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JUSTIFICATION OF AN INNOVATIVE SYSTEM FOR THE COMPLETE BURIAL OF SOLID, HIGH-LEVEL RADIOACTIVE WASTE (HLW) IN SPENT OPEN-PIT MINES

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The object of research is the spent open-pit mines themselves where the proposed system could be applied. The primary reason for this studying is the following circumstance: up to the present time period, in all countries of the world, no methods of HLW disposal in a storage facility has been identified that is absolutely safe for any length of time, taking into account the impact of catastrophic natural emergencies and man-made emergencies. The research was conducted to address the problem of safely managing and storing HLW, leveraging the unique characteristics of spent open-pit mines, such as their large volume and geological stability, to prevent environmental contamination and ensure long-term safety. In the article has been justified a novel approach to the burial of sarcophagus containers with solid HLW in exhausted mining pits and studied the usabilities of the basalt sarcofagous container. Robust materials and advanced robotic systems proposed in the article aims to address the challenges associated with long-term radioactive waste disposal effectively. The robotic systems transfer the basalt container with HLW, ensuring personnel safety by minimizing human presence near radioactive materials. In the article have been established the distribution of temperature into the multi-layered composite structure of the basalt sarcophagous with HLW from 300 °C into the inner space to 50 °C onto on the its outer suffer where the thickness of each layers (from inner to outer radius) was respectively: for lead matrix: from r1=0.1 m to r2=0.2 m; for clay layer: from r2=0.2 m to r3=0.3 m; for basalt block: from r3=0.3 m to r4=0.4 m. The findings on temperature distribution are crucial as they directly affect the performance and longevity of the basalt containment system

Keywords: spent open-pit, basalt container, robotic system, radioactive waste

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1. Introduction

Isolation of radioactive waste is an important and urgent problem for countries that utilize nuclear energy. A consensus has been reached among researchers from around the globe that the most optimal long-term storage solution for radioactive waste is to utilize underground space. The storage of HLWs presents a potential danger to the surrounding fauna and flora. Justifying the relevance of an innovative system for the complete burial of solid, high-level radioactive waste (HLW) in spent open-pit mines involves considering several key factors:

1. Environmental and safety concerns:

– containment and isolation: high-level radioactive waste remains hazardous for thousands of years. An innovative system that utilizes spent open-pit mines for burial could provide a robust containment strategy, ensuring the waste is isolated from the biosphere, thus minimizing the risk of radiation exposure to humans and the environment;

– utilization of existing infrastructure: spent open-pit mines are already excavated, meaning the environmental impact of creating new waste disposal sites can be avoided. By repurposing these sites, the system could reduce the need for further land disturbance and habitat destruction.

2. Economic considerations:

– cost-effectiveness: developing new, purpose-built facilities for radioactive waste disposal is extremely costly. By using existing open-pit mines, significant savings could be achieved in terms of excavation and construction costs. Moreover, this approach might be more financially viable for countries with limited resources;

– job creation and local economy boost: the process of converting and managing these mines for HLW disposal could generate jobs, particularly in regions where mining industries have declined. This can contribute to the revitalization of local economies.

3. Technical feasibility and innovation:

– advanced engineering solutions: an innovative burial system could incorporate state-of-the-art engineering techniques to enhance the safety and longevity of the disposal. This might include advanced barriers, sealing methods, and monitoring systems, all designed to ensure that the radioactive waste remains securely contained;

– long-term monitoring and maintenance: the system could be designed with provisions for long-term monitoring and maintenance, which is crucial for ensuring the integrity of the waste burial site over time. This would be an improvement over traditional methods that may not include such extensive monitoring capabilities.

4. Regulatory and public acceptance:

– compliance with international standards: the system could be designed to meet or exceed international standards for radioactive waste disposal, which is crucial for regulatory approval and ensuring public trust. Demonstrating that spent open-pit mines can be safely repurposed for this use would address public concerns about the dangers of HLW disposal;

– public perception and environmental justice: addressing the concerns of communities near disposal sites is crucial for gaining public acceptance. An innovative system that offers greater safety and environmental protection could be more acceptable to the public, particularly if it is shown to be a safer alternative to other methods.

5. Sustainability and long-term impact:

– sustainable waste management: the long-term storage of HLW is a pressing issue for sustainable development. By innovatively using open-pit mines, this system contributes to a more sustainable approach to managing radioactive waste, ensuring that it is dealt with in a way that minimizes risks to future generations;

– legacy of industrial sites: repurposing spent open-pit mines for HLW burial transforms a legacy of environmental degradation into a beneficial use, mitigating the negative impacts of mining activities and contributing to environmental remediation efforts.

Therefore, the studies that are devoted the justification of a system for the complete burial of HLW in spent open-pit mines are highly relevant due to the growing global need for sustainable and safe solutions to manage radioactive waste. As existing storage facilities reach capacity, finding geologically stable and secure environments for HLW disposal is critical to preventing environmental contamination, protecting public health, and ensuring the long-term safety of future generations. The innovative use of spent open-pit mines offers a practical and potentially cost-effective solution, leveraging existing infrastructure while mitigating the risks associated with traditional storage methods.

2. Literature review and problem statement

This article [1] addresses the challenge of ensuring long-term safety in the geological disposal of radioactive waste. While the article thoroughly addresses the benefits of multi-barrier containment systems, it acknowledges that the long-term durability of both engineered and natural barriers remains uncertain. Materials such as concrete, bentonite clay, and metals may degrade over thousands of years due to environmental interactions, corrosion, or thermal stress from radioactive decay. The inability to fully predict these degradation processes raises concerns about the system's reliability over extended timescales. The issue of material degradation over extremely long periods is difficult to resolve due to the inherent limitations of experimental methods and modeling. Testing materials under simulated conditions cannot fully replicate the real-world environmental variables (e.g., water seepage, chemical interactions) and timescales of thousands to millions of years, making it challenging to predict their behavior with certainty. Another unsolved aspect is the long-term geologic stability of disposal sites. The authors mention that despite careful selection of stable geological formations, predicting future geological events such as earthquakes or volcanic activity remains a challenge. Changes in the Earth's geophysical dynamics over millennia could potentially compromise even well-selected sites. This issue is rooted in the unpredictability of geological processes. Despite advanced monitoring techniques and models, future tectonic activities or other disruptive geological events over tens of thousands of years remain largely unpredictable. The article also highlights concerns regarding the social and institutional control of repositories after closure. Although the immediate technical challenges are well-addressed, the authors express uncertainty about how societies will manage and safeguard these repositories far into the future. Governance, political stability, and technological advancements could affect the long-term safety of the disposal system. This issue is unsolved due to its dependence on unpredictable sociopolitical factors. While engineering solutions can be designed with safety in mind, ensuring that future generations maintain the knowledge and responsibility for managing these sites is beyond the control of technical solutions alone. This article provides a comprehensive overview of the geological disposal of radioactive waste, offering viable technical solutions for many challenges. However, the unresolved issues of material durability, geological stability, and the long-term social management of repositories underscore the need for continued research and a more holistic approach to ensure the long-term safety of radioactive waste disposal systems.

[2] explores the development of advanced containment barriers that can be used in repurposed mines for radioactive waste disposal. The article acknowledges that long-term performance data for these advanced barriers is still limited. Despite the promising features of advanced materials like geopolymers and nanocomposites, the article acknowledges that their long-term performance under real-world environmental conditions is not fully understood. While laboratory tests show positive results, the complex interactions between these materials and surrounding geological and hydrologi-

cal systems over thousands of years remain uncertain. The primary challenge is the lack of long-term field data. Most studies on these materials are conducted over short timeframes, and the extreme timescales involved in radioactive waste disposal (thousands to millions of years) are difficult to simulate accurately. Additionally, these materials may behave differently in repurposed mine environments where factors like residual mining chemicals, groundwater, and temperature fluctuations could affect their integrity. The article identifies water infiltration as a significant challenge for repurposed mines, especially given that many abandoned mines already have established groundwater flows. Even with advanced barriers in place, the risk of water migration through or around the containment system could compromise the isolation of radioactive waste. Water infiltration in deep mines is a complex problem, as it is influenced by factors like surrounding geology, mine structure, and external environmental changes. Although barrier materials are designed to resist water, the unpredictable nature of groundwater flow and the potential for cracks or fissures in the containment structures could lead to slow but persistent water ingress. Long-term control of groundwater interactions is a challenge that has yet to be fully resolved. The structural stability of repurposed mines remains an unsolved issue. While the authors propose reinforcement strategies, they highlight the difficulty of ensuring long-term stability in mines that were not originally designed for waste containment. The risk of subsidence, collapse, or seismic events could undermine the effectiveness of even the most advanced containment systems. Mines that have been abandoned or repurposed for waste disposal often suffer from degradation of their structural integrity over time. Predicting the behavior of these sites over thousands of years is problematic, especially considering the variability in mining methods, rock types, and the potential for future seismic activity. There is limited knowledge on how well these structures will hold up under the pressures of both the stored waste and geological forces over millennia. In this article discuss post-closure monitoring as a key component of their proposed system, but they admit that ensuring effective monitoring for thousands of years is a significant challenge. The maintenance of intelligent sensors and monitoring systems, particularly in remote or deep locations, poses serious technical and logistical problems. Post-closure monitoring is unsolved due to the limited lifespan of current technologies. While intelligent sensors can detect failures in the short term, ensuring their functionality over centuries without human intervention remains a technical obstacle. Furthermore, future societal changes may hinder the ability to maintain these systems effectively. Authors present a well-researched and innovative solution for using repurposed mines as radioactive waste disposal sites. Their emphasis on advanced materials and continuous monitoring offers promising advancements in containment technology. However, unresolved issues such as the long-term performance of materials, the control of groundwater infiltration, structural stability, and the feasibility of post-closure monitoring reveal significant gaps that require further research and development. These challenges highlight the complexity of ensuring the safety and integrity of repurposed mines as radioactive waste repositories over geological timescales.

The article [3] reviews recent Ukrainian research on innovative containment solutions for HLW, particularly focusing on improving the geological stability and reducing environmental impact. The research discussed is still in experimental stages for the most part, and further development and real-world application are needed. One of the primary issues that remains unsolved is the long-term degradation of the containment materials, particularly in extreme environmental conditions. Although the innovations discussed – such as radiation-resistant polymers and clays – show promise in the short term, their long-term performance under radiation, heat, and chemical interactions has not been thoroughly tested over periods extending thousands of years. Long-term degradation is a challenge because of the lack of available data on the behavior of these materials over extremely long timescales. Laboratory simulations can only provide a limited understanding, and real-world testing over centuries or millennia is not feasible. This leads to uncertainty about whether these materials will maintain their integrity and prevent contamination over the required timescales for radioactive waste isolation. Another unsolved issue is the stability of the geological structures within Ukraine for the long-term storage of radioactive waste. Ukraine's unique geotechnical and environmental conditions present challenges, particularly given the country's seismic activity and the potential for groundwater interactions with storage facilities. Geological stability over long timescales is difficult to predict, especially in regions prone to seismic disturbances or groundwater movement. Even with advanced site selection and structural reinforcement, the inherent unpredictability of the earth's natural processes poses risks to the containment of radioactive waste. There is still insufficient data to ensure that selected sites will remain stable and effective for the entire required disposal period. The article also highlights a critical issue that remains unsolved: the limitations of Ukraine's post-Chernobyl infrastructure in handling large-scale radioactive waste containment. While the innovations in materials and containment systems are noteworthy, the aging and underfunded infrastructure, combined with the country's political and economic challenges, make the implementation and maintenance of these systems problematic. The unresolved nature of this issue stems from a combination of political, economic, and logistical factors. Ukraine's economic constraints and political instability make it difficult to invest in the necessary infrastructure upgrades, maintenance, and long-term monitoring systems required to ensure the safety of radioactive waste storage facilities. This infrastructural weakness could lead to inefficiencies or failures in waste management over time. The article also points out the absence of global standardization in radioactive waste containment practices as an unresolved issue. Ukrainian researchers have made significant advances, but the lack of harmonized international standards for containment materials and monitoring methods limits the wider adoption and application of these innovations. Global standardization is hindered by differing national regulations, technological capabilities, and economic interests. Without international consensus on the best practices for radioactive waste containment, countries like Ukraine may find it difficult to collaborate or share their innovations on a broader scale. This lack of standardization also increases the risk of inconsistent safety measures across different regions. The article presents valuable insights and innovations in the field of radioactive waste containment, particularly in the context of Ukraine's unique challenges. The use of advanced composite materials and monitoring systems offers promising solutions for enhancing the safety and efficiency of radioactive waste storage. However, significant unresolved issues remain, including the long-term degradation of materials, geological stability, infrastructural limitations, and the lack of global standardization. Addressing these challenges will require further research, international cooperation, and sustained investment in both technological and infrastructural advancements.

