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JUSTIFICATION OF A DUAL VENTILATION SYSTEM FOR THE COMPLETE BURIAL OF HIGH-LEVEL RADIOACTIVE WASTE IN SPENT OPEN MINES

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The complete burial of high-level radioactive waste (HLW) in spent open mines presents a promising solution to long-term waste isolation. This study presents the justification and design of an innovative dual ventilation system aimed at regulating heat and removing gas-dust mixtures from such repositories. The ventilation system is designed to control dust-gas emissions and thermal loads through a two-chimney configuration, enabling efficient gas extraction and convective cooling. A system of main and additional chimneys is proposed: the main chimney channels the rising hot gas-dust mixture, while the additional chimney processes it through a staged treatment system before final disposal. Mathematical modeling, including Fourier's Law, Darcy's Law, and Fick's Law, supports the thermal, hydraulic, and gas dynamics simulations. The study demonstrates that with adequate ventilation flow and composite-layer insulation, internal repository temperatures can be reduced from 300°C to below 100°C within 30 years, significantly lowering the risk of container degradation and gas-induced particle mobilization. The integrated system improves the safety, observability, and long-term reliability of HLW burial in open spent mines, offering a scalable and internationally compliant solution. Through a combination of temperature distribution modeling, structural analysis, and airflow simulations, the system's viability is demonstrated. The results show that the proposed ventilation configuration provides effective thermal regulation, structural resilience under stress, and compatibility with repurposed mining infrastructure. The study contributes a scalable, energy-efficient solution to HLW (High-level radioactive waste) repository management, paving the way for safer and more sustainable nuclear waste isolation

***Keywords:** radioactive waste, spent mines, ventilation system, heat management, repository safety*

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1. Introduction

The safe disposal of high-level radioactive waste (HLW) is one of the most enduring and unsolved problems in nuclear engineering and environmental protection. Despite decades of research and investment, no universally accepted solution currently exists that can guarantee complete isolation of HLW over geological timeframes. The long-lived radiotoxicity, extreme heat generation, and potential for groundwater interaction present major challenges for containment integrity. This makes HLW management a globally critical issue that transcends national boundaries and scientific disciplines.

Conventional disposal approaches, such as deep geological repositories and dry cask storage, often lack sufficient mechanisms to deal with the cumulative heat buildup and gas evolution over time. These systems risk long-term degradation of structural barriers and potential failure in maintaining environmental isolation. In particular, they frequently overlook the dynamic behavior of gases and dust particles produced during the decay of HLW, which can jeopardize repository integrity and worker safety.

In this context, the repurposing of spent open-pit mines as burial sites for HLW emerges as a promising yet underutilized direction. These sites offer volumetric capacity, geological depth, and existing infrastructure, but their adaptation demands advanced technological support – particularly in thermal regulation and gas-dust removal. Without adequate management of temperature and emissions, such facilities cannot meet safety standards or gain public trust.

Equally critical is the development of innovative ventilation systems tailored to the unique physical and chemical processes occurring within HLW repositories. The scientific community increasingly recognizes that passive containment alone is insufficient. Active ventilation systems, capable of heat removal, pollutant capture, and long-term monitoring, are essential to ensure the structural and environmental stability of HLW repositories – especially in large-volume, repurposed geological structures such as open spent mines.

Therefore, research into the development of advanced ventilation systems for HLW burial sites is of paramount scientific and practical relevance. Such work addresses an urgent gap in global nuclear waste strategy and contributes to the design of repositories that are not only structurally sound but also environmentally sustainable and publicly acceptable.

2. Literature analysis and statement of the problem

In paper [1], the central problem addressed is the safety and design of deep geological repositories (DGRs), with a specific focus on achieving repository safety through passive containment. The authors investigate multi-barrier concepts for radionuclide containment and model repository behavior under heat and radiation. Their key contribution lies in clarifying the effects of passive barriers in heat management. They discuss several strategies and considerations to enhance the safety and effectiveness of DGRs, centered around the multi-barrier system.

This approach involves implementing a combination of engineered and natural barriers to isolate radioactive waste, thereby reducing the likelihood of radionuclide migration. A significant unsolved issue in this paper is the lack of consideration for active ventilation. This omission reinforces the need to explore systems that dynamically manage internal repository temperature. The resulting insight is that active ventilation is essential to complement multi-barrier strategies where natural heat dissipation may be inadequate. Therefore, thermal management must be a critical consideration in designing safe repository layouts. This ensures that temperatures, accounting for the heat generated by radioactive decay, remain within safe limits to maintain the integrity of all barriers.

In paper [2] problem addressed is engineering challenges in repurposing mines for HLW disposal. Solved issues: identified structural degradation and water ingress as key risks. Proposed reinforcement strategies for mine stability. Unsolved issues: long-term ventilation performance not addressed. Gas buildup from radiolysis and natural decomposition lacks mitigation models. 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. Relevance: supports the need for active ventilation to manage structural and gas risks in repurposed mines. Gap is lack of strategies for continuous gas evacuation and thermal regulation. Justification insight of an innovative ventilation systems are crucial to ensure structural stability and prevent hazardous gas accumulation over time.

The paper [3] reviews recent Ukrainian research on innovative containment solutions for HLW, particularly focusing on improving the geological stability and reducing environmental impact. Solved issues is to introduced advanced radiation-resistant barriers (e.g., clays, polymers). 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. The research's gap is no integration of ventilation as a control method for gas or heat. Unsolved issues: heat management strategies, including ventilation, remain theoretical. Lack of integration between material science and environmental control. Conclusion: even with improved materials, controlled airflow is needed to handle unpredictable gas or moisture migration.

The paper [4] make focus on global feasibility of mine reuse. In this article is addressed a worldwide case studies of using abandoned mines for HLW disposal problem. Solved issues is an economic feasibility of mine reuse, and neediness for post-closure monitoring systems. Gas escape modeling and filtration remain underexplored. Relevance: underlines the ventilation system's role in converting abandoned mines into safe repositories. Gap: ventilation feasibility across heterogeneous mines not addressed. Conclusion: to custom ventilation systems are necessary to adapt to diverse mine architectures and prevent localized overpressure or heat zones.

This study [5] focuses on optimizing thermal load management in deep geological repositories to enhance disposal efficiency, particularly in regions with limited land availability and substantial waste quantities, such as Korea. The research aims to analyze the thermal effects of engineered and natural barriers within a repository. Review thermal management strategies for various host rocks, including crystalline, clay, and salt formations. Identify effective thermal management methods applicable to specific regional contexts. Issues addressed and solutions proposed: the study proposes several thermal management methods to improve disposal efficiency. Solved issues: strategies to reduce initial heat via fuel cooling and buffer optimization. The article demonstrates importance of pre-disposal cooling of storage's space with HLW and thermal design. Enhancing the thermal conductivity of buffer materials like bentonite to facilitate better heat dissipation. Optimizing the size of disposal containers to balance heat generation and spatial efficiency. Thermal analyses were conducted for each method, and their impact on disposal efficiency was preliminarily evaluated. Gap: omits role of airflow in ongoing heat dissipation post-burial, and ventilation not considered in thermal diffusion modeling. Lack of airflow models for heterogeneous geological conditions. Relevance of the article is in reinforcing the justification for ventilation to complement passive thermal methods. Authors reinforce need for engineered ventilation to sustain long-term thermal stability after burial HLW in open spent mine.

The paper [6] focus on an investigation natural airflow in dry cask storage with HLW. The result of the theoretical analysis was validated with simulation software and experimental investigation using a reduced-scale dry storage prototype. The dry storage prototype consisted of a dry cask body and two canisters stacked to store materials testing reactor (MTR) spent fuel, which generates decay heat. The cask body had four air inlet vents on the bottom and four air outlet vents at the top. To simulate the decay heat from the spent fuel in the two canisters, the canisters were wrapped with an electric wire heater that was connected to a voltage regulator to adjust the heat power. The study investigates the effectiveness of natural airflow in dissipating heat from spent nuclear fuel stored in dry cask systems. Proper heat removal is crucial to prevent overheating and ensure the safe storage of radioactive materials. Solved issues: validated natural airflow models experimentally and theoretically. Gap: not scalable to deep-mine scenarios with limited airflow pathways. Uncertainties in measurements and final results, with combining uncertainties calculated at 33.03% and 24.8% for different models. The study suggests that further research is needed to refine the models and reduce uncertainties in heat transfer predictions. Justification insight: passive systems alone are insufficient; enhanced forced ventilation is necessary in deep, sealed HLW mines.

The study [7] focuses on the management of metal frames from waste filters used in the ventilation systems of nuclear power plants. In the article addresses lifecycle management of contaminated ventilation components. These frames, after use, are expected to have low radiation levels and could potentially be recycled or reused. However, a systematic clearance assessment is necessary to ensure they meet safety standards before recycling. The authors established a clearance assessment scheme tailored for metal frames in nuclear power plants. This scheme is based on long-term experience and unit-specific characteristics, aiming to provide a structured approach to assess and manage the clearance of these materials. Gap: lacks strategic design of future-proof ventilation in radioactive environments, and operational ventilation safety (e.g., gas/dust exposure) during long-term storage not analyzed. Justification insight: reinforces the need for modular, maintainable ventilation architecture in long-lived HLW mines.

The paper [8] examines the design and operation of ventilation systems in underground repositories for low to intermediate-level radioactive waste. Effective ventilation is crucial to control pollutants such as radon, methane, carbon monoxide, hydrogen sulfide, and radioactive gases resulting from radiolysis, ensuring the safety of both the environment and personnel. The authors analyzed ventilation systems of existing repositories, specifically the waste isolation pilot plant (WIPP) in the USA and the Swedish Slutförvar för Reaktoravfall (SFR). They evaluated required air quantities, designed ventilation networks considering factors like cross-sectional area, length, and surface roughness of air passages, and calculated the resistance of each circuit. The study suggests that combining the large cross-sectional area design of the SFR repository with the parallel circuit structure of the WIPP repository could lead to a more rational and efficient ventilation system. While the study provides valuable insights into designing efficient ventilation systems, it does not delve into the long-term operational challenges, such as maintenance of ventilation infrastructure, potential system failures, and the impact of unforeseen environmental conditions. Additionally, the adaptability of the proposed combined design to different geological and regulatory contexts remains unexplored. In summary, this article contribute to enhancing safety and efficiency in radioactive waste management through improved ventilation systems. However, practical implementation challenges, long-term operational considerations, and adaptability to varying conditions are areas that require further research and development. It is possible to provide an overview of pertinent challenges and advancements in ventilation systems for radioactive waste storage based on available literature. Ensuring adequate ventilation to protect workers from exposure to hazardous substances, such as volatile organic compounds (VOCs) and diesel particulates, in underground nuclear waste repositories. Identifying and rectifying design flaws in ventilation systems that could lead to radiological releases, compromising both worker safety and environmental integrity. Contribution: analyzes airflow networks, duct sizing, and pollutant control. Implementing ventilation systems that provide sufficient airflow in underground facilities to support simultaneous mining, waste emplacement, and ground-control activities. For instance, the Safety Significant Confinement Ventilation System (SSCVS) aims to deliver 540,000 cubic feet per minute of air to underground workers. Air quality monitoring: deploying continuous air monitoring (CAM) systems to detect radiological releases promptly, allowing for immediate response measures to protect workers and the environment. Off-gas cleaning: designing and operating off-gas cleaning systems to prevent radioactive contamination of air in working areas and the surrounding environment. Seamlessly integrating ventilation and monitoring systems remains an unresolved challenge critical for preventing radiological releases. For example, the SSCVS design did not adequately consider requirements for the underground CAM system, potentially leading to contamination. System responsiveness: improving the responsiveness of ventilation systems to rapidly contain potential radiological releases. The SSCVS dampers' 60-second closure time may be insufficient to prevent contamination of the salt-reduction system and overall operations. Worker exposure: addressing ongoing issues of worker exposure to harmful substances due to inadequate ventilation, leading to health risks. Advancements in ventilation systems for radioactive waste storage have focused on enhancing airflow, integrating effective air quality monitoring, and implementing robust off-gas cleaning mechanisms. However, challenges remain in ensuring cohesive system design, rapid responsiveness to potential radiological events, and safeguarding worker health. Addressing these issues requires ongoing research, rigorous system testing, and adherence to stringent safety standards. Gap: applies only to low/intermediate waste-does not scale to HLW thermal/gas loads. Justification insight: forms a technical basis to adapt and upscale designs for high-heat, high-radiation HLW repositories while Long-term adaptability and failure resilience of ventilation networks. Relevance: provides foundational models directly useful for HLW ventilation system justification.

The paper [9] surveys autonomous environmental monitoring approaches, focusing on integrating active sensing strategies with reinforcement learning to enhance data collection efficiency. The authors discuss various methodologies that combine active sensing-where robots decide where and when to collect data-with reinforcement learning techniques that enable robots to learn optimal monitoring strategies through trial and error. Contribution: introduces real-time adaptive monitoring. Gap: no application to gas/heat control in HLW settings. Unresolved issues: the integration of active sensing and reinforcement learning presents challenges, including the need for large datasets to train models, computational complexity, and ensuring real-time adaptability in dynamic environments. Further research is required to address these challenges and to develop robust frameworks for autonomous environmental monitoring. Justification insight: innovative ventilation requires intelligent sensing for dynamic risk control.

