

ASSESSING GEOLOGICAL VERSUS PURPOSE-BUILT STORAGE SOLUTIONS FOR SAFE RADIOACTIVE WASTE MANAGEMENT

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Abstract: This paper compares two methods for radioactive waste management: geological disposal and purpose-built storage. Geological disposal relies on natural geological formations for long-term isolation but faces challenges such as irretrievability and geological stability. In contrast, purpose-built storage offers flexibility, enhanced monitoring, and the ability to adapt to different waste types, though it requires continuous maintenance and presents higher operational risks. A comprehensive risk analysis and modeling help determine the optimal solution, balancing environmental safety and practical feasibility. The study highlights the importance of technological advancements and continuous monitoring to ensure safe management for future generations.

Keywords: *environmental impact, nuclear waste safety, purpose-built storage, radioactive waste management, risk analysis*

INTRODUCTION

Nuclear activities generate radioactive waste that must be managed under strict safety and regulatory conditions. Radioactive waste includes all materials in gaseous, liquid or solid form, for which no further use is foreseen, and which are controlled by the competent national authorities [1]. Due to the radiological hazard and the long-term impact on the environment, radioactive waste management is one of the most complex and sensitive components of the nuclear field [2].

Radioactive waste results from uranium mining and processing activities, nuclear power generation, and institutional applications such as medicine, research, industry, and agriculture. Unlike conventional waste streams, radioactive waste follows a rigorously controlled management cycle designed to ensure containment, traceability, and long-term environmental protection [3].

The management of this waste consists of successive stages, which include collection, sorting, characterization, treatment, conditioning, interim storage, transport and final disposal. Each stage has a clear function, namely: collection and sorting aim to separate and pre-treat the waste, characterization determines its physical, chemical and radiological properties [4, 5], treatment reduces the volume or modifies the characteristics of the waste, conditioning ensures appropriate packaging for handling and transport, interim storage provides controlled isolation with monitoring capacity and final disposal ensures long-term isolation [6 – 8]. The structured sequence of these stages is illustrated in Figure 1, which presents the radioactive waste management cycle and highlights how the operational and long-term safety phases are connected [9].

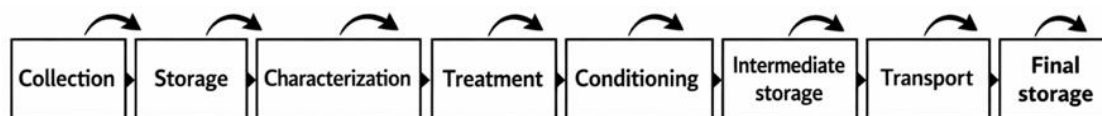


Figure 1. The radioactive waste cycles

Long-term management of radioactive waste can be achieved through two main strategies: deep geological disposal and purpose-built or designed storage facilities. Geological disposal relies primarily on natural geological barriers to provide isolation from the biosphere for very long periods. This approach aims to provide passive safety but involves irreversible decisions and reliance on long-term geological stability. In contrast, purpose-built storage facilities rely on designed containment systems, controlled environments, and continuous monitoring. These systems offer operational flexibility and retrievability, but require sustained institutional oversight and maintenance [10, 11].

The difference between the two approaches reflects the need to balance long-term environmental protection with structural reliability, risk controllability, operational flexibility and adaptability to evolving European standards. In regions where geological conditions are uncertain or where retrievability and monitoring are considered essential, alternative controlled storage concepts may represent viable solutions.

The objective of this paper was to compare geological disposal with a purpose-built modular underground storage concept from both structural and risk perspectives. The methodology integrated finite element modeling of the proposed structure with qualitative risk analysis in order to evaluate structural stability, operational flexibility, and long-term safety implications. The analyzed concept was based on staged isolation, enhanced

monitoring, and the possibility of controlled intervention, which allows for a higher level of anthropogenic control and reduces exclusive reliance on natural geological barriers [10, 11].

The comparative analysis addresses both deep geological disposal and engineered modular underground facilities, evaluating mechanical reliability, operational safety, and the main risk categories associated with each approach. Particular attention was given to structural integrity, groundwater protection, as well as monitoring and retrievability capacity [12]. By correlating numerical simulations with risk assessment, the study contributes to clarifying the technical feasibility and trade-offs between passive geological isolation and controlled engineered solutions [12].

