



Technical Key Challenges for Optimisation of Geological Disposal Facilities for High-level Waste

Work Package 13

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Authors	Jiri Svoboda, Philipp Herold, Anne-Catherine Dieudonné, Arnaud Dizier, Gauthier Fontaine, Ville Rinta-Hiiri, Alan Tkaczyk, Petr Vecernik, Nadja Zeleznik

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Verified (WP Leader)	Philipp Herold (BGE)	23/03/2026
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Executive Summary

As programmes for high-level waste repositories advance and move into construction and operational phases, optimisation naturally becomes a central focus. Its importance stems from the longterm nature of repository projects, where evolving boundary conditions require continuous adaptation. New waste types, technological progress, and insights gained from operational experience are examples of such changing boundary conditions.

The EURAD2 Strategic Study Work Package “HLW Repository Optimisation Including Closure” (OPTI) aims to foster a shared understanding and provide recommendations on methodologies and future activities related to optimisation. During two workshops, waste management organisations (WMOs), technical safety organisations (TSOs), research entities (REs), civil society organisations (CSOs), regulators, and the OPTI enduser group exchanged views on what optimising a disposal programme entails, their respective roles in the process, and how optimisation can be implemented.

Optimisation is not a standalone task, but rather a cross-cutting principle that interacts with various aspects of the repository and all knowledge domains of the EURAD Roadmap¹ in different ways. In technical domains, optimisation is addressed directly. Themes such as pre-disposal, engineered barrier systems, disposal facility design, and safety assessment include optimisation through the refinement of technical solutions, safety strategies, and system performance. Optimisation should be understood as a continuous, iterative, and multi-stakeholder process in which safety remains the central driver, but economic, technical, and societal factors also play essential roles.

Based on the perspectives of the four actors WMOs, TSOs, REs, and CSOs a range of conceptual and practical approaches to optimisation were identified. These approaches to optimisation cover a large spectrum, from radiological impact minimisation and design flexibility to multicriteria analysis, iterative refinement, and the use of digital tools.

During the discussions, key topics were identified, themselves encompassing a broad spectrum of issues. These key topics are driven by strategic, scientific, and technical considerations. Clearly, engagement with these topics is not confined to EURAD2 or potential future EURAD programmes. The addressed topics are of relevance for the entire radioactive waste management programme and all stages of repository evolution. Nevertheless, it is possible to establish a systematic and wellfounded mapping of the key topics to the EURAD SRA themes. Six key topics were identified. Four of them are related to DGR components and a scientific/technical optimisation. Two topics are not component-related. The six key topics are:

- Closure design and closure monitoring
- Backfilling design and performance
- Disposal waste packages
- Tunnel support structures in clay and claystone formations
- Governance of RWM
- Multi-criteria optimisation framework

¹ EURAD Roadmap: A generic roadmap for implementing radioactive waste management, leading to geological disposal https://www.ejp-eurad.eu/sites/default/files/2021-08/EURAD%20Updated%20Roadmap%20Guide_%20Issue%202.pdf

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1. Introduction

As deep geological repository programmes advance and move into construction and operational phases, optimisation naturally becomes a central focus. The evolution of disposal concepts from early-phase descriptions requires several licensing phases, iteration rounds, performance assessments, and the development of a safety case, but also the proof that it can be implemented in an industrial way with evolving methods and tools. Furthermore, the relevance of optimisation stems from the long-term nature of repository projects, where evolving boundary conditions require continuous adaptation. New waste types, technological progress, and insights gained from operational experience are examples of such changing boundary conditions. Due to this dynamic environment, optimisation must be understood as an ongoing, inclusive and holistic process that engages all stakeholders within a radioactive waste management (RWM) programme, including civil society. When approached in this way, optimisation strengthens technical and economic performance, enhances long-term safety as well as operational safety, and ensures the flexibility and robustness needed to navigate future developments.

In the Oxford Dictionary [1] the term optimisation is defined as “*the action of making the best or most effective use of a situation or resource.*” In detail, the terminology and understanding of optimisation vary across programmes, countries, and different stakeholders. The ICRP [2, 3] considers the optimisation of protection as one of the three key principles of the system of radiological protection: the principle of justification, the principle of optimisation of protection, and the principle of application of dose limits. The ICRP defines the optimisation of protection as “*achieving the best level of protection under the prevailing circumstances*”.

EURAD-2 WP OPTI was initiated to develop a mutual understanding and provide recommendations on methodologies and future activities related to the optimisation of high-level radioactive waste (HLW) geological disposal facilities (GDFs) systems, structures, and components (SSCs). OPTI provides a platform for interaction between members of the three EURAD-2 colleges, as well as civil society organisations (CSOs), regarding the optimisation of HLW GDFs. Furthermore, OPTI liaises with interested end users, including regulators. The WP OPTI green paper [4] gives further details about optimisation in the context of GDFs.

Optimisation is not a standalone task, but rather a cross-cutting principle that interacts with all knowledge domains of the EURAD Roadmap [5] and Strategic Research Agenda (SRA) [6] in different ways. In technical domains, optimisation is addressed directly. Themes such as pre-disposal, engineered barrier systems, disposal facility design, and safety assessment include optimisation through the refinement of technical solutions, safety strategies, and system performance. This includes domains such as 3.4.1 (EBS system), 5.2.2 (Optimisation), and 5.4.3 (Accident safety), which directly reference optimisation. The development, establishment, and operation of SSCs is always linked to an optimisation process.