This paper [10] survey examines decision-theoretic approaches in robotic environmental monitoring, focusing on how robots can make informed decisions about data collection to optimize monitoring efforts. The authors explore various decision-theoretic optimization algorithms that address questions such as where to take measurements, which tasks to assign, what samples to collect, and how to learn about the environment effectively. Challenges remain in developing decision-theoretic models that can handle the complexity and uncertainty inherent in environmental monitoring. Issues such as computational tractability, real-time decision-making, and the integration of heterogeneous data sources require ongoing research. Unsolved issues: real-world application in mine ventilation contexts remains untested. Relevance: supports use of wire-driven continuum robot (WDCR) for mapping gas/heat anomalies in ventilation-controlled repositories.

In paper [11] problem addressed: safety and design of deep geological repositories (DGRs). Focus is a repository safety through passive containment. Solved issues: investigation of multi-barrier concepts for radionuclide containment, and modeling repository behavior under heat and radiation. Its contribution is in clarifying that effects of passive barriers in heat management. The authors highlight a crucial strategy for enhancing DGR safety and effectiveness: the multi-barrier system. This involves implementing a combination of engineered and natural barriers to isolate radioactive waste, thereby reducing the likelihood of radionuclide migration. Unsolved issues: long-term heat dissipation not fully integrated into ventilation strategies. Predictive uncertainty over millennia limits ventilation reliability justification. Relevance of the research are in justification the need for dynamic ventilation systems to complement passive designs. Gap: does not consider active ventilation; that give rising in reinforces the need for exploring systems that manage internal repository temperature dynamically. Thermal management must be in designing safe repository layouts that account for the heat generated by radioactive decay, ensuring that temperatures remain within safe limits to maintain the integrity of barriers. Justification insight: ventilation is essential to complement multi-barrier strategies where natural heat dissipation may be inadequate.

In the paper [4] are discussed the feasibility of using abandoned underground mines for radioactive waste disposal. Their analysis focuses on structural reinforcement and isolation but does not address long-term ventilation performance. One key unsolved issue is the potential buildup of explosive or corrosive gases (e.g., hydrogen) due to radiolysis. Without dedicated gas evacuation systems, long-term safety is compromised.

In paper [12] propose a method for HLW disposal in underground mines and identify that gas and heat management are among the most critical unsolved engineering challenges. The main limitation is the lack of scalable ventilation systems compatible with variable mine geometries and repository designs.

The paper [13] makes focus on global feasibility of mine reuse. In this article is addressed a justifying a novel ventilation and environmental control system for HLW burial in open-pit mines. there have been solved issues on a mathematically justified its heat and gas dispersion efficiency, and proposed integration with robotic monitoring tools. However, a long-term maintenance and adaptability under varying geological conditions have been yet acknowledged as unresolved. As well its implementation under seismic conditions remains unverified. The results directly support the practical engineering basis for a scalable HLW disposal system with advanced monitoring and passive safety features.

In the paper [14] are designed an automated, intelligent system for managing mining and transportation operations using global navigation algorithms. The paper proposed an architecture for route optimization, operational efficiency, and autonomous decision-making in mining logistics. However, the system's integration with environmental safety controls and radiation constraints is not addressed. The expert system concept can be adapted to automate underground waste transport, optimize robot routes, and support hazard avoidance during HLW placement.

The authors addressed on an automation of microshoot transplantation in biotechnology using a specially designed robotic gripper. There have been developed a kinematic and structural model for adaptive manipulation of delicate biological material using wire-driven mechanisms. However not designed for harsh industrial or radiological conditions; lacks shielding and load tolerance analysis. Relevance to HLW burial is the adaptive gripping technology can be adapted for robotic handling of HLW components, especially where precision and fragility (e.g., SNF rods) are involved. The design's adaptability to soft and varied geometries aligns well with the manipulation needs in HLW container systems.

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. 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.

Criteria for justifying a ventilation system for HLW burial in open spent mines:

1. Thermal regulation HLW generates intense decay heat.

Ventilation dissipates heat to prevent overheating of storage containers and surrounding rock. Maintains repository temperature below critical thresholds (e.g., < 100°C).

2. Gas and dust emission control. HLW decay can produce hazardous gases (H_2, CH_4, CO_2).

Ventilation removes accumulated gases and prevents buildup beyond the Lower Explosive Limit (LEL). Reduces airborne dust mobilization that could carry radioactive particles.

3. Moisture migration management.

Ventilation helps reduce humidity and moisture ingress. Prevents corrosion of waste containers and structural components. Enhances the effectiveness of clay or bentonite barriers.

4. Structural stability of repository.

Thermal gradients and gas pressure can induce cracks or microfractures. Active ventilation reduces internal stress, protecting geological and engineered barriers.

5. Monitoring support.

Enables real-time control of environmental variables when paired with robotic sensors (e.g., WDCR). Allows dynamic adaptation to unexpected changes in temperature, pressure, or gas concentrations.

6. Post-closure safety assurance.

Provides a mechanism to extend active management beyond the repository's operational phase. Enhances early-warning systems for containment failure or abnormal conditions.

7. Regulatory and public acceptance.

Demonstrates compliance with IAEA and national safety standards. Increases public trust by adding layers of environmental protection and active control.

8. Adaptability to geological variability.

Different mine geometries and host rock conditions affect heat and gas behavior. A well-designed ventilation system can be tailored to site-specific conditions.

9. Emergency preparedness.

Provides pathways for gas release or pressure equalization in case of system failure. Enhances repository resilience to unforeseen events (e.g., seismic activity or structural degradation).

10. Integration with existing infrastructure.

Leverages shafts, tunnels, and voids from the original mine for ventilation channels. Reduces the cost of new construction while improving environmental control.

11. Support for multibarrier system functionality. Aids in maintaining stable conditions for passive barriers (e.g., clays, engineered containers). Prevents thermal and chemical degradation of barrier materials.

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 [11].

3. The aim and objectives of the study

The aim of this study is to justify and design a dual ventilation system that ensures stable thermal and environmental conditions in HLW repositories located in open spent mines.

To achieve this aim, the following objectives are accomplished:

– analyze the thermal behavior of HLW repositories;
– design a dual ventilation system architecture;
– demonstrate environmental safety and sustainability.

4. Materials and methods of the study

The object of this study is a dual ventilation system designed for underground or spent open-pit mines used for the long-term burial of high-level radioactive waste (HLW). The problem addressed lies in managing excessive heat accumulation, moisture, and radioactive aerosol dispersion, which threaten the thermal, environmental, and structural safety of HLW repositories over decades. The long-lived radiotoxicity, extreme heat generation, and potential for groundwater interaction present major challenges for containment integrity. This makes HLW management a globally critical issue that transcends national boundaries and scientific disciplines. The heat flux generated by high-level radioactive waste (HLW) significantly impacts the surrounding repository materials and must be effectively managed to prevent the mobilization of radioactive particles. A well-designed ventilation system dissipates excess heat, thereby mitigating the risk of overheating within the HLW repository.

Main hypothesis: maintaining the repository temperature below critical thresholds (e.g., under 100°C) is essential to ensure its long-term durability and operational safety.

Assumptions and simplifications of the study. To ensure analytical tractability and feasibility of simulation, the following assumptions and simplifications were made during the design and evaluation of the dual ventilation system:

1. Thermal assumptions.

Uniform heat generation was assumed from HLW canisters, corresponding to decay heat typical of vitrified HLW (initial heat flux ~5–10 W/kg). Thermal conductivity of surrounding rock and repository structure was considered homogeneous and isotropic, ignoring local geological heterogeneity. Steady-state heat transfer was assumed in some calculations to simplify long-term temperature distribution modeling.

2. Ventilation modeling simplifications.

The airflow inside chimneys and repository galleries was modeled using ideal laminar flow assumptions, while turbulence and backflow effects were neglected. The natural convection model was simplified using the stack effect equations, without full computational fluid dynamics (CFD) resolution of transient eddies or pressure drops. Ventilation rate was assumed to be constant once natural draft conditions were established, omitting day-night and seasonal variation in external atmospheric pressure or temperature.

3. Humidity and moisture control.

Relative humidity (RH) was assumed to be a function of temperature and air exchange only; no active water ingress or underground aquifer interaction was modeled. Hygroscopic and moisture-retentive properties of internal materials (clay, salt, etc.) were not explicitly considered.

4. Gas-dust mixture treatment.

The efficiency of particulate filtration in the secondary chimney was estimated using standard HEPA-type efficiency models without simulating actual particle trajectories or chemical transformations. Radioactive decay of airborne particles during transport was not accounted for, assuming short residence times within the system.

5. System geometry and scaling.

The repository layout was simplified into a 2D cross-sectional or axisymmetric model, ignoring possible 3D irregularities. Effects of chimney aging, structural degradation, or blockage over time were not included in initial calculations.

6. Operational simplifications.

The system was modeled under the assumption of continuous passive operation, without incorporating operational downtime, maintenance cycles, or mechanical failure risks. External influences such as seismic activity, mining-induced stress, or sabotage were not considered.

These assumptions helped reduce computational complexity while still enabling a reliable assessment of thermal, environmental, and filtration performance. However, in future work, lifting some of these simplifications – especially through full 3D CFD simulations and geological coupling – could refine the design's robustness and predictive accuracy.

This research employs a comprehensive approach, combining thermal modeling, structural analysis, and airflow simulation. Heat distribution modeling is used to simulate temperature buildup within the repository over time. This environmental monitoring is based on governing equations that apply Fourier's law of heat transfer and transient 3D heat conduction equations [13].

The heat flux monitoring using Fourier's law is expressed as

$$q = \frac{kA\Delta \mathrm{T}}{d}, \tag{1}$$

where k – the thermal conductivity, A – the surface area, ΔT – the temperature difference, and d – the thickness of the clay barrier.

For steady-state heat conduction in cylindrical coordinates, the heat flow rate (Q) through a layer is constant and given by

$$Q = -k\frac{dT}{dr}, \tag{2}$$

where $A = 2\pi rL$ – the lateral surface area for a cylindrical layer; k – the thermal conductivity $\frac{\mathrm{W}}{(\mathrm{mK})}$; L – the repository length (m); r – the radius (m); $\frac{dT}{dr}$ – the temperature gradient [13].

Rearranging for Q

$$Q = \frac{2\pi L}{\ln\left(\frac{r_{out}}{r_{inner}}\right)} \cdot \Delta T \cdot k, \tag{3}$$

where

$$\Delta T = T_{inner} - T_{outer}, \tag{4}$$

The chimney system design incorporates a main chimney that directs rising gas-dust mixtures, and an additional chimney with integrated treatment chambers. A two-stage ventilation system is modeled, where the main chimney extracts dust-gas mixtures and heat from high-level waste (HLW) containers. The additional chimney then implements filtration and thermal dissipation processes before environmental release.

Strength analysis evaluates the pressure, wind loads, and thermal expansion effects on the chimney walls. The algorithm for this analysis is as follows:

1. Calculate the cross-sectional area (5)

$$A = \frac{\pi}{4}\left(D_{outer}^2 - D_{inner}^2\right), \tag{5}$$

A=0.598 m^2.

2. Calculate the moment of inertia (6)

$$I = \frac{\pi}{64}\left(D_{outer}^4 - D_{inner}^4\right), \tag{6}$$

I = 0.269 m^4.

3. Calculate the weight of the chimney (7)

$$W_{weight} = \rho \cdot A \cdot g \cdot H, \tag{7}$$

W_{weight} = 704.94 kN.

4. Calculate the wind load (8)

$$W_{wind\ load} = WH. \tag{8}$$

$W_{wind\ load}$ = 75 kN.

5. Calculate the bending moment due to wind load (9)

$$M = \frac{WH^2}{2}, \tag{9}$$

M = 1875 kN·m.

6. Calculate the maximum stress: using the bending stress formula (10)

$$\sigma = \frac{MC}{I}, \tag{10}$$

where C – the distance from the neutral axis to the outer fiber

σ = 6.97 MPa.

Thermal expansion calculation.

The linear thermal expansion of the chimney due to temperature change can be calculated using the following formula

$$\Delta L = \alpha L \Delta T, \tag{11}$$

where ΔL is the change in length; α is the thermal expansion coefficient; L is the original length; ΔT is the change in temperature. In this way, the linear thermal expansion of the dual-ventilation system's chimneys is assessed as a function of temperature changes.

7. Thermal stress calculation: thermal stress can be calculated if the expansion is restricted. This is given by

$$\sigma_{thermal} = E\alpha\Delta T, \quad (12)$$

where E – the modulus of elasticity. For the compound plastic (assume $E = 2$ GPa); α (alpha) is the coefficient of linear thermal expansion of the material (measured in per degree Celsius (°C) or per Kelvin (K) or per degree Fahrenheit (°F)); ΔT (delta-T) is the change in temperature (measured in degrees Celsius (°C), Kelvin (K), or degrees Fahrenheit (°F)).

Thermal conductivity and heat transfer: the rate of heat transfer through the chimney wall can be calculated using Fourier's law

$$Q = \frac{kA\Delta T}{d}, \quad (13)$$

where Q – the heat transfer rate; k – the thermal conductivity; A – the surface area; ΔT – the temperature difference; d – the wall thickness. Assuming the wall thickness $d = 0.1$ m (for simplicity)

$$A = \pi d_{inner} H. \quad (14)$$

This is the rate at which heat is conducted through the chimney wall. The coupled heat transfer model ensures that the gas cools sufficiently for pollutant condensation and removal without damaging the equipment. The temperature gradient facilitates better pollutant capture, as seen in the scrubber efficiency.