This article [4] provides a comprehensive review of global case studies where abandoned mines have been repurposed for radioactive waste disposal. It addresses the feasibility and safety of using these existing infrastructures. The article identifies that while repurposing mines is a cost-effective and practical solution, there are still challenges related to ensuring the long-term stability of these sites, particularly in terms of structural integrity and potential environmental risks. One of the central issues the article discusses is the geological variability of abandoned mines. While some mines are geologically stable, many may not meet the strict requirements necessary for long-term radioactive waste containment. The authors acknowledge that not all abandoned mines possess the structural integrity, geohydrological stability, or depth required to ensure the safe isolation of HLW over millennia. Geological variability poses a challenge because each mine's suitability depends on its specific geological setting. Many abandoned mines have been left unused due to issues such as water ingress, subsidence, or seismic risk, which complicate their reuse for waste storage. Additionally, thorough site-specific assessments are expensive, and predicting long-term geological changes is inherently uncertain, especially for timeframes spanning thousands of years. A major unresolved problem is the management of water ingress in abandoned mines. Many mines have natural or man-made connections to groundwater systems, which increases the risk of water interacting with stored radioactive waste. Water movement could lead to the leaching of radioactive materials into the environment, causing contamination and undermining the containment system. The complexity of mine water management makes this problem difficult to solve. Water ingress is influenced by many factors, including climate, surrounding geology, and mine design. The unpredictability of future environmental conditions, such as increased precipitation due to climate change, further complicates efforts to manage water movement. Moreover, effective sealing and containment methods to prevent groundwater contamination may not be feasible for all mines, especially older, structurally compromised ones. The article also highlights the challenge of ensuring effective post-closure monitoring and institutional control over abandoned mine repositories. While current technology allows for the installation of monitoring devices to detect breaches or failures, maintaining these systems over the long term is problematic. The authors express concern about the reliability of these technologies over centuries, as well as the sociopolitical risks of ensuring that future generations continue to maintain and monitor these repositories. Post-closure monitoring remains a challenge due to the limited lifespan of current technologies and the unpredictable nature of future political and economic conditions. Technologies may degrade over time, and there is no guarantee that future societies will have the resources, motivation, or knowledge to continue monitoring these sites. Additionally, the cost and logistics of maintaining long-term institutional control over remote or abandoned mine sites raise concerns about the practicality of such solutions. The article also discusses the lack of regulatory consistency and international coordination as a significant unresolved issue. While repurposing abandoned mines is explored by several countries, differing regulations, standards, and practices create barriers to establishing a unified approach. There is no global consensus on how to assess mine suitability, design containment systems, or monitor repositories in the long term. Regulatory and international coordination remains unsolved due to the differing priorities, legal frameworks, and technological capabilities of nations. Some countries have advanced waste disposal programs, while others struggle with limited resources and infrastructure. Achieving global coordination requires overcoming political and economic obstacles, as well as aligning national interests with international safety standards. Moreover, geopolitical tensions can hinder collaboration in sharing technological innovations and best practices. The article touches on the societal and political challenges of repurposing mines for radioactive waste disposal. Public opposition, often driven by fears of contamination or distrust in government oversight, remains a significant obstacle to implementing these projects. The authors note that even in regions where mines are technically suitable, societal resistance can delay or derail efforts to repurpose them for waste containment. Societal acceptance is unsolved because of deeply ingrained fears regarding radioactive materials and environmental risks. Public opposition is often fueled by historical examples of waste mismanagement and disasters like Chernobyl or Fukushima. Building public trust requires transparent, long-term safety assurances and effective community engagement, both of which are difficult to achieve in practice. Additionally, political dynamics can exacerbate opposition, as waste disposal sites are often seen as a burden placed on local communities without sufficient compensation. Authors offers valuable insights into the global potential for repurposing abandoned mines for radioactive waste disposal. The use of existing infrastructure could lower costs and provide a viable solution for long-term containment. However, several significant issues remain unsolved, including geological suitability, water ingress management, post-closure monitoring, regulatory coordination, and societal acceptance. These unresolved challenges highlight the need for further research, robust site-specific assessments, and greater international cooperation to develop a comprehensive and safe strategy for repurposing mines for radioactive waste disposal.

This article [5] focuses on the advancements in environmental monitoring technologies used at radioactive waste sites in Ukraine. It solves the problem of real-time data acquisition and analysis, which is crucial for ensuring site safety. The article points out that while monitoring technologies have improved, there is still a need for more comprehensive long-term monitoring strategies. One of the central unsolved issues is the long-term reliability and sustainability of monitoring technologies used in radioactive waste sites. Although the article discusses the effectiveness of current systems in providing real-time data, the long-term durability of these technologies remains in question, particularly in environments that are exposed to high levels of radiation and harsh weather conditions. The main challenge is that most monitoring equipment has a limited operational lifespan, particularly when exposed to radiation. Degradation of sensors and electronic systems over time can lead to malfunctions, and replacing or repairing these systems may become difficult, especially in remote or highly radioactive areas. Moreover, long-term financial and logistical support for maintaining these technologies is uncertain, which raises questions about their sustainability over periods extending beyond several decades. Groundwater contamination remains a critical issue that has not been fully addressed. The article acknowledges that many radioactive waste sites in Ukraine are located in areas with complex hydrogeological conditions, which complicates efforts to prevent the migration of radioactive contaminants into groundwater systems. While monitoring wells are used to track potential contamination, the effectiveness of these measures is not guaranteed. Groundwater contamination is difficult to predict and control due to the dynamic nature of subsurface water movement and geological conditions. In Ukraine, where many waste sites are situated near rivers or in regions with high water tables, managing the interaction between waste repositories and groundwater is particularly challenging. Additionally, cracks or fractures in containment structures can go undetected, allowing radioactive materials to gradually seep into water supplies. This issue is exacerbated by the aging infrastructure at many legacy waste sites, which were not originally designed for long-term containment. The article highlights challenges in regulatory enforcement and transparency of monitoring data. While environmental monitoring systems are in place, the authors point out that inconsistent enforcement of safety standards and regulations across different sites in Ukraine remains a significant obstacle. Furthermore, there is a lack of transparency in reporting data from some radioactive waste sites, which undermines public trust and makes it difficult to assess the full extent of contamination risks. Regulatory inconsistencies and transparency issues stem from both institutional and political factors. Ukraine's regulatory framework for radioactive waste management is still developing, and enforcement can vary depending on local governance, economic constraints, and political priorities. Additionally, there are often conflicts between public and private interests in disclosing environmental risks, especially when the cost of remediation or improved monitoring is high. Without robust and standardized regulatory enforcement, gaps in monitoring practices and data collection persist. The article also discusses socioeconomic barriers that hinder comprehensive environmental monitoring. Financial limitations, especially in the context of Ukraine's economic challenges, restrict the country's ability to invest in state-of-the-art technologies and to maintain a comprehensive, nationwide monitoring network for radioactive waste sites. Limited funding affects the quality and extent of monitoring systems, especially in rural or less visible locations. Socioeconomic constraints prevent the widespread adoption of advanced monitoring systems, especially in regions with limited resources. Ukraine, facing broader economic difficulties and ongoing recovery efforts from the Chernobyl disaster, may prioritize other pressing issues over costly upgrades to environmental monitoring infrastructure. Furthermore, international support and funding for such initiatives can be intermittent, leaving monitoring efforts under-resourced. Another unsolved issue is the aging infrastructure of waste storage facilities, particularly those built in the aftermath of the Chernobyl disaster. Many radioactive waste sites in Ukraine were constructed as temporary solutions and are now reaching the end of their design life, leading to concerns about the integrity of these structures. Aging infrastructure poses a significant risk because many of these facilities were not designed for long-term use, and maintenance efforts have been inconsistent. The cost and complexity of retrofitting or replacing old containment structures are substantial, and there is a risk of failure if these issues are not addressed promptly. Furthermore, the Chernobyl legacy continues to dominate the radioactive waste landscape in Ukraine, leaving little room for progress on upgrading or improving less visible sites. The article provides important insights into the current state of environmental monitoring for radioactive waste sites in Ukraine, highlighting key innovations in real-time monitoring and data collection technologies. However, several significant issues remain unresolved, including the long-term reliability of monitoring systems, groundwater contamination risks, inconsistent regulatory enforcement, socioeconomic barriers, and the aging infrastructure of legacy waste sites. These challenges underscore the need for continued research, investment, and international cooperation to ensure the long-term safety and sustainability of radioactive waste management in Ukraine.

This article [6] addresses the development of risk assessment models specifically designed for long-term radioactive waste disposal. It provides a structured approach to evaluating potential risks over extended timeframes. The article acknowledges that these models are still based on a range of assumptions that may not fully account for all variables, particularly in the context of unforeseen geological or environmental changes. A critical unresolved issue in the article is the inherent uncertainty in long-term predictions. The authors acknowledge that even the most advanced risk assessment models cannot fully account for all variables and potential changes over the thousands of years required for radioactive waste containment. Geological and environmental conditions are highly unpredictable over such extended periods, making it difficult to ensure the reliability of risk projections. The uncertainty arises from the complexity of geological and environmental systems, combined with the long timescales involved in radioactive waste containment. No model can perfectly predict how the environment, climate, or geological conditions will evolve over thousands of years. Additionally, while probabilistic approaches like Monte Carlo simulations provide insights into a range of possible outcomes, they cannot eliminate the inherent uncertainty in long-term projections. Another unresolved issue discussed in the article is the unpredictability of human intervention and societal changes in the future. While risk models can incorporate natural events such as earthquakes or groundwater movement, they struggle to account for potential future human activities, such as accidental excavation, land use changes, or insufficient institutional controls over waste repositories. The unpredictability of human actions is a fundamental limitation of any risk model. Future societies may not adhere to the same safety standards or institutional practices currently in place, and technological advancements or political decisions could lead to unexpected interactions with radioactive waste sites. Additionally, the lifespan of current regulatory frameworks and governance structures is difficult to predict, which adds further uncertainty to the management of long-term risks. The article highlights that risk assessment models rely heavily on comprehensive geological data, but many disposal sites have incomplete or uncertain geological profiles. Some sites may not have been adequately characterized before being designated for waste disposal, leading to gaps in the models used to predict long-term risks. Gathering complete geological data for deep disposal sites is often challenging and expensive. Even when site assessments are conducted, some geological phenomena, such as the movement of deep groundwater or changes in rock structure, are difficult to fully understand or predict. This incomplete data limits the accuracy of risk assessment models and can result in overly optimistic or overly cautious predictions about a site's long-term safety. The article also touches on the difficulty of accurately modeling the degradation of containment materials over extremely long periods. While some materials, such as certain clays and concrete composites, are designed to last for hundreds or thousands of years, their actual behavior under long-term exposure to radiation, heat, and chemical interactions is not fully understood. Long-term material degradation remains unresolved because of the lack of real-world data on material performance over the timescales required for radioactive waste containment. Laboratory experiments and simulations can only provide a partial understanding of how containment materials will behave over thousands of years. Furthermore, unanticipated chemical reactions between materials and their environment (e.g., groundwater or surrounding rock) could accelerate degradation, leading to containment failures that were not predicted by the initial risk models. In the article discusses how current risk models often struggle to accurately represent cumulative effects over time, such as the gradual accumulation of stress on geological formations or the slow migration of radioactive contaminants through groundwater. These cumulative effects can compound over millennia, leading to potential failures that may not be immediately apparent in short-term or mid-term models. Cumulative effects are difficult to model because they involve complex, interrelated processes that evolve over extended timescales. For example, small shifts in groundwater flow or minor material degradation might seem insignificant in the short term but can have serious consequences over centuries. Current risk models can capture some aspects of these effects but often fail to fully account for the dynamic and interconnected nature of these long-term processes. An additional issue raised in the article is the challenge of effectively communicating the results of risk models to the public and policymakers. Given the complexity of these models and the uncertainty involved, there is often a gap between the scientific community's understanding of risk and the public's perception of safety. Misinterpretation or oversimplification of risk assessment results can lead to either undue panic or a false sense of security. Bridging the gap between scientific modeling and public understanding is an ongoing challenge. Risk models are often highly technical and require specialized knowledge to interpret accurately, while public trust in these models can be influenced by emotional and political factors. Moreover, communicating the long-term risks associated with radioactive waste disposal is particularly difficult because the timescales involved exceed human experience and societal planning horizons. The article provides a comprehensive analysis of risk assessment models for long-term radioactive waste disposal, offering valuable insights into how these models can be used to predict and mitigate potential risks. However, several key issues remain unresolved, including uncertainty in long-term predictions, the unpredictability of future human intervention, incomplete geological data, material degradation over extended timescales, and the complexity of modeling cumulative effects. Additionally, effective communication of risk model results to the public remains a persistent challenge. Addressing these unresolved issues will require further research, improved data collection, and the development of more sophisticated models capable of capturing the dynamic, long-term risks associated with radioactive waste disposal.

