# Impact report to Member States and End Users

Work Package 13

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## Executive Summary

Optimisation is a fundamental element of geological disposal programmes, shaping decisions from the earliest conceptual studies through to construction, operation, and closure. Because these programmes evolve over many decades, they must remain adaptable to changing boundary conditions. New waste types, technological progress, and insights gained from operational experience continually reshape the context in which optimisation takes place.

The EURAD 2 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 within disposal of high-level radioactive waste and spent fuel. 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 Roadmap[1] 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.

This impact is reflected in the key topics identified. Building on the shared understanding of optimisation developed in WP OPTI a list of optimisation topics that can be further investigated from technical, environmental, economic and socio-technical perspectives was formulated. The collected topics form the core input and serve several purposes:

- to compile a consolidated list of optimisation challenges covering structures, systems, components and processes relevant to HLW repositories;
- to capture the main drivers behind these challenges, such as long-term and operational safety, robustness, cost, sustainability, and environmental and societal impacts;
- to identify at which stages of an HLW repository programme (e.g. concept development, licensing, construction, operation or closure) these challenges are most relevant;
- to assess links to existing EURAD Strategic Research Agenda[2] (SRA) topics and to ongoing national or international activities;
- to evaluate the potential of selected topics to evolve into dedicated R&D work packages in the second wave of EURAD-2.

[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

[2] EURAD Bureau. (2023): Update of the EURAD Strategic Research and Knowledge Management Agenda (SRA), of deliverable D1.9 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

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# 1. Introduction

The strategic study work package OPTI (High-level waste repository optimization including closure) was initiated as part of EURAD-2 to develop a mutual understanding and provide recommendations on methodologies and future activities related to optimisation of systems, structures and components (SSC) in a geological disposal facility (GDF) for high-level radioactive waste (HLW) , including spent nuclear fuel (SNF). OPTI provided a platform for interactions between members from the three EURAD colleges as well as civil society organisations (CSO). The exchanges in OPTI started with a collection of the views of the different OPTI participants, centred around the “why?”, the “how?” and the “when?” there are needs and priorities for optimisation. Views on the possible scope for optimisation at the different phases of a radioactive waste disposal programme, the main challenges for optimisation, and the best or existing approaches to optimisation were collected.

In the WP OPTI it is consensus that optimisation is not a search for a single perfect solution but an ongoing effort to improve repository design, safety, feasibility, and societal legitimacy within the constraints of the actual conditions. Safety, however, remains the primary consideration and should never be compromised. This term covers various aspects and drivers. Additionally, there are differentiations and varying priorities among the actors. Safety in general means the state of being protected from a risk. This can be achieved with the avoidance or reduction of the impact of a risk or the reduction of the probability of occurrence.

Waste management organisations (WMO) tend to approach optimisation with a focus 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, technical safety organisations (TSO) place safety at the centre of their perspective. Safety in general (including radiological protection) means the state of being protected from a risk. They expect optimisation to be holistic, addressing the entire system rather than individual components.

Research entities (RE) contribute by expanding the scientific and technical basis for optimisation, 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.

Civil society organisations (CSO), meanwhile, emphasise transparency, trust, and the ethical dimensions of optimisation. Similar to the other actors CSO 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. Civil society organisations understand themselves as a form of oversight of the general RWM.

Based on perspectives of the four actors, the WP OPTI Green paper [1] identifies a range of conceptual and practical approaches to optimisation, from impact minimisation and design flexibility to multi-criteria analysis, iterative refinement, and the use of digital tools such as repository management systems. 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.

Optimisation is not a standalone task, but rather a cross-cutting principle that interacts with all knowledge domains of the EURAD Roadmap [2] 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. Further, programme management 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. This underlines the need for continuous improvement, stakeholder involvement and adaptive decision-making throughout the lifecycle of a radioactive waste management programme.