Besides classical technical optimisation, a broader sense of optimisation is related to the RWM programme, and this can be optimised as well. In this case, optimisation is included in a broader sense. For example, Programme Management with the SRA domains 1.1.4 (Safety, security and use of resources) and 1.5.1 (Integrated waste management routes and strategic options) is touched. This creates the structures, processes, and transparency needed to ensure that optimisation occurs in a justified, traceable, and socially legitimate way, while also being linked to optimisation as a holistic approach. Optimisation is both a technical endeavour and a societal process. This underlines the need for continuous improvement, stakeholder involvement, and adaptive decision-making throughout the lifecycle of a radioactive waste management programme.

The importance of optimisation varies across the themes and domains. It is essential to identify the most relevant topics and challenges. Clear priorities for future work must be established. This paper summarises the key topics and associated challenges for optimising HLW GDFs, as identified in the OPTI Work Package. It highlights areas where further actions are needed. It also describes potential opportunities for addressing specific optimisation challenges within EURAD-2 and beyond.

2. Challenge

Within OPTI, the four actors WMOs, TSOs, REs and CSOs aim to develop a mutual understanding of optimisation and provide recommendations on methodologies and future activities related to the optimisation of SSCs in HLW GDFs. The WP OPTI green paper [4] summarises their discussions and explores how the different actors involved in the geological disposal of HLW understand and approach the concept of optimisation. It is a consensus that optimisation is not a search for a single perfect solution but an ongoing effort to improve the repository with regard to compliance with the safety requirements, the technical design and societal legitimacy within the constraints of the actual conditions, in other words, the prevailing circumstances.

These conditions and limits, summarised under the term 'prevailing circumstances', include regulatory requirements, available scientific knowledge, technological maturity, financial resources, and societal expectations. While these circumstances can change over time, there is always an overlap or common ground. It is in this overlap that optimisation takes place. It is a dynamic environment in which decisions must be made and revisited over time. This area of overlap is described as the 'space for optimisation'. Optimisation in this space is achieved through the interaction of different actors with each other and the prevailing circumstances. Each actor has their own role and perspective on optimisation. The actors' views on optimisation can be briefly summarised as follows.

WMOs tend to approach optimisation with a focus on compliance with the safety requirements and in general on regulatory compliance, safety, practical feasibility, and cost. They often refine safety assessments, reduce unnecessary conservatism, integrate new technologies once they are sufficiently mature, and manage costs across the repository's lifecycle.

While acknowledging all these considerations, TSOs place protection at the centre of their perspective. They expect optimisation to be holistic, addressing the entire system rather than individual components. They treat economic and operational considerations as means to reach the overarching goal of protection.

REs contribute by expanding the scientific and technical basis for optimisation, for instance by developing advanced modelling tools, exploring new materials and engineered barrier concepts, and supporting knowledge transfer across the community. Their work helps maintain flexibility by identifying emerging technologies that may become relevant in future design iterations.

CSOs, meanwhile, emphasise transparency, trust, and the ethical dimensions of optimisation. They insist that safety must remain non-negotiable and caution against optimisation processes that appear driven primarily by cost savings or operational convenience, highlighting the importance of societal legitimacy in long-term waste management. CSOs understand themselves as a form of oversight within the general RWM programme.

Based on the perspectives of the four actors, the WP OPTI green paper [4] identifies a range of conceptual and practical methods and approaches to reach the optimisation targets. Relevant methods are, e.g., iterative refinement and the application of digital tools, including Repository Management Systems. Optimisation should be understood as a continuous, iterative, and multi-stakeholder process in which safety is the primary objective, but economic, technical, and societal factors also play essential roles.

During the discussions, different key topics were identified. They encompass a broad spectrum of issues, driven by strategic, scientific, and technical considerations. Clearly, engagement with these topics is not confined to EURAD-2 or potential future EURAD programmes. Nevertheless, it is possible to establish a systematic and well-founded mapping of the key domains to the EURAD SRA themes. The following key topics and associated challenges were identified for further detailed investigation.

Closure consists of different components, and its design must optimise between various objectives, including long-term safety, cost-effectiveness, passive safety, and compliance with regulatory and societal constraints. Monitoring after closure can help to assure safety and support retrievability, but it

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may also compromise isolation (through intrusive monitoring) and increase costs. Closure design and closure monitoring are addressed in different SRA themes, such as Theme 5 (Design), especially domains 5.1.1 (design requirements) and 5.5.2 (monitoring). In SRA Theme 3 (EBS) especially the domains 3.3.3 (plugs and seals) and 3.4.1 (EBS system) are relevant.

Backfilling materials must be adapted and optimised in close interaction with the DWP (Disposal Waste Package) and the other components of the near-field. Optimisation challenges are linked to the provision of long-term safety functions under evolving thermal, hydraulic, mechanical, and chemical conditions. A sound knowledge of backfill design and performance is essential. Optimisation includes the type of bentonite used, or the use of other montmorillonite-rich clays or mixtures, backfill design parameters (e.g. moisture content and pellet characteristics), control of alteration of backfilling materials and the resulting change in properties (e.g. potential loss of swelling capacity in bentonite) and alternative backfilling materials including the compositions and raw materials. Backfilling design and performance are already addressed in SRA Theme 5 (Design) domains 5.2.2 (optimisation) as well as SRA Theme 3 (EBS) domains 3.3.1 (buffer) and 3.3.2 (backfill).

Different reference concepts for the **disposal waste package** in various host rocks exist. Optimisation of these designs is important in order to respond to changed or modified requirements, or to more precise knowledge about the actual site conditions. New technologies in manufacturing and materials science can also lead to optimisation. It is important to emphasise that optimisation of the DWP affects at the same time other components in the near-field, e.g. the backfill or buffer. The DWP is included in the SRA Theme 3 (EBS), especially the topics 3.2.1 (HLW and SF containers) and 3.2.3 (novel containers).