MATERIALS AND METHODS

A modular underground storage concept has been developed to allow for the phased placement of waste and the controlled isolation of individual compartments. The facility is structured into storage sections that can be sequentially filled and subsequently sealed, thus limiting the spread of potential incidents and allowing for targeted intervention, if necessary.

The location of the waste containers in the rock-excavated galleries and the configuration of the constructed anthropic barrier are shown in Figure 2.

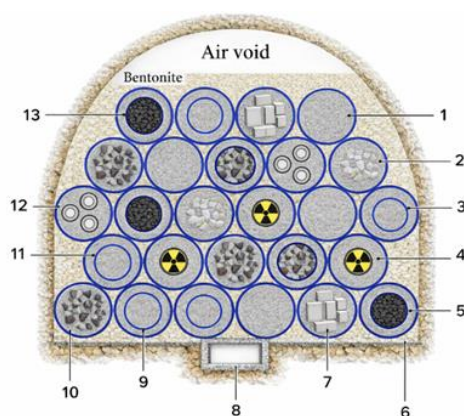


Figure 2. Arrangement of containers in rock excavated galleries:

1 - ash/sludges concentrated in a concrete matrix; 2 - contaminated and activated metals in a concrete matrix; 3 - 60-liter drum made of mild steel; 4 - sealed sources in steel/stainless steel containers; 5 - 220-liter drum made of mild steel; 6 - concrete base; 7 - graphite thermal columns in a concrete matrix; 8 - concrete drainage; 9 - 100-liter drum made of mild steel; 10 - plastics, glass waste, rubber, metals, ash, and ballast, lightly compacted, in a concrete matrix; 11 - 80-liter drum made of mild steel; 12 - liquid waste in glass/plastic bottles with absorbent powder; 13 - spent ion exchange resins, bituminized.

This configuration illustrates the spatial distribution of the containers, the presence of concrete matrices and the integration of isolation materials designed to ensure isolation and mechanical stability.

A comparative analysis was carried out regarding the long-term implications of material degradation on performance, geomechanically interactions between the host rock, the constructed barriers and the potential influence of hydrogeological variability on the effectiveness of the isolation [13, 14]. Particular emphasis is placed on the distinction between the passive safety principles inherent in deep geological repositories and the active monitoring and maintenance capabilities incorporated in the modular repository concept. This additional perspective allows for a more comprehensive assessment of the resilience, adaptability and risk mitigation potential, both under expected operational conditions and in low probability disruptive scenarios.

The overall spatial organization of the underground facility, including the main gallery and cross galleries, is shown in Figure 3. This layout ensures both accessibility for operational activities and structural continuity within the underground excavation.



Figure 3. Main gallery and cross gallery for storage

Operational flexibility has been achieved by means of a phased storage strategy. As illustrated in Figure 4, individual sections are filled progressively and can be closed independently once maximum capacity is reached.

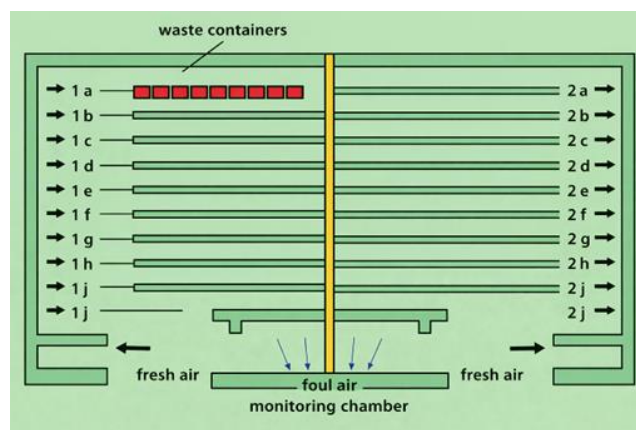


Figure 4. Waste storage plan diagram

The storage process starts in section 1a and is carried out over time, and once section 1j is filled, section 1a will no longer pose a hazard. This approach allows early

compartments to undergo radioactive decay processes while later sections remain operational, thus introducing a temporal dimension to safety management. The final configuration of the storage deposit and the covering soil mass is shown in Figure 5. The overburden load generated by this soil mass was taken into account in the structural modeling phase in order to simulate realistic long-term loading conditions.