# 2. Key findings

Across all participating member states, WP OPTI generated a set of insights and benefits that proved broadly applicable, regardless of program maturity or inventory size. One of the most significant outcomes was the development of a more harmonized understanding of what “optimisation” means in the context of radioactive waste management. Through the held workshops, participants collectively recognised that optimisation is not a single technical decision but an iterative, multidimensional process that must integrate safety, feasibility, economic considerations, and societal expectations. This shared conceptual clarity helped member states compare their approaches more effectively and identify areas where their practices could be strengthened or streamlined.

This was especially discussed during the second workshop in Prague, where the objectives were to discuss the internal Draft Green Paper (Deliverable 13.1), exchange on the review of this document, and further discuss the two case studies to be developed as part of building a mutual understanding of optimization approaches for waste disposal facilities and their management in RWM programmes and safety cases. In summary, there is just one optimisation process with different parameters, boundary conditions and stages. The boundary conditions are represented by the prevailing circumstances. Starting from those prevailing circumstances, a limited frame or space for optimisation can be defined. This space for optimisation can be filled by various drivers for optimisation, see Figure 2-1. The optimisation process must take into account the prevailing circumstances, including the regulatory framework, the state of knowledge and the available technical and industrial limits. The prevailing circumstances, and thus the space for optimisation, may evolve for instance following governmental or regulatory decisions, the acquisition of new knowledge and the accumulation of experience.

The optimisation process is driven by several drivers, which can be categorised as follows: drivers related to optimising protection, resources and the decision-making process. As shown in Figure 2-1, these drivers are interconnected, meaning that optimisation according to one driver may affect optimisation according to another. Furthermore, optimising one component of a GDF (or even one characteristic of a component) may affect others. These interactions require a holistic approach to optimisation, in which the potential impact of optimisation options on the entire GDF is compared iteratively based on multi-criteria analyses.

Optimisation is a stage-wise or level-wise process. The safety case gives the overall safety envelope for this process. The different levels can be associated with the levels of a requirement management system. Further optimisation is linked to a decision-making process and requires a change management system.

Optimisation is a multi-criteria process. As part of regular updated safety cases the optimisation helps to reduce conservatism. It is important to couple all the SSCs and parameters for a holistic optimisation. Optimisation of the decision-making process is part of the holistic approach. Changes in the design must base on criteria and it is a process done by all stakeholders. Optimisation can further include an improvement of the robustness.

