachate Collection System	✓	✓	✗	✗	✗	✓
Concrete Batch Plant	✗	✓	✓	✓	✓	✗
Air Compressing Station	✗	✗	✓	✓	✗	✗
Repackaging Plant	✗	✗	✗	✗	✓	✗
Water Treatment Plant	✓	✓	✓	✓	✓	✓

Notable differences in common facilities of the management options are listed below:

- The Deep Borehole option is assumed to be built on an existing site, so existing utility connections and onsite gas storage would be available for use. Additionally, a repackaging plant is required for the Deep Borehole since waste would need repackaging to specific size containers for borehole disposal. The Repackaging Plant would be connected to the Material Reception/Transfer Building. Repackaging may be required for other long-term management options, but this is not covered in the cost estimate.
- Rolling Stewardship does not require a Material Reception/Transfer building, as the waste will be placed directly into the facility.
- Management options that dispose of waste in rock (Shallow Rock Cavern, DGR, and Deep Borehole) do not require leachate collection systems since leachate will not be present.
- An air compressing station is required for facilities with underground personnel access to provide service air and breathing air.

2.4 Facility-Specific Cost Factors

Each of the six long-term waste management options has unique physical, operational, and regulatory characteristics that contribute to the cost estimate. These significant facility-specific cost factors are discussed next. A further technical description of the individual waste management facilities is provided in Appendix A.

2.4.1 Concrete Vault

Design and Construction – The materials and labour required for the construction of the concrete vaults are the most significant cost of the Concrete Vault option. It is noted that the concrete vaults are assumed to be cast-in-place, resulting in a high labour cost. The use of precast concrete construction and optimization of concrete vault sizing may provide additional cost savings, subject to further investigation.

2.4.2 Shallow Rock Cavern

Site Selection – The cost estimate was prepared for an unspecified site, but the cost for site selection is estimated to be higher than the other near-surface repositories (Concrete Vault and Engineered Containment Mound). The higher cost is attributed to challenges in finding a suitable near-surface rock formation.

Design and Construction – The highest cost of the Shallow Rock Cavern is expected to be for the labour, materials, and equipment required for underground excavations and development. In particular, the excavation of the underground vaults that will contain the disposed waste.

2.4.3 Engineered Containment Mound

Design and Construction – The design and construction of the ECM are similar to the Concrete Vault, with the exception that the ECM uses trenches constructed of water-proof materials rather than concrete vaults. This reduces the cost of construction compared to the Concrete Vault but still adds a significant cost to the overall facility.

2.4.4 Deep Geological Repository

Placement Room Construction and Backfill – Lateral development (excavation), construction, and backfill of the DGR Placement Rooms are expected to be the most significant cost of a DGR. Most of this cost is attributed to the labour and materials associated with backfilling the placement rooms once placement operations are complete.

Shaft Construction – Another significant cost of the DGR is the construction of the DGR shafts, including the headframe and hoisting systems. Most of this cost is attributed to the labour, materials, and equipment associated with shaft sinking.

2.4.5 Deep Borehole

Design and Construction – The design and construction cost for borehole drilling is expected to be the majority of the facility cost for large facilities with many boreholes. The high cost is attributed to the number of boreholes required to dispose of large quantities of waste (for example, see Table A-1). It is noted that changes in the repository volume will significantly change the cost of borehole design and construction.

Repackaging – The repackaging plant design and construction will be significant costs for the Deep Borehole option. The high cost of this facility is attributed to the design of the specialized automated/remote controlled process systems required for repackaging ILW.

2.4.6 Rolling Stewardship

Long Term Storage Building Design and Construction – The storage building(s) construction for long-term storage of the radioactive waste is expected to be the most significant factor in the overall facility design and construction cost, but costs are much smaller compared to the cost of facility monitoring and maintenance.

Facility Monitoring – The facility monitoring phase is the most significant cost element of the Rolling Stewardship option and is substantially more costly than other long-term management options. The high cost associated with Rolling Stewardship is primarily due to the ongoing monitoring, administration, security, and maintenance costs. Maintenance includes the labour and materials required for building maintenance and waste container inspections/touch-ups.

Conventional Waste Disposal – Facility decommissioning may commence once the waste has decayed to the extent that it is no longer considered a radiological hazard (i.e., several hundred years for LLW). During decommissioning, the waste cost assumes the transportation and disposal to a conventional landfill.

3. Evaluation Summary

3.1 Unit Costs of Long-Term Management Options

The unit cost summary and accuracy range for each long-term management option are presented in Table 3-1 and Figure 3-1. These costs are indicative and are only intended to provide a comparison between each option based on assumptions made in this study. These unit costs do not represent the total project cost for the implementation of any selected long-term management option.

The estimated average facility cost is presented alongside the estimated low and high costs based on the accuracy range selected for each facility. The accuracy ranges are adjusted for each facility based on the design basis available, general concept development level, and experience in related projects of cost estimate staff.

- The ECM, Concrete Vault, and DGR were assigned a narrower accuracy range of -30% to +50%, given the concept design development level available to Hatch.
- The Shallow Rock Cavern accuracy range was selected as -30% to +100%, given the uncertainty associated with finding a site with suitable near-surface geology to meet the isolation and containment requirements of the facility.
- The Rolling Stewardship and Deep Borehole options were assigned a wider range of estimate uncertainty (-50% to +100%) given that a significant portion of the costs are spread over a much longer period of several hundred years, compared to several decades for other options.

Table 3-1: Cost Summary of Each Long-Term Management Option.

