Deliverable 3.3: Policy paper on mutual understanding of alternative radioactive waste management strategies

Work Package 03 ASTRA

DOI: **10.5281/zenodo.19254475**

Co-funded by the European Union under Grant Agreement n°101166718.

Dissemination level: PU
Date of issue of this report: **31/03/2026**

Document information

Project Acronym	**EURAD-2**
Project Title	**European Partnership on Radioactive Waste Management-2**
EC grant agreement No.	**101166718**
Work Package Title	ASTRA - **A**lternative RWM **STRA**tegies
Deliverable No.	**3.3**
Deliverable Title	**Policy paper on mutual understanding of alternative radioactive waste management strategies**
Lead Beneficiary	**COVRA**
Contractual Delivery Date	**March 2026**
Actual Delivery Date	**March 2026**
Dissemination Level	**PU**
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To be cited as: (2026): Policy paper on mutual understanding of alternative radioactive waste management strategies. Final version as of 31/03/2026 of deliverable 3.3 of the European Partnership EURAD-2. EC Grant Agreement n°101166718.

Acknowledgement
This document is a deliverable of the European Partnership on Radioactive Waste Management 2 (EURAD-2). EURAD-2 is co-funded by the European Union under Grant Agreement N° 101166718.

Status of deliverable		
	By	Date
Delivered (Lead Beneficiary)	M. Vuorio (COVRA)	15/02/2026
Reviewed (Reviewers) Version1	Erika Holt (PMO, 25.2.2026)	25/02/2026
Reviewed (Reviewers) Version 2 (optional)	Alexandru Tatomir (EURAD-2 KM, BGE)	02/03/2026
External review	Daniel Galson	16/03/2026
Verified (WP Leader)	M. Vuorio (COVRA)	26/03/2026
Approved	Marta López-García (PMO representative, Amphos 21)	30/03/2026
Submitted to EC (Coordinator)	Andra	31/03/2026

Executive Summary

This paper presents EURAD's strategic view on key challenges and emerging opportunities on storage life extension, alternative waste management solutions like deep borehole disposal (DBD), and shared international waste management solutions, as well as the management of waste containing naturally occurring long-lived radionuclides.

Long-term storage

Over the last few decades, in some European countries, storage facilities are now being used for much longer periods than originally anticipated mainly because of the long timescale for implementation of disposal facilities. In the near term, research, development, and demonstration (RD&D) efforts should prioritise creating a reliable technical basis for decision-making and closing information gaps, and development of practical solutions for ageing management and adaptation to minimize environmental impacts. The long-term RD&D programme should remain compatible with evolving nuclear strategies and societal expectations.

DBD

DBD is increasingly recognised as a promising alternative or complement to mined geological repositories for the disposal of high-level waste and spent nuclear fuel. Implementation of the technology has been limited by a perceived lack of technology readiness level, since no full-scale demonstration has yet been completed. RD&D efforts should prioritise resolving the most critical technical uncertainties, including demonstrated experience in precise emplacement of HLW/SF and sealing of such boreholes to the required level at the depths and diameters envisioned for DBD, exploring the long-term performance of borehole seals and plugs, and understanding corrosion processes and their control under *in-situ* conditions. A further priority is the development and demonstration of techniques to confirm that stagnant groundwater conditions persist at disposal depths, following borehole construction and waste package emplacement.

SIMS – Shared solutions

Small-Inventory Member States (SIMS) must fulfil similar technical and regulatory requirements to Large-Inventory Member States (LIMS), while operating with fewer resources, making it difficult to justify or afford dedicated national infrastructure. Shared or multinational approaches can mitigate some of the constraints, but they introduce further challenges around regulation, governance, allocation of long-term responsibilities and liabilities. Progressing waste management approaches and strengthening the resilience in waste management of SIMS, this paper proposes a dual-focus approach: shared RD&D on waste management solutions and shared knowledge management (KM) activities.

NORM

A common challenge for both SIMS and LIMS is management of high-volume long-lived naturally occurring radioactive material (NORM waste). To address the challenges a coordinated European pathway that combines near-term practical support with longer-term strategic development is proposed.

All these topics are included in the EURAD Roadmap domains (Themes 1, 2 and 5) and are especially challenging for Member States with small inventories.

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1. Introduction

This policy paper sets out EURAD's position on storage life extension, alternative waste management solutions like deep borehole disposal (DBD), and shared international waste management solutions, as well as the management of waste containing long-lived naturally occurring radioactive material (NORM). Based on the work conducted, we present here recommendations and proposals for actions to address identified gaps in knowledge and understanding as well as prioritisation of these actions.

Storage has always been a necessary part of radioactive waste management. Over the last decades, in some European countries, storage facilities are now used for much longer periods than originally anticipated, and in some programmes, storage is being treated in practice as a long-term management option, either because of the unavailability of disposal facilities or lack of reliable information on the stored inventories. For many older facilities, documentation is incomplete, inconsistent or has been lost. These data gaps can affect the credibility of safety assessments, hinder optimisation of monitoring programmes, and delay decisions on disposal. In the near term, research, development, and demonstration (RD&D) efforts should prioritise creating a reliable technical basis for decision-making and closing information gaps. A further near-term priority is the development of practical solutions for ageing management and adaptation to minimize environmental impacts. The long-term RD&D programme should remain compatible with evolving nuclear strategies and societal expectations.