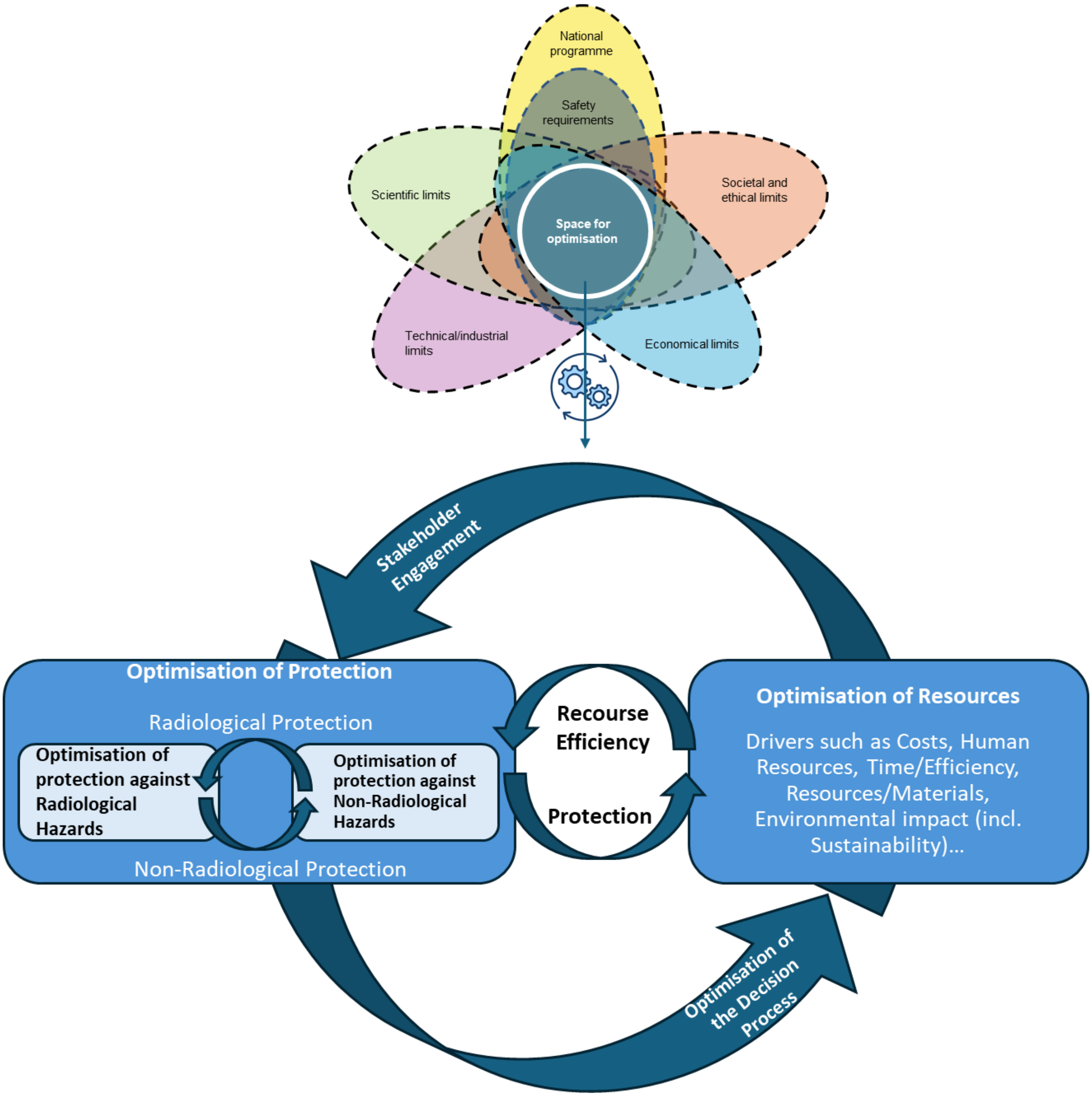


Figure 2-1: *Optimisation process and its drivers, within the optimisation space, based on* the OPTI Green Paper [1]

The workshops also revealed a strong interest in developing future guidance to support optimisation practices. Many partners expressed the need for a structured framework that could help them document, justify, and communicate optimisation decisions more effectively. Such guidance could take various forms, including integration into the methodological common outline, the development of a dedicated EURAD guideline, or incorporation into Knowledge Management activities. Whatever the format, the demand for guidance reflects a shared desire for greater consistency, transparency, and comparability across national programmes.

The workshops also highlighted the value of bringing together a uniquely broad group of stakeholders. Unlike many previous optimisation initiatives, which tended to focus primarily on technical experts or regulatory perspectives. This diversity created a richer discussion environment and allowed participants to explore optimisation from multiple angles. The presence of CSOs, in particular, broadened the conversation beyond technical performance and encouraged participants to consider transparency, legitimacy, and long-term societal trust as integral components of optimisation. Their contributions underscored that optimisation is not only about engineering efficiency but also about ensuring that decisions are understandable, justifiable, and aligned with societal values.

A clear trend emerged across the participating member states: countries with advanced, mature programmes tended to focus on technical optimisation, such as refining engineering designs and enhancing operational efficiency. Their challenges were often quantitative and related to long-term performance assessment or design iteration. Efforts to improve modelling approaches were frequently undertaken in parallel with these activities. In contrast, early-stage programmes or those with smaller inventories were more concerned with what could be described as "soft" optimisation or optimisation targets. For these member states, the priority was to strengthen governance structures, clarify decision-making processes, improve stakeholder engagement, and build internal capacity. These differences reflect the varying stages of programme development, but they also demonstrate the flexibility of the optimisation concept. Regardless of maturity level, each member state found meaningful ways to apply the principles discussed in WP OPTI.