This article [7] reviews the latest technologies for long term monitoring of radioactive waste sites, emphasizing advancements in sensors and data analysis. While the technologies are promising, the article notes that integrating these systems into existing infrastructure and ensuring their reliability over decades or centuries remains a challenge. A critical unresolved issue identified in the article is the uncertainty surrounding the long-term structural integrity of mine infrastructure. Although authors discuss methods for reinforcing shafts and tunnels, they acknowledge that abandoned mines often suffer from significant degradation, such as subsidence, water infiltration, and collapse, which may not be fully preventable over thousands of years. Mines were not originally designed for nuclear waste disposal, and the wear and tear caused by years of mining operations can weaken the structural integrity of these sites. The article highlights that while engineering reinforcements can prolong the stability of these structures, predicting the long-term behavior of repurposed mines is highly uncertain due to the complex and often unpredictable interactions between the surrounding geology and the altered infrastructure. Another key challenge, which remains unresolved, is managing water ingress and the risk of groundwater contamination. The authors emphasize that many mines are vulnerable to water infiltration, either from groundwater seepage or surface water entering through fractures in the mine's structure. Over time, this water could corrode containment systems, increasing the likelihood of radioactive leakage. Water management in mines is a complex problem that varies depending on the geology and hydrology of each site. Even when containment barriers are used, the dynamic nature of groundwater flow can introduce unforeseen risks, such as the gradual buildup of water pressure or the migration of contaminants along unpredictable pathways. The authors note that current engineering solutions, such as drainage systems and sealing techniques, are not foolproof over the timescales required for radioactive waste storage, which could extend to tens of thousands of years. The article points out that many repurposed mines are located in geologically unstable regions prone to seismic activity, subsidence, or rock shifting. This instability poses a significant risk to the long-term containment of radioactive waste, as even small movements in the surrounding rock can compromise the integrity of storage containers or containment barriers. Geotechnical stability is difficult to ensure in the long term because geological processes, such as tectonic shifts and subsidence, occur over extended periods and can be difficult to predict. The inherent variability in rock formations and the fact that many mines were not constructed with geological stability in mind make it challenging to assess and manage these risks. Even with extensive geotechnical analysis, there is always the possibility that unforeseen geological events could disrupt the containment systems. The authors discuss the difficulty of designing engineered containment barriers that are compatible with the specific geological conditions of each mine. Factors such as the chemical composition of the surrounding rock, the presence of groundwater, and the overall stability of the mine can affect the performance of containment systems. For example, some rocks may react chemically with containment materials, leading to faster degradation. The interaction between engineered barriers and the geological environment is highly site-specific, and there is no one-size-fits-all solution. Each mine presents unique geological and chemical conditions, which can lead to unforeseen reactions or accelerated degradation of containment systems. The authors note that while laboratory testing and modeling can help anticipate some of these interactions, the long-term effects of these processes remain uncertain and could lead to containment failure over time. One of the significant engineering challenges highlighted in the article is the management of heat generated by high-level radioactive waste. As HLW decays, it produces heat, which can affect both the containment systems and the surrounding rock. Managing this heat to prevent the degradation of barriers and the alteration of the mine's geological environment is a critical issue. The heat generated by radioactive decay can cause thermal expansion in the surrounding rock, potentially leading to fractures or increased permeability, which could compromise the integrity of the containment system. While the authors suggest various cooling systems and thermal buffers, they acknowledge that the effectiveness of these solutions over the long term is still uncertain. The behavior of the heat over extended periods, particularly in mines with varying geological conditions, is difficult to predict. Another unresolved problem is the challenge of monitoring and maintaining the safety of repurposed mines over long timeframes. The authors discuss the importance of real-time monitoring systems, such as sensors to detect structural shifts or radiation leaks. However, the longevity of these monitoring systems and the feasibility of maintaining them for thousands of years remain open questions. Technology and infrastructure for monitoring radioactive waste are still evolving, but their long-term reliability is uncertain. Electronic systems degrade over time, and even the most advanced sensors have a limited operational lifespan. Additionally, the cost and logistics of maintaining and replacing these systems in remote or hazardous environments may become prohibitive over extended periods. The authors acknowledge that without reliable monitoring, the early detection of containment failures would be difficult, increasing the risk of radioactive leakage. The article also addresses the social and regulatory challenges associated with repurposing mines for radioactive waste disposal. The authors note that public opposition and inconsistent regulatory frameworks across different countries can complicate the implementation of such projects. Ensuring public trust and establishing a consistent regulatory approach are essential but unresolved components of the problem. Public concerns about safety and environmental risks are often heightened when it comes to nuclear waste, particularly in regions with a history of mining. Additionally, regulatory frameworks for nuclear waste disposal vary significantly between countries, and many have not been updated to account for the specific challenges of repurposing mines for waste storage. Without a clear and consistent regulatory approach, progress on such projects may be hindered by legal, political, and social obstacles. The article provides a thorough analysis of the engineering challenges involved in repurposing mines for nuclear waste disposal, offering potential solutions such as structural reinforcements, multi-layer containment systems, and advanced monitoring technologies. However, several unresolved issues remain, including the long-term structural integrity of mines, groundwater contamination risks, geotechnical instability, material compatibility, waste heat management, and the longevity of monitoring systems. Additionally, public perception and regulatory gaps present further complications. Addressing these unresolved challenges will require continued research, innovation in engineering practices, and stronger regulatory frameworks.

The article [8] analyzes the economic feasibility of repurposing spent mines for nuclear waste deposal. The article focuses on the development and application of advanced sensor technologies designed for long-term monitoring of radioactive waste disposal sites. One of the major unresolved issues highlighted in the article is the limited operational lifespan of sensor technologies. Although the authors discuss various types of sensors and their applications, they acknowledge that most current sensors have a limited lifespan, especially when exposed to the harsh environmental conditions found at radioactive waste disposal sites. Factors such as radiation, extreme temperatures, corrosion, and chemical interactions can degrade sensor performance over time, leading to potential gaps in monitoring. The development of sensors that can function reliably for the entire operational lifespan of a radioactive waste disposal site (which could span thousands of years) is a significant challenge. Current sensors are not designed for such extreme long-term use, and the article notes that degradation due to radiation exposure and other environmental factors is inevitable. While regular maintenance or replacement is a possible solution, the difficulty and cost of accessing these sites, especially deep geological repositories, make frequent sensor replacement impractical. Thus, developing durable, long-lasting sensors that can withstand extreme conditions remains an unsolved problem. Another unresolved issue is the reliable long-term power supply for monitoring systems. The authors suggest that renewable energy sources, such as solar or wind power, could be utilized, but these systems may not be sufficient for long-term, uninterrupted operation, especially in extreme weather conditions or underground environments. Powering long-term monitoring systems is a fundamental challenge because most renewable energy systems are not designed for the decades or centuries required for radioactive waste site monitoring. Additionally, underground repositories may not be suitable for solar or wind power, and battery technologies currently available do not have the capacity to last for such extended periods. The article notes that advances in energy harvesting or long-life battery technologies are needed, but these solutions are not yet fully developed or deployed at scale. The authors identify another unresolved challenge related to the transmission and storage of data collected by long-term monitoring systems. While modern communication technologies can transmit real-time data from sensors to centralized monitoring facilities, ensuring data integrity and accessibility over long timeframes remains a significant hurdle. Data transmission infrastructure, like sensors, may degrade over time, and ensuring that the data remains accessible and interpretable by future generations is a complex task. Data transmission and storage are complicated by the long timescales involved in radioactive waste management. Over centuries, technologies and communication standards may change, and future generations may not be able to access or understand the data collected by current systems. The article mentions that current data storage solutions, such as cloud-based systems or physical storage devices, are not designed for the multi-millennial timescales required for waste disposal monitoring. Additionally, the reliability of communication networks in remote areas is another unsolved issue, particularly when dealing with long-term underground repositories. While authors propose the use of integrated sensor networks, they acknowledge that fully integrating sensor data with predictive models for site safety is still an unresolved issue. Predictive models rely on accurate, real-time data from sensor networks to assess potential risks, such as the likelihood of containment failure or the migration of radioactive material. However, current sensor networks may not be sophisticated enough to provide the high-resolution data needed to feed into complex models. The integration of real-time data with predictive models is challenging because it requires highly accurate, consistent, and comprehensive data inputs over long periods. Sensor networks, particularly in extreme environments, often suffer from data gaps due to equipment failure or environmental interference. The authors also point out that the accuracy of predictive models depends heavily on the quality and completeness of the data they receive. Inadequate or incomplete data from sensor networks can lead to flawed predictions, making it difficult to reliably forecast long-term risks at waste disposal sites. The article discusses the potential of remote monitoring systems but highlights that accessing and maintaining sensors and monitoring equipment in hazardous, radiation-prone areas remains a critical issue. While remote systems can reduce human exposure to dangerous environments, they still require occasional maintenance, calibration, or replacement. However, the difficulty of physically accessing these sites, especially in deep geological repositories, complicates the long-term reliability of these systems. Access to remote or hazardous radioactive waste sites is inherently difficult and risky. Even with robotic systems or remote technologies, routine maintenance of sensors and monitoring equipment over long periods is challenging. The authors acknowledge that while some autonomous systems are being developed, they are not yet capable of handling the complex tasks required for the ongoing operation of monitoring networks in such harsh environments. The costs and risks associated with maintaining these systems in radioactive or difficult-to-reach areas remain significant obstacles. Another unsolved issue discussed in the article is the challenge of adapting monitoring technologies to account for long-term environmental and geological changes. Radioactive waste repositories, especially those located underground, may be affected by shifts in the surrounding geology, climate change, or other environmental factors. Monitoring systems need to be able to detect and respond to these changes, but predicting and preparing for such shifts remains a complex task. Environmental and geological changes are difficult to predict over the long term, and sensor technologies must be adaptable to detect and account for these changes. The authors note that current monitoring systems are often designed with a specific set of environmental conditions in mind, but these conditions may change over time due to natural or anthropogenic factors. Developing sensors that can adapt to shifting environments, or accurately predict these changes, remains a significant challenge in the field of long-term monitoring for radioactive waste disposal. The article provides valuable insights into the use of sensor technologies for the long-term monitoring of radioactive waste sites. They propose advanced sensor networks and monitoring solutions to address the challenges of detecting radioactive leaks, environmental changes, and containment failures. However, several key problems remain unresolved, including the limited durability of sensor technologies, reliable power supplies for remote monitoring systems, long-term data transmission and storage, integration of sensor data with predictive models, and the difficulties of maintaining equipment in hazardous areas. Additionally, adapting monitoring systems to long-term environmental and geological changes remains a complex and unsolved issue. Overcoming these challenges will require significant technological advancements and further research to ensure the long-term safety and stability of radioactive waste disposal sites.

In [9], the article explores the economic feasibility of using exhausted or repurposed mining sites for the long-term storage of nuclear waste. The primary focus is on analyzing the costs associated with converting spent mines into nuclear waste repositories and comparing these costs with other disposal methods, such as deep geological repositories and above-ground storage facilities. One of the major unresolved issues in the article is the long-term economic viability of repurposing spent mines for nuclear waste disposal. While the authors provide a detailed cost-benefit analysis of initial construction and short-term maintenance, the long-term economic challenges remain less clear. In particular, the costs associated with maintaining and monitoring these sites for potentially thousands of years are not fully accounted for in their models. The complexity of estimating costs over such long timeframes is a significant limitation. The authors acknowledge that factors like inflation, technological obsolescence, and changing regulatory requirements could drastically alter the cost structure over time. Furthermore, the economic models used in the article are based on assumptions that may not hold up over centuries. For instance, the cost of maintaining monitoring systems, dealing with unforeseen containment failures, or responding to changes in environmental conditions could increase significantly, making the long-term viability of such projects uncertain. Another unresolved issue is the variability in economic and geological factors across different mining sites. The authors acknowledge that not all mines are suitable for nuclear waste disposal due to geological instability, water ingress, or structural degradation. However, their economic analysis largely treats spent mines as a homogenous category, without fully accounting for the site-specific costs and risks that could arise. Mines differ significantly in terms of their geological characteristics, structural integrity, and proximity to populated areas. These variations can have a substantial impact on both the initial costs of repurposing the mine and the long-term costs of maintaining a safe repository. For example, mines located in seismically active regions or those prone to flooding would require more expensive engineering solutions to ensure safety, which could negate the cost savings of using existing infrastructure. The authors do not provide a sufficiently detailed analysis of these site-specific factors, leaving the economic feasibility of many potential sites in question. Authors focuses primarily on the financial costs and benefits of using spent mines for nuclear waste disposal, but they do not fully integrate environmental and social costs into their economic models. While they briefly mention potential environmental risks, such as groundwater contamination, and social concerns, like public opposition to nuclear waste repositories, these factors are not comprehensively quantified or included in their overall feasibility assessment. The economic feasibility of nuclear waste disposal cannot be assessed in isolation from the environmental and social impacts. Public resistance, environmental degradation, and the potential for accidents or leaks could impose significant financial and reputational costs on the project. The authors acknowledge these concerns but fail to provide a detailed framework for integrating them into their cost-benefit analysis. This omission leaves an important aspect of the problem unresolved, as the success of such projects depends heavily on public acceptance and the ability to mitigate environmental risks. Another unresolved issue discussed in the article is the lack of a clear regulatory and policy framework for repurposing spent mines for nuclear waste disposal. The authors highlight that while many countries have established regulations for nuclear waste disposal in purpose-built facilities, the repurposing of spent mines falls into a regulatory gray area in many regions. This uncertainty could lead to delays, increased costs, and difficulties in securing necessary permits and approvals. Developing a comprehensive regulatory framework for repurposing spent mines would require significant coordination between multiple stakeholders, including government agencies, local communities, and international organizations. The process of establishing new regulations and guidelines could take years, if not decades, and could impose additional costs on the project. The authors do not provide concrete solutions for overcoming these regulatory challenges, leaving a critical aspect of the feasibility assessment unresolved. One of the significant unresolved issues is the question of long-term liability and funding for the maintenance and monitoring of nuclear waste sites. Authors briefly mention that the costs of monitoring and site management would need to be borne by future generations, but they do not address how these costs will be funded or who will be held responsible if something goes wrong in the future. Long-term liability is a major challenge for any nuclear waste disposal project. The financial responsibility for maintaining these sites, which could last thousands of years, is difficult to assign. Governments may not be willing or able to commit to funding these projects indefinitely, and private companies may not have the financial resources to cover the costs over such extended periods. The authors do not propose a clear mechanism for ensuring that sufficient funds will be available for monitoring, maintenance, and potential remediation efforts in the future, leaving a crucial aspect of the economic feasibility unresolved. Although the article touches on the potential for technological advancements to reduce costs, the authors do not adequately address the risks associated with relying on future technologies. They suggest that improved monitoring systems or containment technologies could lower long-term costs, but they do not provide detailed projections or account for the possibility that these technologies may not be developed or deployed at the necessary scale. The assumption that technological advancements will lower costs is speculative and introduces uncertainty into the economic analysis. While it is possible that future technologies could make long-term monitoring and maintenance more efficient, it is also possible that new technologies may introduce unforeseen costs or challenges. The authors do not fully explore these risks, which leaves a gap in the economic feasibility assessment. The article offers a valuable contribution to the discussion on the economic feasibility of repurposing spent mines for nuclear waste disposal. Their analysis suggests that using existing mine infrastructure could be a cost-effective alternative to building new facilities. However, several key issues remain unresolved, including the long-term economic viability of these projects, site-specific economic and geological considerations, the integration of environmental and social costs, regulatory and policy challenges, long-term liability and funding, and technological uncertainty. Addressing these issues will require further research, more comprehensive economic models, and a clearer regulatory framework to ensure that repurposing spent mines for nuclear waste disposal is both economically and practically feasible in the long term.