Deep borehole disposal (DBD) is increasingly recognised as a promising alternative or complement to mined deep geological repositories (DGRs) for the disposal of high-level waste and spent nuclear fuel (HLW/SNF). Due to its reduced operating scale and potential cost effectiveness compared to traditional mined repositories, it appears an attractive option, especially for Small-Inventory Member States (SIMS). However, implementation of the technology has been limited by a perceived lack of technology readiness level and operational experience specific to DBD, since no full-scale demonstration has yet been completed. RD&D efforts should prioritise resolving the most critical technical uncertainties, including demonstrated experience in precise emplacement of HLW/SF and sealing of such boreholes to the required level at the depths and diameters envisioned for DBD, exploring the long-term performance of borehole seals and plugs, and understanding corrosion processes and their control under in-situ conditions.

SIMS face common sets of challenges when developing and implementing radioactive waste management solutions. They must fulfil technical and regulatory requirements comparable to Large-Inventory Member States (LIMS), while operating with fewer resources. The small scale of inventories makes it difficult to justify or afford dedicated national infrastructure. Shared or multinational approaches can mitigate some of the constraints through economies of scale and pooled expertise, but they introduce further challenges around transport regulation, governance, allocation of long-term responsibilities and liabilities. Progressing waste management approaches and strengthening the resilience in waste management of SIMS, we propose a dual-focus approach: shared RD&D on waste management solutions and shared knowledge management (KM) activities.

One common challenge for SIMS and LIMS is management of NORM wastes, which is widespread among the Member States, but many programmes still remain at an early stage. To address the challenges for NORM waste management, a coordinated European pathway that combines near-term practical support with longer-term strategic development is proposed.

All of these topics are included in the EURAD Roadmap domains Theme 1 National Programme Management, Theme 2 Pre-disposal and 5 Disposal facility design and optimisation [Appendix C], and are especially challenging for SIMS.

The work in this report was carried out in EURAD-2 Work Package (WP) ASTRA in collaboration with Civil Society experts. The ASTRA work organisation and some information of the methods used is presented in Appendix D.

2. Challenges

In the following sections the challenges identified by ASTRA participants are described and proposals on how these challenges should be addressed are made for each topic. Civil society input is included in each topic description. The challenges discussed correspond to key areas of the Strategic Research Agenda (SRA) [1] including the following sections: 2.2.4 for long-term storage, 5.1.1 for DBD, 1.5.1 for SIMS, and 1.3.3 for internationally shared waste management solutions. The main SRA drivers guiding ASTRA were “Tailored Solutions”, “Societal Engagement” and “Innovation for Optimisation”, which frame the approach adopted in this paper.

2.1 Long-Term Storage

Storage has always been a necessary part of radioactive waste management (RWM). SNF and other radioactive waste types must be held for various durations so that heat and radioactivity have time to decrease prior to further management; many other radioactive wastes can pass through storage as a short step before treatment or disposal. Over the last few decades, in some European countries, temporary storage facilities are now used for much longer periods than anticipated when they were constructed, and in some programmes storage is being treated in practice as a long-term management option, mainly because of the unavailability of disposal facilities [2].

This shift is often not the result of a single decision, but of a combination of technical, economic, institutional and societal factors. Although disposal concepts are available, their implementation is often delayed. For some programmes it has therefore seemed more practical to extend the use of existing storage facilities while waiting for clearer strategies, improved financing conditions or potential shared solutions. As a consequence, there are facilities that now operate beyond their original design lifetimes, or without a clearly defined end date. This situation is manageable, but extending storage introduces a distinct set of challenges for operators, regulators and society that must be addressed explicitly rather than treated as routine business.

Survey and workshop results ([2], [3], [4]) highlight several recurring technical issues of extended storage, foremost among them the progressive degradation of physical barriers. Metal containers and structural components can corrode due to humidity, chemical interactions within the waste matrix and external influences, while concrete structures may crack or lose protective properties over time. Where degradation advances, reconditioning or overpacking of waste packages is often required and can be challenging.

At the same time, not all facilities were designed or licensed with long-term operation in mind. In several programmes, storage facilities were originally labelled interim without a firm lifetime definition, and later extensions have been decided case-by-case. This can make it difficult to plan when and how to move from storage to disposal.

Reliable information on the stored inventories is essential to understand the challenge. For many older facilities, documentation is incomplete, inconsistent or has been lost. These data gaps can affect the credibility of safety assessments, hinder optimisation of monitoring programmes, and delay decisions on retrieval or transfer to disposal.

Waste characteristics themselves are not static. Over long periods, physical and chemical changes can mean that some older packages no longer meet current waste acceptance criteria (WAC) for intended disposal routes. Evolving regulatory expectations and improved understanding of long-term performance can further widen the gap between “as stored” and “as required for disposal”. Emerging waste streams, including those expected from Small Modular Reactors and new research infrastructures add uncertainty: existing storage concepts and facilities were not necessarily designed with these wastes in mind, and options for their conditioning and final disposal are still under development.

External hazards could compound these internal issues. Older storage designs often did not account for the accelerating impacts of climate change, and increasing risks from floods, wildfires, and extreme weather now require stronger attention to the resilience and adaptation of long-term radioactive waste

storage systems. From civil society's view the option of long-term interim storage involves a number of problems concerning transparency and participation, especially in cases of inadequate assessment of environmental impacts of these facilities. Public concerns also include increases in security risks due to large amounts of SNF/HLW stored in one place.

Taken together, ageing infrastructure, data gaps, evolving waste streams and hazards, and uneven transparency show that extended storage cannot be managed as "business as usual", and instead requires targeted research and coordinated action. Key needs include clearer definitions of facility and package lifetimes linked to safety reviews, better tools to anticipate ageing and support timely decisions, robust recovery and digitalisation of legacy data, adaptation of storage concepts to climate and external hazards, and transparent frameworks for public information and participation. Addressing these needs through joint RD&D and shared learning is essential to ensure that long-term storage remains a controlled and reversible stage of waste management, rather than an open-ended burden passed to future generations.