The involvement of CSOs further enriched the discussions. Their perspectives helped illuminate how optimisation processes are shaped not only by technical constraints but also by organisational cultures, communication practices, and public expectations. Social science was shown to be particularly valuable in areas such as stakeholder engagement, decision-making under uncertainty, and organisational learning. At the same time, participants recognised that social science is not required for every R&D topic; its contributions are most impactful when human or societal factors play a significant role in shaping optimisation outcomes.

This impact is reflected in the key topics identified in the white paper [4]. OPTI Task 4 focuses on identifying and structuring key optimisation challenges relevant to the design, implementation and operation of a GDF for high-level radioactive waste including SNF. Building on the shared understanding of optimisation developed in OPTI, it provides a well-founded and transparent list of optimisation topics that can be further investigated from technical, environmental, economic, and socio-technical perspectives.

To support this objective, a structured collection of optimisation topics was carried out. The main purpose of this data collection was to gather, in a consistent manner, optimisation challenges perceived as relevant by different actors involved in HLW repository programmes, including the three colleges and civil society organisations (CSOs). This approach ensures that the resulting list of topics reflects a broad range of views and priorities, rather than a purely technical or single-stakeholder perspective. Figure 2-2 illustrates these key topics. The collected topics form the core input and serve several key purposes:

- to compile a consolidated list of optimisation challenges covering structures, systems, components and processes relevant to HLW repositories;
- to capture the main drivers behind these challenges, such as long-term and operational safety, robustness, cost, sustainability, and environmental and societal impacts;
- to identify at which stages of an HLW repository programme (e.g. concept development, licensing, construction, operation or closure) these challenges are most relevant;
- to assess links to existing EURAD Strategic Research Agenda (SRA) topics and to ongoing national or international activities;
- to evaluate the potential of selected topics to evolve into dedicated R&D work packages in the second wave of EURAD-2.