In [10], the article discusses the potential use of basalt, basalt fibers, and modified graphite as materials for containing and isolating nuclear waste in repositories. The authors propose that these materials could enhance the long-term safety and stability of nuclear waste repositories, particularly in mitigating the risk of radioactive leaks and environmental contamination. One of the unsolved issues identified in the article is the uncertainty surrounding the long-term durability of basalt fibers in nuclear waste repositories. While basalt fibers are praised for their mechanical strength and resistance to radiation, their performance over the extended timescales required for nuclear waste isolation (potentially thousands of years) remains largely untested. The authors note that there is limited data on how basalt fibers will behave when exposed to the unique conditions within a repository, including high radiation doses, heat, and potential chemical interactions with groundwater. Testing the long-term durability of materials like basalt fibers is inherently difficult because the timescales involved are far beyond what can be simulated in a laboratory setting. While accelerated aging tests can provide some insights, they cannot fully replicate the complex environmental conditions within a nuclear waste repository. As a result, the long-term behavior of basalt fibers remains an area of uncertainty, and more research is needed to determine whether these materials can reliably maintain their integrity over thousands of years. Another unresolved issue is the potential for chemical interactions between basalt-based materials and groundwater. The authors acknowledge that while basalt is chemically inert under many conditions, the interaction of basalt with groundwater, especially in repositories where water ingress is possible, could lead to degradation of the containment structures over time. This could pose a risk to the long-term containment of radioactive waste if the structural integrity of the repository is compromised. Predicting the exact chemical interactions that could occur between basalt-based materials and groundwater is complex, as it depends on a variety of factors such as the composition of the groundwater, the temperature of the repository, and the presence of other materials. The article does not provide detailed analysis or experimental data on this issue, and further research is needed to fully understand the long-term chemical stability of basalt in nuclear waste repositories. Until these interactions are better understood, the safety of using basalt in such applications remains uncertain. While the authors highlight the thermal stability of basalt and modified graphite, they do not fully address the challenges of managing the heat generated by decaying radioactive waste. Although modified graphite is proposed as a material with excellent thermal conductivity, the article does not provide a comprehensive solution for how the overall repository structure would dissipate the significant heat produced by HLW over time. Managing the heat generated by radioactive waste is a critical issue in repository design, as excessive heat can damage containment materials and compromise the repository's safety. While modified graphite may help with heat dissipation, the authors do not offer a detailed plan for integrating this material into a broader system that can effectively manage the thermal load over the long term.

The lack of a clear strategy for heat management leaves an important part of the problem unresolved, as the failure to adequately control temperature could lead to material degradation or even the release of radioactive contaminants. Another challenge that remains unsolved is the scalability of producing basalt fibers and modified graphite for large-scale nuclear waste repositories. While the materials themselves are promising, the authors do not discuss the feasibility of producing them in the quantities needed for constructing full-scale repositories. This is particularly relevant for basalt fibers, which are not as widely produced or utilized as other materials like steel or concrete. The production of basalt fibers and modified graphite on the scale required for nuclear waste repositories would likely involve significant logistical and economic challenges. The authors do not provide data on the current production capacity for these materials or the potential costs associated with scaling up their use in repository construction. Without this information, it is difficult to assess whether the proposed materials can be practically implemented in large-scale nuclear waste disposal projects. The article focuses primarily on the material properties of basalt and graphite but does not fully explore how these materials would integrate with existing repository designs. Many nuclear waste repositories are based on well-established designs that use multiple engineered barriers and geological isolation to contain waste. The introduction of basalt-based materials into these systems could require significant modifications to existing designs, which may introduce new technical challenges. The integration of new materials into complex systems like nuclear waste repositories is a non-trivial task. Existing repository designs are the result of decades of research, testing, and regulatory approvals, and any changes to these designs would need to be thoroughly tested and validated. The authors do not address how basalt and modified graphite would be incorporated into these systems or what new challenges might arise as a result of these changes. Without a clear plan for integrating these materials into existing repository designs, the feasibility of using them remains uncertain. Finally, the article does not discuss the regulatory and safety approval processes required for using basalt and graphite in nuclear waste repositories. Any new materials proposed for use in such critical applications would need to undergo extensive testing and approval from regulatory bodies to ensure their safety and reliability. The authors do not provide details on how these materials would meet the stringent requirements for nuclear waste disposal. The regulatory approval process for materials used in nuclear waste repositories is highly rigorous, and new materials must undergo extensive testing to demonstrate their suitability. The authors do not outline a pathway for how basalt fibers and modified graphite would be tested and approved for use in repositories, leaving a key aspect of the problem unresolved. Until these materials are validated and approved by regulatory bodies, their practical application in nuclear waste disposal will remain speculative. The article provides a promising look at the potential use of basalt, basalt fibers, and modified graphite in nuclear waste repositories. These materials offer several advantages, including high thermal stability, resistance to radiation, and chemical inertness, which could make them suitable for long-term containment of radioactive waste. However, several key issues remain unresolved, including the long-term durability of basalt fibers, the potential for chemical interactions with groundwater, the challenges of heat management, the scalability of material production, integration with existing repository designs, and the regulatory approval process. Addressing these challenges will require further research and testing to ensure that these materials can be safely and effectively used in nuclear waste repositories.

Based on the critical analyses of the various approaches to high-level radioactive waste (HLW) burial in spent mines, several crucial areas of research remain unresolved, which are vital for creating truly innovative storage facilities for the complete burial of HLW. These unsolved research areas span materials science, long-term safety, economic feasibility, and regulatory frameworks:

1. Long-term durability of containment materials. Unsolved Issue: despite promising materials like basalt, basalt fibers, and modified graphite, their long-term durability under high radiation, heat, and chemical interactions with groundwater remains uncertain. Basalt fibers, for instance, offer strength and radiation resistance, but their behavior over millennia is poorly understood.
2. Heat management in repositories. Unsolved Issue: managing the heat generated by decaying HLW remains a challenge. Modified graphite offers good thermal conductivity, but an overall thermal management strategy that integrates different materials and designs is lacking.
3. Environmental interactions and groundwater contamination. Unsolved Issue: the interaction between repository materials and groundwater poses a long-term contamination risk. Although basalt and similar materials are chemically inert, their behavior in diverse geological conditions over thousands of years is still unclear.
4. Comprehensive risk assessment models. Unsolved Issue: existing risk assessment models do not fully account for all the potential long-term hazards associated with HLW storage, including unforeseen environmental events, material degradation, and human interventions.
5. Integration of advanced monitoring technologies. Unsolved Issue: monitoring HLW repositories for thousands of years requires sophisticated, durable sensors capable of providing continuous data on radiation, heat, and structural integrity. Current sensor technologies are not optimized for such long-term applications.
6. Scalable production of innovative materials. Unsolved Issue: the production and scalability of advanced materials such as basalt fibers, modified graphite, and other innovative containment materials are not fully developed to meet the massive requirements of full-scale HLW repositories.
7. Economic feasibility and life-cycle cost analysis. Unsolved Issue: the overall economic feasibility of HLW repositories, particularly those using innovative materials and designs, remains poorly understood, especially regarding the long-term costs of monitoring, maintenance, and potential site remediation.
8. Regulatory frameworks and public acceptance. Unsolved Issue: despite advances in materials and engineering, the regulatory and societal hurdles for HLW disposal remain significant. Public distrust and stringent regulatory requirements can delay or block the implementation of new technologies.
9. Addressing human interference. Unsolved Issue: human activities – intentional or accidental – pose a long-term risk to HLW repositories. Current designs do not fully address how future generations may interact with or disrupt repositories.
10. Adapting repository designs to diverse geological conditions. Unsolved Issue: while much of the research focuses on specific materials or risk factors, less attention is

given to how repository designs can be adapted to different geological settings. Given that the success of a repository depends heavily on its location, adaptable designs are crucial.

The research landscape for designing innovative HLW storage facilities highlights several unsolved challenges, ranging from material science to long-term environmental risks and economic feasibility. These research gaps are critical for ensuring the safe, efficient, and sustainable burial of HLW in spent mines or other repository designs. Addressing these unresolved areas through interdisciplinary collaboration and advanced technologies will be essential to achieving fully functional, secure, and globally accepted HLW storage solutions. The collective analysis of the above studies presents a multifaceted view of the challenges, potential solutions, and unsolved issues in the design of storage facilities for the final burial of high-level radioactive waste (HLW). Despite advancements in material science, engineering, and economic considerations, several criteria emerge as crucial for developing an innovative and effective HLW repository. These criteria, drawn from the critical analyses, highlight the balance between technological feasibility, long-term safety, and regulatory acceptance:

1. Long-term durability and stability: across all the reviewed approaches, the long-term durability and stability of containment materials are critical. Whether focusing on basalt-based barriers, modified graphite, or advanced fiber composites, the ability to withstand the intense radiation, high temperatures, and potential chemical interactions over millennia is a common concern. For an innovative HLW storage facility, materials must be rigorously tested not only for their immediate mechanical properties but also for their ability to endure extreme conditions over thousands of years.

2. Comprehensive environmental and risk assessment: effective HLW storage facilities must be designed with a thorough understanding of environmental interactions and risks. These include potential groundwater contamination, seismic activity, and other geological factors. Studies on risk assessment and environmental monitoring point to the need for: site-specific geological analysis to ensure that the repository location minimizes environmental risks. Advanced monitoring technologies for early detection of containment failures or environmental contamination. Risk modeling to predict long-term impacts and potential accident scenarios.

3. Multilayered barrier systems and engineering design: the use of multilayered composite barriers, such as basalt-based systems, or engineered containment systems, emphasizes the importance of redundancy in the design of HLW repositories. A robust facility should incorporate multiple layers of defense to ensure that any single failure does not lead to environmental contamination. Key design features should include: multiple containment layers using a combination of engineered and geological barriers to provide redundant protection. Innovative materials that combine high strength, low permeability, and chemical stability (e.g., basalt fibers, modified graphite). Mechanical and structural integrity over time, with particular attention to materials that can resist long-term degradation under high temperatures and radiation.

4. Economic feasibility and practicality: the economic aspect of developing HLW storage facilities is a major concern, particularly in the context of repurposing existing infrastructure, such as spent mines. Economic feasibility must account for: initial construction costs versus the benefits of utilizing existing infrastructure. Long-term funding for monitoring, maintenance, and potential site remediation. Regulatory compliance and potential delays in securing permits for innovative designs or materials.

5. Regulatory approval and public acceptance: regulatory challenges and public acceptance are critical factors in the success of any HLW burial facility. Without clear regulatory frameworks or public trust in the safety of such facilities, even technically sound designs can face significant hurdles. Adhering to strict safety standards established by national and international regulatory bodies. Engaging with the public to ensure transparency, particularly in the site selection process and the long-term safety of the repository. Developing flexible regulatory frameworks to accommodate innovations in materials and repository designs.

6. Long-term liability and institutional commitment: the unresolved issue of long-term liability remains a significant obstacle. The financial and institutional commitment required to manage HLW repositories for thousands of years must be accounted for in the design and implementation stages. Long-term success will depend on: clear assignment of liability for future maintenance and potential accidents. Sufficient funding reserves to ensure that the repository can be monitored and maintained indefinitely. Institutional safeguards to prevent future generations from bearing the financial and environmental burden of poorly managed waste.

7. Technological innovation and monitoring: advances in long-term monitoring technologies are essential for ensuring the safety and integrity of HLW storage facilities. Future storage facilities must integrate: state-of-the-art sensor technology capable of monitoring radiation levels, structural integrity, and environmental factors over the long term. Automated systems for early warning and intervention in case of leaks or containment breaches. Data management platforms to store and analyze vast amounts of monitoring data over extended time periods.

An innovative storage facility for the complete burial of HLW must combine cutting-edge materials science, advanced engineering, and rigorous environmental and economic assessments. The criteria identified from the analyses – durability, multilayered barriers, risk assessment, economic feasibility, regulatory compliance, long-term liability, and technological innovation – should guide the design process. Addressing these unsolved issues with holistic, site-specific, and technologically integrated solutions will be key to ensuring the safe and sustainable burial of HLW.

3. The aim and objectives of the study

The aim of this study is to develop an approach that ensures the safety and reliability of sarcophagus containers with HLW for a critical period of time.

To achieve this aim, the following objectives are accomplished:

– to justify a novel approach to the burial of sarcophagus containers with solid high-level waste (HLW) in exhausted mining pits;

– to study the basalt sarcophagus container.

4. Materials and methods

The object of research is the spent open-pit mines themselves where the proposed system could be applied. The hypothesis is based on the assumption that the functional and economic advantages of basalt and composite materials will translate into tangible benefits in the practical application of HLW containment in spent quarries. The use of sarcophagus containers constructed from basalt blocks with composite layers for the burial of solid high-level waste (HLW) in old mines provides a superior solution compared to traditional methods. The research primarily employed theoretical simulations and computational modeling to explore the feasibility and effectiveness of a novel storage system for solid high-level waste (HLW) in spent open-pit mines. The methodology involved several key components: economic modeling: economic cost-benefit analysis tools were used to evaluate the cost-effectiveness of the proposed storage system. This included assigning weights to various criteria, scoring alternatives, and ranking them to select the optimal design. The analysis leveraging a patent information and expert knowledge to evaluate different designs, providing a robust framework for decision-making. Based on the transformation of the results of expert analysis [6], it is proposed to take into account the following indicators for evaluating the effectiveness of the storage system for disposal of solid HLW:

1. Enhanced monitoring systems (X_1):

– real-time monitoring: implement real-time monitoring systems (e. g., sensors for temperature, radiation, and structural integrity) within the pit and around the containers. This will provide continuous data on the condition of the waste and the effectiveness of the isolation barriers;

– remote monitoring: develop remote monitoring capabilities to allow for off-site tracking and management, reducing the need for on-site personnel.

2. Material innovations (X_2):

– consider incorporating advanced composite materials for the containers that could offer better durability and resistance to radiation and heat;

– self-healing materials: research the potential use of self-healing materials for both the lead matrix and the clay layer to automatically repair minor cracks or damage, enhancing long-term containment integrity.

3. Robotic and automation enhancements (X_3):

– invest in more advanced robotics with AI capabilities to improve precision and efficiency in handling and placing the containers;

– automated transportation: fully automated transportation systems, possibly including autonomous vehicles for moving the containers from the surface to the burial site.

4. Energy recovery and utilization (X_4):

– integrate thermoelectric generators into the containment system to convert the heat from the HLW directly into electricity, providing an additional energy source;

– steam engine optimization: optimize the design of the rotary steam engine mentioned in the previous description to maximize efficiency and reliability in electricity generation.