Long-Term Management Option	Cost [CAD/m^3]* Low	Average	High	Applied Accuracy Range
Engineered Containment Mound	1,900	2,700	4,200	-30% to +50%
Concrete Vault	3,500	5,000	7,500	-30% to +50%
Shallow Rock Cavern	3,300	4,700	9,500	-30% to +100%
Deep Geological Repository	18,300	26,200	39,300	-30% to +50%
Deep Borehole	123,000	247,000	493,000	-50% to +100%
Rolling Stewardship (300 years)	3,200	6,300	12,700	-50% to +100%
Rolling Stewardship (500 years)	4,400	8,900	17,800	-50% to +100%
Rolling Stewardship (1,000 years)	7,600	15,200	30,500	-50% to +100%

* Cost is reported in 2021 Canadian dollars with no future price escalation nor discounting to net present value. Cost estimate excludes transportation costs and potential cost savings due to the co-location of multiple facilities.

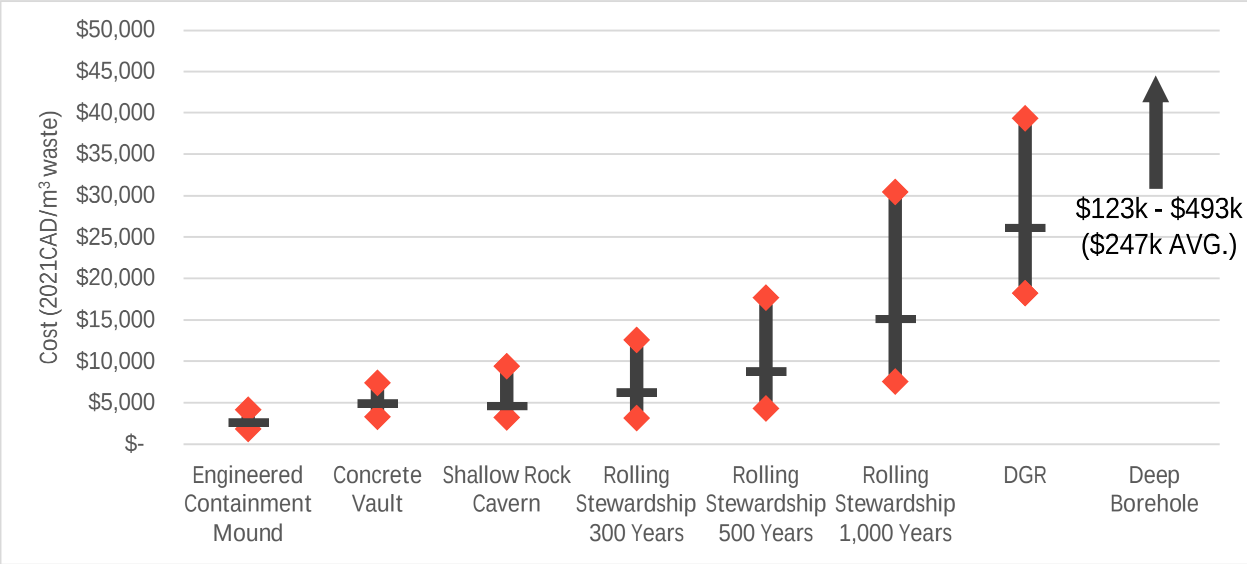

Figure 3-1: Graph of Cost Summary of Each Long-Term Management Option, Including Accuracy Range[4]

The cost estimate results in Table 3-1 and Figure 3-1 show that the four near-surface long-term management options have the lowest estimated costs (ECM, Concrete Vault, Shallow Rock Cavern, and Rolling Stewardship for 300 years), and the ECM has the lowest average cost overall. It should be noted that the accuracy ranges overlap; therefore, careful consideration and further studies are required to determine which option will be most economical for a given waste type. Rolling Stewardship applied for longer periods of time (beyond 300 years) is considered cost-prohibitive compared to other LLW disposal options.

The long-term management of ILW is noted as considerably more expensive than LLW. This result is expected given the additional cost of construction for deep underground disposal methods. Furthermore, the Deep Borehole option was found to be an order of magnitude more expensive than the DGR. This is primarily attributed to the high cost of borehole construction and the small volume of waste that can be contained in a single borehole.

Observations and recommendations made based on the cost estimate results are discussed in further detail in Section 4 of this report.

3.2 Cost Breakdown

The fraction of the management option costs associated with different lifecycle phases are shown in Figure 3-2. It is noted that the costs incurred in the monitoring phase is the majority of the Rolling Stewardship cost, whereas the ones associated with the design and construction phase are the most significant costs for the other options. The operational phase costs are also a significant part of all near-surface disposal options. The Deep Borehole has a notable higher cost in the design and construction phase due to borehole construction.

[4] Note that the DGR and Deep Borehole costs are estimated are based on smaller reference waste inventory size than other options.