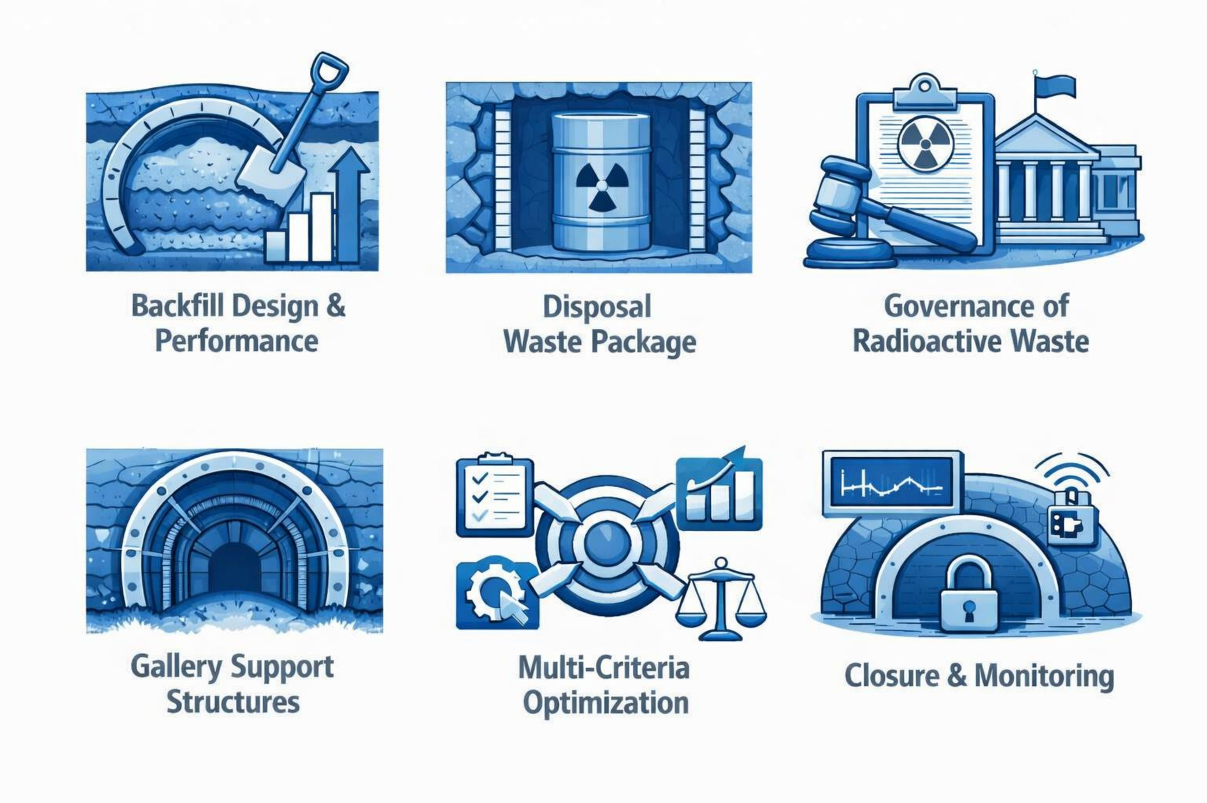


Figure 2-2: Illustration of the six key topics identified and discussed in the WP OPTI

The impact of WP OPTI becomes particularly clear when looking at how different member states applied its outcomes. For OPTI, respectively optimisation, a separation can be made between early stage and advanced member states, rather than large inventory member state (LIMS) or small inventory member states (SIMS). With a mature disposal programme, the discussions prompted a shift from a more holistic one towards a predominantly technical optimisation. While advanced programmes already have detailed engineering designs and long-term safety assessments, the workshops highlighted the importance of integrating societal and organisational considerations into optimisation decisions. As a result, the programme expanded its optimisation criteria, improved the documentation of its decision-making processes, and strengthened internal mechanisms for evaluating alternative design options. This led to a more balanced and transparent optimisation approach that better aligned technical performance with societal expectations and regulatory requirements.

During the discussions in WP OPTI the closure of the repository and corresponding engineered barrier system (EBS) were of special interest for the WP members. As one of two case studies, the closure of HLW repositories was selected. 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 may also compromise isolation (through intrusive monitoring) and increase costs. Closure design and closure monitoring are addressed in different EURAD 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.

Clay and claystone as host rock for a deep geological repository offers beneficial properties regarding the long-term behaviour, especially the confinement and the retardation. Clay and claystone provide a sorption capacity and in the undisturbed rock transport processes are diffusion dominated. Permeability of gases and liquids are very low. In opposite to these advantages the mechanical behaviour is more challenging. The low to medium mechanical strength, in combination with a time-depended rheological behaviour (consolidation and creep) and a strong dependency to the water content challenges the excavation process and requires a permanent support structure inside the underground openings. Even though the feasibility of a geological disposal of radioactive waste has been demonstrated in URLs or deep tunnels, support structures need to be designed to comply with functional and safety requirements.

The drivers for optimization of support structures are linked to different stages of the repository lifecycle. 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).Two main drivers can be identified. Around them various challenges exists. During the construction phase the harmonization of construction method and lining installation based on the THM requirements from operational period are of special importance. A specific topic related to this is the monitoring of rock and lining during construction and later operation. For the post-closure period the drivers are different, mainly driven by chemical process class and safety relevant considerations. Concrete and corrosion products will interact with the host rock and the sealing material(s), steel components and corresponding corrosion products will interact with the host rock and the sealing material(s), steel corrosion introduces gas generation and gas pressure build-up. Additives and organic components required to manufacture and install the concrete could affect radionuclide transport.

In contrast, early-stage member states with an emerging programme used WP OPTI to establish a foundational optimisation framework. Without extensive technical data or mature designs, the programme focused on optimising governance, planning, and stakeholder engagement. Participation in WP OPTI helped the member states develop a clearer programme roadmap, identify priority areas for capacity building, and improve coordination among national stakeholders. As a result, WP OPTI supported a step towards more coherent and transparent programme structures, thereby providing a solid foundation for future technical optimisation as the programmes evolve.