The delayed, time-dependent rheological behaviour of clays and claystones, as well as concrete structures, generally results in the progressive convergence of deep underground structures. This leads over time to the evolution of mechanical loading on tunnel **support structures**. The design of these support structures must be optimised to reduce repository costs while ensuring stability throughout the operational life. The main challenge in optimisation lies in how to predict and account for the delayed behaviour of the host formation and concrete structures in the design of a geological disposal facility. Support structures in clay and claystone formations are part of the SRA Theme 5 (Design), especially the domains 5.1.1 (design requirements) and 5.2.3 (manufacture, inspection and testing).

The **governance of RWM** is important for interaction between stakeholders, and especially with civil society. The main governance challenge is ensuring transparent, inclusive, and well-coordinated decision-making that maintains public trust while balancing long-term safety, security, and resource use. An optimised decision-making process, including elements like the legal framework and the characteristics of transparency and public participation, is key for such a successful RWM programme. Other key topics include the balance between safety and security, and the interaction between retrievability and abandonment/passive safety. Furthermore, it is essential to understand cost optimisation and to have appropriate financial systems for RWM. Finally, from a multigenerational perspective knowledge management is essential. RWM governance is already reflected in the SRA Theme 1 (National Programme Management), especially domains 1.1.1 (national RWM policy), 1.1.3 (public information and participation) and 1.1.4 (safety, security and use of resources).

A **multi-criteria optimisation** (MCO) framework that integrates safety-case evidence, cost functions, and environmental and social indicators provides a valuable tool for informed decision-making. — Uncertainty and robustness analysis must be part of that. Approaches of this kind are already applied in several national programmes. For an MCO to be effective, it must be structured so that the various relevant factors (as named above: safety-case arguments, cost considerations, and environmental and societal) are made commensurable and remain fully traceable under the prevailing conditions. The MCO framework is addressed in SRA Theme 1 (National Programme Management), particularly in domain 1.1.4 (safety, security and use of resources).

3. Proposed way forward

3.1 Closure Design and Closure Monitoring

During the discussion of closure optimisation, key challenges in the design and implementation of closure systems for geological disposal facilities were identified (see Appendix C). Timing and planning are difficult because closure can take place far in the future and over a long period, requiring knowledge of the future conditions in the repository and flexibility to integrate new information, technologies, and regulatory requirements. Technical uncertainties include the selection of suitable backfill and sealing materials, the reliability of plugs in varying geological conditions, integrating different parts of the disposal facility, and continuously adapting plans as materials, modelling, and monitoring technologies develop. Regulatory, environmental, and societal factors can simplify or complicate closure planning, as regulatory frameworks may change over time, public acceptance is essential, and closure concepts must be consistent with evolving environmental and sustainability goals.

Monitoring of closure was identified as one of the key topics, and the case study showed that although monitoring can increase confidence in closure performance, its design must not compromise the passive safety functions of the repository. Key considerations include the operational reliability period of monitoring equipment and the need to define in advance which deviations from the expected repository evolution require special measures. It is also important to assess whether monitoring systems need to be replaced at some point and how such new provisions can be implemented without compromising the safety of the final disposal facility.

To address these challenges in closure design and monitoring, short-term research and development should focus on developing adaptive closure design frameworks, advancing experimental and modelling research, and developing adapted monitoring techniques.

Longer-term actions (beyond EURAD-2 and possibly EURAD-3) should include full-scale demonstrations of closure systems and passive monitoring strategies. Such full-scale demonstrations are required in nearly all national programmes prior to licensing. The demonstration activities benefit from international collaboration to share experiences. WMOs should lead technical development, and REs should support them in experimental and modelling work. The regulatory body, made of authorities and the TSOs, should support with their expertise. Further, societal stakeholders need to be involved at an early stage to align expectations and define acceptable monitoring strategies.

The benefit of implementing these actions is that they reduce technical uncertainties and enable less conservative and more cost-effective closure plans. The plans will also strengthen the safety demonstration presented to the regulators and confidence of the public. An optimised, more adaptive and cost-effective closure plan supports the passive safety function of the disposal facility.

Further long-term related activities include the ongoing updating of closure plans as new data, technologies, or regulations become available. In this context, methods for flexible and adaptable planning of the closure, related SSCs, as well as their monitoring, have to be introduced,

3.2 Backfilling design and performance

The backfill is a central component in the EBS of the HLW repository. The disposal cells (e.g. tunnels and boreholes) as well as all galleries in the underground can be backfilled. Together with the other near-field EBS components, the backfill design and corresponding performance ensure the long-term safety and functionality. Backfilling materials must operate in close interaction with the DWP and the surrounding near-field geology. The primary functions of the backfill are to provide mechanical support, to limit water flow, and to maintain favourable geochemical conditions. The performance can be influenced by the backfilling design and by the material selection, preparation, and installation. As a result, optimisation requires a systematic evaluation of material properties, emplacement techniques, and the expected evolution of the repository environment over the relevant timescales after closure.

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While bentonite remains the reference material for many repository concepts due to its swelling capacity, low hydraulic conductivity, self-sealing capacity, and sorption capacity, in some designs the main component of the backfill is the crushed rock itself. However, the type of bentonite used can significantly influence performance. Variations in mineralogical composition, especially the proportion and charge characteristics of montmorillonite, affect swelling pressure, thermal/mechanical/hydraulic stability, and resistance to chemical alteration. Therefore, optimisation may involve selecting bentonites with tailored properties or considering alternative montmorillonite-rich clays that offer improved performance under specific thermal, mechanical, hydraulic, or chemical conditions.

