Deliverable 3.1: Green paper - Position paper on mutual understanding on alternative RWM strategies(*)

Work Package 03 **ASTRA**

DOI: 10.5281/zenodo.18173945

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

(*) This deliverable has been produced without using any Artificial Intelligence tools.

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.	**3.1**
Deliverable Title	**Green paper - Position paper on mutual understanding on alternative RWM strategies**
Lead Beneficiary	**COVRA**
Contractual Delivery Date	**September 2025**
Actual Delivery Date	**November 2025**
Dissemination level	**PU (PUBLIC)**
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To be cited as:

Pfingsten, W., Vuorio, M., Prevot L., Begg J., Prasad S., Fuzik K., Kudriashova Y., Hontar Y., Bornhöft M.C., Horvat B., Zeleznik N., McGrath Z., Browning K., Wickham S., Mraz G., Geisler-Roblin A., Hooge N.H., Swahn J., Kardzhilov P., de Butler M. (2025): Green paper - Position paper on mutual understanding on alternative RWM strategies for tasks. Final version as of 03/10/2025 of deliverable D3.1 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)	W. Pfingsten (PSI)	08/09/2025
Verified (WP Leader)	M. Vuorio (COVRA)	08/09/2025
Reviewed (Reviewers)	D. Galson (Independent)	18/09/2025
Review KM (KM WP Leader)	A. Tatomir (BGE)	21/10/2025
Approved (PMO)	M. Lopez (AMPHOS21)	08/102025
Submitted to EC (Coordinator)	Andra	27/11/2025

Executive Summary

The EURAD-2 Strategic Study (StSt) Work Package "**A**lternative RWM **STRA**tegies" (ASTRA) analyses 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 were already mentioned in EURAD-1 WP ROUTES recommendations, they are included in the EURAD road map domains (Themes 1, 2, 5), and they are especially challenging for Small Inventory Member States (SIMS) and therefore should be addressed in more detail in a EURAD-2 2nd Wave activities.

In each ASTRA task the collection of information relies on surveys (questionnaires, interviews, 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 are contributing to all ASTRA surveys to ensure that relevant questions from a CS perspective are included. The results of the surveys are further 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.

With respect to end-of-life storage facilities/waste packages, highest priority identified was exchange of knowledge, practices, cases, lessons learnt including SIMS - LIMS data exchange, the development of approaches for defining end-of-operation storage and containers lifetimes, planning for facility closure, and future remediation, and the development of predictive tools for assessing packages and barriers ageing, degradation and related risk assessment, which should be investigated in a EURAD-2 2nd wave RD&D WP.

Similar for DBD, where a EURAD-2 2nd wave RD&D WP should address the need for the development of a guidance framework for a DBD safety case. This framework would help define the safety functions for key components of this disposal option, which was agreed to be fundamental for regulatory approval and gaining public confidence. In addition, a generic safety case methodology should allow to define safety functions, followed by application to specific sites, accounting for differences in the strategic context that exist between countries, and, most importantly, a deep borehole field test (DBFT) is required to demonstrate the feasibility of borehole drilling to the required depths and diameters, installing casing, waste package emplacement and retrieval, and borehole sealing. In this context, CS has a strong interest in showing retrievability, while also acknowledging the lower risk of human intrusion for DBD compared to DGR.

For alternative waste management solutions, key components education, training, stakeholder engagement and sharing experience and knowledge between LIMS and SIMS were prioritised, especially considering that SIMS face often the problem of less resources. As a fundamental step, waste characterisation was identified, in parallel with transparency, public participation, and clear communication for shared and single countries solutions. Areas of common interest and drivers were identified, as for example, cooperation of countries interested in developing Small modular Reactors (SMR) / Advanced Reactors (AR) and should be dealt with in a EURAD-2 2nd wave RD&D WP.

In contrast, for NORM waste, a StSt has been initiated by ASTRA partners and stakeholders. This has been proposed to EURAD-2 2nd wave call via the TSO college, based on a common understanding that the management of NORM and DU waste across Europe remains fragmented, with significant variations between MS in definitions, practices, and long-term planning, which requires first a dedicated StSt.

So far, the large participation in ASTRA meetings and surveys in the first year of the work programme by participants, end users and stakeholders confirm the value of the different tasks in ASTRA for the diverse needs of national RWM programmes, the gaps existing for some countries, but also the large number of existing country-specific waste management options and solutions that are available already

as well as the decision to go on with the EURAD-2 2nd wave call with different WPs, RD&D and StSt, respectively.