2.2 Deep Borehole Disposal

DBD is increasingly recognised as a promising alternative or complement to a mined DGR for the disposal of HLW/SNF. DBD appears an attractive option, especially for countries with small quantities of higher activity waste and with no active DGR programme. Moreover, the potential operational hazards associated with creating mined repositories are not present with DBD. The underlying concept involves radioactive waste packages being emplaced in boreholes drilled to depths of several kilometres, into a highly stable geological and hydrogeological environment. Safety is primarily provided by the thickness of the geological barrier, which serves to isolate the waste from the biosphere, and by the absence of flowing groundwater, which limits transport of radionuclides. DBD offers long-term isolation of waste far from human populations and surface ecosystems, reducing the risks of geological disturbances (e.g., faulting or seismic activity, uplift, erosion, or glaciation effects) and inadvertent human intrusion.

Despite the apparent benefits, implementation of DBD has been limited by a perceived lack of DBD technology readiness amid a global landscape of disposal options dominated by a preference for mined repositories. While many of the enabling drilling and emplacement technologies are relatively mature and widely used in the hydrocarbon, mining, and geothermal industries, the application of these technologies to radioactive waste disposal remains relatively undeveloped. There is limited operational experience specific to DBD, and no full-scale demonstration has yet been completed. As a result, uncertainties remain regarding demonstrating deep drilling operations at the required depths and diameters envisioned for DBD, exploring the long-term performance of borehole seals and plugs, corrosion processes and their control under *in-situ* conditions, the ability to demonstrate reliable monitoring at relevant depths and emplacement and retrieval operations for radioactive waste packages containing HLW/SNF. The need to reduce such uncertainties is shared by the international radioactive waste management community, particularly SIMS that may benefit most from DBD, but which have fewer resources to resolve them.

The impacts of these uncertainties are multifaceted. From a cost perspective, the absence of a mature and demonstrated disposal concept increases the risk of conservative design assumptions, duplicated research efforts, and inefficiencies across national programmes. Delays in establishing confidence in DBD can also prolong interim storage, with associated operational costs. In terms of safety, uncertainty in long-term performance may prevent regulatory acceptance and public confidence, despite the inherent advantages offered by the greater geological isolation DBD provides. The lack of clarity around feasibility and safety can slow strategic decision making and may in turn limit the ability to integrate DBD into long term waste management planning.

Addressing these challenges through targeted RD&D activities would significantly enhance the credibility of DBD as a disposal option internationally. There are many areas of the technology that would benefit from further scientific insight. Advances in any one aspect would provide the momentum needed to generate further interest in this option. For example, improving the maturity of the safety case

would reduce technical uncertainties, support regulatory engagement, and enable more informed comparisons with DGR solutions. Such progress would allow end users to better understand the benefits that DBD could offer. It would also help to build the trust of the broader civil society for DBD, by showing that the technical and safety case is robust for both long-term environmental safety and security. In addition, civil society concerns about the potential retrievability of disposed waste packages over different timescales will need to be part of a broader public debate.

Resolving the issues discussed above via international cooperation would strengthen confidence in DBD as a viable disposal option, and support more flexible, efficient, and sustainable RWM strategies. Given the potential for DBD to provide an option for both SIMS and LIMS, development of the technology is compatible with the EURAD-2 SRA driver of developing tailored solutions for the management of various radioactive waste types in Europe. Moreover, by promoting research and innovation in this field, it offers the opportunity for optimisation of radioactive waste management routes to meet the needs of Member States.

2.3 Alternative waste management solutions for SIMS

2.3.1 Analysis of management strategies for small amounts of waste (including shared solutions)

SIMS face distinctive and common sets of challenges [3] when developing and implementing RWM solutions. They must fulfil technical and regulatory requirements comparable to LIMS, while operating with substantially fewer financial, technical, and human resources.

A critical first step is establishing robust waste characterisation and segregation at source, as gaps in knowledge or heterogeneity in waste streams can increase uncertainty and lead to conservative (and expensive) management choices. Maintaining compliance with regulatory expectations and disposal-oriented waste acceptance requirements can be particularly demanding where treatment, conditioning, or packaging routes are limited. Concurrently, the small scale of inventories (particularly per waste stream) makes it difficult to justify implementing dedicated national infrastructure, and cost efficiency, proportionality, and access to specialised capacities become significant constraints. As a result, many programmes remain dependent on interim arrangements and existing infrastructure, which can prolong storage periods and extend strategic uncertainty about end-state solutions. Shared or multinational approaches can mitigate some of these constraints through economies of scale and pooled expertise, but they introduce further challenges around transport regulation, governance, allocation of long-term responsibilities and liabilities, and the need for consistent decision-making across jurisdictions.

Legitimacy of and public confidence in waste management solutions are built on transparency, stakeholder engagement, and credible public participation, both for national and shared approaches. These preconditions are difficult to sustain with limited institutional capacity, a constraint commonly faced by SIMS. Additionally, for shared multinational solutions, concerns regarding unclear long-term liability, oversight and safety assurance must be addressed. Creating a level playing field between stakeholders by applying the highest standards and independent oversight is essential [5]. Both for national and shared approaches, intergenerational stewardship grounded in the precautionary principle needs to be included, where monitoring and responsibility are transferred between generations until a passively safe management option is implemented. Without ongoing international cooperation, structured knowledge exchange, and robust planning, SIMS may struggle to transition from interim waste management arrangements towards durable, publicly accepted, and technically robust long-term waste management pathways.