Mixtures are also being considered to optimise properties in terms of expected performance or for environmental considerations involving the management of excavated materials. Thus, mixtures combining bentonite, sand, hydraulic binders, or crushed rock can be designed to improve thermal behaviour, swelling, mechanical strength, and fluid transport properties. Technological objectives such as ease of installation may also be considered. Mixtures such as bentonite-sand blends or bentonite combined with crushed rock may also be engineered to balance swelling behaviour with mechanical strength and ease of emplacement. For such tailored mixtures, quality management and assurance during the design process, but also during manufacturing and later installation, is essential.

Backfill design parameters play an equally important role. Block, grain, or pellet size (and shape), moisture content, density, and compaction method and pressure influence the initial and long-term performance, especially the hydraulic behaviour of the backfill or the mechanical strength. For example, optimising pellet characteristics can reduce heterogeneities and improve the rate at which the backfill hydrates and develops swelling pressure. Similarly, controlling the initial water content helps to manage early-stage suction gradients and reduces the risk of preferential flow paths. These design considerations must be aligned with the thermal output of the DWP, as elevated temperatures can accelerate mineralogical transformations that may degrade performance.

Another key challenge in backfill optimisation is understanding and mitigating long-term geochemical alteration processes. Bentonite, while highly stable, can undergo changes such as ion exchange or partial transformation to non-swelling minerals under certain geochemical conditions. These processes may reduce swelling capacity or increase hydraulic conductivity, potentially compromising barrier performance. Reusing excavated crushed rock could limit the chemical interactions with host rock, but this choice is not neutral considering the exogenous materials such as concretes. Consequently, research focuses on predicting alteration pathways, identifying conditions that minimise detrimental reactions, and evaluating whether alternative materials or engineered mixtures offer greater resilience.

Finally, the exploration of alternative backfilling materials, such as geopolymers, engineered clays, or other industrial by-products, opens additional opportunities for optimisation. These new or alternative materials may provide improved thermal stability, reduce sensitivity to chemical alteration, or provide more sustainable sourcing of raw materials. Their integration into repository designs requires careful assessment of compatibility with the other EBS components, long-term geochemical evolution, and safety criteria derived from the safety assessments.

In the short term, continuous research and development must focus on the technical uncertainties associated with the material behaviour of backfilling. This includes the selection and characterisation of suitable backfill materials tailored to the corresponding national program. Of increasing importance is the establishment of robust quality assurance procedures, from laboratory testing through to large-scale production.

Long-term, an ongoing adaptation to new technologies and potentially new materials will also be essential. In addition, further development of backfill installation techniques and the integration of these processes across different repository sections will be required.

3.3 Disposal Waste Package

The disposal waste package (DWP) serve as physical barrier in terms of ensuring both, operational and long-term, safety of the deep geological repository (DGR). DWPs vary according to the type of waste being disposed of, as described in the next paragraphs. DWPs for Spent Nuclear Fuel (SNF) are highly engineered, shielded containers designed for long-term containment in the DGR. These packages typically consist of corrosion-resistant canisters (e.g. copper or steel) designed for thousands of years of containment. In many countries, the design of DWPs for SNFs is already at an advanced stage and depends on the types of SNFs, legislative requirements, the expected environment, and interactions in the DGR.

Disposal packages for vitrified waste typically consist of corrosion-resistant steel or copper canisters and possibly overpacks. For final application, it can be proposed to design such a DWP for one or more inner containers with vitrified waste. The overall dimensions of this type of waste package and the final canister and overpack materials will be determined based on mechanical strength requirements and the corrosion resistance needed to ensure a required service life.

ILW waste packages are designed for disposing of all other types of waste (solidified liquid waste, activated materials, etc.). Due to the variability of the forms of ILW, different dimensions and shapes of DWPs have been proposed for differing types of ILW. The main materials considered for fabrication of these types of waste packages are reinforced concrete or steel. The outer dimensions of the DWP will be determined by the inner volume and the thickness of the wall, which will be based on strength calculations (the fulfilment of the respective mechanical strength requirements) and the required service life (degradation of the DWP and the loss of its safety function), and other requirements if the waste packages are also used during interim storage (e.g. radiation protection).

The container is a key barrier in the EBS system. Optimisation of its material and design must be based on safety functions, host environment, and interactions with other barriers. Progress in optimisation depends on the state of the national concept and approach to radioactive waste disposal. Some countries are optimising only the maximum lifetime of the metal container, others are more focused on system optimisation, which includes compatibility with rock, flexible material options, operational and manufacturing robustness, while others are still only focused on methodology and process/regulatory optimisation.

Container material optimisation focuses on material selection (metals, composite concepts, and inorganic binders and composites), material compatibility (with waste and waste matrices and surrounding environment, including effects of corrosion), dimensions (wall thickness / corrosion allowance as a compromise between lifetime and weight and cost), mechanical properties (strength, toughness, resistance to deformation, etc.).

It is mandatory to conduct research work on the durability of the container materials in order to assess their stability over a long period, depending on the repository concept. Some of the innovative approaches to the design of SNF and HLW DWP are described in EURAD-2 WP InCoManD [7] and are based on results of previous projects like EURAD CONCORD [8] or EURAD ACED [9].

Repository concepts in the three host rocks (crystalline, clay, salt) impose different boundary conditions that should be reflected in the DWP optimisation. Detailed timing and planning of further research are difficult to coordinate, as different countries and their national concepts are at different stages of development, as well as national legislative requirements. In the short-term period, research could be focused on increasing knowledge and a detailed understanding of material interactions, supplemented by improved modelling, as already started in the EURAD-2 WP InCoManD. In the long-term period, semi- or real-scale experiments could be planned using the infrastructure of underground research laboratories. Further the investigation of alternative materials such as ceramics should be continued to close existing scientific and technological gaps.