Keywords

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

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Glossary

ANCHORS	EURAD-2 R&D WP on hydraulic-mechanical-chemical evolution of bentonite for barriers optimisation
AR	Advanced reactors
CLIMATE	EURAD-2 StSt on Impact of climate change on nuclear waste management
CS	Civil Society
CSO	Civil Society Organisation
DBD	Deep Borehole Disposal
DBFT	Deep Borehole Field Test
DGR	Deep Geological Repository
EIA	Environmental Impact Assessment
FORSAFF	EURAD-2 StSt on Waste management for SMRs and future fuels
GDF	Geological Disposal Facility
HLW	High-Level Waste
IAEA	International Atomic Energy Agency
ICARUS	EURAD-2 R&D WP on Innovative characterisation techniques for large volumes
ILW	Intermediate-Level Waste
ICS	Interaction with Civil Society
KM	EURAD-2 work package Knowledge Management
LIMS	Large Inventory Member States
LDF	Live Discussion Forum
LLW	Low-Level Waste
LTS	Long-Term Stewardship
MS	Member State
NEA	Nuclear Energy Agency
OPTI	EURAD-2 Strategic Study on HLW Repository optimisation including closure
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RE	Research Entity
RMS	Requirements Management System
ROUTES	EURAD-1 Strategic Study on Waste Management Routes in Europe from Cradle to Grave
RW	Radioactive Waste
RWM	Radioactive Waste Management
SIMS	Small Inventory Member States

SITEX	Sustainable Network for Independent Technical Expertise on Radioactive Waste Management
SMR	Small modular reactors
SNF	Spent Nuclear Fuel
TSO	Technical Safety Organisation
UMAN	EURAD-1 Strategic Study on Uncertainty Management Multi-Actor Network
WAC	Waste Acceptance Criteria
WMO	Waste Management Organisation
WP	Work Package
WS	Workshop

1. Introduction

The EURAD-2 Strategic Study Work Package "**A**lternative RWM **STRA**tegies" (ASTRA) analyses 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. All these topics above are included in the EURAD road map domains (Theme 1 - domains 1.1.1-4, 1.2.4, 1.2.5, 1.3.2-4, 1.5.1, 1.5.2; Theme 2 – domains 2.1.1-4,,2.2.3, 2.2.4, 2.3.1, 2.3.2;Theme 5 – domains 5.1.1, 5.1.4, 5.2.1, 5.2.3, 5.2.5, 5.5.1, 5.5.3) [1], and are especially challenging for Member States with small inventories (SIMS) and which should be addressed in more detail in a EURAD-2 2nd Wave WP as an outcome of ASTRA.

The ROUTES Work Package (WP) in EURAD-1 (called EURAD before) [2] identified several Research & Development (R&D) needs and opportunities for collaboration between Member States (MS), which led to the ASTRA WP on three technical tasks related to alternative predisposal and disposal waste management strategies accompanied by interaction with CS, a separate task interacting with the technical tasks (see Figure 1, left):

As detailed in the ROUTES recommendations, alternative RWM strategies need to be considered for waste types for which there are currently no (long-term) management routes, or where such routes could be optimised for challenging waste forms, or where the original disposal solution proposed/considered under the national concept has been updated. These alternative strategies may be considered by countries at different programme stages and with different volumes of waste (SIMS/LIMS). The technical tasks together with interaction with CS task have been chosen to identify specific RD&D needs and optimisation of national waste management programmes and, to define detailed programmes for R&D and/or StSt WPs to be investigated in EURAD-2 2nd wave by current ASTRA partners, end users and stakeholders.

The definition of a common interest programme for EURAD-2 2nd WPs relies on individual task's surveys to collect information on the needs and available technologies of the participants, whereby CS was participating in the preparation of the ASTRA surveys to ensure that questions of interest to CS were included. The results of the surveys were and will be further discussed in workshops, the outcomes of which feed into ASTRA deliverables, i.e., Green Paper, White Paper and EURAD-2 2nd wave proposals. Lines of work exemplified for Task 5 are shown in Figure 1 (right).