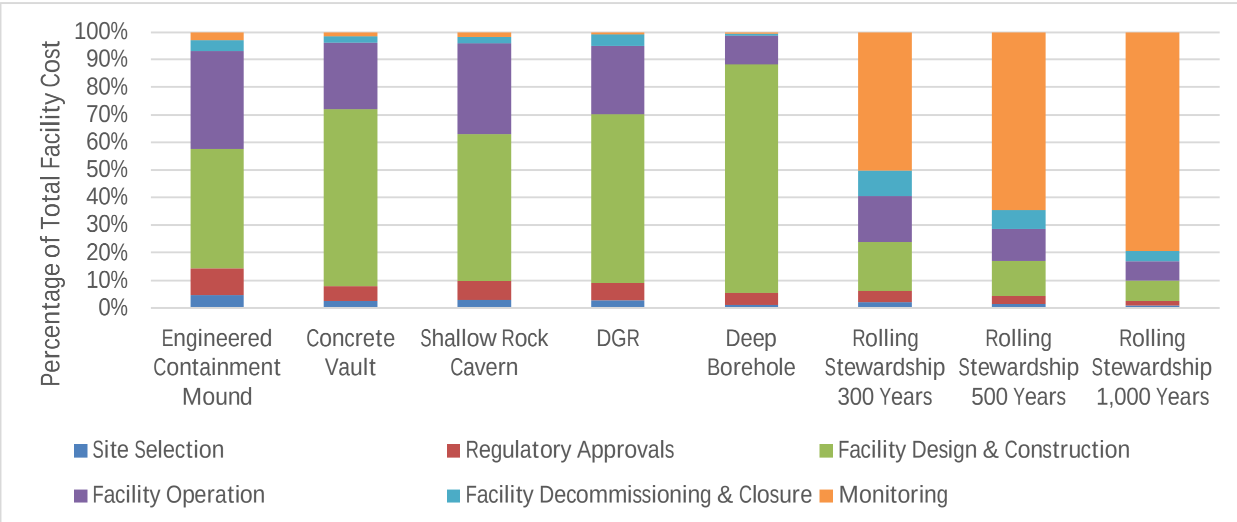

Figure 3-2: Cost by Development Phase for Each Long-Term Management Option

Figure 3-3 shows the fixed and variable cost components for each management option. In general, variable costs increase proportional to the volume of waste, whereas fixed costs do not change based on the volume of waste. The Deep Borehole facility has a very high variable cost compared to the fixed cost because a higher waste volume requires more borehole drilling, which is a very expensive task. Rolling Stewardship has a very high fixed cost because most of the lifecycle cost is due to monitoring, which requires a minimum staff and maintenance required regardless of the volume of waste.

The concrete vault has a higher variable cost due to the cost of concrete, which scales based on the number of vaults required in the facility. The DGR has a higher variable cost due to the cost of deep underground placement room development and backfill, which also scales with the quantity of waste.

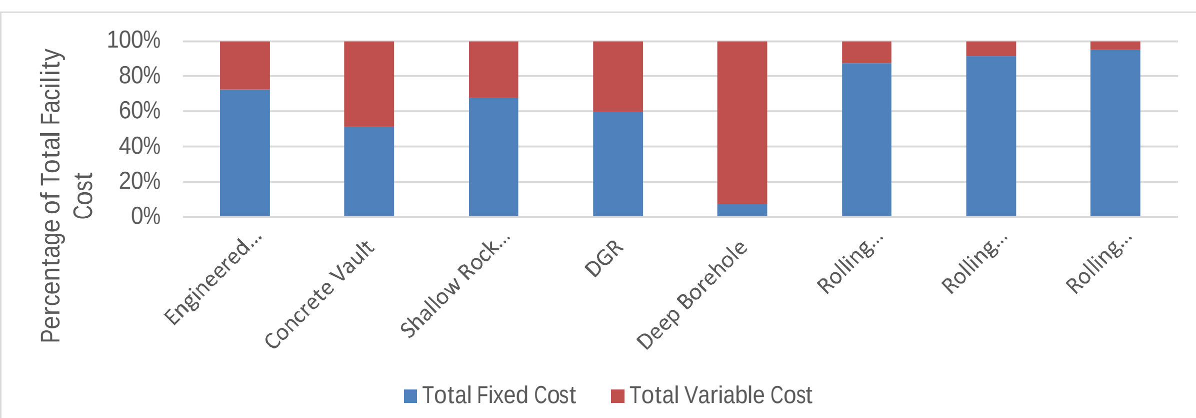

Figure 3-3: Fixed and Variable Cost of Each Long-Term Management Option

3.3 Facility Size and Economies of Scale

The reference facility size used in this study was based on the current best estimate of the Canadian L&ILW inventory. Any significant changes to the L&ILW waste volumes will change the costs estimated in this study. In general, this relationship follows the principle of economies of scale, with larger facilities predicted to have a lower per-unit cost. Figure 3-4 presents the approximate change to the average unit cost for each option versus facility size. Also, note that the uncertainty of the estimate increases as the facility capacity deviates from the base case.

The Deep Borehole is not shown in Figure 3-4, given the different scale of cost and waste volumes involved. The Deep Borehole facility benefits less from economies of scale when dealing with large waste volumes such as those in Figure 3-4 (50,000 m^3 to 300,000 m^3). However, as discussed in the technical report [1] and Section 2.4.5, a Deep Borehole facility is more likely to be used for waste volumes of approximately 100 m^3 to 10,000 m^3. Within this smaller range of waste volumes, the same principle of economies of scale applies to the Deep Borehole.