5. Environmental impact mitigation (X_5):

– implement biodiversity offsetting projects to compensate for any ecological disruption caused by the burial site. This could include creating new habitats or enhancing existing ones nearby;

– water management: develop advanced water management systems to prevent contamination of local water sources and manage any runoff from the site.

6. Community and stakeholder engagement (X_6):

– public engagement: conduct regular public engagement and communication activities to inform and involve local communities and stakeholders in the process. Transparency can build trust and acceptance;

– stakeholder involvement: involve stakeholders in decision-making processes, particularly in site selection, transportation routes, and reclamation plans.

7. The objective is to ascertain the degree of protection afforded by a storage facility for containers with solid, highly radioactive waste from the consequences of natural or man-made disasters (X_7).

8. The value of the reduction in the cost of transporting one ton of solid highly radioactive waste by container is to be determined (X_8). For system modeling experience can be defined as a numerical value.

In this model, the first nine criteria (X_1)–(X_8) constitute the basic part. To gain a more comprehensive understanding of the efficacy of an innovative storage system for the disposal of solid HLW in spent open-pit mines, an additional parameter to the basic model is proposed. This parameter, designated (X_9), represents the degree of perception of an architectural information system that has undergone innovative changes in accordance with the requirements of its effective functioning, or its adaptability. The matrix of the main operational parameters of the mathematical model of the prospective appearance of an innovative storage system for the disposal of solid HLW in spent open-pit mines is presented in the form of the presence of operational parameters marked “1”, and or their absence – “0”. The objective of this study is to develop and create a mathematical model for the construction of a promising appearance of the storage system for the disposal of solid HLW in spent open-pit mines, their functional and structural assessment of Xi is based on the folding of a system of particular criteria to a generalized criterion of the required effect (efficiency). The implementation of the algorithm for selecting many criteria involves the construction of a generalized criterion by linear convolution of the criteria. It can be demonstrated that the generalized criterion is expressed as a linear combination of the values of the remaining criteria:

$$U(x)=w_i x_i, \tag{1}$$

where w_i is the weight (importance) of the i-th criterion assigned by experts; x_i is quantitative assessment according to the X_i-th criteria. The structure of the appearance of the storage system for the disposal of solid HLW in spent open-pit mines system is changing due to ongoing activities aimed in increasing the value of one or another of its parameters. The solution of the problem comes down to rebuilding the structure of the state of an appearance of the storage system for the disposal of solid HLW trying to bring it closer to the final target state. The economic part of the calculation block of the presented methodology begins with determining the need for financial resources to implement the plan for the formation of a new look for the storage system for the disposal of solid HLW in full and the time required to achieve this goal with a given level of funding, which are determined by the formula:

$$F=(Ki-Ci)\cdot Si, \tag{2}$$

where F is the need for additional financial resources for the implementation of the program for the formation of a new look for the one at a given level of funding; Ki is the value of the i-th parameter of the prospective its appearance; Ci is the value of the i-th parameter of the existing shape of the storage system; Si is the price per unit of the i-th measure of the formation of a new look for the one. Term T, during which the program for the formation of a new look of the storage system will be implemented, is determined by the formula:

$$T=F/E, \tag{3}$$

where T is the period during which the program for the formation of a new image of the storage system for the disposal of solid HLW in spent open-pit mines will be implemented; E is the need for additional financial resources for the implementation of the program for the formation of a promising image of the storage system for the disposal of solid HLW in spent open-pit mines at a given level of funding. After that, the rate of deviation of the initial state of the existing shape of the storage system for the disposal of solid HLW from its final target state is calculated, expressed as a percentage, which is determined by the formula:

$$N=(Ci/Ki)/I, \tag{4}$$

where N is the norm of its an existing state; I is the total number of parameters characterizing the structure of the existing appearance of the one [6].

The final solution of the problem comes down to finding the maximum value of the norm of deviation of the achieved parameters of the state of the prospective appearance of the storage system for the disposal of solid HLW in spent open-pit mines for a given level of funding:

$$H\max;\ H=(Pi/Ki)/I, \tag{5}$$

and:

$$E=(Pi-Ci)\cdot Si, \tag{6}$$

where H is the norm of the achieved state of the prospective appearance of the storage system for the disposal of solid HLW in spent open-pit mines; Pi is the value of the i-th parameter of the achieved perspective appearance of the storage system; Si is the price per unit of the i-th measure of the formation of the prospective image of the storage system for the disposal of solid HLW in spent open-pit mines; E is a given level of (allocated) funding for the formation of a perspective image of a storage system within a certain period of time (usually within one year); Ki is the value of the i-th parameter of the final target perspective appearance of the storage system for the disposal of solid HLW in spent open-pit mines; Ci is the value of the i-th parameter of the existing shape of the storage system; i is the serial number of the structure parameter of the existing shape of the storage system for the disposal of solid HLW in spent open-pit mines.

The long-term disposal of solid HLW have been designing into the rocks of an abandoned quarry (Fig. 1, 3). In the Table 1, are represented the calculation results of the innovative burial for HLW. This is achieved by placing HLW, which are, for example, fuel elements of nuclear reactor assemblies of a nuclear power plant, in a container. The container is constructed from a block of hard rock that does not allow radionuclides to pass through (Fig. 2). This may be, for example, basalt, granite, etc. The dimensions of the container are significant, for example, a diameter of up to six meters, and the weight may be up to 1000 tons or more. A special cavity and/or cavities are formed in the block of hard rock, and it is planned to place HLW in it and/or in them. HLW are preliminarily delivered from the nuclear power plant in an intermediate container to an assembly and handling point built near the abandoned quarry and/or a section of a natural depression. It is planned to transfer the intermediate container to the innovative container for HLW using a manipulator of an industrial robot (Fig. 3) [11]. This eliminates the need for personnel near the innovative container for HLW, which ensures safe working conditions. The sarcophagus-container is transported using an innovative skip mechanism with a gravity counterweight, which reduces the cost of transporting one ton of HLW and improves the ecology of the quarry space (Fig. 3). Subsequently, the innovative container with HLW is lowered onto the upper surface of a layer of plastic rock, such as clay, formed in the mined-out space of a worked-out quarry or on the bottom of a natural depression (Fig. 1). This is achieved by utilizing the innovative mechanism, which ensures that layers of clay are formed around all the side walls and the upper base of the innovative container with HLW, the geometric dimensions of which are scientifically calculated. The study did not involve physical experiments but was based on economic simulations and computational comparisons. Validation was achieved by comparing economic models with real world case studies where similar approaches had been implemented, assessing the accuracy of the predicted cost savings. The models were validated against historical geological data and by comparing simulation results with known outcomes from existing disposal sites. In order to giving a rise, the reliability of an innovate storage with HLW initially placed into lead matrix prior to its encapsulation within the basalt container serves to augment the overall protective measures.

Structural design modeling: the sarcophagus container, made of basalt with composite layers, was modeled to ensure it could withstand impermeability, durability, and both static and dynamic loads over extended periods. Composite material modeling was also used to simulate the behavior of the composite layers within the container, optimizing the material composition and layering. The innovative sarcophagus container, constructed from a basalt block, comprises composite layers lead, clay and basalt and depicts a unified single design with a cavity case (Fig. 2). This cavity case contains a lead matrix (Fig. 2), into which solid highly radioactive waste (not shown in Fig. 2) is placed. Between the lead matrix (innermost layer) and the basalt block (outermost layer), clay layers are placed. In the formed cavity, the value of the thickness of the wall of the sarcophagus-container between any section of the surface of the cavity in the sarcophagus-container and any section of the outer surface of the block of the sarcophagus-container, which is constant along its entire length, is determined in according with IAEA requirements. In that way to determining the values the thickness of each layer at which migration of solid HLW radionuclides from the cavity is excluded during the required critical period. The time period (in accordance with IAEA requirements, not less than one hundred thousand years.

Thermal analysis: the software was used to model heat transfer within the container, particularly the ability of the basalt and composite layers to insulate the HLW and prevent thermal degradation of the materials over time. To describe the heat conduction through a multi-layered composite structure such as the one has been described (lead matrix, clay layer, basalt block), let's use the heat conduction equation for steady-state heat transfer in cylindrical coordinates (assuming radial symmetry). Composite layers: lead matrix (innermost layer); clay layer (middle layer); basalt block (outermost layer). In the research have been defined the boundary conditions: assuming the inner surface of the lead matrix is at temperature T_1=300 °C and the outer surface of the basalt is at T_2=50 °C. If to provide specific values for r_1, r_2, r_3, r_4, T_1, T_2, and thermal conductivities k_{lead}, k_{clay}, k_{basalt} it is possible to derive the exact temperature distribution. Where for lead matrix: r_1=0.1 m (inner radius); r_2=0.2 m (outer radius); k_{lead}=35 W/(m·K), for clay layer: r_2=0.2 m (inner radius); r_3=0.3 m (outer radius); k_{clay}=0.6 W/(m·K) and for basalt block: r_3=0.3 m (inner radius); r_4=0.4 m (outer radius); k_{basalt}=1.7 W/(m·K). Assuming the continuity of boundary conditions it is possible to illustrate the temperature distribution across the layers. Plugging in the boundary conditions and continuity conditions to find the constants and the complete temperature distribution across the composite structure. It has been established for the temperature distribution using the heat conduction equation and continuity conditions (Fig. 4). The application of a clay layer, which transforms into ceramic upon exposure to heat, for the final encapsulation into composite layers serves to provide an additional barrier against radionuclide migration. In addition, using the multi-layered approach using clay for sealing and isolating the containers within the spent open-pit mines is significantly giving a rise its robust and reliability. The process for filling gaps and ensuring uniform coverage is meticulous and aims to create a reliable isolation system. The final step of covering the pit with overburden material and restoring the natural landscape is crucial for environmental reclamation.

Validation: the proposed models were validated by comparing simulation results with historical geological data and known outcomes from existing disposal sites. The models were further validated by describing the heat conduction through the composite structure using theoretical calculations and ensuring that the design met established guidelines, such as IAEA requirements. Overall, the research relied on a combination of theoretical methods, computational modeling, and validation through comparisons with real-world data to assess the feasibility and safety of the proposed HLW disposal system in spent open-pit mines. The research primarily used theoretical simulations and did not involve physical experiments. The proposed models were validated by describing the heat conduction through a multi-layered composite structure such as (lead matrix, clay layer, basalt block), the heat conduction equation for steady-state heat transfer in cylindrical coordinates was used.

5. Results of justification for a system burying solid, high-level radioactive waste

5. 1. Justification a novel approach to the burial of sarcophagus containers with solid high-level waste (HLW) in exhausted mining pits

Based on the functional-economic approaches innovative automated method have being developed by specialists for the preparation and burial of sarcophagus containers with solid HLW. Currently, specialists have developed several variants of ones. The problem is solved in two stages. At the first stage, the need for funds and the duration of the period of time necessary to achieve the goal are determined. In the conditional example, they are, respectively, 160 units and 1.0 years. The norm of the initial state of the appearance of the information security subsystem is determined as a percentage. In the conditional example, it is equal to 60 %. At the second stage, the calculation is detailed, where the achieved calculated indicators are determined relative to the final, target parameter of the state of the perspective appearance of the information security subsystem. The structure of the achieved perspective appearance of the information security subsystem has changed significantly, the value of one parameter (in the conditional example it has the numbers 7 and 8, which was 5 % and 7 correspondently and on the initial state, has reached 100 % [6]. The results of calculating the parameters of the functional-economic model for assessing the prospective appearance of the method for the preparation and burial of sarcophagus containers with solid HLW during a given period of time, performed for a conditional example, are shown in Table 1. In Fig. 1, there is a perspective appearance of the storage system for the disposal of solid HLW in spent open-pit mines. The objective of the research is to enhance the reliability of long-term isolation and disposal of solid HLW and to optimize the efficiency of its disposal. Additionally, the research aims to exclude the presence of technical personnel during the reloading and transportation operations of sarcophagus containers with HLW. Finally, the research endeavors to reduce the cost of disposal of one ton of HLW. The storage system for solid HLW in spent open-pit mines is the long-term burial of these wastes in the rocks of a spent mining pit. This is achieved by placing solid HLWs, which are, for example, fuel elements of assemblies (fuel elements) of a nuclear reactor of a nuclear power plant into a container made of a block of strong rock (Fig. 2) that does not permit the passage of radionuclides, for example, basalt, granite, etc. [10]. The dimensions of the container are significant, for example, diameter up to six meters, mass up to 1000 tons and more. A unique cavity and/or cavities are created within the solid rock block, and it is proposed that fuel elements and/or fuel rods be placed within them. The solid HLW is initially transported from the nuclear power plant in an intermediate container to the assembly and transshipment point constructed at the waste pit and/or natural depression site. The transfer of fuel elements and/or fuel assemblies from the intermediate container to the innovative solid HLW container is to be carried out using an innovative industrial robot arm (Fig. 3). This eliminates the necessity for personnel to be present in the vicinity of the innovative container for HLWs, thereby ensuring safe working conditions.

At the periphery of the quarry, a platform (7) has been constructed on which a robot manipulator is installed for the unloading and preparation of the sarcophagus containers (2) containing the heavy radioactive waste. The robotic platform is situated at the point of transfer of the sarcophagus container and at the base of the quarry for its ultimate disposal (Fig. 3). It may be installed, for example, in a cut trench (not shown in the figures). The bottom surface of the robotic platform 7 is located above the elevation mark, which is equal to or greater than the height of the skip body. The robotic platform 7 is situated on the section of the earth's surface in proximity to the design contour of the quarry, shown in Fig. 3. The robot manipulator comprises a support post, a horizontal crossbar, a handling robot manipulator, and a phalanx gripper. The apparatus is designed for the handling of the sarcophagus container 2 with radioactive waste into the skip bodies 12, which are equipped with a braking device and/or braking devices (not shown in the figures).