Information gathering within ASTRA builds on and takes account of information already compiled in other EU projects:

- The ROUTES and UMAN WPs within EURAD-1, already referred to above.
- The recently completed HARPERS [4] project, which aimed to establish and clarify the benefits and added value of more aligned and harmonised regulations and standards for prioritised topics related to decommissioning and the initial phases of radioactive waste handling, including shared processing facilities between MS including WPs on Cross Border Waste Facilities/Services (WP3) [5], Circular Economy (WP4) [6], Advanced Technologies (WP5) [7] and Regulatory Framework (WP6) [8].
- The PREDIS project [9] and, in particular, the output of WP7, which considered various management issues for cemented waste packages in interim storage, such as monitoring, modelling, managing data, application of digital twins, and economic, environmental, and safety impacts of the technologies and approaches developed and tested in WP7 [10, 11, 12, 13]. The latter evaluation was based on a value assessment methodology which compared the performance of alternative technologies with current practices, highlighting their advantages and challenges across various assessment topics. The assessment topics included operational and transport safety, environmental impact, impact on disposability/long-term safety, implementation and timescales, technical readiness, and cost.

The ASTRA project team includes 21 partners and three associated partners from 17 countries. A broad mix of stakeholders is included in the work package: 3 WMOs, 8 TSOs, 9 REs and 1 Civil Society Organisation (CSO) (Nuclear Transparency Watch, liaising with additional CSOs). In addition, more than

30 interested members from the EURAD-2 end-user group (including regulators) and stakeholder group have expressed interest in ASTRA. High interest in ASTRA in the preparatory phases of EURAD-2 as well as the large participation in ASTRA meetings (see Appendix A and B) and surveys in the early phases of the work programme by participants, end-users and stakeholders confirm the need for studies covered by ASTRA tasks.

The foreseen deliverables and milestones are / will be achieved to support already proposed StSt from the TSO college, R&D proposals to be submitted until 10th December 2025, and the White paper:

- D3.1 – Green paper WP3.
- D3.2 – State-of-the-art assessment of TRLs and R&D requirements for deep borehole disposal of radioactive wastes.
- D3.3 – White paper WP3.
- D3.4 – Outcome/impacts report to Member States and End Users WP3.

- MS27: Workshop on TRLs for DBD (Meeting note).
- MS38: Workshop on building mutual understanding about RWM strategies for long-term. storage exceeding the design lifetime (Meeting report).
- MS60: Workshop on alternative RWM strategies for long-term storage exceeding the design lifetime (Meeting note).MS61 Workshop for RWM strategies for the disposal of waste bearing naturally occurring long-lived radionuclides (Meeting note).
- MS70: Management strategies for small amounts of waste in SIMS (Report).
- MS81: Report from pluralistic workshop, and central aspects from civil society vision. (Report).

Figure 1 – ASTRA poster contribution at EURADWASTE2025. Warsaw, Poland (left, snapshot - for details see ASTRA-poster-EURADWASTE2025*) and some of the ASTRA partners at EURAD-2 kick-off in Ghent during a brief ad hoc meeting (right).*

2. RW long-term storage

In many European countries, storage facilities for RW that were originally designed as temporary or intended for a limited operational period are now being used beyond their designed lifetimes [14, 15, 15]. This situation is the result of a complex interplay of technical, economic, institutional, and societal factors that have hindered the implementation of long-term RWM strategies. One of the key reasons for the extended or exceeded use is the delay in the implementation of disposal solutions. Although technical concepts for repositories exist, their development and construction require years or decades of planning, design, licensing, and extensive public consultation. Another important factor is the absence of, or significant delays in, developing national or regional long-term RWM programmes, often linked to postponed political decisions or institutional uncertainty. Finally, the economic dimension also plays a crucial role. The construction of new storage or disposal facilities requires substantial capital investment. In countries with limited volumes of RW or small nuclear sectors, decisions are sometimes made to defer investments in new infrastructure until regional or international shared solutions emerge, or financial conditions improve. Therefore, the prolonged use of RW storage facilities in Europe (and wider) is rather a necessary strategy shaped by a combination of technical, economic, political, and social circumstances. However, a strategy of storage extension introduces new challenges for both facility operators and national regulators, who must ensure that facilities remain safe and secure throughout extended operational periods that may exceed initial design lifetimes.