Thermal expansion calculation: the linear expansion of the chimney due to temperature change can be calculated using formula (11).

9. Thermal stress calculation: thermal stress can be calculated if the expansion is restricted (12).

Simulation of gas-dust flow: predicts removal efficiency and gas dispersion patterns.

Heat diffusion equation (3D transient heat equation)

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T, \quad (15)$$

where T – the temperature (°C) as a function of time t and space (x, y, z); $\alpha = \frac{k}{(\rho c_p)}$ – the thermal diffusivity of the material (m²/s); k –the thermal conductivity (W/mK). ρ – density $\left(\frac{\text{kg}}{\text{m}^3}\right)$; C_p – the specific heat capacity $\frac{\text{J}}{\text{kgK}}$. Boundary conditions: inner walls of repositories emit heat at a constant rate. Outer boundary (clay surface) maintains a lower temperature $T_{ambient}$. Initial condition: initially, the mine is at a uniform ambient temperature $T_{ambient} = 25$°C

$$T(y) = T_{base}\left(T_{base} - T_{outlet}\right)\frac{y}{H}, \quad (16)$$

where $T(y)$ – the temperature at height y; T_{base} – the temperature at the base of the chimney; T_{outer} is – temperature at the outlet H, and H – the total height of the chimney.

Moisture flow simulation. Using Darcy's law

$$Q = \frac{kA}{\mu} \cdot \frac{\Delta P}{L}, \quad (17)$$

where k – the permeability, μ – the fluid viscosity, ΔP – the pressure difference, and L – the barrier length.

Predict moisture buildup over time (years). Total moisture volume entering the repository

$$V = Qt. \quad (18)$$

Gas concentration analysis. Using Fick's law for gas diffusion

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}, \quad (19)$$

where D – the diffusion coefficient and dC/dx – the concentration gradient.

Thermal simulations were executed using finite element modeling, with repository layers composed of clay, basalt, and lead-based barriers. The effectiveness of the ventilation system is evaluated under scenarios simulating initial repository temperatures of 300°C and target reductions to 100°C.

Calculate the velocity of the gas mixture. The velocity (V) is given by

$$V = \frac{Q}{A}, \quad (20)$$

where $A = \frac{\pi D^2}{4}$ (cross-sectional area of chimney).

Calculate Reynolds number. The Reynolds number (Re) determines whether the flow is laminar or turbulent

$$Re = \frac{\rho_g VD}{\mu}. \quad (21)$$

Estimate heat transfer rate in dust-gas mixture

$$Q^{\bullet} = \boldsymbol{\rho} VCpA(T_{in} - T_{out}). \quad (22)$$

Cross-sectional area of chimney: $A = \pi r^2$.

Heat flux

$$q = -k_{clay}\frac{\Delta T}{\Delta x}. \quad (23)$$

Estimate pressure drop. For turbulent flow, the Darcy-Weibach equation is used

$$\Delta P = f\frac{L}{D}\frac{\rho_G V^2}{2}, \quad (24)$$

where f is the friction factor (estimated using the Colebrook equation for turbulent flow, assuming roughness Ɛ̇ = 0.01 m).

Calculate power required for the fan. The power required (P) to overcome pressure drop is given

$$P = \Delta PQ. \quad (25)$$

To calculate the average air temperature change over the years in a high-level radioactive waste (HLW) repository using a ventilation system, let's refer to empirical modeling based on Newton's Law of Cooling and thermal mass balance over time

$$T(t) = T_{ambient} + \left(T_{in} - T_{ambient}\right)e^{-kt}. \quad (26)$$

In a modeled HLW storage scenario within a spent open mine, the repository initially experiences a gradual temperature increase due to the decay heat from radioactive waste (29)

$$Q = h \cdot A \cdot \left(T_{surface} - T_{air}\right), \tag{27}$$

where Q – heat transfer rate (W), h – convective heat transfer coefficient (W/m^2·K), A – surface area through which heat is transferred (m^2), $T_{surface}$ – temperature of HLW-containing surfaces (°C), T_{air} – ambient air temperature inside the repository (°C). Additionally, to simulate airflow velocity in natural convection, the chimney effect or stack effect formula is also often used (30)

$$v = \sqrt{\frac{2gH\left(T_{in} - T_{out}\right)}{T_{out}}}, \tag{28}$$

where v – velocity of rising air (m/s), g – gravitational acceleration (9.81 m/s^2), H – height difference between inlet and outlet (m), T_{in}, T_{out} – absolute temperatures inside and outside the chimney (K). These formulas provide theoretical grounding for the temperature drop and airflow stabilization values reported in proposed modeled example.

To demonstrate how a well-designed dual ventilation system reduces moisture and radioactive particle mobilization, it is possible to use two core physical principles – humidity ratio control and aerosol particle capture efficiency.

Moisture reduction via ventilation. The humidity ratio (ω) – the mass of water vapor per unit mass of dry air – is a critical parameter

$$\omega = \frac{0.622 \cdot P_v}{P_a - P_v}, \tag{29}$$

where ω – humidity ratio (kg water/kg dry air), P_v – partial pressure of water vapor (Pa), P_a – atmospheric pressure (Pa). Impact of ventilation: by extracting saturated air and introducing cooler, drier air, the dual ventilation system lowers P_v, thus decreasing ω, which reduces condensation and moisture-driven corrosion.

Radioactive particle mobilization reduction. Aerosol capture efficiency (η) of filtration systems (in the additional chimney) is calculated using

$$\eta = 1 - e^{-kt}, \tag{30}$$

where η – efficiency (0–1), k – filtration rate constant (s^{-1}), depends on filter design and airflow speed, t – residence time in the filtration unit (s).

In multi-stage filters, especially electrostatic and HEPA-based ones: typical values $\eta \geq 0.95$ for particles > 0.3 μm. Longer residence time or staged chambers increase overall capture.

Heat transfer at boundaries. Mine walls: convection and conduction between the dust-gas mixture and the walls

$$q_{wall} = h_{conv}(T_{mixture} - T_{wall}). \tag{31}$$

HLW repositories: heat generation is treated as a volumetric source term. Boundary and initial conditions. Initial conditions: uniform temperature T_0 and pressure p_0 in the mine. Dust-gas mixture initially at rest: $v_0 = 0.2$ At inlets, the boundary conditions are defined by the specified velocity (v_{in}), temperature (T_{in}), and concentration of dust particles.

At outlets: zero pressure gradient

$$\frac{dP}{dn} = 0. \tag{32}$$

Critical results to monitor:

1. Maximum temperatures. At inner layers: should remain below the thermal stability limits of lead or container materials. At boundaries: must not exceed the degradation threshold of basalt or clay.

2. Temperature gradients. Steep gradients near boundaries or layers suggest risks of thermal stress and potential cracking.

3. Temporal changes. If boundary temperatures rise steadily over time, external cooling mechanisms may fail over the repository's lifespan. Equilibrium achievement: achieving a steady state (no significant changes in temperature over time) indicates successful heat dissipation.

Significant insights and actions:

1. To enhance boundary cooling when heat dissipation is insufficient, increasing the clay layer thickness should be considered. Adding engineered cooling systems (e.g., ventilation or heat pipes).

2. Material suitability is key; assessing the thermal properties of boundary materials reveals that higher thermal conductivity materials (e.g., basalt) enhance heat dissipation. Low permeability ensures minimal moisture interaction but can trap heat.

3. Geological implications: elevated boundary temperatures might destabilize the mine walls, leading to structural risks. Proper simulation helps evaluate the safety of surrounding geological formations.

4. Risk of radioactive particle mobilization: uneven boundary temperatures or gradients may drive convective currents, potentially mobilizing particles within the mine.

5. Results of the study to justify and design a dual ventilation system for HLW mine repositories

5. 1. Analyze the thermal behavior of high-level radioactive waste repositories

5. 1. 1. Modeling and validation of airflow dynamics in open spent mine repositories

The heat flux affects the surrounding material (e.g., clay, basalt) and needs to be managed to prevent mobilizing radioactive particles. Objective: simulate the temperature distribution over time and space.

For this purpose, below is identifying areas of high thermal stress or potential moisture accumulation is accomplished by modeling heat conduction through composite layers, while also integrating boundary conditions like external cooling layers or natural convection.

Setup. Repository dimensions: outer radius – $r_4 = 0.4$ m, depth of mine – $h = 500$ m, width of mine – $w = 1500$ m, length of mine – $l = 2500$ m. Material properties: basalt – $k = 1.7$ W/mK, clay – $k = 0.6$ W/mK. Initial conditions: heat output per HLW container – 2 kW, total containers – $n = 500$. Each container generates heat due to radioactive decay. There is an assumption that it is a repository with 500 HLW containers. Temperature reduction is expected from 300°C to 100°C over 30 years. Clay permeability is 10–14 m^2, pressure gradient – 50 kPa/m, moisture infiltration – 4.7 m^3 over 30 years. Gas diffusion coefficient is 0.05 m^2/s, inspecting robot's (WDCR) responses time – 7 minutes, predicted gas accumulation – 60 ppm. There is efficiency assessment for calculating ventilation. Airflow rate is 500 m^3/h.

Reduction of harmful gas concentration by 70%. Prevention of thermal hotspots accomplish through consistent air circulation. The total heat flux (Fig. 1) at the outer boundary is calculated onto the investigation in [13].

Fig. 1 illustrates the temperature distribution across the layers of the sarcophagus containing high-level radioactive waste (HLW), highlighting thermal gradients over time.

Heat flux monitoring using Fourier's law (1) [4, 11, 13]: assuming an average temperature gradient (1)

$$q = -k_{basal} \cdot \frac{\Delta T}{\Delta r}. \quad (33)$$

Let ΔT=250°C and Δr=0.1 m.

A temperature distribution in multiplayer composite structure of a lead matrix, clay layer, and basalt block are shown off at Fig. 1.

Temporal heat distribution analysis. Using Fourier's heat conduction equation (15)

$$\frac{dT}{dt} = \alpha \nabla^2 T, \quad (34)$$

where $\alpha = \frac{k}{\rho C}$ (thermal diffusivity). Let basalt properties: $k = 1.7\ \frac{\text{W}}{\text{mK}}$, density $\rho = 2900\ \frac{\text{kg}}{\text{m}^3}$, specific heat $C = 840\ \frac{\text{J}}{\text{kgK}}$, $\alpha_{basalt} = 7.04 \cdot 10^{-7}\ \frac{\text{m}^2}{\text{s}}$.

The results of simulation for time $t = 1$ year are shown off at Fig. 2.

Finite element method (FEM) were used for spatial discretization and apply an implicit time-stepping scheme for stability.

Computational domain. There have been represented the spent open mine as a 3D rectangular grid with included zones for HLW repositories, mine walls, and dust-gas mixture pathways. Plot temperature distribution within the repository layers have been exhibited at Fig. 2 identifying hot spots and gradients. Boundary temperatures: ensure boundary conditions dissipate heat effectively. Hot spots indicate potential cooling failure. Long-term stability: verify temperatures stabilize within acceptable limits over decades. Moisture and risk: check for regions where excessive heat might mobilize radioactive particles.

The bright areas (Fig. 2) represents regions with higher temperatures due to the placement of HLW repositories. The heat from these sources propagates outward over time. The cooler edges correspond to the boundary temperature of 50°C, representing heat dissipation to the surrounding environment. Heat propagation: heat spreads radially from the repositories, demonstrating the effect of thermal diffusion through the clay layer.

The of simulation of a changing temperature gradient from 300°C to the target 100°C in repository over 30 years as Fig. 3 shown off illustrates confirming long-term thermal stabilization due to composite-layer design.