3.4 Tunnel Support Structures in Clay and Claystone Formations

Clay and claystone formations are considered host rocks for deep geological repositories due to their strong capacity to confine and delay the migration of radionuclides. These formations exhibit high sorption potential and, in undisturbed conditions, mass transport is predominantly governed by diffusion due to their extremely low permeability to both gases and liquids. These characteristics underpin their strong containment performance.

Despite these advantages, the mechanical behaviour of clay and claystone presents significant challenges for underground construction. Their low to medium mechanical strength, combined with pronounced time-dependent rheological behaviour (consolidation and creep) and a high sensitivity to water content, complicates the design and construction. These characteristics result notably in the development of an excavation damaged zone and significant, ongoing convergence, thereby requiring the installation of permanent, specifically designed support structures in accordance with the DGR requirements.

Although the technical feasibility of geological disposal in clay formations has been demonstrated through experiments conducted in underground research laboratories (URLs) and deep tunnels, feedback from these facilities indicates that the design of support structures remains a critical issue. In particular, meeting stringent functional and safety requirements over long time periods (at least until the end of the operational phase or the end of the retrievability period) continues to pose challenges, as highlighted by experimental observations from facilities such as the HADES underground research laboratory [10, 11].

From the outset, the repository concept should take into account the construction method, structural design, monitoring strategy, and waste package emplacement and retrievability strategy. An important aspect is the integration of the full excavation and lining installation process into the design and planning of support structures. The design of an adequate support system must account not only for the loads imposed by the host rock during excavation and construction, but also for the operational phase, during which tunnels remain open and are ventilated. The design accounts for the sequence and rate of excavation, the timing of support installation, and the interaction between the ground and the support over time. Considering these aspects in an integrated manner is essential to ensure both the structural performance of the lining and the overall feasibility during the GDF lifetime. The initial design and monitoring strategy should explicitly consider the possibility of long-term retrieval during or after closure. However, the integration of dedicated retrieval facilities is technically very challenging.

Depending on their function and location, such as access galleries or disposal galleries and cells, the support structures may consist of concrete linings or steel liners, in accordance with the selected repository concept. The choice of steel liners, reinforced concrete, and plain concrete varies among national programmes depending on specific design requirements, e.g. some of which impose restrictions on the use of steel in order to limit corrosion processes and the associated generation of gas.

The design of the support structures and corresponding elements must comply with requirements established by national waste management programmes as well as by international organisations, such as the International Atomic Energy Agency (IAEA) [12] and national and international underground societies [13]. These high-level requirements are subsequently translated into design requirements and engineering specifications, which form the basis for optimisation studies of the tunnel lining.

The design of support structures involves consideration of multiple interacting factors related to environmental conditions and perturbations induced by the GDF in the host formation. Some of these factors directly affect the design of the support structure, while others can be managed by adapting the repository layout. For instance, thermal effects associated with heat-emitting waste, as well as gas production resulting from corrosion of metallic elements (e.g. reinforcement) or radiolysis, are primarily addressed at the repository layout level. This is achieved by adjusting parameters such as the spacing between disposal galleries or cells, the cooling period prior to disposal, the length of disposal galleries,

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and the quantity of radioactive waste per gallery or cell. These effects are therefore not considered direct design loads for the support system.

Within the framework of the strategic study OPTI, several key aspects directly influencing the support design were examined, including:

- (1) construction method and excavation rate;
- (2) GDF depth and associated in situ stress conditions;
- (3) tunnel functions, shape and diameter;
- (4) time-dependent host formation (anisotropic) behaviour;
- (5) time-dependent behaviour of concrete structures, including the impact of environmental-induced ageing of concrete;
- (6) final linings monitoring analysis approach, in a way to reduce mechanical uncertainty.

The design of support structures for deep geological repositories in clay and claystone is inherently complex, as favourable containment properties are counterbalanced by challenging, time-dependent mechanical behaviour. This complexity is further amplified by the interaction of multiple design factors, as outlined above, and by the absence of clearly defined design requirements and engineering specifications, which can significantly hinder optimisation efforts.

One of the key challenges lies in the integration of design criteria and in their translation into clear, quantitative requirements and technical specifications suitable for engineering design. This step is essential, as criteria are often not expressed in an operational form. Establishing such requirements would provide a consistent basis for evaluating and comparing alternative design solutions within a given programme, thereby reducing uncertainties and supporting robust optimisation. This should be done in the short-term period.

Another focus has to be the integration of the full excavation and liner installation process in the design and planning of the support structures.

Finally, another key challenge lies in ensuring the long-term stability of the support system and the integrity of the multi-barrier system throughout the GDF lifetime. This requires a good process understanding and modelling capability of the time-dependent behaviour of the host formation, support structure, and their interaction.

3.5 RWM Governance

The key challenges in RWM governance include both scientific, technical (e.g., magnitudes of the timescales, complexity of the waste forms and barrier materials, quantities and qualities of heterogeneous data), and societal aspects (diverse and disparate opinions, motivations, and communication approaches). The development of mutual understanding and consensus between incongruous views and expansive information can be complex and challenging. Implementers, scientific experts, regulators, policymakers, and stakeholders should cooperate to carefully navigate the ever-growing domain of knowledge and data related to RWM.