2.3.2 Evaluation of RWM strategies for the disposal of NORM wastes

NORM wastes, including uranium, radium, thorium and depleted uranium (DU), arise across Europe from a wide range of industrial activities, and from the nuclear fuel cycle [7]. For example, 12 of the European Union Member States have Uranium Mine and Mill Tailings (UMMT) [8]. NORM waste

management remains fragmented and unevenly developed among Member States, creating a complex landscape of regulatory, technical and strategic challenges. A major challenge arises from inconsistent definitions and regulatory classifications of NORM and DU. In some countries, DU is treated as a strategic or safeguarded material rather than radioactive waste, leading to divergent WAC and regulatory expectations across Europe. Such variability complicates cross-border learning, collaboration, and the potential for shared solutions, particularly for SIMS. Technical maturity is also uneven: although most countries apply measures spanning minimisation, conditioning, storage and disposal, their ability to implement these steps depends heavily on national capacity, infrastructure and regulatory drivers. Treatment options beyond cementation and storage remain limited, with relatively little coordinated RD&D into alternative conditioning processes, reuse pathways or volume-reduction technologies.

Disposal readiness represents a further cross-cutting concern. Near-surface engineered facilities and geological disposal are both being considered across Europe, yet few facilities for NORM wastes above clearance limits are operational, and most programmes remain pre-operational. Several countries currently lack a defined disposal route or concrete plans for one. This situation is exacerbated by the limited maturity of safety cases, particularly for DU-bearing wastes, where experience is confined to a small number of advanced states. Radium-rich materials pose additional challenges due to a lack of shared understanding regarding conditioning practices and long-term performance. For SIMS, these technical and regulatory uncertainties are compounded by restricted financial and human resources, limited access to specialist facilities, and difficulty sustaining national programmes for comparatively small waste streams. Without coordinated European action, these combined challenges threaten to perpetuate prolonged interim storage, fragmented regulatory approaches and stalled national disposal programmes.

3. Proposed way forward

This section identifies recommendations for the next RD&D steps as well as the benefits or impacts expected from them.

3.1 Long-Term Storage

ASTRA studied the challenges that can arise when radioactive waste is stored for periods exceeding the design lifetime of storage containers and/or storage facilities. When storage lasts longer than originally planned, the challenge is rarely a single technical flaw. It was suggested that, to address these challenges in a structured way, the RD&D should follow three complementary phases: first building the data and decision-making foundations, then developing and demonstrating practical technical solutions to strengthen long-term barrier performance and resilience, and finally ensuring preparedness for future waste streams and durable societal stewardship over the decades ahead [4].

In the near term, RD&D efforts should prioritise creating a reliable technical basis for decision-making and closing information gaps. These include:

- Defining operational thresholds. RD&D should focus on creating practical operational thresholds, methods to determine design life, remaining life, and end-of-use for both facilities and packages, and to translate these into clear decision gates within periodic safety reviews, inspections and monitoring.
- Predictive tool development. RD&D should focus on development of validated predictive tools and “inventory look-up tables” for assessing packages and barriers ageing, degradation and related risk assessment.
- Digitalisation and information recovery. This line of work should focus on recovering lost or paper-based historical data into digital formats to improve risk assessments and transparency with civil society.

A further near-term priority is the development of practical solutions for ageing management and environmental adaptation. These include:

- Advanced monitoring and inspection. RD&D should focus on non-destructive monitoring techniques and on-site inspection tools that do not require breaching containment, and long-term experiments to develop protocols for monitoring package ageing.
- Material science and countermeasures. Screening, development and testing technical measures that keep safety functions effective (maintenance, repairs, barrier strengthening, corrosion control, environmental control), demonstration performance with clear safety metrics. RD&D should address specific degradation scenarios, such as alkali-silica reactions in concrete or the behaviour of highly activated polyvinylchloride. Development of corrosion-resistant materials and durable overpacking solutions is essential for strengthening existing barriers.
- Climate and hazard adaptation: RD&D teams should update hazard screening to include compound events (e.g., simultaneous floods and utility loss) and develop a catalogue of upgrade options for older facility designs to ensure climate resilience.

A long-term programme should remain compatible with evolving nuclear strategies and societal expectations. These include:

- Characterisation of emerging waste. Proactive RD&D is required to define conditioning and storage frameworks for emerging waste from, e.g. Small Modular Reactors and research reactors, before they become operational burdens.
- WAC evolution. RD&D could focus on the chemical and physical evolution of waste matrices over decades to prevent non-compliance with final disposal criteria and to design bridging methods for shared facilities.
- Stewardship and participation. Develop and test transparent governance and public involvement models for long-term interim storage, using periodic safety reviews and lifetime extensions as key decision points. This should include clear communication with the public on safety and security assessments and monitoring, robust local and national participation structures following the Aarhus Convention [6].

Delivering this RD&D requires an integrated approach, involving operators and waste management organisations (WMOs) to provide practical implementation and data collection, regulators and Technical

Support Organisations (TSOs) to establish defensible, safety-based criteria for extensions and decision gates, Research Entities (RE) to develop the models, methods, and materials needed for the coming decades, and Civil Society Organisations (CSO) to strengthen transparency, participation structures and intergenerational stewardship.

3.2 Deep Borehole Disposal

Work carried out in ASTRA has established a generic DBD concept for the purpose of clarifying safety function definitions and identifying priority RD&D needs [9]. The most critical technical uncertainties around DBD implementation were identified as:

- Demonstrating deep drilling operations at the required depths and diameters envisioned for DBD.
- Exploring the long-term performance of borehole seals and plugs.
- Corrosion processes and their control under *in-situ* conditions.
- Demonstrating reliable monitoring at relevant depths.

Emplacement and retrieval operations represent a high-priority RD&D area, as these operations are technically complex and have not yet been demonstrated for radioactive waste packages containing HLW/SNF. Addressing these topics would support confidence in operational safety, which is a key barrier to implementing DBD at present.