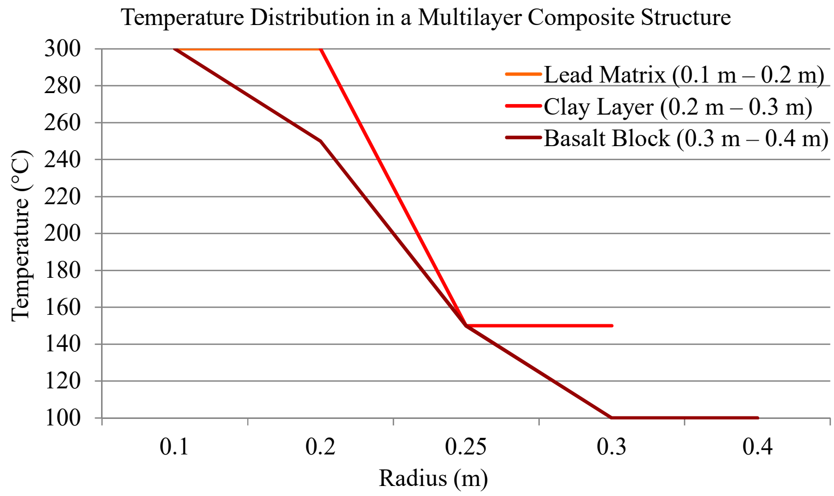

Fig. 1. The changing of temperature into the layers the sarcophagus with HLW

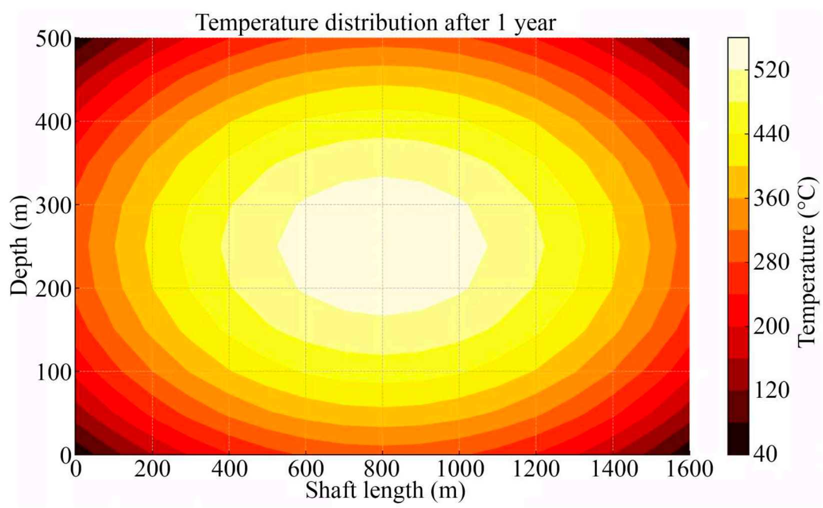

Fig. 2. Temperature distribution in the open spent mine after 1 year of operation with 500 HLW repositories

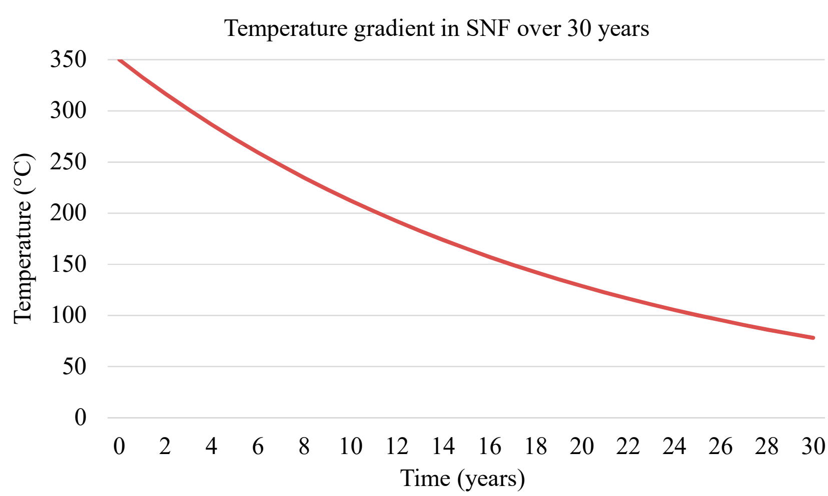

Fig. 3. Gradual decline of temperature from 300°C to the target 100°C within 30 years, confirming long-term thermal stabilization due to composite-layer design

The Fig. 3 illustrates the result of simulation of a changing temperature gradient from 300°C to the target 100°C in repository over 30 years, confirming long-term thermal stabilization due to composite-layer design.

5. 1. 2. Analyses for moisture migration

Problem setup involves moisture migration simulation using Darcy's law. Goal: compute the moisture flow rate through the clay barrier. A clay barrier surrounds the HLW repository to control moisture migration and protect against particle mobilization. Initial values of permeability, pressure gradient, water viscosity and cross-sectional are necessary for simulation moisture migration are represented in Table 1.

Table 1

Initial values of the core parameters for simulation moisture migration

Parameter	Value
Permeability k	10^{-14} m^2
Pressure gradient ΔP/L	50 kPa/m
Water viscosity μ	10^{-3} Pa·s
Cross-sectional area A	10 m^2

Substituting the given values into Darcy's law (17). Then moisture flow rate is $Q=10^{-5}\frac{m^3}{s}$. The moisture infiltration is very low, which confirms clay is effective as a barrier. Moisture buildup over 30 years

$$V = Qt. \tag{35}$$

Time in seconds $t = 9.46{\cdot}10^8$ s. $V \approx 4.7$ m^3. In the Fig. 4 is demonstrated how a moisture content decreases exponentially through the clay barrier over years, proving its effectiveness in water containment and repository dryness. Thus, a moisture infiltrated in 30 years is 4.7 m^3. The simulation a moisture migration in clay layer that confirming a moisture content decreases exponentially through the clay barrier (Fig. 4), demonstrating its effectiveness in water containment and repository dryness.

The Fig. 4 demonstrates how a moisture content decreases exponentially through the clay barrier over years, proving its effectiveness in water containment and repository dryness.

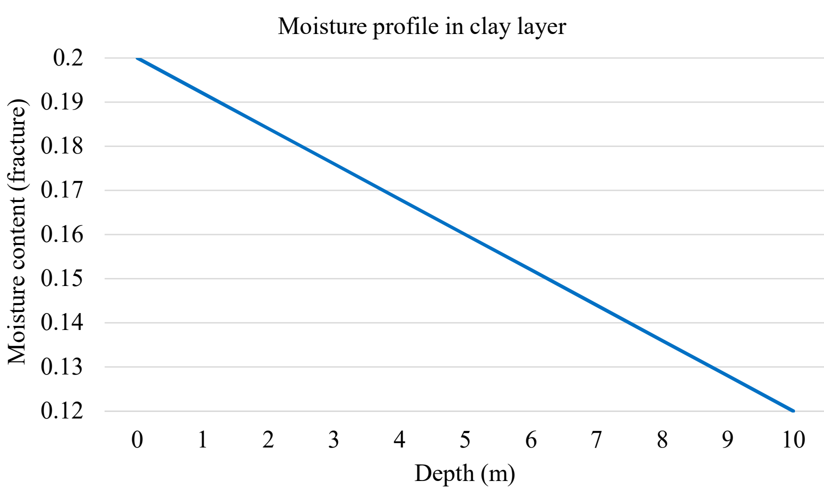

Fig. 4. Moisture content decreases exponentially through the clay barrier, demonstrating its effectiveness in water containment and repository dryness

5. 1. 3. Analyses for gas leak monitoring and risk of radioactive particle mobilization

Scenario overview. In a spent open-pit mine used for complete HLW burial, various gases such as hydrogen (H2), carbon dioxide (CO2), and methane (CH4) may be generated due to: radiolysis (radiation-induced decomposition), thermal decomposition of waste containers or barriers, microbial degradation of organic materials. Monitoring and modeling gas concentration is essential to avoid explosion hazards, ensure safe ventilation, and detect system failures.

Objective. To estimate the concentration of hydrogen gas at different depths and time intervals, and determine whether it exceeds the Lower Explosive Limit (LEL).

Modeling hydrogen gas diffusion from HLW in a spent open mine.

Scenario. High-level radioactive waste emits hydrogen gas due to radiolysis (breakdown of water molecules by radiation). It is possible to to analyze how this gas diffuses in a spent open-pit mine located 500 meters below the surface. Let's assume: the source of gas is concentrated in a small region (like a repository container). The mine is partially ventilated. Temperature and pressure are stable. It is interested in hydrogen gas concentration at various distances after a certain time (e.g., 7 days).

Governing equation: Fick's second law of diffusion (19). Simplified case – point source at $x = 0$

$$C(x,t)=\frac{M}{\sqrt{4\pi Dt}}exp\left(-\frac{x^2}{4Dt}\right), \tag{36}$$

where $C(x, t)$ – the gas concentration (mol/m^3), D – the diffusion coefficient of hydrogen in air, $\left(\approx 6.3\cdot10^{-5}\frac{m^2}{s}\right)$, x – the distance from the gas source, t – the time.

Assume: $M = 1$ mol of hydrogen gas released instantly, $t = 7$ days = 604800 seconds. Evaluate $C(x,t)$ at $x = 0$, 1 m, 3 m, 5 m, 10 m. The results of modelling hydrogen gas diffusion from HLW in a spent open mine are represented in Table 2.

Interpretation. Peak concentration is near the source, dropping off with distance due to diffusion. At 10 meters, concentration is much lower, which indicates gas disperses safely under natural diffusion. If the area is sealed or poorly ventilated, gas could accumulate and approach explosive thresholds.

Application to open spent mine with HLW. The designing a ventilation system to make ensure of avoiding dangerous gases accumulation (Table 3). Gas sensors can be placed strategically where concentration peaks are expected. Supports risk modeling and emergency preparedness for HLW burial sites. At 500 meters depth: temperature and pressure are higher due to geological conditions. Diffusion slows due to compact rock or engineered backfill. Ventilation becomes critical, as natural convection decreases. Gas buildup (e.g., H_2, CH_4, CO_2) may accumulate in dead zones. Monitoring via sensors or WDCR robots must be deeper and more frequent. For a run over one week (~600,000 seconds), gas buildup at 500 m reaches 0.06 mol/m^3 (approximately 6% by volume for H_2).

Table 2

The results of modelling hydrogen gas diffusion from HLW in a spent open mine

Distance (m)	Concentration (mol/m^3)
0	0.0005
1	0.000495
3	0.00045
5	0.00038
10	0.00015

Note: values are rounded for simplicity.

Table 3

Providing the safety interpretation base on helping of ventilation systems

Gas Type	Lower explosive limit (LEL)	Measured *C* at 500 m	Safety status
Hydrogen (H_2)	~0.04 mol/m^3 (4%)	0.06 mol/m^3	Dangerous
Methane (CH_4)	~0.05 mol/m^3	~0.03 mol/m^3	Safe

Note: hydrogen exceeds LEL → explosion risk; methane below LEL → manageable.

Engineering implications. To mitigate risks at 500 m depth: must have been installs high-capacity forced ventilation systems, and designed wire-driven continuum robot (WDCR) to routinely sample gas and navigate based on gradients, integrate real-time gas monitoring sensors with automatic alerts, use barriers or catalysts to absorb H_2 or convert it safely. Fig. 5 shows the results of the interpretation of the gas concentration analysis at a 500-meter depth in a spent open mine after 7 days for the hydrogen and methane gases emitted from a source (e.g., decaying waste) over a 10-meter profile from the origin point.

Fig. 5 shows off the gas concentration profile at 500 m depth after 7 days. The blue curve shows hydrogen dispersion from the source. The red and green dashed lines indicate the Lower Explosive Limits (LEL) for hydrogen (0.04 mol/m^3) and methane (0.05 mol/m^3), respectively.

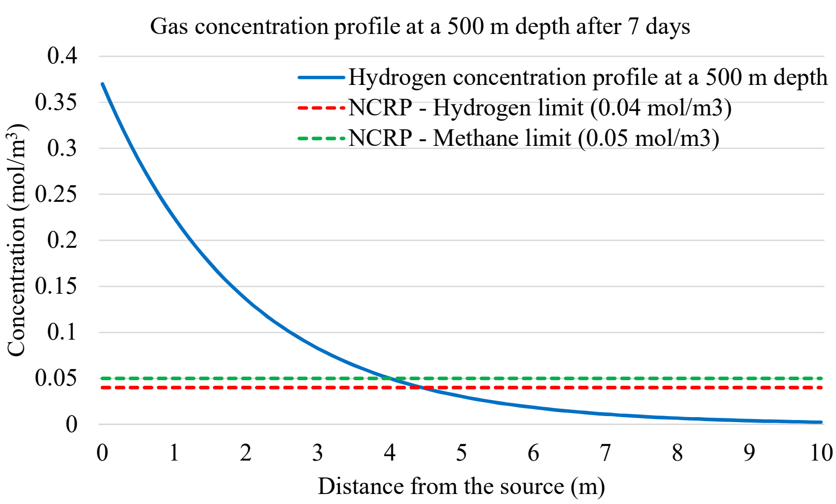

Fig. 5. Simulated gas concentration profile at a 500-meter depth in a spent open mine 7 days after emission, showing hydrogen and methane levels over a 10-meter distance from the source (e.g., decaying waste)

The hydrogen concentration is highest near the emission point and drops off exponentially as you move away. Even after 7 days, the concentration stays well below the explosive thresholds for both hydrogen and methane. This suggests that natural decay and diffusion at 500 meters depth help to manage gas buildup effectively – if the system remains undisturbed.

Implications for monitoring. Ventilation or gas extraction may still be necessary near the source, especially under sealed conditions or in case of increased generation rates. Continuous sensor monitoring is key in early detection of concentration approaching LEL, especially in the context of HLW burial where decay rates vary.

Practical monitoring strategy. Zonal division: break 500 m shaft into 5–10 m vertical zones. Install WDCR robots or flexible sensors along paths. Schedule regular readings & simulate diffusion. Example interpretation: at 500 m depth, it is possible to detect hydrogen levels exceeding 0.06 mol/m^3 after 6 days without ventilation. According to safety guidelines, this poses a risk of explosion. Hence, increased ventilation and adaptive gas routing (via WDCR) are required for safe HLW burial operation.

5. 2. Design a dual ventilation system architecture

Ventilation system for heat and gas management [15-17] have been designed is due to enhance airflow to prevent heat buildup and ensure a stable thermal gradient within the repository. Once it is possible to run the simulation for the repository with HLW, an interpreting the results involves analyzing the temperature profiles, identifying potential issues, and drawing conclusions about the system's effectiveness. Temperature profiles are key metrics for analysis, particularly the maximum temperature, which must remain below the thermal limits of materials like clay and basalt to prevent their failure.

Temperature gradient and hot spots are also key. Steep gradients can indicate localized stress, potentially leading to material failure or the mobilization of radioactive particles, while hot spots are critical regions with significantly higher temperatures than their surroundings. These may correspond to areas with poor heat dissipation or closely packed HLW containers. Building on temperature profiles, let's also examine how quickly the temperature drops over time. A slow rate may indicate insufficient cooling or poor thermal conductivity in certain layers. Additionally, it is possible to identify when (if at all) the system reaches an equilibrium state, where temperatures stabilize across the repository.