This was reflected as well in the idea of a multi-criteria optimisation (MCO) framework and digital tool that unifies safety-case evidence, cost functions, and environmental and societal indicators within a single, traceable decision space. Under the title IMCORE this idea was proposed as a second wave topic. Such a framework should establish an integrated optimisation approach that makes these diverse factors comparable across lifecycle stages while preserving full transparency of underlying evidence. Building on this foundation, the framework incorporates advanced uncertainty and robustness methods, including sensitivity studies, probabilistic uncertainty quantification, regret and satisficing metrics, and Pareto stability analyses. Design decisions can be stress-tested against realistic variability and future scenarios. The accompanying digital tool provides open interfaces to safety-case modelling, enhancing reproducibility, transparency, and cross-domain consistency in design evaluations. Practical value is demonstrated through pilot applications on representative repository components, revealing key performance drivers and feasible optimisation pathways. Ultimately, the work supports higher-quality, evidence-based decisions by identifying where additional information most effectively reduces uncertainty and by translating project experience into shared methodological guidance for broad programme adoption.

Other member states reported additional benefits, such as improved internal communication on optimisation, a better understanding of how to balance competing criteria, and increased awareness of societal expectations. These experiences illustrate the broad applicability of WP OPTI's outcomes and demonstrate that optimisation can be meaningfully integrated into programmes at any stage of development.

# 3. Evaluation of Impact

The objective of WP OPTI was to develop a mutual understanding and provide recommendations about methodologies and further activities for the optimization of specific HLW deep geological repository systems, structures and components (SSCs) and procedures. Linked EURAD roadmap [2] themes are:

*Engineered Barrier Systems* (Theme 3)

*Disposal Facility Design and Optimization* (Theme 5)

*Safety Case* (Theme 7)

The primary theme is *Disposal Facility Design and Optimization*, as the name of the WP already indicates. Thus, the relevant EURAD SRA [3] topics were identified in this theme as well. Most important for WP OPTI was the topic 5.2.2 *Optimisation (of the facility components and design)*. The most relevant driver behind this topic and the WP OPTI is the *Innovation for Optimization.* In addition, the *Implementation Safety* and *Societal Engagement* were identified as relevant drivers as well.

Key topics and relevant SSCs already identified during the preparation of WP OPTI:

- Optimization of buffer and backfilling composition and installation methods
- Optimization of closure process, (gallery) sealing design, location and installation methods
- Design of gallery support structures and flexibility in changed geo-mechanical conditions, especially in claystone

During the work in the WP OPTI additional key topics were identified and included in the discussion:

- Disposal waste packages
- Governance of RWM
- Multi-criteria optimisation framework

A subset of EURAD SRA [3] drivers and expected impact topics was selected to guide the focus in WP OPTI on optimisation of GDFs for HLW. This initial selection reflected the anticipated technical scope of the work package, which aimed to identify optimisation challenges, explore methodological approaches, and support the exchange between different national programmes. As the work progressed, however, the discussions, expert workshops, and cross-disciplinary exchanges revealed a broader and more interconnected set of issues than originally foreseen. This resulted in a more comprehensive alignment with the SRA than initially planned.

Overall, WP OPTI addressed the SRA drivers more holistically than expected, particularly in areas related to system understanding, long-term safety, engineering feasibility, and governance. The six key topics demonstrate this expanded alignment.

The EURAD SRA [3] identifies several high-level drivers: ensuring long-term safety, improving technical robustness, enhancing the ability to implement new technologies, supporting decision-making, and strengthening societal confidence. WP OPTI's work addressed each of these, though with varying emphasis.

Long-term safety was addressed more deeply than initially planned. Topics such as closure design, backfilling performance, and tunnel support structures directly relate to the evolution of engineered barriers and their interactions with the host rock. These topics map strongly to SRA themes on barrier performance, THMC processes, and safety functions. The discussions revealed that optimisation cannot be separated from safety considerations, and this reinforced the centrality of safety as a driver.

Technical robustness and ability to implementation were addressed more broadly than expected. The inclusion of disposal waste packages and tunnel support structures reflects a shift toward practical engineering considerations that influence repository construction and operation. These topics connect to SRA themes on waste form and package evolution, construction methods, and operational safety.