A further near-term priority is the development and demonstration of techniques to confirm that stagnant groundwater conditions persist at the target disposal depth following borehole construction and waste package emplacement. This is essential to underpin the safety concept of DBD, which relies heavily on the absence of advective groundwater transport. Targeted studies using data from existing deep boreholes should also be undertaken to improve understanding of host rock conditions at typical DBD depths (up to 5 km depth) in different geological environments and host rocks. These studies should focus on hydrogeological and pore fluid properties, geochemical and redox conditions, microbial activity and its potential influence on corrosion processes, and factors affecting radionuclide migration, including sorption. Overall, this work would reduce key uncertainties across crystalline, sedimentary, and other potential host rock formations.

In the longer term, once key technical uncertainties have been addressed and reduced, the focus should move from concept definition to demonstrating that DBD can operate as a safe disposal system. This includes further development of DBD-specific safety functions and the definition of operational and long-term safety requirements, supported by dialogue with regulators, technical experts, Civil Society (CS), and international organisations such as the International Atomic Energy Agency and the Nuclear Energy Agency. DBD-specific safety demonstrations need to be undertaken to ensure that all safety functions are robustly addressed throughout the full lifecycle of the disposal system. As confidence in system performance increases, the generic DBD concept can then be optimised with respect to cost and operational efficiency provided that all safety functions continue to be fully satisfied.

These RD&D activities should be undertaken through international collaboration, involving WMOs, REs, TSOs and industry experts (particularly the drilling sector). Engagement with CS through professional risk communication practice should also form an integral part of future work, as transparency and open dialogue on topics such as retrievability, long-term safety and security are essential for building trust with broader publics.

3.3 Alternative waste management solutions for SIMS

3.3.1 Analysis of management strategies for small amounts of waste (including shared solutions)

Progressing waste management approaches and strengthening the resilience in waste management of SIMS, a dual-focus approach is proposed: RD&D on management solutions, supported by shared KM activities.

To address the challenge of identifying credible alternatives for SIMS, RD&D should concentrate on enabling proportionate, disposal-oriented management routes that remain technically feasible at small scale, whilst reducing uncertainty and reliance on prolonged interim arrangements. The near-term objective, and a fundamental step, is accurate waste characterisation and segregation at source. This should be complemented by targeted development and qualification of waste treatment techniques suitable for small inventories, such as immobilisation and volume reduction. Regulatory compliance and alignment with waste acceptance expectations must be treated as primary design constraints, because they directly underpin both safety assurance and public confidence. Currently, the most valuable RD&D outputs would reduce uncertainties in the decision-making process. These include a consolidated, transparent decision-support framework with guidance on end-of-life practices for waste packages and storage facilities, as well as validated predictive modelling to anticipate package degradation and barrier performance under changing environmental conditions. The benefit would be twofold: earlier identification of credible management routes for each waste stream, reducing the likelihood of later rework and repackaging, and improved capability to justify life-extension and end-of-life decisions for facilities and packages based on evidence rather than conservatism. Participatory exchanges with all stakeholders and the public in the decision-making process will help to build trust in proposed management routes.

In addition, international cooperation should be advanced as a structured complement to national measures, focusing first on enabling conditions and demonstrable service models. This proposal includes two knowledge-transfer mechanisms: a continuation of Live Discussion Forums (problem-focused exchange forums), and a direct SIMS-LIMS demonstrator to support SIMS by analysing existing solutions and identifying best practices across the waste management lifecycle. These mechanisms are not “nice to haves”; they are intended as hands-on accelerators translating technical work into implementable solutions. For LIMS, such engagement also provides strategic value by helping to avoid negative impacts from poorly implemented solutions, supporting European harmonisation of approaches, and offering opportunities to provide further expertise. As an intermediate-term objective, and as a consequence of the continuous dissemination of best practice, these can lead to harmonised methodologies for radioactive waste management across borders.

In combination, these steps deliver a clear impact: lower uncertainty and lower cost through earlier and farsighted decisions, improved technical robustness of small-inventory routes, and a more credible, transparent pathway for SIMS to move from interim-focused arrangements towards durable long-term solutions, supported where appropriate by shared services and demonstrator-led learning.

3.3.2 Evaluation of RWM strategies for the disposal of NORM wastes

To address the challenges, ASTRA outlines a coordinated European pathway that combines near-term practical support with longer-term strategic development, aligned with the proposed second-phase actions and future research directions. A first priority is the harmonisation of waste classification approaches and decision-support tools for NORM and DU. Developing common guidance on when such materials should be considered waste, alongside shared criteria for selecting between near-surface and geological disposal options, would help establish consistent regulatory expectations and enable more transparent national decision-making. In parallel, targeted efforts to accelerate technical solutions are required, including joint studies on conditioning options for Radium-bearing and Uranium-bearing materials, as well as pilot projects exploring reuse, recycling and circular-economy approaches that could reduce disposal volumes and optimise resource efficiency.

Strengthening safety case development is another critical component of the way forward. Establishing a reference safety-case architecture for NORM and DU, together with focused knowledge transfer from countries with existing experience, would enable less-advanced programmes to progress more rapidly and credibly. Such actions are particularly important for DU, where current expertise is sparse. At the same time, structured support mechanisms for SIMS should be expanded through matchmaking with expert partners, possible shared access to specialised facilities and datasets, and common training programmes. These measures represent an essential second-phase step toward enabling smaller programmes to move beyond prolonged storage and engage realistically with disposal planning.