Task 3 of the ASTRA WP was initiated to study alternative RWM strategies in situations where RW is stored for periods exceeding the design lifetime of storage containers and/or storage facilities. To support the study, a dedicated questionnaire was prepared and circulated to partners and end users, with 22 responses received from 15 countries. The Task 3 questionnaire covered the current status of RW storages and its barriers, options for extending the lifetime of storage facilities and containers, quality and accessibility of RW-related data, main challenges, risk assessment approaches, potential future RWM strategies, funding principles and their availability, and current practices for public communication, trust-building, and stakeholder involvement in decision-making processes.

The information collected, along with insights from a dedicated workshop involving task partners and end-users, which brought together parties interested in the long-term storage of RW, has contributed to a deeper understanding of the condition and long-term management needs of RW storage facilities across Europe. The workshop also helped to identify key challenges associated with storage facilities and containers that have exceeded their intended design life, and to prioritise the most pressing gaps and issues faced by participating countries. The compiled findings will be captured in ASTRA WP Milestone MS38 [16].

Storage facilities used beyond their intended design lifetime face a number of problems that affect their long-term safety, infrastructure resilience, and the feasibility of eventually transferring the RW to disposal facilities. Survey and workshop participants reported several challenges, which can be summarised as follows:

- **Degradation of physical barriers**: One of the most pressing concerns is the gradual deterioration of storage and container barriers. Metal containers are prone to corrosion due to moisture and chemical interactions within the waste matrices, which can lead to loss of containment and potential radioactive releases. Degradation of containers often requires complex and costly reconditioning or repackaging operations to maintain safe storage. Concrete facilities that hold graphite or cemented waste may begin to lose their insulating properties over time, and the decline of engineered barriers can lead to accidental releases or radionuclide migration into the environment, thereby deteriorating the surrounding radiological conditions. In long-term and prolonged storage, material ageing management is an important part of keeping updated knowledge about the technical condition of safety-relevant barriers properties. Additional monitoring and modelling support will be necessary for decision-making processes in order to predict aging of waste packages and foresee potential measures to guarantee long-term safety [10, 17].
- **Technical feasibility of extended operation**: Many storage facilities undergo technical condition assessments, safety upgrades, and the introduction of new control and monitoring systems. In cases where operational conditions remain acceptable and no immediate risk is posed to the public or environment, regulators in some countries permit continued use of existing facilities until final solutions become available. Periodic safety assessments help track facility conditions, but they do not always ensure timely decision-making regarding the decommissioning of gradually degrading infrastructure.
- **Lack of up-to-date data records and loss of historical records**: In many cases, data gaps and the deterioration or loss of historical records make it difficult to maintain accurate inventories of RW held in long-term storage. Inaccuracy or lack of data complicates long-term risk assessments and effective decision-making. Addressing the issue requires targeted strategies to recover or reconstruct lost information and to carry out additional inspections and analyses where required.
- **Waste Acceptance Criteria (WAC) non-compliance**: Over time, the physical and radiological characteristics of waste may evolve due to changes in generation, packaging, or conditioning practices. As a result, some waste packages may no longer meet the original WAC for final disposal (see HARPERS recommendations [4-8]) and may require repackaging or additional conditioning before acceptance.

- **Unclear or missing lifetime definitions**: In some cases, facilities were designed for "temporary" storage without clearly defined maximum operational timeframes, which leads to strategic uncertainty in long-term RWM planning. When the existing agreed and implemented national strategy lacks comprehensiveness, decisions tend to be made on an *ad hoc* basis, and temporary storage facilities may become *de facto* long-term storage solutions.
- **Climate change and external impacts**: Climate-related risks such as flooding, wildfires, or extreme weather events, which may not have been considered in the original facility designs, are becoming more prominent and require increased attention considering the resilience of RW long-term storage systems and incorporation of climate adaptation strategies.
- **Emerging waste streams**: New types of RW, such as waste from small modular reactors (SMRs), are gradually introducing additional uncertainty. Existing infrastructure, including storage facilities, was not designed to handle new waste types, and there may be no current capacity or planning to develop separate specialised infrastructure for emerging waste types.