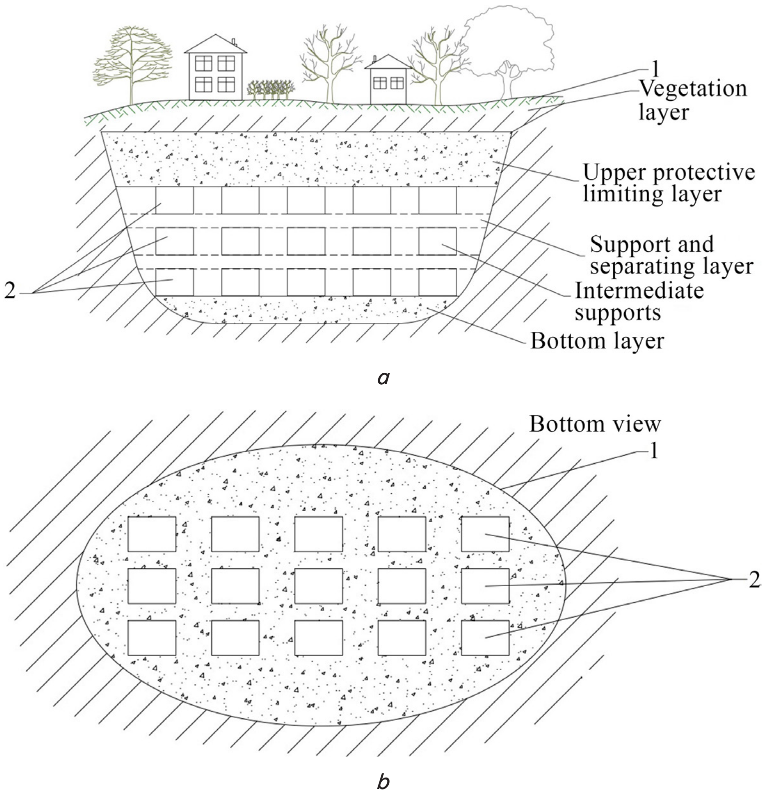

Fig. 1. Depicts a general diagram of storage facility 1, which is a previously mined quarry with a rocky base for the final disposal of a sarcophagus-container: *a* — front view; *b* — upper view

Table 1

Initial data and calculation results of the perspective view of the method for the preparation and burial of sarcophagus containers with solid HLW for a conditional example

The appearance of the storage system for the disposal of solid HLRW in spent open-pit mines					
Allocated funds, unit	Required funds, unit	Time to achieve the goal, year	Initial state norm, %		The rate of the achieved state, %
100	160	1.0	60		95
Calculation results					
Parameter name	Initial state	Required appearance	Unit price	Received appearance, %	Perspective appearance (goal achievement), %
Enhanced monitoring systems	10	20	2	100	100
Material innovations	20	40	2	100	100
Robotic and automation enhancements	20	40	2	100	100
Energy recovery and utilization	10	20	5	100	100
Environmental impact mitigation	8	16	5	80	100
Community and stakeholder engagement	20	34	10	100	100
The objective is to ascertain the degree of protection afforded by a storage facility for containers with solid, highly radioactive waste from the consequences of natural or man-made disasters	5	10	5	100	100
The value of the reduction in the cost of transporting one ton of solid highly radioactive waste by container is to be determined	7	15	5	80	100

The transportation of the sarcophagus-container is carried out using an innovative skip mechanism with the use of gravity counterweight, which reduces the cost of transportation of 1 ton of HLW and improves the ecology of the intra-carrier space. Subsequently, the innovative container with HLW is lowered to the upper surface of the layer of plastic rock, for example, clay, formed in the excavated space of a waste pit or at the bottom of a natural depression, using the aforementioned innovative mechanism. The innovative container with HLWs is constructed with clay layers around all side walls and the top base. The dimensions of the HLWs are calculated using scientific methods. The HLWs within the innovative container are capable of reaching temperatures of up to 300 °C for extended periods, potentially lasting up to one million years. Consequently, the rock block is subjected to heating. Special cavities (holes) are formed in specific locations within the container, either near certain sections or within the inner sections located at the bounding outer surfaces. The innovative rotary steam engine comprises a series of structural elements, the function of which is to facilitate the circulation of a working fluid, such as water. As a consequence of the elevated temperature of the block, it undergoes a phase transition into a vapor state. The innovative rotary steam engine generates electricity through the action of water vapor, which is then used for practical purposes.

The innovative storage facility for the disposal of solid highly radioactive waste is illustrated by the figures presented in Fig. 1, which depicts a general diagram of the storage facility. This facility is a worked-out quarry with a rocky base, which is intended for the final disposal of a sarcophagus-container 2 made of a basalt block. Fig. 2 illustrates a unified single design of the sarcophagus container 2, which has a cavity case 3 installed in the cavity of the sarcophagus container 2. This cavity case contains a lead matrix 4 (Fig. 2) with solid highly radioactive waste (not shown in Fig. 2). The cavity case is secured by locking devices of the cavity case 5 with a shell 6. Fig. 3 depicts the transportation network utilized to transfer the sarcophagus container (2) containing the heavy nuclear waste to the disposal facility (1). At the periphery of quarry 1, a platform (7) has been constructed, upon which a robot manipulator is installed for the unloading and preparation of the sarcophagus containers (2) with the aforementioned nuclear waste. The robotic platform is situated at the point of transfer of the sarcophagus container and at the base of the quarry for its ultimate disposal (Fig. 3). It is installed, for example, in a cut trench (not shown in the figures). The lowest surface of the structure is situated above the elevation mark, which is equal to or greater than the height of the skip body. The robotic platform, designated as 7, is situated on the section of the earth's surface that is in proximity to the design contour of the quarry (Fig. 3). The robot manipulator comprises a support post, a horizontal crossbar, a handling robot manipulator, and a phalanx gripper. Its purpose is to facilitate the handling of the sarcophagus-container with radioactive waste into the skip bodies, which are equipped with a braking device or devices (not shown in the figures). The robot manipulator comprises a support post (8), a horizontal crossbar (9), a handling robot manipulator (10) (Fig. 3), and a phalanx gripper (11). It is designed for the handling of the sarcophagus container (2) with radioactive waste into the skip bodies (12), which are equipped with a braking device and/or braking devices (not shown in the figures). Each individual skip body (12) is designed to accommodate the sarcophagus container (2) with HLW and the requisite machinery and mechanisms (not depicted in Fig. 1) that will be utilized at the base of the quarry during the burial process. The container 2 with HLW (excavator, trolley car, electric self-propelled bucket loader, etc.) is transported with a hinged side panel 13 and/or hinged side panels 13. The skip body 12 is equipped with supports 14, such as railway wheel pairs, rollers, etc., which exhibit different wheel diameters on opposite sides (Fig. 3). On one side of the supports (wheels) 14, the rim of the support 14 has a double ridge, while on the other side, it is smooth. Upon approaching a siding, the support wheel 14 with a double flange exerts a force on the skip body, causing it to switch to a specific track, as determined by the wheel with a double flange. The body 12 with the supports 14 is transported along the rail transport tracks 15 (Fig. 3), which are constructed on the section of the surface of the non-working side of the quarry 1. Each of these tracks can have a longitudinal axis that is rectilinear and/or concave and/or convex-concave and/or rectilinear-concave-convex, etc. (Fig. 3). The skip 12 is propelled by drives 16 and/or 17 (Fig. 3), which are counterweight devices that move under the influence of the force of gravity generated by any liquid placed in the tank of the counterweight device 16 (17) is operated without the use of any lifting machine along a special overpass 18, which has the ability to adjust the angle β, which is the angle of inclination of its longitudinal axis with the horizontal axis (Fig. 3). The movement of the rope 19 and/or 20, which is responsible for moving the skip body 12, is reversible. Its direction changes every time the skip body 12 reaches the end of the rail (transport) track 15. One component of the traction rope 19 and/or 20, which is equipped with a braking mechanism and/or multiple braking mechanisms (not depicted in Fig. 3), is affixed to the skip body 12. A section of the other the end of the traction rope (19 and/or 20) is placed on the pulley driver (21 and/or 22) (Fig. 3) and connected to the counterweight (23 and/or 24). The traction rope 19 and/or 20 is equipped with a protective device for safeguarding its outer surface from moisture and icing (not depicted in Fig. 1–3). Fig. 5 illustrates the control structure of the robotic method for the preparation and final disposal of sarcophagus-containers 2 with heavy radioactive waste in exhaust quarries 1.

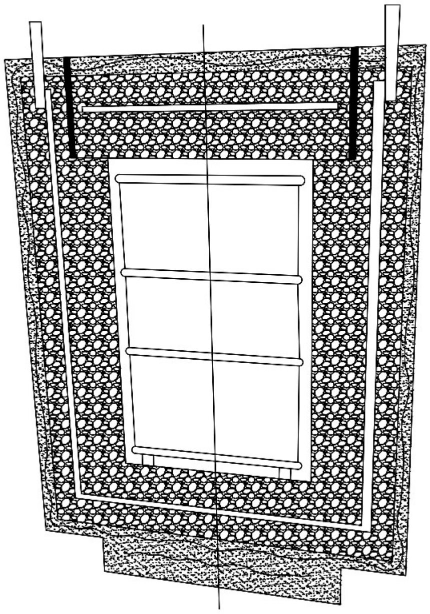

Fig. 2. Unified single structure of the Sarcophagus-Container 2

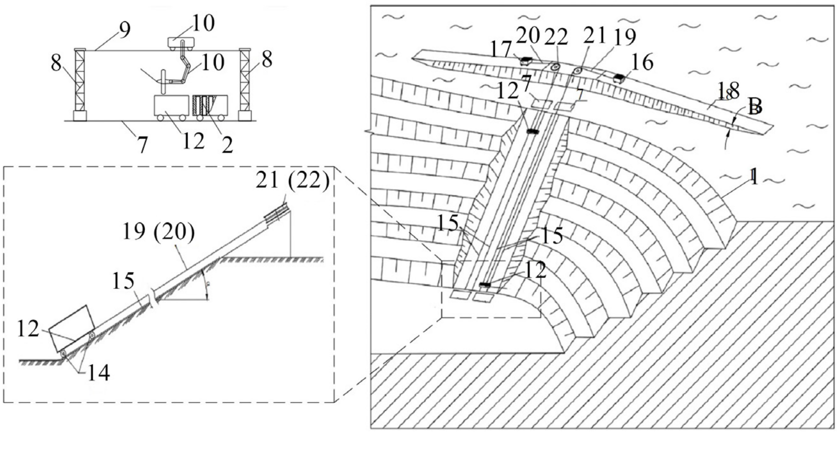

Fig. 3. The network transporting Sarcophagus Container 2 with heavy radioactive waste to Facility 1: 1 — terraced structure designed for stepwise material transport; 2 — primary material loading area; 7 — supporting base for the conveyor system; 8 — support columns providing stability to the system; 9 — structural beam for horizontal support; 10 — pulley mechanism facilitating movement of the conveyor; 11 — robotic arm or gripper used for precise material handling; 12 — conveyor belt for material transport across levels; 14 — ground level where initial material collection occurs; 15 — guiding elements ensuring smooth material flow along the conveyor; 16 — intermediate support for the conveyor structure; 18 — final unloading area where material is deposited; 19 — upper inclined section of the conveyor for material transfer; 20 — additional supporting mechanism for the inclined section; 21 (22) — dumping mechanism that controls material unloading at the top level

An illustrative example of the proposed technology in action is the burial of heavy waste radioactive waste. The process begins with the construction of a layer of imported clay at the bottom of quarry 1, which is at least 30 cm thick and leveled and compacted to form a flat horizontal pla form. This is then covered with a special waterproof film, which is not shown in Fig. 1–3. Fig. 2 depicts a unified, single structure of the sarcophagus-container 2, constructed from basalt blocks. This structure contains a cavity-case 3, which is installed within the cavity of the sarcophagus-container 2. The cavity-case 3 is utilized to contain a lead matrix 4 (Fig. 2), which is subsequently placed within the sarcophagus-container 2 with the heavy waste radioactive waste (Fig. 2). The locking mechanisms of the cavity case 5 with the shell 6 ensure the fixation of the position of the solid HLW in the matrix 4.

The transfer of operations from the intermediate container to the sarcophagus-container 2 for HLW is to be carried out using an innovative robot-manipulator. This eliminates the necessity for personnel to be present near the transfer robot-manipulator for the sarcophagus-container 2 with solid HLW, thereby ensuring safe working conditions. The transportation of the sarcophagus-container 2 with solid HLW is carried out using an innovative skip mechanism with the use of a gravitational counterweight, which reduces the cost of transporting one ton of HLW and improves the ecology of the quarry space. Sarcophagus-containers 2 with HLW are transferred to skips 12 of the transportation system for the purpose of moving HLW to storage facility 1, where it is ultimately disposed of (Fig. 1–3). In order to halt the movement of the skip body 12, the operator must release the grip of the grab (not shown in Fig. 1–3) on the traction cable 19 and/or 20, which is rigidly mounted on the body of the skip body 12. It is important to note that while the cable 19 and/or 20 continues to move, it should not stop. The transportation system ensures the installation of sarcophagus containers 2 with solid HLW in the storage facility 1 (burial site) in a vertical and/or practically vertical plane in several rows. For example, two or more rows of sarcophagus containers 2 with HLW may be installed, wherein each of them is located in a corresponding vertical row of sarcophagus containers 2 with HLW. The corresponding vertical row of sarcophagus containers with HLW is also in a row and/or in rows thereof. The longitudinal axis of each of these rows is located horizontally and/or practically horizontally in a layer of plastic rock (for example, clay) formed in the mined-out space at the bottom of the worked-out quarry 1. And/or on the bottom section of a natural depression (ravine, hollow, gully, canyon, etc.), with the construction of products-referred to here as “traps”-under the lower, above the upper bases and opposite all the side walls of each sarcophagus-container 2 with solid HLW (Fig. 1) for a sharp reduction or practical elimination of the force of seismic dynamic impact of an earthquake and various man-made and natural emergency situations on the body of each sarcophagus-container 2 with heavy nuclear waste, ensuring a high degree of reliability and safety of each sarcophagus-container 2 with heavy nuclear waste for an unlimited period of time, for example, up to one million years or more. The elimination of the force of seismic dynamic impact of an earthquake and various man-made and natural emergency situations on the body of each sarcophagus-container.