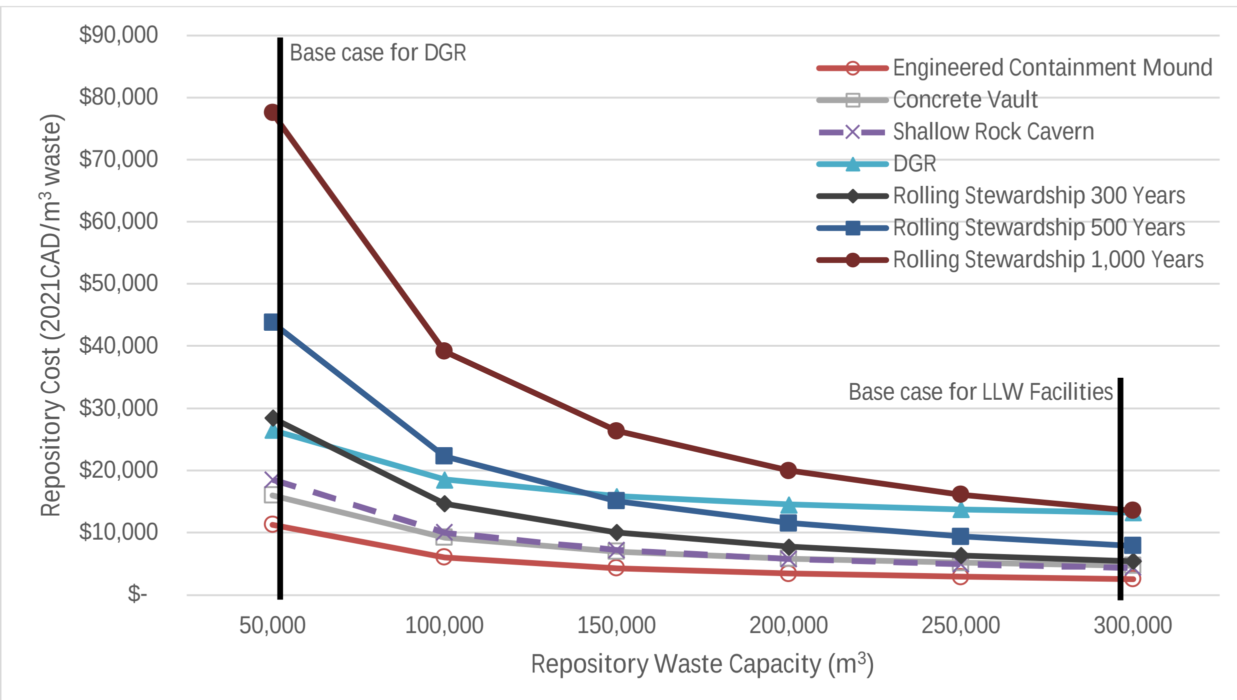

Figure 3-4: Indicative Affect of Facility Size on Per Unit Cost. (Accuracy Range and Deep Borehole Not Shown for Clarity)

3.4 Cost Dependence of Operating Period

Another significant factor that influences the costs is the duration of the operations phase (waste emplacement period). In all management options except for the Deep Borehole, the operations period was assumed to be about 50 years. The majority of operational costs are due to labour and facility maintenance over the 50-year period. There is an opportunity for cost savings by decreasing the length of the operations phase and increasing the facility's annual throughput. Table 3-2 provides the dependence of the cost based on the duration of the operational period. Note that the cost dependence shown is indicative only. This is because the uncertainty of the estimate increases as the facility’s operating phase deviates from the base case at which the estimate was developed.

This evaluation is not relevant to the Deep Borehole option since the operating period depends on the number of boreholes.

Table 3-2: Cost Dependence Based on Duration of Operational Phase.

Duration of the Operational Period	Average Cost[2]/m[3]						
	ECM	Concrete Vault	Shallow Rock Cavern	DGR	Rolling Stewardship		
					300 Yrs	500 Yrs	1,000 Yrs
10 years	$1,900	$4,000	$3,500	$20,900	$5,500	$8,000	$14,400
20 years	$2,100	$4,200	$3,800	$22,100	$5,700	$8,200	$14,600
30 years	$2,300	$4,500	$4,100	$23,300	$5,900	$8,400	$14,800
40 years	$2,500	$4,700	$4,400	$24,500	$6,100	$8,600	$15,000
50 years[1]	$2,700	$4,900	$4,600	$25,700	$6,300	$8,800	$15,200

[1] A base case at which the estimate was developed

[2] Accuracy Range NOT Shown

3.5 International Experience

The study reviewed international LLW disposal projects and their life cycle costs based on publicly available information. The reviewed facilities primarily utilized near-surface disposal solutions (e.g., Concrete Vault and Shallow Rock Cavern). Figure 3-5 shows the results of this benchmark study.

There is an inverse correlation between unit costs and the capacity of the facility (trendline in Figure 3-5), which confirms the economies-of-scale effect discussed previously. The lowest capacity facilities (Dukovany, Olkiluoto and Loviisa) have the highest unit disposal cost, which is expected, and the unit costs decrease as the size of the facility increases.