The work demonstrated that optimisation must consider not only long-term performance but also the feasibility and reliability of engineered systems during the operational phase.

Decision-making and governance, while initially recognised as relevant, became significantly more prominent during the WP. The identification of "Governance of RWM" as one of the six key topics shows that optimisation is not purely technical but is shaped by institutional, regulatory, and societal processes. This aligns with SRA themes on knowledge management, stakeholder involvement, and programme governance. WP OPTI discussions highlighted that optimisation decisions must be transparent, traceable, and justifiable to diverse stakeholders.

The SRA's expected impacts include improving confidence in safety cases, supporting harmonisation across national programmes, enabling innovation, and strengthening cross-disciplinary integration. WP OPTI contributed to these impacts in several ways.

Confidence in safety cases was strengthened through the identification of optimisation challenges that directly influence safety-relevant components. By clarifying where uncertainties remain, WP OPTI names future research that can reduce uncertainty and improve safety case robustness.

Harmonisation across programmes was advanced by comparing optimisation challenges across different national contexts. The six key topics represent areas where multiple programmes face similar issues, enabling shared learning and coordinated research efforts.

Innovation and methodological development were addressed through the multi-criteria optimisation framework. This topic reflects the need for structured, transparent approaches to balancing safety, feasibility, cost, and societal expectations. It aligns with SRA ambitions to develop advanced tools and methodologies that support evidence-based decision-making.

Cross-disciplinary integration emerged as a major outcome. The WP brought together experts in engineering, geoscience, safety assessment, and social sciences, revealing interdependencies that were not fully anticipated at the start. This integration aligns strongly with the SRA's emphasis on system-level understanding and holistic programme development.

In this context the interaction with the CSO has to be highlighted as well. The CSO representatives from Nuclear Transparency Watch (NTW) were right from the beginning integrated in the WP and the WP board as well. CSO as an important actor in the RWM was given an equal role alongside the three colleges. As a Europe-wide network of NGOs, citizen initiatives, and independent experts, NTW pursues the goal of strengthening transparency and public participation in the field of nuclear industry. This role is indispensable, especially in the context of repository research, where technical, safety-related, and societal questions are closely connected and influence one another.

Within EURAD 2 WP OPTI, NTW actively contributed to ensuring that the needs, expectations, and concerns of the public are systematically taken into account. The organization not only brought in its long-standing experience in nuclear governance, but also acted as a voice ensuring that optimization processes are not considered solely from a technical perspective. Through participation in workshops and scientific exchange, NTW worked to ensure that transparency, traceability, and societal acceptance are established as equal factors to the technical aspects.

It turned out particularly important that NTW served as a bridge between the research community and the public within the project. The exchange with the larger CS groups was an essential part of NTW work in the WP. Further the WP members directly exchanged with the CS larger group during their workshops. NTW as CSO emphasized that optimization in the field of nuclear waste management does not simply mean increasing efficiency, but above all strengthening trust, safety, and long-term responsibility. In doing so, CSO played a key role in helping EURAD 2 WP OPTI develop a more comprehensive understanding of optimization as a process that connects technical excellence with societal legitimacy.

Through its engagement, NTW has demonstrated the importance of the continuous involvement of civil society in European research programs. NTW not only helped shape the content but also reaffirmed the principle that decisions on nuclear waste can only be sustainable and robust if they are made with active public participation. At the same time, the collaboration highlighted that EURAD, as a scientific technical consortium, cannot cover all research questions related to nuclear waste management. The topics introduced by CSOs often touch on sociotechnical issues, whose resolution will require the involvement of humanities and sociotechnical expertise.

# 4. Conclusion

The discussions held in EURAD 2 WP OPTI mark a significant step toward a more transparent, evidence-based, and methodologically consistent approach to design optimisation in radioactive waste management programmes. The proposal to establish a structured multi-criteria optimisation framework and provide a digital tool capable of integrating safety evidence, cost considerations, and environmental and societal indicators, offers member states a practical foundation for more balanced and traceable decision-making. At the same time, OPTI highlights several key topics where further research and development would meaningfully strengthen the applicability, maturity, and long-term value of optimisation across national programmes.