All of the above challenges require a comprehensive, integrated approach to long-term RW storage management. Strategic planning, robust data systems, proactive safety reviews, and adaptive regulatory frameworks are essential. Equally important is international cooperation, which enables countries to exchange experience, develop harmonised approaches, address common challenges and strengthen collective understanding and promote safe, sustainable RW management across Europe. Survey and Workshop participants expressed shared interest and needs to further explore and discuss opportunities for:

- exchange of knowledge, practices, cases, lessons learnt and potential problems that could occur due to operation of extended storage and conditioned waste packages (including SIMS - LIMS data exchange);
- development of approaches for defining end-of-operation storage and containers lifetimes, planning for facility closure, and future remediation; and
- development of predictive tools for assessing packages and barriers ageing, degradation and related risk assessment, and further technical solutions for ageing management, maintenance, strengthening safety barriers, retrievability of RW packages, and repacking for subsequent storage or disposal.

Contribution from civil society experts

Long-term interim storage is the option used in most European countries and is therefore a focus of civil society. If interim storage facilities were not designed for long-term operation, the risk will be increased by effects of ageing and due to outdated designs.

From civil society's view the option of long-term interim storage involves a number of problems:

- Old interim storage facilities were often built before the environmental impact assessment (EIA) laws came into force. Therefore, neither an adequate assessment of impacts on the environment and human health was conducted, nor was legally secured public participation on national and transboundary level enabled.
- There is a lack of public participation procedures during storage operation. Some countries have local committees at the siting communities, but no nationwide or even transboundary procedures are foreseen. Periodic Safety Reviews represent good points in time to broaden public participation. This would strengthen a shared culture for safety and security and could contribute to developing an intergenerational stewardship culture.
- Information on interim storage design lifetime is in general not publicly available. It is therefore not obvious to CS when a lifetime extension procedure of facilities and storage containers would have to be conducted. And it is not even clear yet if such a lifetime extension procedure would be carried out with an EIA.
- Long-term interim storage of spent nuclear fuel (SNF) could result in large amounts of such fuel located in one place. Security risks like terrorist attacks and acts of war have become of higher importance in recent years. Interim storages, especially when it comes to long-term use, need to be secured against these types of attacks. The public is concerned and needs to be provided confidence that such events have been considered in store design and management.
- From an ethical perspective, long-term storage exceeding the container and/or interim storage facility design lifetime, puts pressure on future generations and violates the polluter-pays

principle. To provide solutions for time-related problems such as this, the development of an intergenerational stewardship culture is needed.

3. Deep borehole disposal (DBD)

DBD entails the emplacement of radioactive waste packages in boreholes drilled to depths of several kilometres in a stable geological environment. Safety is primarily provided by a combination of (i) the thickness of the geological barrier, which serves to isolate the waste from the biosphere, and (ii) the stagnant hydrogeochemical and hydrogeological conditions at depth that ensure long-term passive containment. The small footprint and depth of DBD limits the probability of inadvertent human intrusion and contributes to waste isolation.

Mined geological disposal concepts (hereafter, geological disposal facilities; GDFs) other than DBD have been adopted for radioactive waste disposal in countries with large inventories of SNF or vitrified high-level waste (HLW), such as Sweden, France, Switzerland, and the United States. DBD is seen as a promising disposal alternative to a mined GDF for HLW / SNF both in countries with small waste inventories and for potential multinational repositories [18]. For example, in the EU, SIMS such as the Netherlands, Poland, and Slovenia possess relatively small quantities of HLWand SNF which makes the GDF approach economically unfeasible, in contrast to DBD which may offer better flexibility and economic viability. However, the DBD concept is considerably less mature than disposal in a mined GDF and requires significant research, development, and demonstration (RD&D) efforts.

At the multinational level, DBD options have been recently studied, or are the subject of ongoing study, by the Sustainable Network for Independent Technical Expertise on Radioactive Waste Management (SITEX, [19]), the International Atomic Energy Agency (IAEA, [20]), the European Joint Programme on Radioactive Waste Management (EURAD) Work Package (WP) 'Waste management routes in Europe from cradle to grave' (ROUTES, [18]) and the EURAD-2 WP 'Alternative radioactive waste management strategies' (ASTRA). At the national level, there has been considerable interest in DBD by Sandia National Laboratories in the USA over the past two decades [21], while Australia is developing a 2000-m-deep demonstration borehole [22].