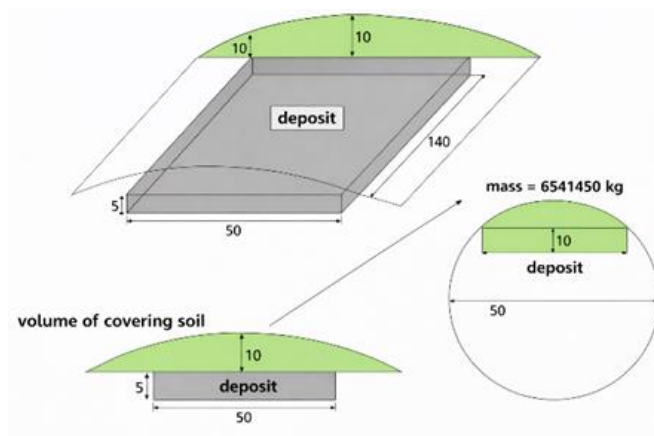


Figure 5. The waste deposit and covering soil mass

At the level of each storage section, the waste containers are separated from structural walls by a multilayer isolation system. The configuration of this barrier system is illustrated in Figure 6.

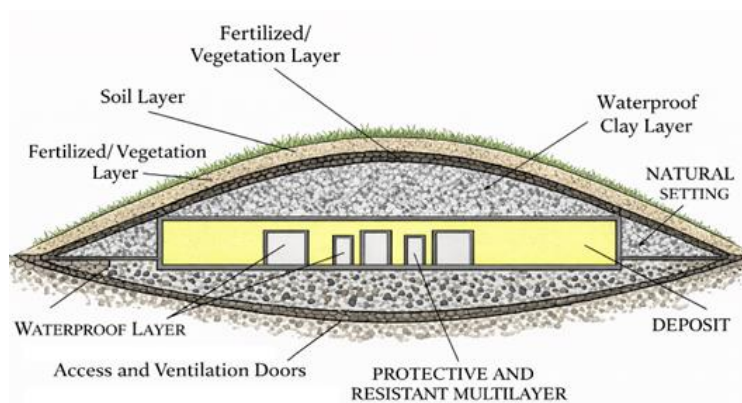


Figure 6. Deposit isolation

The system may include engineered matrices, drainage layers, and clay-based materials selected according to radiological and hydrogeological requirements.

A detailed sectional representation of the storage compartment, including filling materials such as bentonite, clay, and other engineered media, is provided in Figure 7. These materials serve both as chemical retention barriers and as waterproofing elements, limiting the migration of aqueous solutions.

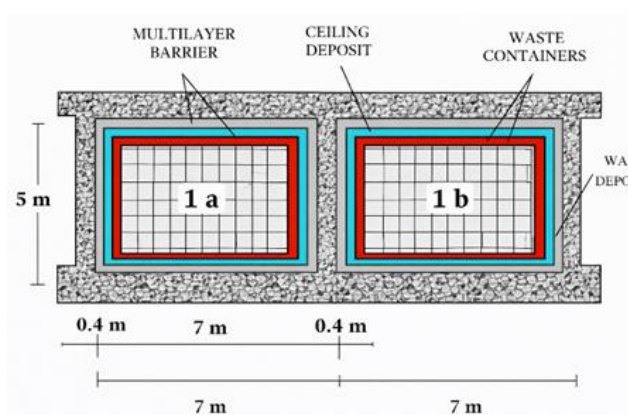


Figure 7. Section in the storage section

The mechanisms for isolating and securing individual storage sections are presented in Figure 8.

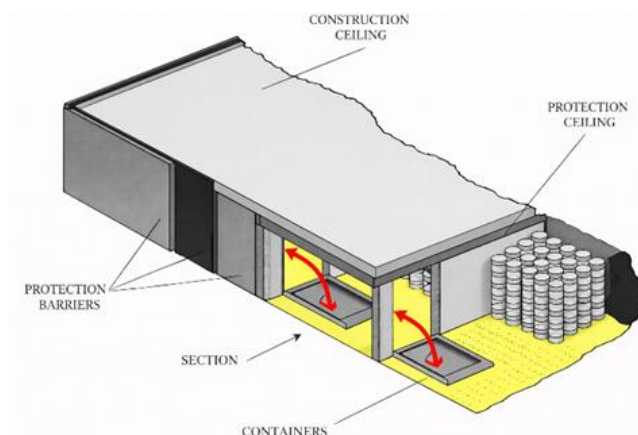


Figure 8. Securing the storage sections

The design allows manual or automated closure in case of detected anomalies, enabling controlled containment of potential incidents and reducing systemic risk within the facility.