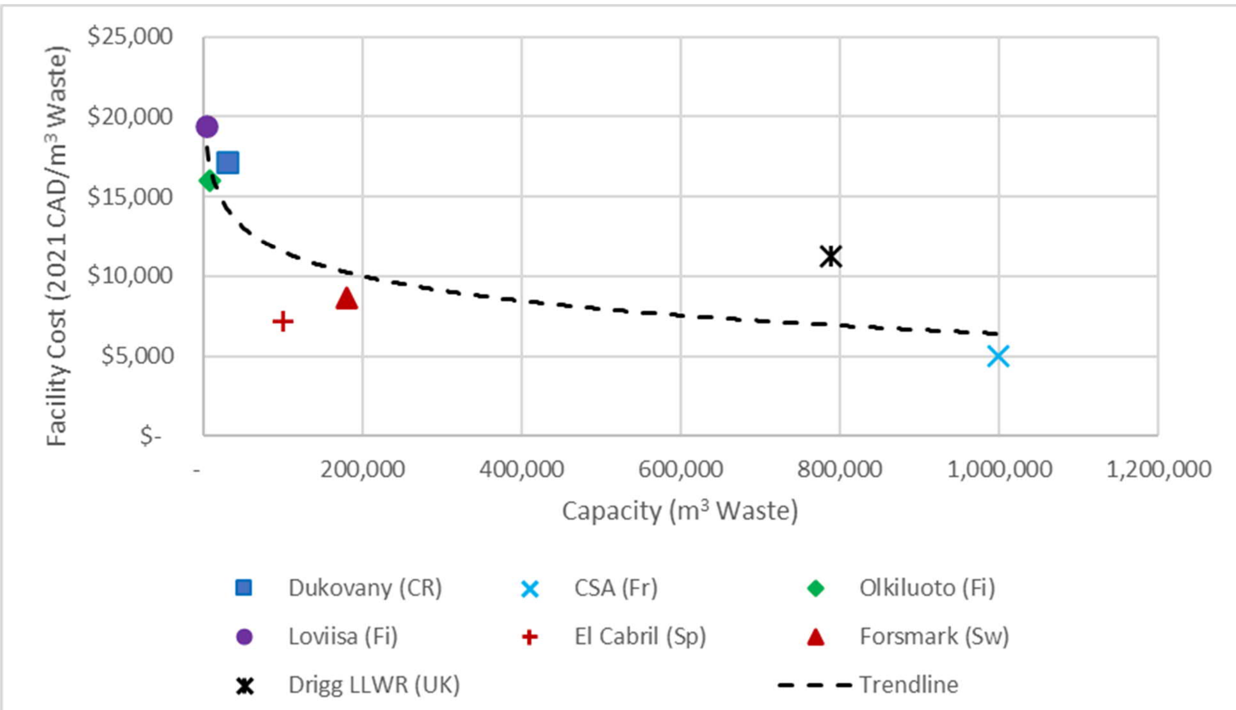

Figure 3-5: International Near Surface Disposal Facility Benchmark Costs

It should be recognized that the costs referenced in Figure 3-5 were prepared by international third parties, each for a specific purpose. These costs may not encompass all the same components as used in this ISRW cost estimate report.

Despite this limitation, this international experience provides useful insight into indicative disposal costs, and it aligns well with the estimates produced in this report.

4. Discussion and Recommendations for Further Study

The purpose of this report was to support the ISRW development by providing an indicative and comparative cost estimate of the six long-term waste management options presented in the technical report [1]. The estimates were prepared according to AACE International Cost Estimating Guidelines and are considered high-level Class 5 estimates. It is further emphasized that this report was prepared to provide a relative cost comparison between individual disposal options based on certain assumptions, and the estimates presented herein should not be used as an absolute cost of the ISRW. More investigation into the number, type(s), and configuration(s) of facilities and transportation costs will be required before a cost can be estimated for the entire strategy. The potential cost of repackaging and/or waste treatment prior to disposal will further affect the cost.

4.1 General Facility Observations

In general, the lowest cost option for LLW management was found to be the Engineered Containment Mound, followed by the Shallow Rock Cavern, the Concrete Vault, and Rolling Stewardship (300-yrs). However, the accuracy ranges of all four of the LLW long-term management options overlap, so further investigation and definition are recommended to confirm the most economical solution for a particular waste type.

For the management of ILW, the DGR was found to be the most economical option.

4.2 Facility-Specific Observations

The average cost of disposal in the Shallow Rock Cavern was found to be lower than the Concrete Vault option. However, the Shallow Rock Cavern is more dependent on the suitability of the site, which must have a high-quality rock formation to provide a suitable natural barrier for the containment of radioactive waste. There is much greater availability of site locations with suitable conditions for the Concrete Vault option because it is less dependent on geology. The costs of both options should continue to be investigated as mining/tunnel boring technologies continue to improve significantly and are becoming more economical. Conversely, the Concrete Vault option is more dependent on the price of commodities, including concrete, which is steadily increasing.

The high monitoring cost for Rolling Stewardship is attributed mainly to maintenance activities and active monitoring for an extended period, where other options have suitable barriers in place to allow the transition to passive monitoring and minimal human intervention. Rolling Stewardship requires ongoing maintenance and monitoring for the lifespan of the radioactive waste. Based on the assumption that the Rolling Stewardship lasts 300 years, costs for this period are comparable to other near-surface disposal options (Concrete Vault and Shallow Rock Cavern). The estimate for longer Rolling Stewardship (500- and 1,000-year options) shows that this option is cost-prohibitive compared to other long-term management options.

If future price escalations and cashflow discounting are applied, it may reduce the estimated net present value cost of Rolling Stewardship. This is because most of the spending occurs during the monitoring period, which is later than other options. However, there is uncertainty about how accurately the current cost estimate methods can predict future costs of labour, commodities, etcetera, spanning several hundred years. For ILW, Rolling Stewardship is expected to require human intervention for up to one hundred thousand years, which is considered cost-prohibitive and not suitable for ILW. Rolling Stewardship is not considered internationally as a permanent solution because it relies on future generations to ensure the continued safety of the facility.

For ILW disposal, the DGR was identified as the least expensive option, costing on average 10 times less than the Deep Borehole per unit volume of waste. It is also noted that the Deep Borehole cannot dispose of the full ILW inventory included in the ISRW study due to dimensional limitations. Therefore, a DGR would be required for some of the ISRW inventory regardless of whether boreholes were used for the disposal of suitable waste. Given the low fixed cost of the Deep Borehole option, it may be suitable for small waste generators (e.g., less than a few hundred cubic metres of waste).

Although the Deep Borehole option was identified as unsuitable for the full ISRW inventory, there is a substantial opportunity to optimize the design to reduce the overall cost by unit volume. The Deep Borehole option has two key limiting factors: the cost of borehole drilling and the limited volume of waste that can fit in each borehole. The development of this technology is evolving with variability in determining the optimal borehole size and container size. The parameters assumed are considered average to conservative based on oil well drilling technology. As such, the cost estimate is very sensitive to the diameter of the borehole. As an upper bounding case for example, if the diameter of the Deep Borehole is 1.75 times larger diameter, the number of boreholes required is reduced by a factor of three. This reduces the cost per cubic metre by a factor under three. Borehole size is highly dependent on available technology, and cost could be optimized as this technology progresses.