Currently, the technical maturity of the DBD concept does not compare to that of a mined GDF. Much of the work that has been performed has looked at conceptual development, safety analysis, and estimates of cost with little experimental or field-based work. Although it is broadly understood that much of the deep borehole drilling technology needed to implement DBD already exists in the hydrocarbon, mining, geothermal and underground nuclear weapons testing industries, it remains untested for radioactive waste disposal applications and will require considerable development [23]. There is a need for a comprehensive RD&D programme covering the technical feasibility and the long-term safety of radioactive waste disposal in a deep borehole.

Task 4 of the ASTRA WP brings together parties interested in the development of DBD as a credible waste management option. Its principal aim is to recognise areas of agreement/disagreement concerning the current state of the technology as well as the associated uncertainties. Moreover, Task 4 looks to identify stakeholder concerns and the RD&D needed to build confidence in the implementation of DBD. A preliminary information-gathering questionnaire concerning DBD options being considered by the countries / organisations / programmes involved in Task 4 was sent out to participants shortly after the start of the WP; a selection of the answers received is summarised in Table 1.

Table 1. Selected responses from information-gathering questionnaire sent to EURAD-2 ASTRA WP participants as part of Task 4. Note that responses represent those supplied by Task participants and are not necessarily official positions of the countries(*) indicated.

		FI	SI	NL	DK	PO	US	EE	NO	UA	CZ
Depth / orientation	Vertical < 3 km	X	X		X			X	X		
	Vertical > 3 km		X	X		TBD	X		X	X	TBD
	Horizontal		X								
Inventory	SNF, HLW	X	X	X		X	X	X	X	X	
	Other (LLW, ILW, HLW)			X	X	X					X
Host rock	Crystalline	X	X			X		X	X	X	X
	Sedimentary		X	X	X	X		TBD			X
Borehole diameter (m)	Large (> 1)			X						X	
	Medium (0.5 < X ≤ 1)	TBD			X	TBD		TBD	X	X	
	Small (≤ 0.5)		X				X				X

(*) FL: Finland, SI: Slovenia, NL: The Netherlands, DK: Denmark, PO: Poland, US: United States, EE: Estonia, NO: Norway, UA: Ukraine, CZ: Czech Republic

The responses recorded in Table 1 demonstrate the differing DBD concepts being considered by the selected countries. The broad range DBD properties in the responses highlights some of the complexities in providing a one-size-fits-all approach to the uncertainties associated with this disposal option.

An important need is the development of a guidance framework for a DBD safety case, as the safety concept for DBD is rather different from that for a mined GDF, and existing guidance applicable to mined disposal is unlikely to be entirely suitable for DBD. Such guidance would help define the safety functions for key components of this disposal option, which is fundamental for regulatory approval and gaining public confidence. In addition, guidance will provide a roadmap for addressing key safety and regulatory aspects and inform how other uncertainties associated with DBD should be addressed. Therefore, it may be expedient to develop a generic safety case methodology to allow definition of safety functions, followed by application to specific sites, which specificity would account for differences in the strategic context that exist between countries, for example, waste retrievability as a regulatory requirement.

Development of a safety case framework would provide a tool to manage and integrate work on resolving uncertainties / closing knowledge gaps, including the development of DBD site selection criteria and site characterisation needs; advancement of drilling tools and techniques to demonstrate that boreholes of the required diameter for waste disposal can be drilled and the waste safely emplaced; justification of the engineered barrier system design, including development of waste packages / overpacks that demonstrate low corrosion rates under the salinity, heat, and hydrostatic conditions that may be encountered at depth; and the long-term stability of materials used to backfill and seal the borehole.

Perhaps most importantly, it is widely considered by national radioactive waste management organisations and other stakeholders that a deep borehole field test (DBFT) is required to demonstrate the feasibility of borehole drilling to the required depths and diameters, installing casing, waste package emplacement and retrieval, and borehole sealing. The feasibility of DBD as a viable and credible disposal option could be fully assessed once this 'proof-of-concept' is successfully validated.

Contribution from civil society experts

The different DBD concepts that have been proposed give rise to many different opinions from CS actors. No strong consensus opinion can be seen so far, perhaps because these concepts have never been studied in detail by CS until now. Another reason may be that the DBD concepts connect to many complex topics of RWM. Two main issues can so far be identified as being important for CS: safety and security, and retrievability.