A holistic and digitally enabled framework can facilitate RWM governance. The goal should be to develop a broadly applicable framework for managing geological disposal programmes under constrained resources and/or limited experience. This could be achieved by converting practical case studies and lessons learned into a comprehensive, scalable framework for structuring governance, defining requirements, planning research and development, and engaging stakeholders. The approach should support enduring, forward-looking governance arrangements and actions, prioritised from the start of the RWM programme and sustained over time.

The OPTI green paper [4] positions optimisation as a holistic endeavour constrained by prevailing circumstances and driven by interacting priorities: protection, resource efficiency, and optimisation of the decision-making process, therefore how decisions are taken is itself a legitimate optimisation target.

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A systematic framework can translate the aforementioned objectives into practical RWM implementation, thoroughly assessing key challenges in governing RWM and defining GDF programmatic requirements. Building on this, a Multi-Criteria Optimisation (MCO) framework for RWM should provide a consistent, auditable basis for planning and programme choices, explicitly guarding against optimisation being perceived as cost-driven convenience by keeping safety non-negotiable while making societal legitimacy visible in the decision logic.

Regarding RWM governance, a way forward is to embed trustworthiness and legitimacy, including different dimensions of trust, directly into the MCO framework for RWM, rather than treating them as ancillary “communication” issues. The WP OPTI green paper [4] already frames optimisation as a holistic endeavour constrained by societal and ethical considerations and shaped by a continuously optimised decision-making process; the next step is to translate these principles into operational criteria, decision rules, and evidence requirements that can be applied consistently at each programme phase. Practically, this requires establishing a dedicated “societal robustness” pillar within the MCO, alongside protection and resource efficiency. Within this pillar, trust should be operationalised through measurable governance attributes, like:

- (1) procedural justice (fair, inclusive, and consistent processes; clear decision rules; demonstrable influence pathways for stakeholder input),
- (2) relational trust (respectful acknowledgement of concerns and uncertainty; credible and independent scrutiny; conflict-sensitive engagement and grievance mechanisms),
- (3) social traceability (durable records of promises, dissent, alternatives considered, and how comments changed or did not change decisions), and
- (4) a fair, planned ahead and continuously optimised participation process, guaranteeing pluralistic discussions and assessments all along the process between all stakeholders, including civil society.

Moreover, the question of closure, post-closure, and related governance issues must be addressed. Optimising closure and the closure process also involves defining the post-closure strategy in advance, as already planned in different national programmes. The conditions for closure should then be the subject of discussions based on several criteria, such as whether or not to monitor the post-closure phase and thus to establish a long-term stewardship culture, the various issues related to retrievability, the proposed methods of preserving the memory of the facility, or the form and duration of the dialogue with all stakeholders.

3.6 Development of Multi Criteria Optimisation Framework

The MCO framework introduced in the previous section can be developed into a valuable instrument for decision-making. The MCO should be structured in such a way that safety case lines of argument, cost, and environmental/societal factors are commensurable and traceable under the prevailing circumstances. This requires the development of a digital tool that integrates safety case evidence, cost functions, and environmental/social indicators, together with uncertainty and robustness analysis. Approaches of this kind can be found in different national programmes.

To avoid vagueness, each sub-criterion should be scored using anchored ordinal scales (e.g. a Likert scale [14]). Criteria must be supported by defined evidence types (documented processes and changes, independent review statements, and repeated measures of stakeholder experience over time). This scale could be adapted throughout the process to better fit a dynamic optimisation framework, embedded in a long-term stewardship culture. In parallel, minimum governance requirements, such as a participation quality standard in line with the Aarhus Convention [15], publication of decision rationales within security limits, and a formal response-to-comments process, should be treated as basic constraints, ensuring legitimacy cannot be “optimised away” through cost or schedule pressures. Long-term stewardship culture is a set of characteristics and attitudes in organisations and individuals that recognises that RWM facilities necessitate an intergenerational governance and management framework relying on comprehensive, transparent, and pluralistic modalities at all phases, including

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beyond closure. Depending on the phase, this might require fair technical and non-technical dialogues, including continuous technical assessment and periodic safety reviews based on transparent monitoring, and the operationalisation of reversibility in decision-making and the transmission of knowledge so that future generations have the capacity to act.

Finally, the MCO's preference-setting (including weighting) should itself follow legitimacy principles. This implies structured, deliberative weighting exercises with balanced representation and transparent documentation of consensus and persistent disagreement, complemented by robustness checks across alternative weighting scenarios. Moreover, the trade-offs of the optimisation process should be clearly identified and discussed in a pluralistic way, to ensure the respective weights of different criteria or constraints are fully explicit and consensual. Implemented in this manner, the MCO becomes not only a tool for technical optimisation, but also a governance instrument that protects long-term trust by making fairness, respect, and accountability visible, assessable, and repeatable throughout the lifetime of the RWM programme.

4. Call to Action

Optimisation is not a standalone activity. It is a cross-cutting principle that interacts with multiple dimensions of repository development and with all knowledge domains of the EURAD Roadmap [5] and the EURAD SRA [6]. In technical areas, optimisation is addressed explicitly. Topics such as pre-disposal, engineered barrier systems, disposal facility design, and safety assessment incorporate optimisation through the refinement of technical solutions, safety strategies, and system performance.

A broad spectrum of conceptual and practical optimisation approaches was identified in OPTI. These range from impact minimisation and design flexibility to multi-criteria analysis, iterative refinement, and the use of digital tools. Optimisation should be understood as a continuous, iterative, and multi-stakeholder process in which safety remains the primacy driver, while economic, technical, and societal considerations also play essential roles. Six key topics for optimisation were identified. In a nutshell, the most relevant aspects of these key topics are:

Closure design and closure monitoring of geological disposal facilities requires an adaptive, long-term strategy that reduces technical uncertainties through coordinated R&D, robust monitoring approaches, and early involvement of regulators and stakeholders to ultimately strengthening safety, confidence, and cost-effectiveness.