The provision of a high degree of reliability and safety of each sarcophagus-container for an unlimited period of time, for example, up to one million years or more. The primary consequence of the devised innovative system for the long-term storage of highly radiative waste in the rocky rocks of the spent nuclear fuel repository is the reliability of the long-term burial of the solid HLW in the rocky rocks of the spent mountain quarry. This can be achieved by placing the HLW, for instance, the heat-producing elements of the assembly of the nuclear power plant, in a container made from a block of strong rocks that do not pass radionuclides, such as basalt or granite. The dimensions of the container should be significant, for example, a diameter of up to six meters, with a mass of at least 1000 t. The container is constructed from a block of strong rocks that do not pass radionuclides, such as basalt or granite. Its dimensions are significant, with a diameter of up to six meters and a mass of 1000 t or more. A special cavity and/or cavity is designed into the block of strong rocks, into which and/or within which the HLW and/or HLWs are placed. Previously, the HLW and/or HLWs were delivered from nuclear power plants in an intermediate container to the assembly and reloading point, which was built from a worked quarry and/or a section of a natural deepening. From the intermediate container to the innovative container with HLW, the overload of solid HLW is provided using an innovative industrial robot manipulator. In this case, the presence of personnel near the innovative container with HLW is excluded, thereby ensuring safe working conditions. The storage system provides for transporting solid HLW containers to the burial site via a transportation network [11]. The sarcophagus-container with HLW is comprised of a body with cavities, or “pencils,” in which the HLW is located. Each pencil is equipped with a locking device. The shell for fixing the position of HLWs is constructed from a basalt block, which is carved to form a cavity of a specific length.

An expert system is developing a novel approach to the burial of containers with solid HLW [6, 11]. The aforementioned articles have already provided a detailed description of the performance of these systems. In addition, the operational parameters of these systems are controlled in consideration of the stochastic conditions of the burial of containers with solid HLW. Furthermore, the technology for substantiating the innovative design of a skip hull of any size, including its carrying capacity, is also described. This technology is applicable to single-rope and multi-rope steeply inclined skip hoists for the highly profitable, safely friendly transportation of sargofagous containers with solid HLW.

5. 2. Study of the basalt sarcophagus container

The sarcophagus container 2, constructed from a basalt block, comprises composite layers. Fig. 2 depicts a unified single design of the sarcophagus container 2, which contains a cavity case 3. This cavity case contains a lead matrix 4 (Fig. 2), into which solid highly radioactive waste (not shown in Fig. 2) is placed. Between the lead matrix (innermost layer) and the basalt block (outermost layer), clay layers are placed.

In the formed cavity, the value of the cross-sectional area, which is constant along its entire length, is determined from the expression:

$$l_{st} \geq l_b \cdot N_{year}, \tag{8}$$

l_{st} is the thickness of the wall of the sarcophagus-container 2 between any section of the surface of the cavity 3 in the sarcophagus-container 2 and any section of the outer surface of the block of the sarcophagus-container 2. This is the distance at which migration of solid HLW radionuclides from the cavity 3 is excluded during the required critical period. The time period (in accordance with IAEA requirements, not less than one hundred thousand years) is denoted by m. The distance of migration of solid HLW radionuclides through the layer of sarcophagus-container 2 made of basalt during one year is represented by m. The number of years of the required critical period of time during which migration is excluded is represented by N_{year}. The migration of solid HLW radionuclides through the layer of sarcophagus-container 2 made of basalt is excluded, for example, amounting to one hundred thousand years. HLW are placed in a matrix 4 made of lead, the thickness of any wall of the matrix 4 being determined by the formula (Fig. 2):

$$L_M \geq k_{lead} T_{cr}. \tag{9}$$

The coefficient k_{lead} represents the features of lead matrix manufacturing technology under specific conditions. The thickness of the lead matrix layer, L_M, is the distance in meters of the lead matrix layer 4 through which the migration of solid HLW radionuclides is excluded during the period of time from the time of placement of HLW in the free space of matrix 4 (Fig. 2) to the time of placement of the sarcophagus-container. The second is composed of basalt, in which the matrix 4 with solid HLW is located in the HLW storage facility 1-HLW burial site. The thickness of the lead matrix layer 4 through which HLW migrates during a unit of time, for example, one year, is denoted by l. The duration of the period of time from the moment of placement of the solid HLW in the matrix 4 is designated by T_{cr}. The sarcophagus container, constructed from a basalt block, is placed within the cavity, which is the location of the matrix, also constructed from lead, with the solid HLW. This matrix is placed within the storage facility, which is the burial site of the solid HLW. The matrix, constructed from lead, with the HLW, is placed within the cavity, which has been created within the sarcophagus. The container 2 is constructed from a basalt block, with a free space between the end of the matrix 4 made of lead and the section of the surface of the cavity limited by the section of the outer surface of the sarcophagus-container made of a basalt block. A layer of clay is then placed (Fig. 2), with the thickness of the clay layer L_{clay} in the cavity determined by the following formula:

$$L_{clay} \geq K_{clay} \cdot l_{year(cr)} \cdot T_{cr}. \tag{10}$$

The coefficient K_{clay} accounts for the specific conditions under which the technology for producing the lead matrix 4 is employed. The thickness of the clay layer transformed into ceramics, $l_{year(cr)}$ is a result of the effect of the temperature of the solid HLW on the clay. This temperature, equal to 280–300 °C, is the point at which the HLW radionuclides migrate during the process a unit of time, m; T_{cr} is the duration of the period of time from the moment of placing the HLW in the lead matrix 4 until the moment of placing the sarcophagus-container 2 made of a basalt block, in the cavity 3 of which the lead matrix 4 with solid HLW is placed, in the storage facility 1, which is the HLW burial site, in years. The HLW is initially transported from the NPP in an intermediate container (not depicted in Fig. 1–3) to the assembly and handling point 7, situated in close proximity to the depleted quarry 1 and/or a section of a natural depression.

Composite layers:

1. Lead matrix (innermost layer).
2. Clay layer (middle layer).
3. Basalt block (outermost layer).

Boundary conditions: ASSUMING the inner surface of the lead matrix is at temperature $T=T_1$ and the outer surface of the basalt block is at temperature $T=T_2$:

1. At ($r=r_1$) (inner radius of the lead matrix), ($T=T_1$).
2. At ($r=r_2$) (outer radius of the basalt block), ($T=T_2$).

Solution for each layer: the general solution for the temperature distribution in a cylindrical layer is given by:

$$T(r)=A\ln(r)+B, \tag{11}$$

where A and B are constants determined by boundary conditions and continuity conditions at the interface:

– layer 1. Lead matrix: for $r_1 \leq r \leq r_2$:

$$T_{lead}(r)=A_1\ln(r)+B_1; \tag{12}$$

– layer 2. Clay: for $r_2 \leq r \leq r_3$:

$$T_{clay}(r)=A_2\ln(r)+B_2; \tag{13}$$

– layer 3. Basalt: for $r_3 \leq r \leq r_4$:

$$T_{basalt}(r)=A_3\ln(r)+B_3. \tag{14}$$

Continuity conditions:

1. At $r=r_2$, temperature and heat flux must be continuous:

$$T_{lead}(r_2)=T_{clay}(r_2),$$

$$k_{lead}\cdot(dT_{lead}/dr)|r=r_2=k_{clay}dT_{clay}/dr|r=r_2. \tag{15}$$

2. At $r=r_3$, temperature and heat flux must be continuous:

$$T_{clay}(r_3)=T_{bazalt}(r_3),$$

$$k_{clay}\cdot(dT_{clay}/dr)|r=r_3=k_{bazalt}dT_{bazalt}/dr|r=r_3. \tag{16}$$

Solving the constants:

1. Use the boundary conditions to solve for B_1 and B_3.
2. Use the continuity conditions to solve for A_1, A_2, B_2 and A_3.

Example: let's assume the following radii: r_1 – inner radius of lead matrix; r_2 – outer radius of lead matrix/inner radius of clay layer; r_3 – outer radius of clay layer/inner radius of basalt block; r_4 – outer radius of basalt block.

With temperatures: $T(r_1)=T_1$. $T(r_4)=T_2$. Plug in the boundary conditions and continuity conditions to find the constants and the complete temperature distribution across the composite structure. If to provide specific values for r_1, r_2, r_3, r_4, T_1, T_2, and thermal conductivities k_{lead}, k_{clay}, k_{basalt} it is possible to derive the exact temperature distribution.

Let's consider an example where it is possible to illustrate the temperature distribution across the layers:

– lead matrix: $r_1=0.1$ m (inner radius); $r_2=0.2$ m (outer radius); $k_{lead}=35$ W/(m·K);

– clay layer: $r_2=0.2$ m (inner radius); $r_3=0.3$ m (outer radius); $k_{clay}=0.6$ W/(m·K);

– basalt block: $r_3=0.3$ m (inner radius); $r_4=0.4$ m (outer radius); $k_{basalt}=1.7$ W/(m·K).

Temperatures: $T(r_1)=T_1=300$ °C, $T(r_4)=T_2=T_2=50$ °C. It has been established for distributing the temperature distribution across those the layers of the sarcophaguous using the heat conduction equation and continuity conditions (Fig. 4).

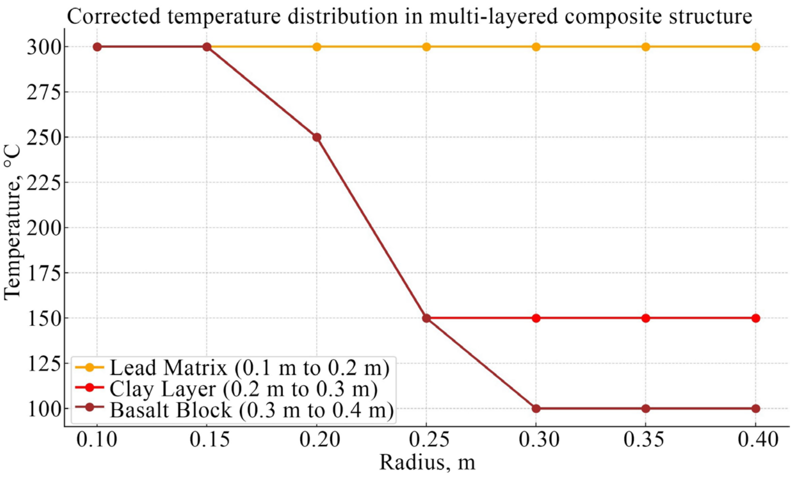

Fig. 4. The changing of temperature into the layers the sarcofagous with HLW

Temperature distribution calculation:

1. Lead matrix layer:

$$T_{lead}(r)=A_1\ln(r)+B_{1.}$$

2. Clay layer:

$$T_{clay}(r)=A_2\ln(r)+B_2.$$

3. Basalt layer:

$$T_{lead}(r)=A_1\ln(r)+B_1.$$

Continuity and boundary conditions:

1. $Atr=r_1$, $T=T_1$:

$$T_{lead}(r_1)=300=A_1\ln(r_1)+B_1.$$

2. $Atr=r_4$, $T=T_2$:

$$T_{basalt}(r_4)=50=A_3\ln(r_4)+B_3.$$

3. $Atr=\mathrm{r}_2$, $T_{lead}(r_2)=T_{clay}(r_2)$:

$$A_1(r_1)\ln(r_2)+B_1=A_2(r_2)\ln(r_2)+B_2.$$

4. $Atr=r_3$, $T_{clay}(r_3)=T_{basalt}(r_3)$:

$$A_2(r_3)\ln(r_2)+B_2=A_3(r_3)\ln(r_3)+B_3.$$

5. Heat flux continuity at $r=r_2$:

$$k_{lead}\cdot(dT_{lead}/dr)|r=r_2=k_{clay}dT_{clay}/dr|r=r_2.$$

6. Heat flux continuity at $r=r_3$:

$$k_{clay}\cdot(dT_{clay}/dr)|r=r_3=k_{bazalt}dT_{bazalt}/dr|r=r_3.$$

Solving the equations. Let's plug in the values and solve for the constants. Then, it is possible to plot the temperature distribution. Let's perform these calculations and create a plot (Fig. 4). Here is the temperature distribution in the multi-layered composite structure:

– lead matrix: from r_1=0.1 m to r_2=0.2 m;
– clay layer: from r_2=0.2 m to r_3=0.3 m;
– basalt block: from r_3=0.3 m to r_4=0.4 m.

6. The study to developing an approach to ensure the safety and reliability of burying a sarcophagus with HLW

The proposed solutions in this article focus on an innovative approach to burying high-level radioactive waste (HLW) using basalt containers in spent mines, with transportation managed by a counterweight-driven winch skip system. Basalt's inherent durability, resistance to radiation, and low permeability make it an ideal material for long-term containment of HLW. This provides superior protection against leakage and environmental contamination. Comparison: in [4] discuss various materials and methods for containing radioactive waste in repurposed mines but may not emphasize basalt specifically. The use of basalt provides a naturally robust solution that may surpass other containment methods discussed in [4] in terms of long-term stability and radiation resistance. In the article make focus on a utilization of spent mines. By repurposing existing spent mines, the approach minimizes environmental impact and capitalizes on existing infrastructure, which reduces costs and expedites implementation. Comparison: in [4] authors also explore repurposing abandoned quarry globally for radioactive waste disposal. However, they focus on a broader range of mines and do not specify the use of a particular material like basalt. Advantages of the proposed study compared to [4]. Material selection and containment: the use of basalt containers specifically tailored for HLW disposal is a key advantage, offering superior durability and radiation resistance compared to more generalized solutions. In [4] authors study addresses a variety of materials and techniques but may not focus on the unique properties of basalt, which could limit the long-term safety and effectiveness of the containment. The proposed study's specific focus on basalt containers may offer a more tailored solution with proven material benefits. Cost and environmental impact: proposed study: the strategy of repurposing existing infrastructure (abandoned quarries) and utilizing a cost-effective transportation system (counterweight-driven winch) significantly lowers both financial costs and environmental impact. Comparison: in [4] study consider various transportation methods within repurposed quarries but does not highlight an energy-efficient system like the counterweight-driven winch. The proposed system in the current study could offer better operational efficiency and safety. Energy efficiency: proposed study: the emphasis on energy efficiency through the counterweight-driven winch system is a notable benefit, offering reduced operational costs and lower energy consumption. In [4] the discussion not specifically address energy-efficient transportation methods, which could be a gap in their approach compared to the current study's focused solution. The proposed study offers a more specialized and potentially more robust solution for HLW disposal by focusing on the use of basalt containers and energy-efficient transportation within repurposed abounded quarries. Compared to [4] it is broader global perspective, the proposed study's approach may provide better long-term containment and operational efficiency, although both studies highlight the benefits of repurposing abandoned mines for radioactive waste disposal.