To evaluate structural feasibility, a three-dimensional model of the storage facility was developed using Solid Edge software. The model incorporated the structural walls, sectional partitions, and the estimated overburden load corresponding to the final soil covering configuration illustrated in Figure 5.

Finite element analysis was performed using COSMOS DesignSTAR in order to simulate stress distribution and structural displacement under long-term loading conditions [15, 16]. The modeling procedure included discretization of structural elements, application of gravitational forces and external loads, and identification of stress concentration zones. The simulations were conducted to determine the optimal wall thickness required to ensure structural stability. The analysis focused on evaluating whether deformation and stress values remained within admissible mechanical limits, thereby confirming the structural viability of the proposed engineered storage concept under realistic operational conditions.

RESULTS AND DISCUSSION

Finite element analysis was conducted to evaluate the mechanical behavior of the proposed modular underground storage facility under long-term loading conditions generated by the overburden soil mass.

The discretized finite element model used for structural simulation is shown in Figure 9.



Figure 9. Deposit discretization

The model included the structural walls, sectional partitions, and the estimated covering load corresponding to the final deposit configuration.

The applied load conditions and boundary constraints used in the simulation are presented in Figure 10. Gravitational forces and distributed overburden pressure were applied to replicate realistic long-term operational conditions.

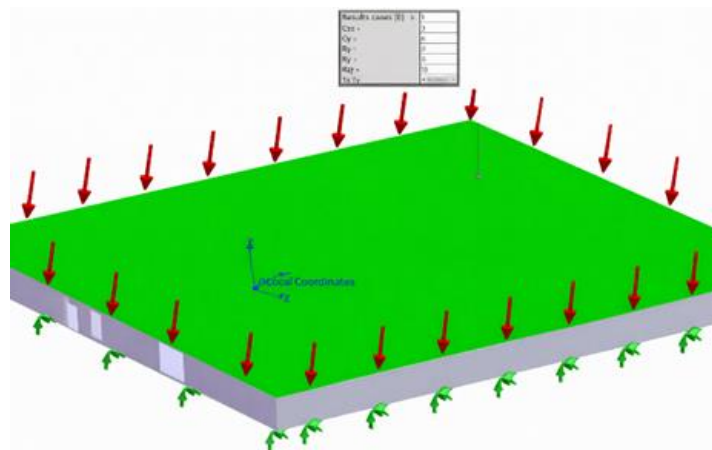


Figure 10. Applying forces

The resulting stress distribution is illustrated in Figure 11, which highlights maximum and minimum stress concentration zones within the structure. The analysis indicated that stress values remain within admissible mechanical limits for reinforced concrete structures under comparable loading scenarios. No critical overstress regions were identified that would compromise long-term structural integrity.

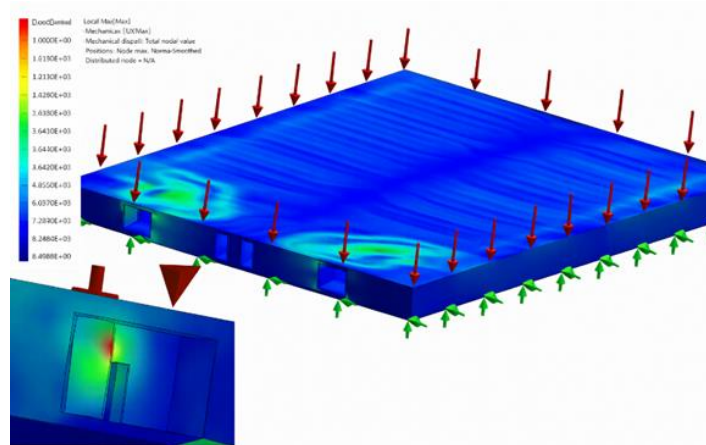


Figure 11. Maximum and minimum strength points

Structural displacement results are shown in Figure 12.