- Short-term research and development should focus on developing adaptive closure design frameworks or a reference framework for adaptive closure design, including criteria for flexibility, retrievability, and monitoring compatibility.
- Short-term research and development should also focus on a catalogue of monitoring triggers that define when deviations from expected evolution require intervention. This can be combined with developing monitoring techniques.
- Long-term actions should include full-scale demonstrations of closure systems and passive monitoring strategies.
- Long-term activities must include the ongoing updating of closure plans as new data, technologies, or regulations are available. In this context methods on a flexible and adaptable planning of the closure, related SSCs as well as the monitoring have to be implemented.

Backfill design and performance for HLW repositories is a multidisciplinary effort that integrates material science, geochemistry, engineering design, and long-term safety assessment.

- Short-term, continuous R&D must focus on the technical uncertainties associated with backfilling. This includes the selection and characterization of suitable backfill materials.
- Create a European material database for bentonite, mixtures, and alternative backfill materials.
- Of increasing importance is the establishment of standardised, robust quality assurance procedures, from laboratory testing through to large scale industrial application.
- Long-term, ongoing adaptation to new technologies and potentially new materials will also be essential.
- Further development of backfill installation techniques and the integration of these processes across different repository sections will be required.

Disposal waste package designs must be developed and validated tailored to different waste types and supported by sustained, internationally aligned research on material performance, degradation processes, and long-term interactions with the geological environment.

- Short-term, research could focus on increasing knowledge and a detailed understanding of material interactions, supplemented by improved modelling.
- Advance research on corrosion mechanisms, including local corrosion, radiolysis effects, and microbiologically influenced corrosion must continue.
- Long-term period, semi- or real-scale experiments could be constructed, monitored, dismantled and analysed using the infrastructure of underground research laboratories.
- Further alternative materials should be investigated to close existing scientific and technological gaps.

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Tunnel support structures for deep geological repositories in clay and claystone are highly complex due to the time-dependent behaviour of both the host formation and the concrete support. Furthermore, the absence of design requirements and design specifications significantly hinders optimisation efforts.

- Short-term the absence of clearly defined design requirements and specifications can significantly hinder future optimisation efforts. This gap has to be closed. The development of clear unified design criteria would enhance optimisation.
- Another focus has to be the integration of the full excavation and liner installation process in the design and planning of the support structures. The design of an adequate support structure must include the excavation process, corresponding load distributions from the rock, but also the construction process.
- Establish a long-term monitoring programme for support structures in URLs (convergence, cracking, chemical ageing). Collect and harmonise the data as input for the further development and benchmarking of constitutive numerical models simulating creep, convergence, and load redistribution. Include the material behaviour of the installed support structures (e.g. concrete, steel, compressible elements).

RWM governance requires coordinated action by implementers, scientific experts, regulators, policymakers and stakeholders to address both technical complexities and diverse societal views. The corresponding actions can start intermediately but may require a long time:

- Optimised decision-making processes, including legal framework and transparency and public participation (T&PP)
- Optimising public knowledge and societal deliberation of RWM issues by achieving a broader societal competences through education and professional risk communication
- Multigenerational perspectives including the concept of rolling stewardship and how to deal with information for the future
- Knowledge management and how to transfer knowledge to a broader public

Multi Criteria Optimisation framework can facilitate RWM governance and support just, enduring geological disposal decisions under constrained resources and should keep safety non-negotiable while embedding a societal robustness pillar that operationalises trust through procedural justice, relational trust, social traceability, and inclusive participation. An MCO digital tool can integrate safety evidence, costs, and environmental/social indicators with uncertainty analysis using traceable sub-criteria, transparent weighting, and robustness checks. The corresponding actions to develop such a framework can start intermediately.

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Appendix A. Keywords

Optimisation, HLW repository, Closure, Disposal waste package, Backfill, Tunnel Support Structures, Governance

Appendix B. List of acronyms and abbreviations

ACED	Assessment of Chemical Evolution of Disposal Systems (EURAD-1 work package)
CONCORD	Coupled Processes in Repository Conditions (EURAD-1 work package)
CSO	Civil Society Organisation
DGR	Deep Geological Repository
DWP	Disposal Waste Package
EBS	Engineered Barrier System
EURAD	European Joint Programme on Radioactive Waste Management
GDF	Geological Disposal Facility
HLW	High Level Waste
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
InCoManD	Innovative Container Materials & Design (EURAD-2 work package)
MCO	Multi Criteria Optimisation
NEA	Nuclear Energy Agency
OPTI	HLW Repository Optimisation Including Closure (EURAD-2 work package)
RE	Research Entity
RWM	Radioactive Waste Management
SNF	Spent Nuclear Fuel
SSC	Systems, Structures and Components
SRA	Strategic Research Agenda
StSt	Strategic Study
TSO	Technical Safety Organisation
URL	Underground Research Laboratory
WMO	Waste Management Organisation
WP	Work Package

Appendix C. Summary of the case study on closure optimisation

OPTI's case study on closure optimisation consisted of interviews with different European waste management organizations, discussing the current status of their closure plans, the methods used to assess closure performance, and the challenges and needs of closure optimisation. Below is a summary table of the case study results concerning the challenges of closure optimisation and possible follow-up actions for closure optimisation.