Looking to the longer term, governance and societal dimensions must be embedded alongside technical progress. Early and structured effective participation of civil society fulfilling both Aarhus [6] and Espoo [10] Conventions, clear accountability arrangements for national or shared disposal solutions, and stewardship models for cases where disposal remains deferred will be vital for maintaining public confidence and regulatory legitimacy. Proposal for a longer-term future is a Strategic Study on NORM and DU stewardship, which extends this approach by integrating circular-economy principles, explicitly incorporating SIMS-specific needs, developing multi-criteria decision frameworks spanning reuse to disposal, and mapping future research, development and knowledge-transfer pathways. Collectively, these actions are expected to help reduce long-term reliance on storage, promote greater alignment across Member States, support progress toward disposal readiness, and encourage transparent and socially robust decision-making processes that strengthen confidence among regulators, implementers, other stakeholders and the public.

4. Call to Action

It is obvious from R&D needs identified in ASTRA that Knowledge Management (KM plays an important role in the proposed short-term and longer-term activities. The proposed establishment of two "exchange-platforms" would improve understanding and application of research results between Member States:

- A structured decision-support database on storage facilities and waste packages, coupled with advanced predictive modelling tools, including digital twins, open to all Member States.
- An institutionalised Live Discussion Forum as a permanent, problem-oriented platform, especially for SIMS–LIMS or advanced-less-advanced Member State exchange option for translating experience into implementation solutions, also for example, on alternative future disposal strategies (e.g., DBD), or to discuss risks to humans and the environment from implementing an option with CS participants.

4.1 Long-Term Storage

Long-term interim storage has become an unavoidable reality for radioactive waste management across Europe. Facilities originally designed for limited operational periods are now expected to perform safely and securely for decades longer than planned, often in the absence of clearly defined disposal timelines. This situation is manageable, but it is not neutral: ageing infrastructure, incomplete or deteriorating data, evolving waste characteristics, climate-related hazards, and insufficient participation in decision making by the public create cumulative risks that demand structured forward-looking action. Continuing to rely on incremental extensions without a shared technical and strategic framework risks locking Member States into reactive decision-making, increasing costs, and transferring burdens to future generations. What is needed is a shift toward proactive, evidence-based management, supported by robust data, predictive tools, transparent governance and fulfilling both Espoo [6] and Aarhus [10] Conventions.

The proposed way forward builds directly on this insight. In the near term, priority should be given to strengthening the foundations for decision-making through recovery and digitalisation of legacy data, clearer definitions of facility and package lifetimes linked to periodic safety reviews, and the development of practical predictive tools to anticipate ageing and degradation. In parallel, targeted RD&D is needed to improve monitoring, barrier resilience and climate adaptation of existing storage facilities. Over the longer term, preparedness for emerging waste streams and socially robust stewardship models should be integrated into long-term storage strategies.

To translate these needs into action, that EURAD community future activities can take forward ASTRA outcomes and continue with the development of a next-generation decision-support framework for end-of-life storage management and disposal options by pooling experience, data and expertise across Member States through coordinated European collaboration. This could include a structured decision-support database on storage facilities and waste packages, coupled with advanced predictive modelling tools, including digital twins, to support timely and defensible decisions on continued storage, reconditioning or transfer to disposal under changing environmental and global conditions.

4.2 Deep Borehole Disposal

It was concluded that in the near term, RD&D efforts should prioritise resolving the most critical technical uncertainties. These include demonstrating deep drilling operations at the required depths and diameters envisioned for DBD; exploring the long-term performance of borehole seals and plugs; understanding corrosion processes and their control under in-situ conditions; and demonstrating reliable monitoring at great depth. Emplacement and retrieval operations also represent a high priority RD&D area, as these operations are technically complex and have not yet been demonstrated for radioactive waste packages containing HLW/SNF. Addressing these topics would support confidence in operational safety, which is a key barrier to implementing DBD at present. A further near-term priority is the development and demonstration of techniques to confirm that stagnant groundwater conditions persist at disposal depths, following borehole construction and waste package emplacement. Studies to

improve understanding of host rock conditions at typical DBD depths (~2–5 km depth) using data from existing deep boreholes are also a near-term priority.

In the longer term, the focus should move from concept definition to demonstrating that DBD can operate as a safe disposal system. This includes further development of DBD-specific safety functions and the definition of operational and long-term safety requirements. DBD-specific safety demonstrations need to be developed to ensure that all safety functions are robustly addressed throughout the full lifecycle of the disposal system.

The next step is to translate these priorities into focused, collaborative studies that can be taken forward by the EURAD community. Such work should build directly on the outcomes of ASTRA and its existing capacities to interact with CS, align with ongoing international initiatives, such as the ongoing work of the International Atomic Energy Agency's Coordinated Research Project on DBD, and aim to reduce key uncertainties. By doing so, the RWM community can make tangible progress towards demonstrating the feasibility of DBD and enabling informed strategic decisions on its potential role within future radioactive waste management programmes.

4.3 Alternative waste management solutions for SIMS

4.3.1 Analysis of management strategies for small amounts of waste (including shared solutions)

There is a requirement to institutionalise and actively support Live Discussion Forums as permanent, problem-oriented platforms to advance the SIMS–LIMS demonstrator as a practical mechanism for translating experience into implementable solutions. Policymakers, regulators, WMOs and TSOs should commit resources and expertise to ensure that these forums move beyond exchange towards structured co-development of proportionate, disposal-oriented waste management pathways appropriate for SIMS. The Forums should be explicitly mandated to address specific challenges faced by SIMS, facilitate transparent dialogue on regulatory expectations and liabilities, and build shared understanding among stakeholders, while the SIMS–LIMS demonstrator must be used to pilot, test, and validate transferable service models under real constraints. Together, these instruments can reduce uncertainty, accelerate learning, and create trust by showing how existing LIMS solutions can be adapted responsibly to small inventories. Without such coordinated action, SIMS risk remaining locked into prolonged interim arrangements; with it, they gain a credible, cooperative pathway towards robust, publicly accepted long-term radioactive waste management solutions.