Designing, closing, and monitoring geological disposal facilities requires an adaptive, long-term strategy capable of reducing technical uncertainties while maintaining safety, confidence, and cost-effectiveness. This demand coordinated research, development and demonstration. In the short term, developing a shared adaptive closure design framework that defines flexibility, retrievability, and compatibility with monitoring requirements, supported by intensified experimental and modelling work could be fostered. A systematic catalogue of monitoring triggers is also needed to clarify when deviations from expected evolution require intervention. Ideally, such a catalogue will be accompanied by the development of monitoring techniques that can be integrated into evolving repository designs. Over the longer term, full-scale demonstrations of closure systems and passive monitoring strategies will be essential. This will be completed by the continuous updating of closure plans as new data, technologies, and regulatory expectations emerge.

Backfill design and performance assessment for HLW repositories similarly call for sustained, multidisciplinary research, development and demonstration (RD&D). Short-term priorities include reducing technical uncertainties related to material selection and characterisation, supported by the creation of a database for bentonite, bentonite mixtures, and alternative backfill materials. Just initiatives already started in WP ANCHORS and have to be extended. Standardised and robust quality-assurance procedures from laboratory testing to industrial scale emplacement are becoming increasingly important to ensure reproducibility and comparability across programmes. Examples for such procedures can be found in advanced programs and have to be further developed and harmonized. Over the long term, adaptation to new technologies and potentially new materials will remain necessary, alongside further development of installation techniques and the integration of backfilling processes across different repository sections.

Waste package design must continue to evolve through internationally aligned research on material performance, degradation processes, and long-term interactions with the geological environment. Short-term efforts should deepen understanding of material interactions and strengthen modelling capabilities, with particular attention to corrosion mechanisms, including localised corrosion, radiolysis-driven effects, and microbiologically influenced corrosion. Over longer timescales, semi or full-scale experiments in underground research laboratories, in addition to those already performed, will be indispensable for validating models, observing real-world behaviour, and refining design assumptions. Exploring alternative materials (e.g. ceramics) will also be necessary to close remaining scientific and technological gaps.

Tunnel support structures in clay and claystone formations present additional challenges due to the time-dependent behaviour of both the host rock and the concrete support. The current absence of unified design requirements and specifications significantly limits optimisation potential and must be addressed as a short-term priority. A more integrated approach to design, one that explicitly incorporates excavation methods, load redistribution, and construction processes, is also required. Long-term progress will depend on establishing monitoring programmes in underground research laboratories to track convergence, cracking, and chemical ageing, and on harmonising these datasets to support the development and benchmarking of constitutive models that capture creep, convergence, and material behaviour.

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# Appendix A. Keywords

Optimisation, Geological Disposal Facility, Safety, Stakeholders

## Appendix B. List of acronyms and abbreviations

| | |
|---|---|
| CSO | Civil Society Organisation |
| GDF | Geological Disposal Facility |
| EBS | Engineered Barrier System |
| EURAD | European Joint Programme on Radioactive Waste Management |
| HLW | High-Level Waste |
| LIMS | Large Inventory Member States |
| MCO | Multi-Criteria Optimisation |
| NGO | Non-Governmental Organisation |
| NTW | Nuclear Transparency Watch |
| OPTI | Strategic study work package on optimization |
| RD&D | Research, Development and Demonstration |
| RE | Research Entity |
| RWM | Radioactive Waste Management |
| SIMS | Small Inventory Member States |
| SRA | Strategic Research Agenda |
| SSC | Systems, Structures and Components |
| SNF | Spent Nuclear Fuel |
| THM / THMC | Thermal-Hydro-Mechanical / Thermal-Hydro-Mechanical-Chemical processes |
| TSO | Technical Safety Organisation |
| URL | Underground Research Laboratory |
| WMO | Waste Management Organisation |
| WP | Work Package |