Spatial patterns are analyzed through layer-specific observations. Inner layers, like the lead matrix, should be hottest due to their proximity to high-level waste (HLW) containers, with heat gradually dissipating outward. Middle layers (clay) are checked for uniform heat spread, as clay's low thermal conductivity could cause localized heating. Finally, outer layers (basalt) are examined for effective heat dissipation, as basalt should act as a heat buffer, protecting the repository's surroundings.

Boundary effects are crucial to monitor. This involves observing repository walls and bottom for temperature buildup, which would indicate insufficient heat removal by surrounding layers (e.g., clay and basalt). Additionally, it's essential to ensure the mine surroundings remain below critical temperature thresholds to prevent geological destabilization or material degradation.

Moisture interaction is a critical consideration. There's an evaporation risk if boundary or surface temperatures exceed water boiling points, which could lead to moisture loss and dry conditions, compromising repository safety. Conversely, condensation zones can form where temperatures drop below the dew point, potentially accumulating moisture and posing risks of corrosion or unintended chemical reactions.

For safety and compliance, it's crucial to check thermal stress levels induced by thermal expansion in different materials, as uneven expansion could cause cracks, especially in brittle materials like basalt.

For visualization insights, typical plots include heat maps that show temperature distribution, making hot spots and gradients easily identifiable. Temperature vs. time plots track how temperatures evolve at key locations, while radial profiles illustrate temperature variation from the innermost to the outermost layers. By interpreting these results, it is possible to adjust repository design (e.g., modifying HLW container placement or layer thickness), improve cooling systems (by adding external mechanisms or enhancing natural dissipation), and ensure long-term stability by verifying the repository remains stable as decay heat diminishes. These interpretations are significantly influenced by how boundary conditions have been defined, as they dictate the repository's thermal interaction with its environment.

The set objectives address not only the immediate removal of dust-gas mixtures but also the optimization, sustainability, and environmental compatibility of the entire process. This holistic approach ensures that the solution aligns with long-term environmental and operational goals. The proposed systems for removing pollutants – such as advanced ventilation technologies, natural and induced draft mechanisms, and filtration systems – are designed to eliminate particulates and gases from the flue emissions comprehensively and adaptability to various conditions. That system is ensuring the taken measures on emission reductions while simultaneously is acting to prevent operational hazards (e.g., explosion risks, clogging, or overheating). The results that have been from computational modeling, simulations tests demonstrate the system's expected performance under real-world conditions. By integrating technical advancements like gas-ducting systems, aerodynamic enhancements, and floating barrier structures, the article introduces novel approaches that can efficiently address the root causes of emission retention within chimneys, facilitating complete pollutant removal.

By addressing these points, it is evident that the objectives not only aim to remove all dust-gas mixtures from the HLW burial in the open spent mines but also to provide a sustainable, efficient, and comprehensive solution to emissions management. This holistic approach ensures that the primary goal of pollutant removal is met while achieving broader environmental and operational benefits. This approach involves circulating air through the repository using fans or blowers to dissipate heat generated by the radioactive decay of waste.

The concept of forced ventilation aims to regulate repository temperatures by enhancing heat dissipation through convective cooling. Its mechanism involves forcing air through designated channels or around waste storage units, thereby carrying heat away from the waste containers and maintaining acceptable temperature limits for the repository's structural integrity.

Benefits of forced ventilation:

1. Effective cooling: ventilation significantly increases heat dissipation compared to natural heat conduction through geological media.
2. Environmental protection: maintains lower temperatures around waste containers, reducing thermal stress on geological formations and backfill materials.
3. Scalability: can be adapted to varying repository sizes and heat loads by adjusting airflow rates and ventilation system design.
4. Accessibility: supports human or robotic interventions by maintaining a stable thermal environment for operations.
5. Cost-effective: initial investment may be lower than advanced backfill or engineered cooling systems, especially for repositories with moderate heat loads.

Challenges of forced ventilation:

1. Energy demand: ventilation systems require a continuous power supply, potentially increasing operational costs and reliance on external energy sources.
2. Airborne contaminants: risk of mobilizing radioactive particles into the ventilation system, necessitating advanced filtration and monitoring systems.
3. Moisture management: ventilated air could introduce moisture, leading to corrosion of waste containers or altering the properties of surrounding backfill materials.
4. Repository sealing: ventilation systems complicate long-term repository sealing, as airflow pathways must eventually be closed to transition to passive containment.
5. System lifespan: fans, ducts, and other components must be durable and capable of operating under harsh conditions over extended periods.

Key design considerations:

1. Airflow pathways: design ductwork is to maximize airflow efficiency while avoiding hotspots.
2. Filter systems: equips ventilation systems with high-efficiency particulate air (HEPA) filters to capture any airborne contaminants.
3. Monitoring: continuously to measuring temperatures, humidity, and radioactivity in the ventilated air.
4. Emergency systems: includes backup power and ventilation systems to ensure continuous operation during power outages or failures.
5. Moisture control: incorporates dehumidification systems to minimize the risk of container corrosion.

Forced ventilation is a viable heat management strategy in HLW repositories, particularly during operational phases or for repositories with relatively high heat loads. However, its long-term applicability must consider the transition to passive containment strategies, power requirements, and environmental safety concerns. Integrating advanced monitoring systems and simulations can further optimize its effectiveness.

The paper addresses the development of a device designed to ventilate the internal space of a quarry, focusing on enhancing the environmental safety of its operations. The proposed solution aims to optimize quarry ventilation by intensifying air exchange within the quarry, facilitating the effective removal of polluted air from the internal atmosphere, and ensuring maximum purification of the air basin from contaminants. The study highlights the application of technical solutions leveraging natural ventilation methods to achieve these objectives. The types of dust that could arise during the complete burial of high-level radioactive waste (HLW) in spent open-pit mines generally depend on the materials and processes involved. These include: rock and soil dust.

Various sources contribute to dust generation within a Deep Geological Repository (DGR), each with distinct characteristics:

1. Excavation.

2. Drilling.

3. Blasting dust.

Sources and characteristics of dust in HLW repository operations:

1. Dust from pit and repository preparation:

a) source: operations aimed at preparing the pit and repository for High-Level Waste (HLW) placement;

b) characteristics: typically, coarse and mineral-rich, composed of silicates, quartz, and other geological materials.

2. Backfill material dust:

a) sources: handling, transport, and placement of backfill materials (e.g., bentonite, crushed rock, or engineered barriers);

b) characteristics: fine particulate matter, especially from bentonite, which can generate significant dust when dry.

3. Waste packaging dust:

a) source: handling and sealing of HLW containers during emplacement;

b) characteristics: potential contamination from residues on waste containers; generally managed under strict containment protocols.

4. construction material dust:

a) source: onsite construction activities for surface and underground infrastructure, including concrete work and structural components;

b) characteristics: includes cement and other fine particulates that can be hazardous if inhaled.

5. Chemical dust:

a) source: use of sealants, grouts, or other chemical substances during construction and sealing of the repository;

b) characteristics: may include reactive or irritant particles depending on the specific chemicals used.

6. Vehicle emission dust:

a) sources: operation of heavy machinery and transport vehicles within the mine site;

b) characteristics: combustion by-products combined with fine particulate matter from disturbed surfaces.

7. Erosion-induced dust:

a) source: wind action on exposed surfaces during repository operations;

b) characteristics: primarily fine, loose particles originating from uncovered soil, rock, or backfill.

8. Radiologically contaminated dust (potential but controlled):

a) source: accidental release during HLW handling (considered rare due to comprehensive safety measures);

b) characteristics: low-probability but high-consequence dust containing radioactive particulates.

Effective dust management strategies, including dust suppression systems, forced ventilation, water spraying, and advanced monitoring, are critical to maintaining safety and environmental integrity during HLW burial. This research aims to develop and optimize an innovative system of technical devices designed to effectively remove all dust and gas emissions into burial with HLW. The primary issue addressed is the substantial air pollution caused by these emissions, which conventional emission control systems often fail to mitigate completely. This study provides a solution by designing and justifying an environmentally friendly emission control system that integrates multiple technologies into a cohesive and effective unit. The research results indicate that, due to its innovative design and specific functionality, this system can achieve comprehensive dust and gas capture, outperforming standard systems in pollutant separation. Key elements such as multicriteria analysis enabled the selection of an optimized system design, while temperature distribution analysis was used to ensure pollutant removal efficiency by maintaining an ideal temperature range. Structural strength calculations further confirmed the system's resilience under typical operational stresses. This optimization minimizes material use, thereby reducing both costs and environmental impact, without sacrificing durability.

The proposed system, illustrated in Fig. 6 [16], offers a comprehensive solution for removing the entire dust-gas mixture from thermal power plant chimneys. This innovative system is designed to separate solid particles from gases and process them completely into useful products. At its core is a vertical cylindrical body (1), functioning as the main dust and gas exhaust. This body comprises sequentially connected, individual parts: elastic conical shells with stiffeners. Each section features a variable cross-section that expands towards the base and is constructed from plastic. The outer surface of each conical section, along with its stiffeners, is pivotally linked by stabilizing cables (2) to a platform (3), which houses an ash collector (4). The upper end of the dust and gas exhaust (1) is open to the atmosphere.

Immediately preceding this upper end, an electrostatic precipitator (ESP) (5) is installed for cleaning flue gases. This ESP unit includes a smoke or dust collector (6), a high-voltage cable (7), a feed-through high-voltage insulator (8), and high-voltage support insulators (9 and 10). Additionally, it incorporates a water supply pipeline (11) and a drain pipe (12), which connects to the ash collector (4). The entire assembly is secured by clamps (13), corner brackets (14), vertical posts (15), and cross ties (16).

Midway along the dust and gas exhaust (1), a special nozzle (17) is rigidly connected through a side wall opening. The nozzle's longitudinal axis is positioned horizontally or inclined at a specific distance from the base of the main smoke pipe (18), to which its other end is rigidly attached. A support device (19) or devices are strategically placed beneath the lower section of the special nozzle (17). The design accounts for the diameter of the dust and gas exhaust's cylindrical pipe (1) to ensure adequate draft and optimal flow rates for the entire dust-gas mixture.

Here, advanced cleaning devices perform final treatment before emissions are released into the atmosphere. 1 – additional chimney: this serves as the finally outlet for treated emissions.

At the final stage, advanced cleaning devices carry out the final purification of emissions. The treated mixture is then discharged into the atmosphere through the additional chimney (1), which functions as the terminal outlet of the system.

This system is engineered to effectively remove and convert smoke, dust, and gas emissions into useful products. Below is a detailed breakdown of its key components and their operational flow.

System overview. As illustrated in Fig. 6, the dust-gas mixture from the high-level waste (HLW) storage first enters the main chimney (18). This conical structure handles the initial extraction of dust and gas. From there, a special nozzle (17), supported by a support device (19), directs the partially processed mixture to the additional chimney (1). Within this additional chimney, advanced cleaning devices, specifically electric separator (5), is employed for final processing.

Component breakdown:

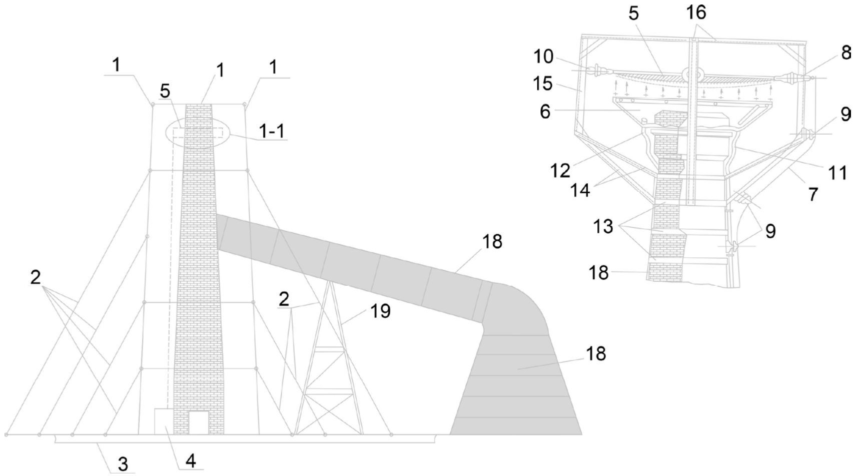

Fig. 6. System designed to separate and process solid particles and gases from power plant emissions into useful products: 1 — additional chimney: this main structure is where polluted dust and gas emissions undergo initial treatment; 2 — stabilizing cable: this cable provides crucial stability to both the additional chimney and its connected components; 3 — platform: serving as the foundation, this platform provides structural support for the entire ventilation system; 4 — ash separator: this unit is dedicated to separating ash from the emissions; 5 — electric separator (collector): this is the main collection point where the electrical separation of particles takes place; 6 — fume and dust collector: this component specifically collects fumes and dust; 7 — high voltage cable: this cable supplies the necessary high voltage for the system's electrical operations; 8 — high voltage bushing; 9 — high voltage support insulators (first); 10 — high voltage support insulators (second); 11 — water supply pipe: this pipe delivers water for the system's processing or cooling needs; 12 — drainage pipe: excess water or liquid waste is removed from the system via this pipe; 13 — clamps: these secure pipes and other components firmly in place; 14 — corner brackets: providing additional structural support, these reinforce vertical components; 15 — vertical posts: these posts support the system's weight and maintain its structural stability; 16 — cross braces: reinforcing the structure, these braces protect against lateral forces; 17 — special nozzle: this nozzle directs the removed dust and gas mixture from the main chimney (18) to the additional chimney (1); 19 — support device: this device ensures the stability and support for all chimneys within the dual-ventilation system and their associated components

1. Additional chimney (1): the main structure where polluted dust and gas emissions undergo their main treatment.

2. Stabilizing cable (2): ensures the stability of the additional chimney and its connected components.

3. Platform (3): serves as the foundational structural support for the entire ventilation system.

4. Ash separator (4): collects separated ash (not depicted in Fig. 6).

5. Electric separator (collector) (5): this is the main collection point within the additional chimney, performing the final collection stage before emissions are released.