4.3.2 Evaluation of RWM strategies for the disposal of NORM wastes

A key priority is the harmonisation of waste classification approaches and decision-support tools for NORM and DU. This could aid the development of common guidance on when such materials should be considered waste, alongside the development of shared criteria for selecting between near-surface and geological disposal options. In parallel, targeted efforts to accelerate technical solutions are required, studies on conditioning options for Radium-bearing and Uranium-bearing materials, as well as exploring reuse, recycling and circular-economy approaches that could reduce disposal volumes and optimise resource efficiency.

Strengthening safety case development (EURAD Roadmap Theme 7) is another critical component of the way forward. Structured support mechanisms for SIMS should be expanded through matchmaking with expert partners, possible shared access to specialised facilities and datasets, and common training programmes. These measures represent an essential second-phase step toward enabling smaller programmes to move beyond prolonged storage and engage realistically with disposal planning.

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Appendix A. Keywords

Alternative RWM strategies, Extended lifetime, Deep borehole disposal, SIMS, LIMS, NORM, Transparency & public participation, Environmental impacts, Intergenerational stewardship culture

Appendix B. List of acronyms and abbreviations

ASTRA	**A**lternative Radioactive Waste Management **STRA**tegies
CS	Civil Society
DBD	Deep Borehole Disposal
DGR	Deep Geological Repository
DU	Depleted Uranium
EURAD	European Partnership on Radioactive Waste Management
HLW	High-Level Waste
KM	Knowledge Management
LIMS	Large-Inventory Member States
MS	Member States
NORM	Naturally Occurring Radioactive Material
RD&D	Research, Development and Demonstration
RE	Research Entity
RWM	Radioactive Waste Management
SIMS	Small-Inventory Member State
SNF	Spent Nuclear Fuel
SRA	Strategic Research Agenda
TSO	Technical Support Organisation
WAC	Waste Acceptance Criteria
WMO	Waste Management Organisation

Appendix C. EURAD Roadmap domains relevant for ASTRA

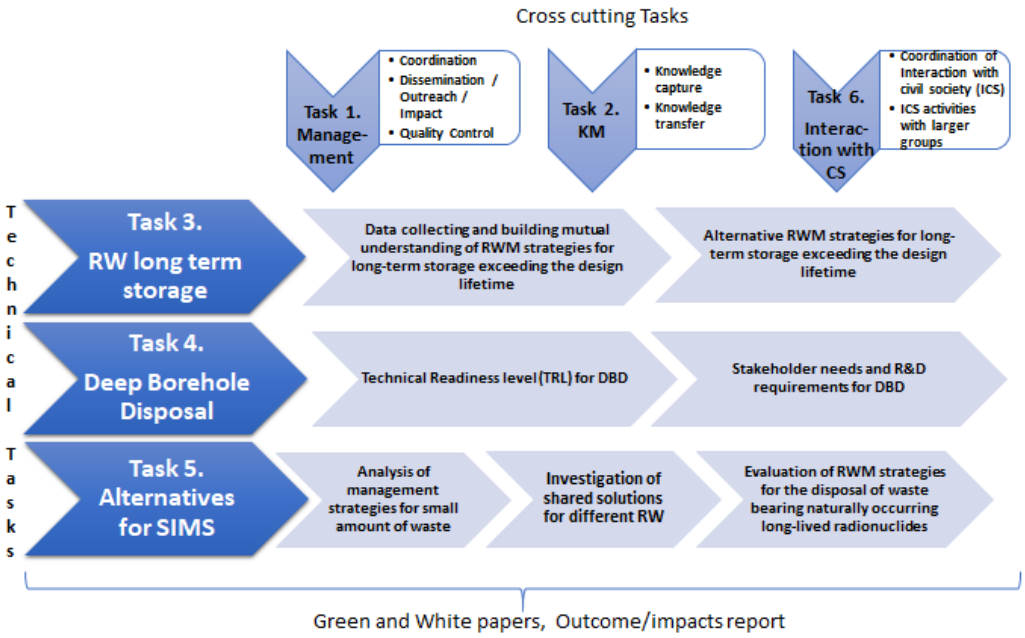
Theme and link	Sub-theme	Domain	Task(s) in ASTRA
1.National Programme Management https://www.ejp-eurad.eu/sites/default/files/2021-05/1_Programme_Management_Theme_Overview.pdf	1.1 Establish the national policy and plan for radioactive waste and spent fuel management activities, from generation to disposal (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).	Tasks 3-6
		1.1.2 Develop and maintain broad timescales and schedule for implementing radioactive waste management activities using a stepwise decision-making process (Timetable for decision making)	Tasks 3-6
		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)	Mainly task 6 jointly with other tasks
		1.1.4 Establish a process for progressive development and optimization of the plan (safety, security, use of resources)	Tasks 3-6
	1.2 Establish and maintain a national regulatory and organisational framework for the timely implementation of all steps of spent fuel and radioactive waste management, from generation to disposal (Programme Organisation)	1.2.4 Implement a system of appropriate oversight, a management system, regulatory inspections, documentation and reporting obligations for radioactive waste and spent fuel management activities (Waste management System)	Tasks 3-6
		1.2.5 Establish and implement a research, development and demonstration strategy with activities clearly related to timeframes, concepts, plans, and milestones defined in the national programme (RD&D Strategy)	Tasks 3-6
	1.3 Ensure that adequate financial and human resources (core capability and supply chain support) are available, and can be adapted to the changing needs of the programme over	1.3.2 Develop and maintain a technical and management skill base within the programme (core capability), meeting national regulatory competence requirements (Skills and Competence Management)	Tasks 3-6
		1.3.3 Use the knowledge, technology and experience gained internationally and co-develop RD+D where possible to improve and consolidate confidence in the scientific	Tasks 3-6