Challenges in closure optimisation		Potential needs for further activities
Timing and Planning	Closure is often planned far in the future → long-term planning and integration with other activities	<ul style="list-style-type: none"> • Ongoing updating of closure plans as new data, technologies, or regulations are available • Planning for future R&D • Flexibility and adaptability in planning • International collaboration
	Knowledge about repository conditions	
	Demonstrations of closure solutions	
Technical uncertainties	Backfill material selection	<ul style="list-style-type: none"> • Ensuring material availability and quality • Development of installation techniques • Development of models • Long-term experiments/mock up on closure solutions (demonstrations) • Multi-criteria optimisation methods • In situ-monitoring during operation
	Placement and properties of plugs	
	Backfill installation technologies	
	Integration between different repository sections	
	Adaptation to new technologies	
Regulatory, environmental, and societal factors	Complexity of regulations and laws (performance, retrievability, monitoring)	<ul style="list-style-type: none"> • Adapting closure concepts to environmental and sustainability goals • Ensuring governmental and public acceptance • Strong scientific basis for long-term safety • Environmental protection after closure
	Regulatory frameworks may change	
	Societal concerns	
	Adaptation to new environmental or sustainability goals	

Table C1 – Summary table of challenges in closure optimisation and linked potential future activities

Appendix D. EURAD Roadmap domains relevant for OPTI

Sub-theme	Domain	Related OPTI key topics
1.1 Establish the national policy and plan for radioactive waste and spent fuel management activities, from generation to disposal (Programme Planning)	1.1.1 Establish and maintain a national plan for radioactive waste management, including a nuclear fuel cycle strategy (e.g., open or closed cycle) for those countries with, or intending to use, nuclear power (National RWM Policy)	RWM Governance
	1.1.3 Ensure that public information on radioactive waste and spent fuel and a process for public participation are available (Public information and participation)	RWM Governance
	1.1.4 Establish a process for progressive development and optimisation of the plan (safety, security, use of resources)	RWM Governance, MCO framework
1.5 Identify and select appropriate disposal routes and concepts for the national radioactive waste inventory (Management Solutions)	1.5.1 Identify and evaluate potentially available concepts and technical solutions for spent fuel and radioactive waste management, taking account of national or local conditions, such as available predisposal and storage options, geological environments, national technical and economic resources and expertise etc. (Integrated waste management routes and strategic options)	RWM Governance

Table D1 – Relevant domains in theme 1 programme management²

² https://www.ejp-eurad.eu/sites/default/files/2021-05/1_Programme_Management_Theme_Overview.pdf

Sub-theme	Domain	Related OPTI key topics
3.2 Identify container materials and waste package designs for each waste form under storage and disposal conditions and confirm properties, behaviour and evolution under storage and disposal conditions (Waste packages, for disposal)	3.2.1 HLW and SF containers (HLW and SF Containers)	DWP
	3.2.3 Containers using advanced materials (Novel Containers)	DWP
3.3 Identify appropriate buffer, backfill and seal/plug materials and designs, and confirm their properties, behaviour and evolution for the selected repository concept (Buffers, backfills, plugs and seals)	3.3.1 Buffer components under storage and disposal conditions (Buffer)	Backfill
	3.3.2 Backfill components under storage and disposal conditions (Backfills)	Backfill
	3.3.3 Plug and sealing components under storage and disposal conditions (Plugs and seals)	Closure
3.4 Confirm integrated EBS system understanding and identify compatible EBS designs and materials for facilities containing multiple waste forms (EBS system integration)	3.4.1 Confirm complete and integrated EBS system understanding, including the design of an optimised interface EBS/repository and the understanding of the interaction with the repository nearfield environment (EBS system)	Closure

Table D2 – Relevant domains in theme 3 engineered barrier system³

³ https://www.ejp-eurad.eu/sites/default/files/2024-06/3_Engineered%20Barrier%20Systems_Theme_Overview.pdf

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Sub-theme	Domain	Related OPTI key topics
5.1 Design and develop a disposal system for the national radioactive waste inventory (Design)	5.1.1 Based on regulatory requirements, safety criteria, and a high-level safety strategy, establish a transparent procedure finally leading to design requirements for the preferred concept option (Design requirements)	Support Structures
5.2 Demonstrate and verify that facility components and barriers can be practically manufactured, constructed and installed in accordance with detailed design requirements and specifications (Constructability, demonstration and verification testing)	5.2.2 Perform a continuous balancing exercise with requirements and technical solutions to balance the risks among the different barriers. Keeping in mind that there is no such endeavour with zero risk, determine which risks can be (reasonably) taken and which cannot be. Any balancing need to include a cost assessment (Optimisation)	Closure, Backfilling, DWP Support Structures
	5.2.3 Establish reliable manufacturing routes to produce facility barriers and components, and inspections plans for how to test for unacceptable defects, and overall quality assurance against specified design tolerances and industry standards (Manufacture, inspection and testing)	Closure, Backfilling, DWP Support Structures
5.4 Develop and maintain operational safety case to demonstrate that the construction, operation and closure of the disposal facility will meet safety standards and be robust against potential faults such that the associated risks are restricted to levels that are as low as reasonably practicable (Operational safety)	5.4.3 Perform design basis accident analysis and optimise with mitigation options for risk reduction for identified faults (Accident safety)	Closure, Backfilling
5.5 Establish and implement an overall plan for meeting with national requirements for monitoring, and if required, reversibility and/or retrievability requirements. (Monitoring and Retrievability)	5.5.2 Establish plans and methods for implementing a monitoring program to be performed during site investigation, construction and operational phases of the repository (Monitoring with regard to onsite investigation, construction and operations)	Closure

Table D3 – Relevant domains in theme 5 disposal facility design and optimisation⁴

⁴ https://www.ejp-eurad.eu/sites/default/files/2021-08/5_Disposal_facility_design_and_optimisation_Theme_Overview.pdf