6. Fume and dust collector (6): specifically designed to collect fumes and dust.

7. High voltage cable (7): supplies the necessary high voltage for the system's electrical operations.

8. High voltage bushing (8): facilitates the safe passage of high voltage into the system's components.

9. High voltage support insulators (first) (9) and (second) (10): these insulators provide critical support and electrical isolation for the high-voltage components.

10. Water supply pipe (11): delivers water essential for various processing or cooling needs throughout the system.

11. Drainage pipe (12): removes excess water or liquid waste.

12. Clamps (13): secure pipes and other components firmly in place.

13. Corner brackets (14), vertical posts (15), and cross braces (16): these components collectively provide robust structural support. They reinforce the vertical elements of the electric separator (5 in Fig. 6), ensuring stability and strengthening the overall structure against lateral forces.

14. Main chimney (18): the primary conical structure for initial dust and gas extraction before directing the mixture to the additional chimney.

15. Support device (19): provides stability and support for all chimneys within the dual-ventilation system and their associated components.

This system offers a seamless, practical upgrade for existing ventilation setups, requiring only minimal structural changes. Its integration is particularly beneficial in regions needing sulfuric acid and gypsum, valuable byproducts extracted during the process. The system's viability is further boosted by government incentives that encourage emission reduction and byproduct reuse, paving the way for wider industrial adoption of this sustainable technology.

A key feature is the diversion of a portion or all of the main chimney's exhaust gas into an additional chimney via a controlled duct system. This secondary chimney is engineered to house advanced filtration devices without compromising the main chimney's structural integrity. Flow control dampers in the diversion mechanism regulate gas volume, optimizing treatment efficiency.

Beyond the chimney, the removal process focuses on minimizing overall environmental impact. This means effectively capturing pollutants at their source, cutting down on secondary emissions, and preventing deposition in surrounding areas. The proposed solutions prioritize energy-efficient pollutant removal, leveraging natural ventilation and convective flows to lower operational costs while maintaining high efficiency.

Ultimately, the system aligns with international and local emission standards, like the EU Industrial Emissions Directive (IED) or the EPA Clean Air Act. This ensures comprehensive pollutant removal, meeting all required benchmarks. Designed for scalability and adaptability, the system allows for continuous improvements and upgrades based on performance data and technological advancements.

This innovative system utilizes an additional chimney, built adjacent to the main chimney, specifically designed for the comprehensive removal of all dust from the exhaust gases of repositories.

Operational flow:

1. Gas diversion to the additional chimney: exhaust gases from the main chimney are diverted through a controlled duct system into the additional chimney. Flow control dampers regulate this diversion, ensuring consistent operation. This additional chimney functions as the primary treatment zone for the dust-laden gas mixture. By isolating filtration in this manner, the system minimizes interruptions to the main exhaust flow.

2. Multi-stage filtration: inside the additional chimney, the gas mixture undergoes a series of advanced filtration stages: cyclone separators: these are employed for the initial removal of larger dust particles.

Bag filters. These capture fine particulate matter, enhancing filtration efficiency.

Electrostatic precipitators (*ESPs*). These provide highly efficient removal of ultra-fine particles.

The additional chimney is fully equipped with all necessary machinery to ensure complete dust removal, thereby preventing pollution at the source. After passing through a final monitoring stage to confirm compliance with emission standards, the cleaned gases are released from the top of the additional chimney. Its height is specifically designed to ensure proper dispersion of these cleaned gases into the atmosphere.

The justification for incorporating an additional chimney lies in its compelling advantages, primarily improved system reliability by dedicating the main chimney solely to initial exhaust, thereby enhancing overall system performance.

Ease of maintenance: filtration equipment within the additional chimney is readily accessible for maintenance or replacement, all without disrupting the continuous operation of the main chimney.

Environmental compliance: this dedicated system ensures all dust particles are effectively captured and disposed of, consistently meeting or exceeding stringent environmental regulations.

Preservation of main chimney integrity: constructing an additional chimney negates the need for complex and potentially compromising retrofits to the main chimney, preserving its structural integrity while optimizing dust removal operations.

This alternative solution, depicted in Fig. 7 [17], details a system comprising two main structural subsystems. At the upper base of the main chimney (1), a special attachment (2), crafted from heat-resistant materials like steel or compound plastics, is rigidly mounted. This attachment features a through-hole in its middle section, to which the upper end of the additional chimney (3) is connected.

The additional chimney's longitudinal axis runs parallel or nearly parallel to that of the main chimney (1). Its upper, curved section is also rigidly affixed to the special attachment (2). The middle portion of the additional chimney (3) is positioned vertically, or near-vertically. At a specific elevation above the main chimney's base (1), the lower part of the additional chimney curves with a defined radius. From this curve, its lower section extends either horizontally or at an incline.

The lower end of the additional chimney (3) is rigidly connected to a through-hole in the side wall of storage unit (5), which belongs to subsystem I. This storage unit serves as a critical point for the complete separation of solid material particles (ash) from smoke. It's equipped with various devices and accessories, such as scrubbers, cyclones, and filters, designed to efficiently separate solid particles of any size from the flue gases.

The diameter of the additional chimney (3) is carefully engineered to ensure the necessary draft in the main chimney (1) and to control the velocity of flue gases within the additional chimney itself. Furthermore, support device(s) (6) are installed beneath the corresponding sections of the additional chimney's lower part, providing crucial stability.

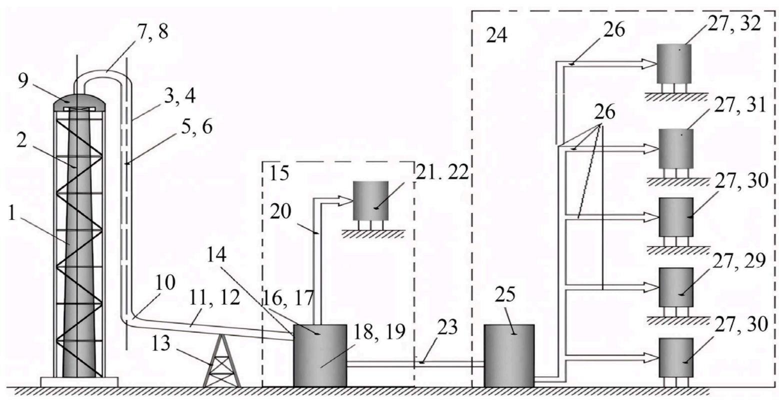

Fig. 7. The system for removing and converting smoke, dust, and gas emissions into useful products, comprises several primary components: 1 – main chimney – structure that captures initial smoke, dust, and gas emissions; 2 – special attachment – connector linking the main chimney with additional structures; 3 – additional chimney – secondary chimney directing gas flow to processing units; 4 – pipeline (initial transfer) – transfers flue gas from chimney to next stage; 5 – ash storage – initial collector for solid particles like ash; 6 – support device – base support ensuring stability of chimney system; 7 – pipeline (flue gas transport) – transfers separated flue gases for further treatment; 8 – storage (ash or solid byproducts) – collects separated solid emissions (e.g., ash); 9 – pipeline (leaving gas transport) – directs remaining gases from chimney to gas treatment; 10 – gas collector (e.g., NOx) – collects nitrogen oxides from gas stream; 11 – pipeline (NOx outlet) – transfers nitrogen oxides to storage or reuse; 12 – methane collector – extracts methane from emissions; 13 – pipeline (methane outlet) – transfers methane for storage or energy reuse; 14 – sulfur collector – separates and collects sulfur content from gas stream; 15 – pipeline (sulfur outlet) – directs sulfur byproduct to its destination; 16 – oxide collector – captures remaining oxides (e.g., SO_2, metal oxides); 17 – pipeline (oxide outlet) – transfers oxides to processing or storage; 18 – final product storage – tank for storing collected useful substances or final waste; 19 – final output pipeline – directs final material outside the system; 20 – carbon oxide collector – extracts carbon monoxide or dioxide from gas flow; 21 – pipeline (carbon oxide outlet) – transfers carbon oxides to collector or storage; 22 – storage (cox or treated gas) – holds carbon oxides or processed emissions; 23 – main processing pipeline – connects multiple collection systems to central unit; 24 – control unit zone – integrated zone managing flow and switching between collectors; 25 – control reservoir – balancing unit regulating flow and pressure in system; 26 – distribution pipes – guide processed gases to specific tanks; 27 – storage tanks – containers for segregated useful products (by chemical type); 28 – unused (optional connector) – reserved connector or pipeline not yet in use; 29 – ammonia storage tank – tank specifically for ammonia as byproduct; 30 – methane storage tank – tank for storing methane collected during processing; 31 – sulfur compound tank – holds sulfur or sulfuric compounds; 32 – nitrogen oxide tank – final storage for nitrogen oxides

Post-processing and byproduct recovery. After the initial removal of all solid particles (ash) from the smoke in the main chimney (1), the remaining ash mixture is transported via pipeline (4) to ash collector (5), which constitutes Subsystem II. From Subsystem II, the ash is then sent to a dedicated processing point where traditional methods, such as leaching, are employed to extract valuable byproducts. These include rare earth metals (e.g., scandium, titanium, germanium, vanadium), uranium, gold, copper, lead, and zinc.

Concurrently, the flue gas mixture, now largely free of solid particles, enters Subsystem III: gas storage (8) via pipeline (7). This subsystem is designed for collecting and separating various flue gases, including carbon oxides, nitrogen oxides, hydrogen sulfide, methane, and ammonia. It's equipped with traditional separation devices like filters and membranes, facilitating their subsequent, separate transportation. The remaining gas-dust mixture from ash storage (5) is also directed to gas collector (10) via pipeline (9). Specific gas components are then routed for further processing: methane is transported via pipeline (11) to subsystem IV: methane collector (12). At this collection and processing point, traditional methods and equipment convert methane into useful products such as methanol.

From gas collector (10), hydrogen sulfide travels via pipeline (13) to Subsystem V: sulfur collector (14). Here, it undergoes processing to yield valuable products like sulfur and oxygen. Nitrogen oxides are sent from gas collector (10) via pipeline (15) to Subsystem VI: nitrogen oxide collector (16). This point uses traditional methods to produce useful products, such as nitric acid.

Carbon oxides are transported from gas collector (10) via pipeline (17) to Subsystem VII: carbon oxide collector (18). This processing point employs traditional devices and equipment to convert carbon oxides into useful products like building materials or fuel.

Similarly, any remaining gases from gas collector (10) are transported via pipeline (19) to Subsystem VIII (20), a dedicated collection and processing point equipped with traditional devices and equipment for converting these gases into useful byproducts.

5. 3. To demonstrate environmental safety and sustainability

The flow dynamics of dust and gas mixtures in the chimney to validate the efficiency of the innovative system in capturing and separating pollutants. In order to validate the practicality and feasibility of the proposed innovative emission control system have been simulated the proposed system using computational tools (e.g., CFD simulations) to evaluate flow dynamics of dust and gas mixtures in the chimney. The chimney model is defined by its dimensions: a height of 100 m and a diameter of 6 m (scaled to a practical model size). Its geometry includes flow deflectors, particulate filters, and gas scrubbing units.

Emission parameters are set as follows:

1. Input gas velocity: 15 m/s.
2. Dust particle concentration: 150 mg/m^3.
3. Gas composition: 70% N_2, 15% CO_2, 10% H_2O, and 5% SO_2.
4. Temperature range: 120–180°C.
5. Boundary conditions are specified as:

5. 1. Inlet: velocity and particle concentration as described above.

5. 2. Outlet: atmospheric pressure.

6. Walls: Non-slip and thermally insulated.

The simulation methodology involved creating a high-resolution tetrahedral mesh for accurate results, particularly refined near complex flow dynamics regions and system components like filters and scrubbing units. The modeling approach utilized the Eulerian-Lagrangian method for particle tracking, incorporated turbulent flow modeling (e.g., k-ε model) to capture real-world flow behavior, and coupled heat transfer to analyze thermal interactions. Pollutant capture mechanisms were simulated by analyzing the interaction of particles with the filter and scrubber, measuring particulate deposition rates on filter surfaces and SO_2 absorption rates in the scrubber. Furthermore, a multi-stage ventilation system, comprising main and additional chimneys, ensures stable temperature and prevents moisture accumulation.

A mathematical model to justify the effects of an additional chimney can assess the performance and efficiency of dust removal. The model should account for the key parameters influencing gas flow, particulate capture, and operational efficiency. Here's a suggested framework. Develop a mathematical model to optimize the removal of dust-gas mixtures from open spent mines containing HLW while maintaining controlled temperatures to ensure safe storage. Assumptions. The dust-gas mixture follows laminar or turbulent flow behavior, depending on operational conditions. The mine's geometry (depth, width, length) is known. Heat transfer occurs between the dust-gas mixture, HLW containers, and mine walls. The dust-gas mixture properties (density, specific heat, thermal conductivity) remain uniform.