4.3 Scaling Factors

It was found that the majority (about 80%) of the facility operational costs for all options except deep borehole are attributed to labour and facility maintenance. Therefore, reducing the overall duration of the waste emplacement period can reduce the cost significantly. Also, it was found that there is a minimum staffing level required to keep the facility operational, which makes the operational cost relatively insensitive to the facility's annual throughput.

Therefore, reducing the operating cost will take innovative planning and scheduling due to the typical waste management cycle driving the long timeframe, i.e., disposal of current inventory, followed by a low volume for disposal, then followed by disposal of waste from decommissioning. Concepts to be explored include:

- Combining emplacement operations via co-locating multiple waste disposal options at the same site; thus, increasing the throughput for fixed labour costs.
- Co-locating waste emplacement operations with potential processing/repackaging facilities, allowing for a shared labour force.
- Placing a facility in care and maintenance during the low volume period, i.e., reduce the placement volume to zero while keeping maintenance and security active.

4.4 Processing Considerations

Except for the Deep Borehole method, this study did not consider the cost of additional waste processing, such as volume reduction, beyond those already planned and quantified by each waste owner. Waste processing methods vary based on the physical properties of the waste but can include:

- Mechanical volume reduction: cutting, segmentation, compaction.
- Incineration.
- Metal melting.
- Decontamination.
- Bulk decontamination (e.g., hydrometallurgy for contaminated concrete).
- Solidification of liquids (including dewatering, vitrification, grouting, etc.).

The large irregular-shaped objects, such as steam generators and heat exchangers, may require a mechanical volume reduction or segmentation to a more manageable size/weight prior to disposal.

Subject to future study, the Integrated Strategy for Radioactive Waste may benefit from an upstream holistic approach to waste processing and minimization. It is important to note the trade-off between the cost of waste processing and the cost savings of volume minimization for disposal. If waste needs to be repackaged or treated prior to disposal, there could be additional cost savings associated with waste minimization methods (i.e., incineration, compaction, metal melting).

4.5 Co-Location versus Decentralized Approach Considerations

A key consideration for the ISRW is the trade-off between a co-located approach versus a decentralized approach. The co-location of multiple waste types and/or facility types could provide an opportunity to combine common facilities (offices, administration, utilities, security, etcetera), reducing fixed infrastructure costs. Additionally, co-location may reduce costs for siting, licensing, and long-term monitoring. The possibility of co-location must consider the safety case for disposing of multiple waste types in close proximity and shall still ensure isolation of separate waste types.

Conversely, a decentralized approach uses multiple long-term management facilities throughout Canada. This approach would reduce the cost of waste transportation to these facilities but may result in higher costs for siting, licensing, and long-term monitoring. Since transportation costs were excluded from this study, a cost-based recommendation cannot be made between the co-located versus decentralized approaches. Further investigation is recommended in conjunction with transportation cost and other non-financial considerations.

4.6 Transportation Considerations

Transportation costs were not considered in this cost estimate. Since the location of the ISRW facility (or facilities) is not defined at this time, the costs associated with transporting the waste cannot be estimated. Nevertheless, a qualitative discussion is included to support future investigations.

Transportation fixed costs include the design, certification, and construction of transportation packages and any required licensing. These fixed costs depend on the type of waste being transported; for example, ILW that requires a specialized transportation package will increase the associated costs.

Transportation variable costs include labour for transportation shipments and maintenance of transportation packages and conveyances (i.e., vehicles). Transportation variable costs depend significantly on the distance of transport and the volume of waste being transported.

Transportation of radioactive waste must comply with the CNSC *Packaging and Transport of Nuclear Substances Regulations* (SOR/2015-145). As such, the transportation package design may need to be certified with the CNSC, depending on the risk level associated with the radioactive waste being transported. Package design certification adds cost to the design of transportation packages. Additionally, transportation package certificates are typically valid for 4-5 years, so long-term use of transportation package designs requires additional operating costs to renew the certificate. All radioactive waste shipments in Canada must also comply with the *Transport of Dangerous Goods Regulations* for Class 7 material. These regulations require special training and radiation protection measures unique to shipments of nuclear substances. These special requirements increase the operating cost of transportation.

Furthermore, some radioactive waste under the ISRW scope may also require a licence from the CNSC to transport. Transportation licensing adds additional cost on a per-trip basis. Additional information on transportation licensing and package certification is available on the CNSC website[5].

Although the transportation of nuclear substances is federally regulated, oversize loads are permitted on a province-by-province basis. As a result, cross-province travel must consider the permitting requirements of each province waste is being transported in. Transportation permits for oversize and overweight shipments may be required depending on the nature of the waste. Transportation permits sometimes require the development of a transport study and escort vehicles that further impact the transportation costs.

[5] http://nuclearsafety.gc.ca/eng/nuclear-substances/packaging-and-transport-of-nuclear-substances/index.cfm

5. References

[1] Hatch Ltd., H365930-00000-200-066-0001, Initial Plan Development - Characterization and Options: Project Report, Nuclear Waste Management Organization, 2021.

[2] Canadian Nuclear Safety Commission, "Low- and intermediate-level radioactive waste," 4 May 2021. [Online]. Available: http://nuclearsafety.gc.ca/eng/waste/low-and-intermediate-waste/index.cfm. [Accessed 30 June 2021].

[3] Ontario Power Generation, "NK38-PLAN-00960-10001 Rev. 2, Preliminary Decommissioning Plan - Darlington Nuclear Generating Station," 2016.

[4] Ontario Power Generation, "P-PLAN-00960-00001 Rev. 2, Preliminary Decommissioning Plan - Pickering Generating Stations A & B," 2016.

[5] Ontario Power Generation, "06819-PLAN-00960-00001 Rev. 2, Preliminary Decommissionin Plan - Bruce Nuclear Generating Stations A and B," 2016.

[6] AACE International, Recommended Practice No. 17R-97 Cost Estimate Classification System, 2011.