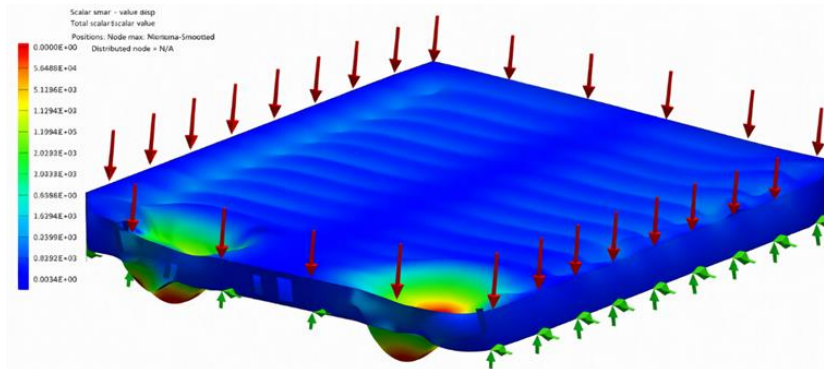


Figure 12. Displacement simulation

The simulation confirmed that deformations remain within acceptable limits, with no excessive displacement observed in the inner or outer walls. Based on the modeling results, an inner wall thickness of 40 cm and an outer wall thickness of 80 cm were determined to provide adequate structural stability under the simulated loading conditions.

These findings demonstrate that the engineered storage concept is mechanically feasible and capable of maintaining structural integrity over extended operational periods.

The evaluation of geological disposal focused on the applicability of minimum sitting criteria related to depth, tectonic stability, permeability, and seismic exposure. Two representative geological scenarios were considered in the assessment: hard rock formations and soft clay-based formations. The conceptual cross-sections of the repository tunnels corresponding to these two geological environments are illustrated in Figure 13. The hard rock configuration emphasizes structural excavation stability, while the clay-based configuration relies primarily on low permeability and self-sealing properties for containment performance.

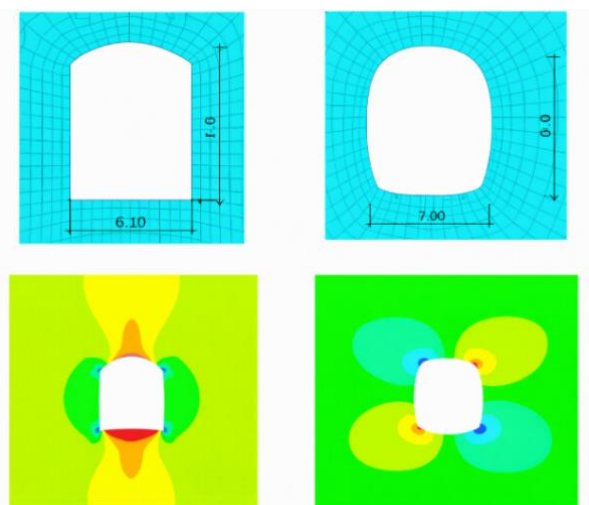


Figure 13. Sections of the burned fuel storage tunnels:
a) hard rocks b) soft rocks (clays)

The analysis indicated that geological disposal performance is strongly dependent on the long-term stability of the host formation. In hard rock environments, structural stability may be high but fissuring and groundwater pathways remain potential concerns. In soft clay formations, low permeability is advantageous; however, long-term mechanical behavior and potential consolidation effects must be considered [17 – 20].

Unlike the engineered storage concept, geological disposal relies primarily on passive natural barriers. Consequently, once waste is emplaced, intervention possibilities are significantly limited [21].

A qualitative comparative risk analysis was performed to evaluate the primary risk categories associated with each disposal strategy.

The principal risk factors identified for geological disposal are illustrated in Figure 14.

		General geological conditions	Hydrogeological	Seismic	Mining	Hydroelectric project	Land use	Transport distance	Distance to inhabited areas	The effect on the population	The effect on the environment
Impact	Very High	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
	High	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	Medium	Light Green	Light Green	Light Green	Light Green	Light Green	Light Green	Light Green	Light Green	Light Green	Light Green
	Low	Dark Green	Dark Green	Dark Green	Dark Green	Dark Green	Dark Green	Dark Green	Dark Green	Dark Green	Dark Green
	Very Low	Very Dark Green	Very Dark Green	Very Dark Green	Very Dark Green	Very Dark Green	Very Dark Green	Very Dark Green	Very Dark Green	Very Dark Green	Very Dark Green
		Very Low	Low	Medium	High	Very High					
		Probability									

Figure 14. Risk analysis for a geological deposit

These include long-term geological evolution, seismic uncertainty, hydrogeological variability, and irreversibility of waste emplacement. Although operational risks after closure are reduced due to passive isolation, the inability to intervene in case of unforeseen geological changes represents a significant long-term uncertainty.