Human and environmental safety is a primary requirement for any disposal option. Preliminary environmental safety assessments for waste packages deposited in a deep borehole at depths below 2-3 km suggest that any future DBD project could be as safe as a mined repository for the same waste type - and maybe safer in the very long-term [21]. This could be important for discussions with and within CS but needs to be verified with complete EIA. The limited preliminary safety assessment work to date limits the possibility to take decisions to start a larger implementation programme within a 5-10 year period. Safety requirements should reach at least the level for mined repositories, with adapted concepts, adapted safety functions and adapted methodology.

DBD has another environmental safety advantage compared to a mined repository: there is a reduced risk of intentional or unintentional human intrusion owing to the greater depth of disposal and the smaller footprint of the DBD disposal area compared to a mined repository for equivalent wastes. The long-term security and safeguards risks would also be reduced for DBD. However, the intrusion and security risks are sometimes not explicitly considered in safety analysis of mined repositories, which limits the basis for CS discussions compared with DBD.

Understanding the potential for retrievability is highly important for CS. Guaranteeing any serious retrievability in deep boreholes after closure seems almost impossible, at least after deposition in boreholes at 3-5 km depth. The potential for retrievability during disposal operations and for a shorter or longer time periods before closure needs to be studied further, including possible complications relating to borehole stability, chemical degradation of waste packages, and complex operations in contaminated situations (e.g. prematurely leaking package). Emplacement of SNF/HLW in both DBD and mined repositories will be done remotely, but the remote dimension is essential to DBD concepts as everything has to be achieved from the surface.

There is a need for a more developed and sophisticated discussion with and within CS about the importance of safety and security aspects and for a comparison of retrievability aspects when discussing the pros and cons of DBD and mined repositories for RWM. This is especially important as possible lower costs and easier siting of deep boreholes may drive DBD development forward in the coming years, while many substantial topics still have not been tackled in enough depth by CS.

4. Alternative waste management solutions for SIMS

SIMS face waste management issues and challenges that are broadly similar to those encountered by LIMS. However, SIMS must address these challenges with significantly fewer resources, which makes the development and implementation of effective solutions particularly challenging.

4.1 Analysis of management strategies for small amount of waste

Effective management of small amounts of waste, particularly in the context of radioactive or hazardous materials, requires a comprehensive and adaptive approach that integrates technical, regulatory, and social considerations [24]. A fundamental step is the accurate characterisation and segregation of waste at the source, which supports informed decisions on treatment, conditioning, and disposal [25]. Techniques such as compaction, immobilisation, and volume reduction play a crucial role in minimising waste while ensuring safety [19]. Temporary storage solutions and the use of existing infrastructure can offer practical interim options until permanent solutions, such as deep borehole repositories, are implemented for suitable waste types.

Regulatory compliance and alignment with established WAC are essential to ensure safety and public confidence [26]. The importance of transparency, public participation, and clear communication is consistently emphasised, as it fosters trust, support, and context-specific solutions well explained to the public. Education, training, stakeholder engagement, sharing experience and knowledge between LIMS and SIMS (like in Task 5 e.g. via Live Discussion Forums (LDFs)) contribute to a culture of responsibility and informed decision-making [27]. Furthermore, integrating community feedback, sharing best practices through case studies, and encouraging collaboration between stakeholders and MS can enhance the effectiveness of waste management strategies. Lastly, regular monitoring, adaptive management frameworks, and continued research and innovation help refine practices, ensuring long-term sustainability and safety in managing even small quantities of complex waste [28].

4.2 Investigation of shared solutions for different types of RW

Consideration of shared solutions for managing different types of RW emphasise international collaboration, integrated strategies, and stakeholder engagement to enhance safety, efficiency, and sustainability [4-8, 19, 24]. Countries and organisations are increasingly cooperating to address common challenges through joint research, shared infrastructure, and harmonised regulatory frameworks. Collaborative approaches foster the exchange of expertise, innovative technologies, and best practices tailored to specific waste types [4-8, 19, 24].

Transparency/open communication, ethical considerations, and public participation in decision-making are key to building trust and achieving public acceptance of shared solutions [28]. The availability of shared solutions can assist with long-term planning and adaptability, helping to ensure that waste management systems are responsive to changing needs, including the needs of future generations. The development of common frameworks, coordinated RD&D, and structured decision-making processes across MS supports the creation of unified, effective practices [26]. Case studies of shared WM solutions from European countries highlight the benefits of shared strategies in diverse regulatory and cultural settings, while continuous feedback loops between different stakeholders and mutual aid agreements (e.g., Chernobyl sarcophagus and related activities) further strengthen resilience and innovation in RW management. Ultimately, shared solutions provide a path toward more coherent, socially responsible, cost effective, and technically robust management of RW across borders [26].