The proposed solutions involves the challenges associated with long-term durability of containment materials, geotechnical stability environment, interactions and groundwater contamination and comprehensive risk assessment models, addressing human interference management and technological innovation and adapting repository designs to diverse geological conditions on based by justifying a novel approach to the burial solid HLW are preliminarily delivered from the nuclear power plant in an intermediate container to an assembly and handling point built near the abandoned quarry and/or a section of a natural depression (Table 1, Fig. 1, 3). This solution capitalizes on already stable environments, avoiding the need for new, potentially less stable containment sites.

The results of the study on the innovative burial method for high-level waste (HLW), which involves placing the waste in a basalt container and transporting it into spent mines using a winch skip with a counterweight drive, can be explained by considering several key factors: material properties of basalt containers. This is achieved by placing heavy radioactive waste, which may include fuel elements of assemblies from a nuclear reactor at a nuclear power plan, in a basalt container (Fig. 2). The container is constructed from a block of hard rock that does not allow radionuclides to pass through. This rock may be basalt, granite, or another hard rock suitable material. The incorporation of advanced composite materials, such as basalt blocks, lead matrices, and clays, has been justified in research as a means of improving the durability and resistance to radiation and heat of containers with high-level waste (HLW). The basalt container represents an integral part of an innovative approach to the burial of sarcophagus containers with solid HLW in exhausted mining pits. This cavity case contains a lead matrix (Fig. 2), into which solid highly radioactive waste is placed. Between the lead matrix (innermost layer) and the basalt block (outermost layer), clay layers are placed. The utilization of basalt for the sarcophagus container is a prudent choice, given its impermeability and durability. Moreover, the rationale behind the thickness of the container walls, which is designed to prevent radionuclide migration in accordance with established guidelines (e. g., IAEA requirements), is also a significant factor (8)–(10). Comprehensive containment: the combination of using a robust basalt container, the stability of abandouned quarry, and the efficient winch skip system provides enhanced safety for HLW disposal. The layering of the composite materials and the values of their radii make sense with HLW containment scenario. Research has been conducted into the potential use of self-healing materials, such as the clay layer, which evidence suggests permits automatic repair of minor cracks or damage, enhancing long-term containment integrity. The temperature distribution across the composite layers (lead matrix, clay layer, and basalt block) in a cylindrical geometry has been analyzed and provided with a description (7), (11)–(16). The use of a counterweight-driven winch skip offers a practical and low-cost method of transporting HLW, addressing these logistical challenges without human interference. This comprehensive approach provides a robust solution to the long-standing challenges in HLW management. In the article have been established the distribution of temperature into the multi-layered composite structure of the basalt sarcophagous with HLW from 300 °C into the inner space to 50 °C onto on the its outer suffer where the thickness of each layers (from inner to outer radious) was respectively: for lead matrix: from r_1=0.1 m to r_2=0.2 m; for clay layer: from r_2=0.2 m to r_3=0.3 m.; for basalt block: from r_3=0.3 m to r_4=0.4 m. The calculated migration distances and the thickness of the layers ensure that radionuclide migration is effectively prevented over this critical period. The research supports the practical implementation of this containment solution in exhausted mining pits or natural depressions. The methodology for transporting HLW in intermediate containers to the burial site and then securely placing it within the basalt sarcophagus-container is well-defined and realistic. The thorough testing and validation of the mathematical models, including the use of numerical solutions and boundary condition analysis, confirm the reliability and accuracy of the proposed design. The findings on temperature distribution are crucial as they directly affect the performance and longevity of the basalt containment system. The testing examples and the use of numerical methods were also ensured to provide evidence that the chosen thermal conductivities and temperatures were realistic. The resulting plots (Fig. 4) illustrate the temperature distribution across the multi-layered composite structure, transitioning from the innermost lead matrix to the outermost basalt block. The study includes a comprehensive analysis of temperature distribution across the composite layers. The correct application of boundary and continuity conditions, supported by both numerical and analytical methods, ensures that the temperatures remain within safe limits, preventing the degradation of the containment materials. The design of the sarcophagus-container is specifically intended to meet or exceed the International Atomic Energy Agency's (IAEA) requirements for long-term safety, which demand containment for at least 100,000 years.

Technical feasibility and innovation: the innovative burial system incorporate state-of-the-art engineering techniques to enhance the safety and longevity of the disposal. The transfer of solid HLW and/or HLWs from the intermediate container to the innovative container with HLW is planned to be carried out using an industrial robot manipulator (Fig. 3). Efficiency of the winch skip system (Fig. 3). The dimensions of the container are significant, with a diameter of up to six meters and a mass of up to 1000 tons or more. A special cavity and/or cavities are formed in the block of hard rock, and it is planned to place fuel elements into it. The sarcophagus container is transported using an innovative skip mechanism with a gravitational counterweight, which reduces the cost of transporting one ton of solid HLW and improves the ecology of the quarry space. This eliminates the necessity for personnel to be present near the innovative container with HLW, which ensures safe working conditions (Fig. 3). The use of a winch skip with a counterweight as a drive to transport the basalt containers into the abandoned quarry offers a reliable and energy-efficient method [11]. The counterweight system minimizes the energy required for transportation, making the process more sustainable. The results demonstrate that this method is both technically feasible and effective in safely placing the HLW into deep geological formations. Then, using the innovative robot (Fig. 3) the container with HLW is lowered onto the upper surface of a layer of plastic rock, for example, clay, formed in the mined-out space of an exhausted quarry or on a section of the bottom of a natural depression. A series of layers of clay are formed around all the side walls and the upper base of the innovative container with HLW, the geometric dimensions of which are calculated using scientific methods (Fig. 1, 3). As a result, that is make sure the waste is isolated from the biosphere, thus minimizing the risk of radiation exposure to humans and the environment. The placement of sarcophagus containers with solid HLW is realized into depleted mining quarry with the rocks by forming there a series of layers of clay in advance. Finally, natural barriers are constructed around the containers with HLW and their upper surfaces. Consequently, all of these facilities will be situated in geologically stable regions, which will provide natural barriers to contain radioactive materials. Furthermore, they will also serve to safeguard groundwater supplies. Consequently, by selecting appropriate sites and engineering appropriate barriers, groundwater contamination can be prevented, which is a significant concern in the disposal of radioactive waste (Fig. 1–3). In this case it is evident that the storage with solid HLW located into spent open-pit will be safeguarded from any potential threats, even located in areas with a high seismic activity risk. The study also highlights the economic benefits of using locally available basalt and existing infrastructure in spent mines. The results could suggest that this approach is not only effective in terms of containment but also cost-efficient compared to other HLW disposal methods.

In the article are not take account the variability in the geological conditions of abandoned mines globally presents challenges in standardizing disposal methods. Additionally, the diverse regulatory and environmental conditions in different countries could complicate the implementation. Proposed study: while the proposed solutions are promising, the long-term performance of basalt containers in varying mine conditions needs further empirical validation. The adaptability of the counterweight-driven winch system across different mine types is also an area that requires further exploration. When applying the results of this study in practice, as well as in further theoretical research, several limitations must be taken into account: The study assumes that spent quarries used for HLW containment are uniformly stable and suitable for long-term waste storage. However, geological conditions can vary significantly between different mine sites, potentially affecting the safety and stability of the waste containment system. Theoretical research should focus on modeling the degradation processes of basalt under various stressors over thousands of years to predict its performance more accurately. Complexity of transport mechanism: the counterweight-driven winch skip system, while energy-efficient, may face operational challenges, especially in remote or difficult-to-access mine locations. Maintenance and reliability of the system in harsh environments could be a concern. The study may not fully address the complex regulatory and safety requirements associated with HLW disposal in different countries. Variations in regulations and public acceptance could limit the application of this solution. The study primarily considers the use of a single or a few mine sites for HLW containment. The scalability of this solution to accommodate large volumes of waste across multiple sites is not fully explored.

While the proposed solution offers promising advantages for HLW disposal, these limitations highlight the need for further practical assessments and theoretical research. Addressing these limitations will be essential for ensuring the successful implementation and widespread adoption of the proposed HLW containment method. The study presents a promising approach to high-level waste (HLW) disposal, but it has several shortcomings that must be acknowledged. Limited empirical validation. The study relies heavily on theoretical models and simulations to predict the performance of the proposed HLW containment system. However, it lacks extensive empirical data or real-world testing to validate these predictions. Implication: without empirical validation, the reliability of the proposed solutions under actual conditions remains uncertain, potentially undermining confidence in the results. Incomplete analysis of long-term effects. The study does not fully explore the long-term effects of environmental factors such as radiation, temperature variations, and mechanical stress on the basalt containers and the overall system. This omission could lead to an underestimation of potential degradation or failure over time, which is critical given the need for HLW containment over thousands of years. Narrow focus on specific geological conditions. The study's focus on using spent mines for HLW disposal assumes that such mines are universally available and geologically stable. It does not consider the variability in geological conditions across different regions or the potential limitations of using certain mine types. Implication: this narrow focus limits the generalizability of the findings, potentially making the solution less applicable in regions with different geological characteristics. The study does not provide a detailed analysis of the economic feasibility of the proposed HLW disposal method. Factors such as the cost of retrofitting mines, constructing basalt containers, and maintaining the winch skip system are not thoroughly explored. The study does not adequately address the regulatory and societal challenges associated with HLW disposal. It overlooks potential hurdles in obtaining regulatory approval and public acceptance for using spent mines and innovative containment methods. Implication: failure to consider these challenges could result in delays or obstacles in the implementation of the proposed solution, particularly in regions with stringent regulations or public opposition to HLW disposal projects.

These shortcomings highlight areas where the study could be strengthened through additional research, empirical validation, and broader analysis. Addressing these issues is crucial for ensuring the robustness, feasibility, and wider applicability of the proposed HLW disposal method. Developing this research involves expanding empirical validation, assessing long-term performance, and ensuring economic and regulatory feasibility. By addressing these aspects, the proposed HLW disposal solution can be refined, validated, and made more widely applicable, ultimately advancing the field of HLW management. Development of advanced modeling techniques. Utilize advanced computational models and simulations to predict the long-term behavior of basalt containers and the overall disposal system. Enhances the ability to anticipate potential issues and optimize the design before implementation, based on detailed and accurate modeling. Developing this research involves expanding empirical validation, assessing long-term performance, and ensuring economic and regulatory feasibility. By addressing these aspects, the proposed HLW disposal solution can be refined, validated, and made more widely applicable, ultimately advancing the field of HLW management. Developing these researches involves expanding empirical validation, assessing long-term performance, and ensuring economic and regulatory feasibility. By addressing these aspects, the proposed HLW disposal solution can be refined, validated, and made more widely applicable, ultimately advancing the field of HLW management.

7. Conclusions

1. In the research have been justified a novel approach to the burial of sarcophagus containers with solid HLW in exhausted mining pits. The proposed solutions effectively close the problematic part of long-term durability of containment materials and technological innovation adapting repository designs to diverse geological conditions as well as geological stability and addressing human interference. The sarcophagus-container by constructed of a basalt the dimensions of which is not limited transported by using an innovative skip mechanism with a gravitational counterweight, which significantly reduces the cost of transporting one ton of solid HLW and improves the ecology of the quarry space. Subsequently, the innovative container with solid HLW is lowered onto the upper surface of a layer of plastic rock, for example, clay, that by covered in advance in the mined-out space of an exhausted quarry or on a section of the bottom of a natural depression. The clay is formed around all the side walls and the upper base of the innovative container with solid HLW, the geometric dimensions of which are scientifically calculated. This is accomplished by interring high radioactive waste, which may include fuel elements of assemblies from a nuclear reactor is placed into a container by constructed from a basalt with the significant dimensions, such as a diameter of up to six meters and a mass of up to 1000 tons or more. The transfer of HLW from the intermediate container to the innovative container with solid HLW is carried out using an innovative industrial robot manipulator. By theses eliminates the necessity for personnel to be present near the innovative container with solid HLW, thus ensuring safe working conditions.

2. The research successfully addresses problem involves the challenges associated with long-term containment and management of as well heat management in repositories. Specifically, the study shows that the temperature remains within safe limits across all layers – lead matrix, clay, and basalt – of the basalt container in a given testing conditions. The distinctive feature of the design is the transformation of the clay layer into a ceramic barrier under high temperatures, enhancing containment integrity. Comprehensive approach in a stable and secure environment provides a robust solution to the long-standing challenges in HLW management. In the research have been established the distribution of temperature into the multi-layered composite structure of the basalt sarcophagous with HLW from 300 °C into the inner space to 50 °C onto on the its outer suffer where the thickness of each layers (from inner to outer radius) was respectively: for lead matrix: from r_1=0.1 m to r_2=0.2 m; for clay layer: from r_2=0.2 m to r_3=0.3 m.; for basalt block: from r_3=0.3 m to r_4=0.4 m. The findings on temperature distribution are crucial as they directly affect the performance and longevity of the basalt containment system. By presenting key results related to the temperature distribution within the multi-layered sarcophagus-container design for HLW containment. These results confirm that the composite structure effectively manages heat, preventing material degradation and ensuring long-term isolation of radioactive waste.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors have used artificial intelligence technologies within acceptable limits to provide their own verified data, which is described in the research methodology section.

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