Appendix A: Facility Types

The following sections provides a further technical description of the individual long-term waste management options, which were considered in the cost estimate development under this report.

A.1 Concrete Vault

The Concrete Vault waste repository concept uses concrete vaults to provide an independent, self-supporting structure, such that emplaced waste containers are not subject to any external structural loads other than from typical waste container stacking. The vault structure also provides containment, adding an additional defense in depth barrier against the potential release of radiological contaminants to the surrounding environment. The exact dimensions of the vaults and thickness of the concrete would be subject to future optimization studies to select the most economical concrete to space utilization ratio.

The Concrete Vault waste repository design would be constructed with independent concrete containment vaults that are built progressively around a central access corridor. The design with the central access corridor would allow for progressive construction as waste is received and for the facility size to be scaled up or down according to waste owner needs.

The containment system would also include a multilayer impervious water barrier and leachate collection system installed below the repository. The water barrier prevents groundwater seepage into the containment or leachate flow into the groundwater. Site selection includes geological considerations to limit groundwater inflow. A temporary mobile cover would be installed over the repository while the vaults are being constructed to provide protection against the elements.

Once the waste emplacement operations complete, the top of the Concrete Vault would be covered with engineered backfill material. The cover provides a drainage slope covered with multiple barriers to prevent water penetration and provide proper drainage away from the repository. Surface water would drain into a run-off pond for monitoring and controlled release. The top layer would be regular soil, sloped and stabilized with grass vegetation to prevent soil erosion. The long-term maintenance would consist of detecting and monitoring any water within the leachate collection system and the surface water run-off in the pond. Regular grass cutting and maintenance would be required to prevent any growth of shrubs and/or trees on the top of the repository.

A.2 Shallow Rock Cavern

The Shallow Rock Cavern concept uses a natural, near-surface (e.g., 50-100 metres underground) formation of low-permeability rock to provide additional containment for emplaced waste containers.

The repository design consists of a network of underground tunnels (vaults) that would be constructed using standard methods and equipment from the mining industry. The size of the tunnels would provide suitable dimensions for stacking a variety of industry-standard waste containers as well as irregularly shaped objects (e.g., steam generator segments). Access to the underground repository would be via two access ramps. The two access ramps support a "flow-through" forced ventilation system. The floor of the access ramps and repository vaults would be designed with paved concrete to provide a smooth driving surface for mobile waste handling equipment.

Upon completion of waste emplacement operations, the access to the repository would be sealed by bulkheads installed at each access ramp. The waste containers, the site's natural geology, and the sealing of all openings provide defense-in-depth containment of the waste and protection against penetration of groundwater into the waste repository.

A.3 Engineered Containment Mound

The Engineered Containment Mound concept uses trenches lined with natural and synthetic materials to achieve containment of low-level waste. Unlike the concrete vaults, in-ground trenches do not provide an independent, self-supporting structure. Thus, the waste would need to be self-supporting (e.g., through the minimization of void space, grouting and/or through waste container reinforcement).

During construction, the top layers of native soil would be removed, and the trenches constructed to the depth required to reach suitable base materials. A multilayer impervious water barrier and leachate collection system would be constructed in the excavated area. This would be topped with a layer of compacted granular material to provide a stable driving surface for the emplacement equipment. A temporary mobile cover was assumed in the cost estimate to protect the open repository from the elements during the operations phase.

The emplacement operation would be similar to the Concrete Vault option, with identical support buildings and infrastructure requirements. The concept in this study does not include any waste grouting in place since this option is primarily intended for bulk waste with minimal void space (e.g., soil and concrete). Hatch has performed a preliminary sensitivity analysis, and results indicate that grouting, if required, would fit within the upper-cost limit shown in Section 3.1.

Once the emplacement operation would be complete, the top of the repository would be covered with engineered fill, layers of water membrane, drainage material and topsoil with vegetation. Drainage would be routed to the run-off pond like the Concrete Vault option. The long-term monitoring and management are also identical to the Concrete Vault option.

A.4 Deep Geological Repository

The Deep Geological Repository concept contains and isolates radioactive waste in a network of tunnels deep underground in a stable rock formation. Multiple engineered barriers, including waste containers, concrete/grout backfill of placement rooms, the site's natural geology, and the sealing of all openings, provide defense-in-depth containment of the waste. DGRs are recognized as the international best practice to dispose of ILW.

The design basis for the DGR used in this cost estimate is based on publicly available information on the Ontario Power Generation (OPG) L&ILW DGR. The NWMO APM DGR for used fuel is also used for reference, where applicable.

At the surface, support facilities would be present to receive transportation packages containing radioactive waste. The DGR is assumed to be constructed at a greenfield site (i.e., no existing infrastructure in place), so support infrastructure such as road access, water/sewage piping, electricity, etcetera, that were discussed in Section 2.3.1 are all included in this cost estimate.

Access between the surface and underground facilities would be achieved via two shafts. The two shafts allow the provision of ventilation circulation throughout the facility as well as separate redundant exits in case of emergency.

The waste containers at the DGR would be transferred underground and into placement rooms for final disposal. The placement rooms would make up a network of tunnels at a depth of several hundred metres. The base case assessed for this cost estimate provided a number of placement rooms sufficient to contain the full ISRW ILW inventory. Once placement rooms would be full of waste containers, the remaining air gaps around the waste containers would be backfilled with concrete/grout for additional containment.

Waste placement and backfill activities would be supported by an underground central services area located near the facility shafts at the same depth as the placement rooms. The underground services area includes general mine infrastructure and equipment maintenance/servicing capabilities.