The risk distribution for the purpose-built storage facility is presented in Figure 15.

		General geological conditions	Hydrogeological	Seismic	Mining	Hydroelectric project	Land use	Transport distance	Distance to inhabited areas	The effect on the population	The effect on the environment
Impact	Very High										
	Hight										
	Medium										
	Low										
	Very Low										
		Very Low		Low		Medium		Hight		Very Hight	
		Probability									

Figure 15. Risk analysis for a purpose-built warehouse

In this case, operational risks related to maintenance, human intervention, and long-term institutional control are more pronounced. However, the design allows retrievability, sectional isolation, and continuous monitoring, thereby reducing systemic uncertainty and enabling corrective actions if necessary.

The risk matrices presented in Figures 14 and 15 were developed by systematically identifying the main environmental, geological, and operational factors that may influence the performance of both geological and engineered storage systems. Each risk factor was qualitatively assessed based on two criteria: probability of occurrence and potential damage severity. These criteria were defined using relative scales (low, medium, high), allowing the positioning of each risk within the matrix. This approach was adopted to provide a comparative and conceptual evaluation of risk distribution between the two storage strategies.

In this study, the term “impact” is defined as the severity of environmental damage associated with each identified risk factor. The impact scale reflects the potential consequences on the environment and system performance, ranging from low or negligible effects to severe environmental damage, as illustrated by the color gradient within the risk matrix.

The comparative analysis indicates that geological disposal minimizes operational dependence but increases long-term irreversibility. In contrast, the engineered modular storage concept introduces higher management responsibility but provides enhanced controllability and adaptability.

CONCLUSIONS

This study comparatively evaluated deep geological disposal and a purpose-built modular underground storage facility by integrating structural finite element modeling with qualitative risk analysis. The objective was to assess not only long-term containment principles, but also structural reliability, operational flexibility, and controllability as safety parameters.

The finite element simulations confirmed that the proposed engineered storage configuration is mechanically stable under long-term loading generated by the covering soil mass. The calculated optimal structural dimensions, namely an inner wall thickness of 40 cm and an outer wall thickness of 80 cm, ensure admissible stress distribution and limited displacement values. No critical stress concentrations or excessive deformation zones were identified, indicating that the modular design can maintain structural integrity under realistic operational conditions.

From a functional perspective, the sectional configuration introduces an additional safety layer by allowing phased emplacement, independent closure of compartments, and localized intervention in case of anomalies. This reduces systemic risk propagation within the facility and enhances accident containment capacity compared to monolithic underground repositories.

The comparative geological assessment highlighted that deep geological disposal relies predominantly on the passive performance of natural barriers. While this approach offers reduced operational dependency after closure, it involves significant irreversibility and dependence on long-term geological stability, including seismic evolution and hydrogeological variability. In contrast, the engineered storage facility shifts the safety paradigm toward anthropogenic control, emphasizing monitoring systems, accessibility, and retrievability.

The risk analysis demonstrated that geological disposal minimizes post-closure operational risks but increases uncertainty associated with long-term natural processes. Conversely, the purpose-built facility entails higher requirements for institutional continuity and maintenance, yet provides improved controllability, adaptability, and the possibility of corrective actions over time.

An important outcome of this research is the recognition that long-term safety cannot be evaluated exclusively through passive geological stability. Structural reliability, intervention capability, and monitoring feasibility must also be treated as critical safety parameters. The integration of mechanical modeling with comparative risk assessment represents the principal methodological contribution of this study.

The findings suggest that in regions characterized by geological uncertainty, active tectonics, or the need for enhanced retrievability, a modular engineered underground storage concept may represent a technically viable and strategically flexible alternative to exclusive reliance on deep geological disposal.

Future investigations should include quantitative probabilistic risk assessment, long-term degradation modeling of barrier materials, and integration of advanced monitoring technologies to further strengthen the comparative evaluation framework.

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