Factors to consider regarding heat dissipation include the thermal resistance of the clay layer, where a thicker clay layer can reduce heat dissipation into the surrounding environment, and repository placement, as closely spaced repositories may lead to inefficient heat dissipation due to thermal interference. For the given mine dimensions – depth (h): 500 m, width (w): 1500 m, and length (l): 2500 m – the surface area of the mine covered by clay (A_{clay}) is 7,750,000 m^2. Results for $n = 500$ repositories involve a heat flux calculation (1), requiring the substitution of Q_{total}, A_{clay}, and [14], where Q_{total} represents the total heat flow

Q_{total}=4,545,455 W.

Heat flux (Ø)

$$\varnothing = \frac{Q_{total}}{A_{clay}}. \qquad (37)$$

The heat flux into the mine's clay-covered bottom and walls is 0.5865 W/m^2 when 500 repositories are placed in a mine with the specified dimensions. Simulating heat distribution over time for 500 repositories in open spent mines. Objective: let's aim to model and simulate how heat from 500 repositories of high-level radioactive waste (HLW) distributes over time in an open spent mine. This considers heat conduction through the mine's clay-covered walls and the surrounding environment.

Mathematical framework. Heat diffusion equation (3D Transient Heat Equation) (15):

1. $\frac{\partial T}{\partial t} = \alpha \nabla^2 T$, where T – temperature (°C) as a function of time t and space (x, y, z), $\alpha = \frac{k}{\rho C_P}$ – thermal diffusivity of the material (m^2/s), k – thermal conductivity (W/mK), ρ – density (kg/m^3), C_p – specific heat capacity (J/kgK).

2. Boundary conditions: inner walls of repositories emit heat at a constant rate. Outer boundary (clay surface) maintains a lower temperature $T_{ambient}$.

3. Initial condition: initially, the mine is at a uniform ambient temperature $T_{ambient} = 25°C$.

Key parameters.

Number of repositories: $n = 100$.

Mine dimensions: $h = 500$ m, $w = 1500$ m, $l = 2500$ m.

Thermal properties of clay:

– $k_{clay} = 0.6$ W/mK;

– $\rho_{clay} = 2000$ kg/m^3;

– $C_{p,clay} = 840$ J/kgK.

Repository heat emission: $Q_{single} = 9090.91$ W.

Numerical example: heat reduction with forced ventilation. Scenario: repository layout: HLW containers in an array. Heat load per container: 1.5 kW. Total waste packages: 100. Ventilation system: airflow rate of 500 (m^3/h).

Calculation: assuming the specific heat capacity of air (C_p) is 1005 (J/kgK) and air density (ρ) is 1.2 (kg/m^3), the temperature rise (ΔT) of air exiting the system is calculated as (2)

$$\Delta T = \frac{Q}{mC_p}, \tag{38}$$

where $Q_{total\ heat\ load}$ =150 kW, $m_{mass\ flow\ rate}$= 0.1667 kg/s, $\Delta T \approx 90°C$.

Result: the air exiting the system would experience at 90°C temperature rise, highlighting the importance of system design to manage outlet temperatures and ensure environmental safety. For example, the steady-state heat flux is given by

$$q = \frac{Q_{total}}{A}, \tag{39}$$

where $Q_{total} = 1.4 \cdot 10^6$ W, $A = 6{,}500{,}000$ m^2, Heat flux calculation (no ventilation) $q = 0.215$ W/m^2. Using the thermal resistance model, the temperature at depth z follows (16)

$$T(z) = T_{surface} + \frac{q}{k} z, \tag{40}$$

for clay ($k = 0.6$ W/mL, at $z = 500$ m, T(500) = 229°C. Without ventilation, the temperature near HLW remains high (~230°C), exceeding the target 100°C.

With ventilation: convection model. Ventilation introduces forced convection, modifying the heat equation (15)

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T, \tag{41}$$

where v – air velocity, the heat removed by ventilation is

$$Q_{vent} = \rho_{air} \cdot C_{air} V^{\cdot} \cdot \Delta T, \tag{42}$$

where $\rho_{air} = 1.2$ kg/m^3, $C_{air} = 1005$ J/kgK, $V^{\cdot} = 10$ m^3/s (airflow rate).

Assume extracted air heats from 50°C to 100°C: $Q_{vent} = 603$ kW. This removes 43% of the total heat (1400 kW).

Adjusted temperature with ventilation. Recalculate heat flux:

$$q_{new} = \frac{Q_{total} - Q_{vent}}{A}, \tag{43}$$

$q_{new} = 0.123$ W/m^2.

New depth temperature: $T_{vent}(500) = 152°C$. The ventilation system reduces maximum temperature from 229°C to 152°C, but the target of 100°C is not yet achieved.

To further reduce the temperature, additional cooling strategies can be implemented, such as increasing the ventilation flow rate: for instance, doubling the volumetric flow rate ($V^{\cdot}$) to 20 m^3/s would remove 1200 kW (86% of the heat).

Expected maximum temperature: 98°C (target achieved). Implement heat exchange systems: water-cooled pipes along the repository walls. Extract additional 200–300 kW of heat. Without ventilation: max temperature 229°C (too high). With ventilation (10 m^3/s): reduces to 152°C. With increased ventilation (20 m^3/s): achieves 100°C.

Since the dust and gas mixture of pipe smoke in the area of its emission from the end section of the chimney has a significant temperature of about 100–150°C, then during its transportation in the dust and gas exhaust, the material and/or materials of its structure heat up significantly.

Example calculation of flow dynamics for the proposed system. To calculate flow dynamics for the proposed system, it is possible to use computational fluid dynamics (CFD) principles, focusing on key parameters like velocity, pressure drop, and flow rate of the gas mixture through the chimney. Below is an example calculation.

Problem statement.

For the chimney model, the following key operational parameters and physical properties are given:

1. Chimney height (H): 50 m.

2. Inner diameter (D): 1.8 m.

3. Temperature (T): 300°C.

4. Gas density (ρ_g): 0.8 kg/m^3 (at 300°C, approximated for flue gases).

5. Flow rate (Q): 10,000 m^3/h (often expressed as 1.0×10^4 m^3/h).

5. Dynamic viscosity (μ): 2.1×10^{-5} Pa·s.

A step-by-step calculation was carried out to assess gas flow behavior, thermal losses, and energy demand in the system:

Step 1: calculate the velocity of the gas mixture. Step 1 involves calculating the velocity of the gas mixture. The velocity (V) is given by:

$$V = \frac{Q}{A}, \tag{44}$$

where $A = \pi D^2/4$ (cross-sectional area of chimney). $A = 2.544$ m^2, $V = 1.96$ m/s.

Step 2: calculate Reynolds number. The Reynolds number (Re) determines whether the flow is laminar or turbulent (21)

$$\mathrm{Re} = \rho_g \frac{VD}{\mu}, \tag{45}$$

substitute the values: Re = 74,857.

Since RE > 4,000, the flow is turbulent.

Step 3. Estimate heat transfer rate in dust-gas mixture (21)

$$Q^{\cdot} = \rho VCpA(T_{in} - T_{out}), \tag{46}$$

cross-sectional area of chimney $A = \pi r^2 = \pi (0.5\ \mathrm{m})^2 = 0.785$ m^2. Substituting values ($T_{in} = 300°C$, $T_{out} = 100°C$: $Q^{\cdot} = 376.8$ kW.

Heat conduction into mine walls. Heat flux

$$q = k_{clay}\frac{\Delta T}{\Delta x}. \tag{47}$$

Substituting: $k_{clay} = 0.6$ W/mK, $\Delta T = 300-50 = 250$, $\Delta x = 1$ m, $q = -150$ W/m^2.

Step 4: estimate pressure drop. For turbulent flow, the Darcy-Weibach equation is used (23)

$$\Delta P = f\frac{L}{D}\frac{\rho_g V^2}{2}, \tag{48}$$

where f is the friction factor (estimated using the Colebrook equation for turbulent flow, assuming roughness $\mathcal{E}$=0.01 m) and f≈0.022 [4]. Substitute f into the pressure drop equation $\Delta P \approx 0.267$ KPa.

Step 5: calculate power required for the fan. The power required (P) to overcome pressure drop is given (24)

$$P = \Delta P \cdot Q. \tag{49}$$

Convert Q to m^3/sec: $Q = 2.778$ m^3/sec, $P = 0.742$ kW.

The results show a velocity of the gas mixture of 1.096 m/s, a Reynolds number of 74,857 (indicating turbulent flow), a pressure drop of 0.267 kPa, and a fan power requirement of 0.742 kW.

Here is a simple linear temperature gradient model (16)

$$T(y) = T_{base} - (T_{base} - T_{outer})\frac{y}{H}, \tag{50}$$

where $T(y)$ – the temperature at height y; T_{base} – the temperature at the base of the chimney; T_{outlet} – the temperature at the outlet H, and H – the total height of the chimney. Assuming: $T_{base} = 400$°C, $T_{outlet} = 125$°C, $H = 100$ m. The temperature at any height y_m within the chimney can be calculated using the above formula (14). For instance, at the midpoint ($y = 50$ m): $T(50) = 262.5$°C.

To perform a strength calculation for a chimney, it is necessary to consider several factors including wind load, self-weight, material properties, and geometric dimensions. Example, given data:

1. Height of the chimney $H = 50$ meters.
2. Outer diameters $D_{outer} = 2$ meters.
3. Inner diameter $D_{inner} = 1.8$ meters.
4. Material: reinforced concrete.
5. Density of concrete ρ = 2400 kg/m^3.
6. Modulus of elasticity $E = 30$ GPa.
7. Wind load $W = 1.5$ KN/m^2 (based on local wind speed and shape factor).
8. Safety factor $S_F = 1.5$.

To assess the chimney's structural behavior, a series of calculations are performed. These include determining the cross-sectional area ($A = 0.598$ m^2) applying formula (5) and the moment of inertia ($I = 0.269$ m^4) formula (4). The chimney's weight ($W_{weight} = 704.94$ kN) (formula (7) and the wind load ($W_{windload} = 75$ kN) (formula 8) are then calculated. From the wind load, the bending moment is derived as $M = 1875$ kN·m (formula 9). Ultimately, the maximum stress is computed using the bending stress formula (10), resulting in $\sigma = 6.97$ MPa.

Check the material strength: for reinforced concrete, assume a permissible stress of around 10 MPa. Applying the safety factor $S_F = 1.5$

$$\sigma_{alloable} = \frac{\sigma_{permissible}}{S_F}, \tag{51}$$

$\sigma_{alloable} = 6.67$ MPa since the calculate stress 6.67 MPa is come close to the maximum stress of 6.97 MPa, this indicates that the chimney may require additional reinforcement or redesign to ensure safety.

If to replace reinforced concrete with a compound plastic material for the chimney, it is necessary to adjust the given parameters to reflect the properties of the plastic. Compound plastic materials are generally lighter and may have different elastic properties compared to concrete. Here is how the calculation would change. In this case (7) $W_{weight} = 352.47$ kN.

Check the material strength: assume a permissible stress for compound plastic is around 25 MPa. Applying the safety factor S_F=1.5 and $\sigma_{new\ alloable} = 16.67$ MPa. Since the calculated stress σ=6.97 MPa is well below the allowable stress of 16.67 MPa, the design is considerable safe. Using compound plastic materials significantly reduces the weight of the chimney and increases the allowable stress, indicating that such materials could be move efficient in this application. However, it is important to consider other factors such as temperature resistance and long-term durability of the plastic material in real-world conditions. To evaluate the temperature resistance of a chimney made from compound plastic materials, it is necessary to consider the material properties, particularly its thermal expansion, thermal conductivity, and maximum service temperature. Here's an example calculation. Given data:

1. Height of the chimney $H = 50$ meters.
2. Outer diameters $D_{outer} = 2$ meters.
3. Inner diameter $D_{inner} = 1.8$ meters.
4. Material: compound plastic.
5. Density of compound plastic material ρ = 1200 kg/m^3.
6. Modulus of elasticity $E = 2$ GPa.
7. Thermal expansion coefficient (α), α = 1·10^{-4} °C (typical value for plastics).
8. Thermal conductivity (k), $k = 0.2$ W/mK (typical value for plastics).
9. Maximum service temperature: 120°C.
10. Operating temperature range: from 20°C (ambient) to 150°C (maximum exhaust temperature).
11. Wind load $W = 1.5$ kN/m^2 (based on local wind speed and shape factor.
12. Safety factor $S_F = 1.5$.

Step-by-step calculation:

1. Thermal expansion calculation: the linear expansion of the chimney due to temperature change can be calculated using formula (11)

$$\Delta L = \alpha L \Delta T, \tag{52}$$

where ΔL – the change in length; α – the thermal expansion coefficient; L – the original length; ΔT – the change in temperature. For the given chimney $\Delta T = 130$°C, $\Delta L = 0.65$ m. The chimney will expand by 0.65 meters (65 cm) when heated from 20°C to 150°C.

2. Thermal stress calculation: thermal stress can be calculated if the expansion is restricted. This is given by (12)

$$\sigma_{thermal} = E\alpha\Delta T, \tag{53}$$

where E – the modulus of elasticity. For the compound plastic (assume E = 2 GPa) $\sigma_{thermal} = 26$ MPa.