Once waste placement operations would be complete, the monitoring period would commence. Access to the underground facility would be retained for the monitoring period. Once the monitoring period is complete, the remaining access tunnels and shafts are assumed to be sealed entirely from bottom to top.

A.5 Deep Borehole

The Deep Borehole concept involves lowering waste disposal containers into deep, narrow boreholes around 1,000 metres deep. Waste containment and isolation would be achieved by the waste containers, the site's natural geology, and sealing of the boreholes.

Since there are no international examples of large-scale use of Deep Boreholes for radioactive waste disposal, a preliminary concept was developed to use as the basis for the cost estimate. This concept for the cost estimate was developed with the following fundamental assumptions:

- Site Selection: The boreholes are assumed to be deep enough to reach basement rock. As a result, site selection for the facility (or facilities) is not as limited by geology as other disposal options. Therefore, the facility (or facilities) is assumed to be located at the location of waste generation/storage. This assumption means the facility would be built on a brownfield site, so the most common site infrastructure would already be present. This assumption will require verification on a site-by-site basis if the Deep Borehole disposal method is pursued. **Note:** As with all long-term waste management options, technical feasibility does not preclude other aspects of the site selection process.
- Boreholes: Borehole construction was based on input from Hatch subject matter experts in deep well drilling in the oil and gas industry. Boreholes would be drilled over one-kilometre vertical depth with a 750 m horizontal section at the bottom for waste disposal. The assumed container diameter is 0.4 m. Based on technological limitations and

ongoing investigations in the United States[6], each Deep Borehole is expected to contain approximately 75 m^3 of disposed waste. These dimensions are considered to be average to slightly conservative assumptions with an upper bounding consideration of 1.75 times larger container diameter yielding approximately three times the storage volume per mere length of useable borehole. Depending on the waste volume that requires disposal, multiple boreholes may be required at a single facility.

- Waste Repackaging: As discussed in the technical report [1], most waste intended for Deep Borehole disposal would require repackaging. This repackaging is assumed to take place in a specialized facility at each Deep Borehole site and is included in this cost estimate.
- Waste Emplacement: Waste is assumed to be emplaced in a controlled manner via a coil tubing unit or similar technology adapted from the oil and gas industry. This equipment has been proven in both vertical and horizontal applications. Waste emplacement is assumed to take place only on the horizontal section of each borehole, as shown on the ISRW website.8
- General Support Facilities: It is assumed that Deep Borehole facilities require similar surface infrastructure to other long-term management facilities (e.g., site roads, grading, offices, amenities, security, utilities, etcetera). Since Deep Boreholes would be constructed on brownfield sites, some of these facilities would already be in place.

As discussed in the technical report [1], Deep Borehole disposal is considered technically suitable for waste categorized as "ILW, Small," such as spent ion exchange resins. This dimensionally small waste comprises approximately 18% of the total ILW inventory under the ISRW scope[7]. Using the preliminary waste inventory information from the technical report for "ILW, Small," Table A-1 shows the approximate number of boreholes that would be required at each site to dispose of all "ILW, Small" if this was the only approach selected for small-dimension ILW.

Table A-1: Approximate Boreholes Required for Disposal of All ILW, Small per Location

Waste Owner and Location	Boreholes Required to Dispose of All ILW, Small*
OPG WWMF	101
AECL/CNL Douglas Point	4
AECL/CNL Gentilly 1	5
AECL/CNL Chalk River	8
HQ Gentilly 2	6
NB Power Point Lepreau	1

* Based on the initial plan and subject to change as this project progresses, see [1] for more information on the waste inventory.

[6] https://radwasteplanning.ca/content/learn-more
[7] It is noted that a separate DGR will be required to dispose of the remaining ILW that is not categorized as “ILW, Small”.

A.6 Rolling Stewardship

The Rolling Stewardship concept combines human controls and engineered barriers to store waste until it is deemed safe for free release or conventional waste disposal. In contrast to the other long-term waste management options, Rolling Stewardship does not involve a disposal solution or natural barriers. Instead, controlled access to the waste is maintained for the lifespan of the facility. Since Rolling Stewardship provides relatively limited "defense-in-depth" compared to other disposal options, continuous active monitoring, inspections, and maintenance would be required for the lifespan of the waste. This monitoring is more onerous than the monitoring required by other disposal options, putting a larger burden on future generations.

Existing facilities that are currently used for the interim storage of LLW and ILW waste employ similar human controls and engineered barriers. However, it is expected that the existing facilities will have insufficient capacity and/or design life to be repurposed for a Rolling Stewardship solution. This is considered a reasonable assumption as most existing interim storage solutions are not designed to last hundreds of years as would be required by the Rolling Stewardship option. As such, the design basis used for this study includes new storage facilities constructed in a greenfield environment (i.e., undeveloped land). The Rolling Stewardship facility would therefore require similar above-ground buildings and utility connections as the other LLW near-surface methods. However, a waste reception/handling building would not be required since waste would be delivered and emplaced directly in the storage facility.

The long-term storage building itself would comprise either a single large building or multiple smaller waste storage buildings. The building construction could be prefabricated metal, precast concrete or poured concrete construction. The prefabricated metal construction was used in the estimate. It was assumed that there would be no liquid waste stored, and the storage facilities would not need any temperature control, i.e., no heating or cooling. The building(s) would be equipped with passive ventilation, and waste would be accessible for regular inspection/surveillance during the full storage period.

The site selection and regulatory approvals are expected to follow the same process as other near-surface disposal facilities (Concrete Vault and ECM).

The operations phase is modelled after the ECM, Concrete Vault, and Shallow Rock Cavern options. Once waste emplacement operations would be complete, the facility would enter the long-term surveillance/monitoring phase. During this phase, there would be a minimum staffing requirement for maintenance, waste package and facility inspections, security, and environmental monitoring.