	many tens of years, from generation to disposal (Programme Resources)	and technical data base, to help reduce risks to successful programme implementation and to avoid unnecessary costs (International Cooperation)	
		1.3.4 Work collaboratively with delivery and specialist organisations nationally and internationally to obtain value for money (Procurement & Supply Chain Arrangements)	Tasks 3-6
	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)	Tasks 3-6
		1.5.2 Perform iterative evaluation of options and concepts at each stage of programme development taking account of international technological advances (Options and Concept selection)	Tasks 3, 5 and 6
2. Pre-disposal https://www.ejp-eurad.eu/sites/default/files/2022-07/EURAD%20Roadmap%20Theme%202_Predisposal_2022-07-01.pdf	2.1 Planning predisposal management of radioactive waste in close cooperation with waste generators (Planning)	2.1.1 Evaluate waste inventory from generators and existing storage, accounting for future waste generation and evolution (Inventory)	Tasks 3 and 6
		2.1.2 Identify parameters and metrics for waste acceptance criteria through whole life cycle (waste acceptance criteria)	Tasks 3, 5 and 6
		2.1.3 Assess potential technologies for the implementation phase, considering cost-benefit ratio and availability (technology selection)	Tasks 3, 5 and 6
		2.1.4 Evaluate options to apply the waste hierarchy to minimise waste volumes at higher impact inventory disposal levels (waste hierarchy)	Tasks 3, 5 and 6
	2.2 Implementing predisposal	2.2.3 Stabilise waste by conditioning prior to long-term storage (Conditioning)	Tasks 3, 5 and 6

	management of radioactive waste to support key risk and hazard reduction, and to help reduce costs and save space at interim storage and disposal facilities (Implementation)	2.2.4 Package waste accounting for future transport and deposition, and maintain safe interim storage of packages (Storage)	Tasks 3, 5 and 6
	2.3 Enhancing predisposal operations through iteration with waste generators and repository operators, to develop and deliver safe and cost-effective solutions (Optimisation)	2.3.1 Implement quality system and management system to ensure accurate detailed records of waste and package characteristics over their lifetime, from production until deposition (Quality & Management Systems)	Tasks 3, 5 and 6
		2.3.2 Evaluate potential for improving and optimising implementation phases with new technologies, to improve costs and environmental impact while maintaining safety and accounting for potential risk scenarios (Optimisation)	Tasks 3, 5 and 6
5 Disposal facility design and optimisation https://www.ejp-eurad.eu/sites/default/files/2021-08/5_Disposal_facility_design_and_optimisation_Theme_Overview.pdf	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)	Tasks 4-6
		5.1.4 Develop and establish qualification procedures, especially with regard to manufacturing and testing requirements, as well as safety demonstration concepts to confirm that structures, systems and components will perform their allocated safety function(s) in all normal operational, fault and accident conditions identified in the safety case and for the duration of their operational lives (Design qualification)	Tasks 4-6
	5.2 Demonstrate and verify that facility components and barriers can be practically manufactured, constructed and installed in accordance with	5.2.1 Develop, adapt and/or buy the technology and systems required to be able to construct and then commission the facility (Pilot-scale, full-scale testing, and active commissioning)	Tasks 4-6
		5.2.3 Establish reliable manufacturing routes to produce facility barriers and components, and inspections plans for how to test for unacceptable defects, and	Tasks 4-6

	detailed design requirements and specifications (Constructability, demonstration and verification testing)	overall quality assurance against specified design tolerances and industry standards (Manufacture, inspection and testing)	
		5.2.5 As a supplement to in-situ testing (cf. 5.2.1), consider simulating facility operations by using remote technologies and models to predict the most important variables of the disposal system implementation processes (Virtual Reality / Digital Twin)	Tasks 4-6
	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)	5.5.1 Establish plans and methods for implementing baseline environmental monitoring programme ready for the start of site characterisation (Baseline monitoring)	Tasks 4-6
		5.5.3 Establish technical feasibility of waste reversal after emplacement and potential waste retrieval after operation and if required, demonstrate in full-scale representative conditions before the start of operations (Retrievability)	Tasks 4 and 6

Appendix D. ASTRA Task organisation



The EURAD-2 Strategic Study (StSt) Work Package "**A**lternative RWM **STRA**tegies" (ASTRA) has analysed selected alternative strategies for radioactive waste management (RWM) including storage life extension, alternative waste management solutions like deep borehole disposal (DBD) and shared international waste management solutions, as well as the management of waste containing naturally occurring long-lived radionuclides (Depleted Uranium-DU, U, Th, Ra). These topics are especially challenging for Small Inventory Member States (SIMS).

In each ASTRA task the collection of information has relied on surveys (questionnaires, interviews and live discussion forums (LDFs)) and literature review to collect the needs and available technologies of participants, stakeholders, and end users. In a special role, Civil Society (CS) representatives have contributed to all ASTRA surveys to ensure that relevant questions from a CS perspective are included. The results of the surveys have further been discussed in task meetings, bilateral task-CS meetings, and workshops with participants (Research Entities (REs), Technical Support Organisations (TSOs), Waste Management organisations (WMOs), CS, stakeholders, end users and "invited guests" for LDFs to obtain a mutual understanding of e.g. country specific situations and needs, an agreed prioritisation of common needs, strategies, and further activities.