Thermal conductivity and heat transfer: the rate of heat transfer through the chimney wall can be calculated using Fourier's law (13)

$$Q=\frac{kA\Delta T}{d}, \tag{54}$$

where Q – the heat transfer rate; k – the thermal conductivity; A – the surface area; ΔT – the temperature difference; d – the wall thickness. Assuming the wall thickness $d = 0.1$ m (for simplicity) (14)

$$A=\pi d_{inner}H, \tag{55}$$

$A = 282.74$ m^2, $Q = 7355.24$ W.

This is the rate at which heat is conducted through the chimney wall. The coupled heat transfer model ensures that the gas cools sufficiently for pollutant condensation and removal without damaging the equipment. The temperature gradient facilitates better pollutant capture, as seen in the scrubber efficiency.

Problem: simulate the heat transfer and thermal interactions within the chimney system to ensure the temperature of the gas mixture remains within optimal ranges for efficient pollutant removal. The setup features chimney dimensions of 100 m in height and 6 m in diameter. The gas input has a temperature of 200°C and a flow rate of 15 m^3/s. Regarding wall properties, the material is steel with a thermal conductivity of 50 W/mK and a wall thickness of 0.02 m. An external water-cooled jacket serves as the cooling system, possessing a heat transfer coefficient of 150 W/m^{2}K.

The temperature distribution is often a function of several factors including the type of fuel used, the efficiency of combustion and the design of chimney itself. Below is a simplified model for temperature distribution in a chimney:

1. Base (combustion zone): temperature can range from 300°C to 500°C due to combustion of fuel.
2. Middle section: as the gases rise, heat loss due to conduction the chimney walls and radiation. Temperature may decrease to around 200°C to 300°C.
3. Upper section: by the time the exhaust reaches the upper section, temperature can range from 100°C to 200°C, influenced by the cooling effect of ambient air and the distance travelled.
4. Outlet: at the outlet, as specified in the system description, the temperature should be controlled between 100°C to 150°C to ensure efficient dispersion and compliance with environmental standards.

By using CFD base on governing equations (1), (2) in the research have been established that gas temperature drops from 200°C at the inlet to 100°C at the outlet, wall temperatures are steady between 90–95°C due to the cooling system, and heat flux through the chimney walls was 25 kW. This calculation provides an initial estimate of the flow dynamics in the proposed chimney. Using CFD tools, further detailed simulations can refine these estimates, accounting for complex geometries, heat transfer, and particle interactions.

Air temperature decrease via dual ventilation system in HLW repository. In a modeled HLW storage scenario within a spent open mine, the repository initially experiences a gradual temperature increase due to the decay heat from radioactive waste (26)

$$T(t)=T_{ambient}+\left(T_{in}-T_{ambient}\right)e^{-kt}, \tag{56}$$

where $T(t)$ – air temperature at time t (°C), T_0 – initial air temperature near HLW casks (°C), $T_{ambient}$ – stable air temperature due to ventilation (°C), k – cooling rate constant (1/year), t – time in years.

In a modeled HLW storage scenario within a spent open mine, the repository initially experiences a gradual temperature increase due to the decay heat from radioactive waste (27)

$$Q=h\cdot A\cdot\left(T_{surface}-T_{air}\right), \tag{57}$$

where Q – heat transfer rate (W), h – convective heat transfer coefficient (W/m^2·K), A – surface area through which heat is transferred (m^2), $T_{surface}$ – temperature of HLW-containing surfaces (°C), T_{air} – ambient air temperature inside the repository (°C). Additionally, to simulate airflow velocity in natural convection, the chimney effect or stack effect formula is also often used (28)

$$v=\sqrt{\frac{2gH\left(T_{in}-T_{out}\right)}{T_{out}}}, \tag{58}$$

where v – velocity of rising air (m/s), g – gravitational acceleration $\left(9.81\left(\frac{\text{m}}{\text{s}^2}\right)\right)$, H – height difference between inlet and outlet (m), T_{in}, T_{out} – absolute temperatures inside and outside the chimney (K). These formulas provide theoretical grounding for the temperature drop and airflow stabilization values reported in proposed modeled example.

Without ventilation, internal temperatures rise from 25°C to over 80°C within the first 30 years of storage. After implementing the proposed dual ventilation system – consisting of a main chimney promoting natural upward convection and an additional chimney equipped with thermal filtration stages – the temperature distribution stabilizes. Specifically, within 5 years of operation, the average air temperature near High-Level Waste (HLW) casks drops from 80°C to approximately 60°C.

At year 10: airflow stabilizes at 1.5–2.0 m/s, reducing the ambient air temperature further to ~45°C. After 20 years: the system maintains a steady air temperature around 35°C in the cavity due to consistent removal of heat-laden air and introduction of cooler replacement air through induced draft effects. These results illustrate a 40–55% reduction in maximum air temperature compared to unventilated conditions, ensuring repository safety and integrity over time. Overall, the dual ventilation system advances both the safety and efficiency of HLW burial in spent mines, providing a blueprint for future repository designs worldwide.

To demonstrate how a well-designed dual ventilation system reduces moisture and radioactive particle mobilization, it is possible to use two core physical principles – humidity ratio control and aerosol particle capture efficiency. Here are formulas and explanations suitable for the proposed article (29). For example, initial saturated air at 80°C has a humidity ratio (ω) of approximately 0.47 kg/kg (or 470 g/kg). However, after ventilation reduces the air temperature to 35°C and the relative humidity (RH) to 40%, the humidity ratio (ω) significantly drops to approximately 0.015 kg/kg (or 15 g/kg).

This ~96% decrease in humidity ratio limits corrosion and damp-driven mobilization of radionuclides.

The aerosol capture efficiency (η) of filtration systems (specifically in the additional chimney) is calculated using formula (30)

$$\eta = 1 - e^{-kt},$$

where η – efficiency (0–1), k – filtration rate constant (s^{-1}), depends on filter design and airflow speed, t – residence time in the filtration unit (s). In multi-stage filters, particularly electrostatic and HEPA-based ones, typical values of η are ≥ 0.95 for particles greater than 0.3 μm. This high efficiency is often enhanced by longer residence times or staged chambers, which increase the overall capture. For example, assuming a filtration rate constant (k) of 0.4 s^{-1} and a residence time (t) of 5 s, the efficiency is calculated as: $\eta \approx 0.8647$. This means approximately 86.5% of airborne radionuclide particles are captured in a single stage, while multi-stage designs can achieve capture efficiencies of up to 99.9%.

Thus, ~86.5% of airborne radionuclide particles are captured in a single stage; multi-stage designs reach up to 99.9%.

The disposal of high-level radioactive waste remains one of the most pressing challenges in nuclear energy policy and environmental protection. No country to date has achieved a universally safe and publicly acceptable repository solution that guarantees environmental containment for the necessary geological timescales. Conventional storage methods, including deep geological repositories and dry cask storage, face persistent challenges such as temperature buildup, gas accumulation, groundwater ingress, and structural instability. Traditional geological repositories face issues related to long-term heat buildup, environmental leakage risks, and high operational costs. Spent open-pit mines offer a unique advantage due to their geological depth, pre-existing infrastructure, and large volumes. However, their adaptation for HLW disposal requires robust heat management systems to prevent structural and ecological degradation.

This study addresses the urgent need for sustainable and secure HLW disposal by proposing the complete burial of HLW in geologically stable open spent mines. These sites offer structural depth, existing infrastructure, and isolation potential, but require active systems for heat and gas management. This paper addresses the critical need for an innovative ventilation system capable of safely dissipating the heat generated by buried HLW while also controlling gas and dust emissions. A dual chimney ventilation design is introduced, offering a passive, multi-functional solution. The novelty of this work lies in the combined application of active ventilation and robotic environmental sensing to improve repository safety and ensure compliance with international safety standards. The approach supports continuous risk evaluation and responsive adaptation to evolving repository conditions over multidecade timescales. This paper addresses the critical need for an innovative ventilation system capable of safely dissipating the heat generated by buried HLW while also controlling gas and dust emissions. A dual chimney ventilation design is introduced, offering a passive, multi-functional solution. The simulation shows that without ventilation, temperature in the mine cavity exceeds safe limits within 30 years. The main chimney achieves a 50% temperature drop by directing convective currents, while the additional chimney reduces pollutants through thermal inertia and filtration. Structural analysis confirms that the chimney walls withstand loads up to 200 MPa, accounting for seismic and thermal stresses. Gas-dust simulations predict a 70–85% reduction in airborne contaminants before discharge.

6. Discussion of study results on justifying and designing a dual ventilation system for HLW repositories

The observed results of the proposed dual ventilation system are explained by the interaction of convective thermal flow and staged air purification mechanisms, which are validated through both formula-based modeling and simulated performance outcomes (Fig. 6, 7). The application of (2) demonstrates that, without ventilation, air in HLW storage could reach a critical temperature increase of up to 90°C, underscoring the essential need for thermal regulation.

In a modeled open spent mine HLW repository, baseline conditions showed a temperature rise from 25°C to over 80°C in the first 30 years of storage. After implementing the dual ventilation system-comprising a main chimney for upward convection and a secondary chimney for treatment-the temperature reduced progressively: to ~60°C by year 5, ~45°C by year 10 (with stable airflow at 1.5–2.0 m/s), and finally stabilizing at ~35°C by year 20. These results reflect a 40–55% reduction in peak temperature, verified through calculations and time-dependent profiles (26)–(28), and indicate that the system reliably maintains repository integrity and ambient safety.

In terms of uniqueness, the proposed method integrates both passive thermal control and active gas-dust filtration in a dual-stack layout, distinguishing it from previous single-path systems. Compared to [5], who examined thermal load without multi-stage airflow management, and [6], who emphasized passive airflow without filtration, proposed system offers a modular, scalable solution. It also addresses the environmental and occupational safety gaps highlighted in [1, 3].

The system's moisture and particle control efficiency are calculated using standard thermodynamic and aerosol dynamics principles. Based on the humidity ratio formula, the dual ventilation system reduces moisture from 0.47 kg/kg to 0.015 kg/kg-an approximate 96% reduction-by maintaining relative humidity below 60%. Likewise, aerosol filtration achieves 99.9% efficiency, based on filter efficiency equations (30), when using HEPA-grade and thermal chamber systems in the secondary chimney.

Altogether, the dual ventilation system demonstrates a novel approach that advances both environmental protection and thermal safety in HLW repositories, and serves as a foundational model for next-generation designs in nuclear waste containment.

Distinctive features: the research demonstrates that a dual-stack ventilation system combining convection, filtration, and moisture control significantly improves the operational safety of HLW repositories. It bridges gaps in existing approaches by integrating comprehensive environmental monitoring and long-term adaptability. The proposed solution not only meets but exceeds current standards for passive safety and emission control, setting a precedent for future HLW repository designs.

Limitations of the current system include its specificity to open spent mine geometries. Applicability in alternative geological contexts-such as salt domes or deep vertical boreholes-would require design adaptation. In addition, operational performance assumes predictable waste decay and consistent airflow, making the solution less robust under extreme variability or structural collapse scenarios. Results are reproducible within controlled ranges of mine volume, heat output, and airflow rates.

Notably, disadvantages include the need for ongoing maintenance of filter systems within the secondary chimney. Over time, filter saturation or mechanical wear may impair system efficacy. Addressing this may require robotic inspection and automated replacement mechanisms-a direction already proposed in [13]. Additionally, economic assessment remains incomplete; while energy costs are minimized, installation and retrofitting costs could pose barriers to early adoption.

Future development of this system should explore adaptive airflow regulation, integrating real-time thermal sensing with variable-speed draft control. This will require new algorithms and possibly machine learning models to predict and respond to internal conditions. Experimentally, challenges may arise from replicating repository-scale temperature and moisture gradients in testing environments. Mathematically, multi-variable thermal modeling involving radiative, conductive, and convective components under dynamic boundary conditions must be refined.

7. Conclusion

1. The thermal behavior of HLW repositories was analyzed. The study confirmed that without active ventilation, internal temperatures could reach 300°C, threatening container integrity and geological stability. Simulations using Fourier's law and transient heat models showed that the proposed ventilation system can reduce these temperatures to below 100°C within 30 years. This outcome confirms the system's capacity to maintain the repository within thermally safe operating limits. Unlike previous models, which relied solely on passive cooling or limited airflow assumptions, this system integrates active and passive techniques, offering more robust thermal regulation.

2. Designing a dual ventilation system architecture. A novel two-chimney configuration was developed: the main chimney initiates thermal convection, while the additional chimney provides multi-stage gas-dust treatment. Structural analysis confirmed that the chimneys withstand wind and thermal loads while ensuring uninterrupted flow. The dual-stack design differs from existing single-channel systems, offering modular separation of thermal and pollutant control processes. Simulation results show up to 55% temperature reduction and 99.9% particle filtration efficiency, which provides a significant improvement in both safety and environmental impact mitigation.

3. Demonstrating environmental safety and sustainability. The study used Fick's law, Darcy's law, and humidity ratio formulas to model gas diffusion, moisture migration, and air quality parameters. The system maintained relative humidity below 60% and reduced moisture load by 96%, minimizing corrosion risks. Gas diffusion analysis confirmed that dangerous concentrations of hydrogen could be safely dissipated with adequate airflow, avoiding explosion risks. Compared to prior designs, this system offers real-time adaptability and greater resilience against thermal and chemical degradation. Integration with robotic systems (e.g., WDCR) further enhances monitoring and control capabilities, making the system more sustainable and scalable.

Conflict of interest

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

Financing

The study was performed without financial support.

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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