Topics identified in Task 5.2 for requiring further analysis are:

1. National context of RW transportation regulation.
2. Drivers of cooperation in different stakeholder groups.
3. Areas of interest for cooperation on shared solutions.
4. Drivers for collaboration in EURAD ROUTES community.
5. Areas of interest for countries pursuing a dual-track approach, not decided yet on shared or national solution.
6. Areas of interest and drivers for cooperation in countries interested in developing Small modular Reactors (SMR) / Advanced Reactors (AR).
7. Governance in joined Deep Geological Repositories (DGR) activities.
8. Comparison of areas of interest and drivers for cooperation based on DGR needs (e.g., common host rock or waste types).

4.3 Evaluation of RWM strategies for the disposal of waste bearing naturally occurring long-lived radionuclides

Work under this topic aims to advance lifecycle management of waste containing high concentrations of long-lived naturally occurring radionuclides. Previous EURAD work identified Radium, Thorium, Uranium (Ra/Th/U), including Depleted Uranium (DU), as challenging. A questionnaire on current inventory management practices was distributed to WP partners and end-user group members, and 21 responses were received from 18 countries. The responses provide insight into current reuse and recycling processes, chosen waste treatment options, current disposal techniques, safety case development, selected disposal programmes, and R&D topics. The key results from the survey are summarised below.

Fourteen countries stated they had Naturally Occurring Radioactive Material (NORM) and DU waste (Czech Republic France, Germany, Greece, The Netherlands, Norway, Poland, Portugal, Slovenia, South Korea, Switzerland, Ukraine, Great Britain, United States), three countries only had NORM waste (Austria, Denmark, Spain, and one country stated they had neither (Belgium). Each country had their own definition of NORM and DU wastes – in particular, seven countries that possess DU do not classify it as RW, and instead classify it as a zero-value asset or safeguard material[1].

There are a variety of waste management techniques implemented or planned for NORM and DU wastes, including waste minimisation, treatment (i.e., re-enrichment of DU), blending with non-radioactive material, reuse/ recycling, conditioning (i.e., encapsulation and cementation), storage and disposal (i.e., some programmes include dedicated disposal sites or landfills for NORM waste (Czech Republic, France, The Netherlands, Slovenia, South Korea, Switzerland, Great Britain)).

The results showed that either an engineered near-surface disposal facility (or similar, i.e., dedicated landfill, silo) or a GDF had been selected for disposal of NORM and/or DU. Generally, both disposal options are in the early development stages, and in many cases a lot more work is required before planned facilities will be operational, including site selection and development of a suitable safety case.

Further workshops and information gathering are planned to gain additional insight into the basis for different management and/or disposal approaches for NORM and DU and the underpinning safety work, and to encourage further information sharing between task participants. Additional questions will be sent out to understand how disposal routes have been chosen and how safety has been demonstrated. Countries with more advanced disposal programmes for NORM and/or DU will be asked to share their solutions to support countries whose lifecycle management and disposal programmes are still under development.

The following topics have been identified to be discussed further for potential 2nd wave R&D proposal:

- **Waste Management Options:** Waste minimisation was not highlighted as a major challenge (mainly specified by countries already implementing these processes); conditioning (e.g., cementation) is common or planned, but more information-sharing on processes and technologies is needed.
- **Reuse & Recycling:** Countries face varied challenges; international collaboration and further R&D could enable viable reuse/recycling strategies and reduce disposal volumes.
- **Treatment Options:** Most countries only store waste; limited treatment methods exist. More research and knowledge exchange are needed to close information gaps on treatment practices.
- **Disposal Programs:** Eight countries have NORM disposal routes (near-surface, engineered landfills). DU disposal is rare. Further sharing on decision-making processes and selection criteria is recommended.
- **Disposal Challenges:** Main issues are logistics, costs/assessments, and volume/timelines; stronger collaboration is needed to address these.
- **Safety Case:** Many countries have NORM safety cases; DU cases are still developing, with Slovenia and South Korea as exceptions. More information should be collected on safety case development and approaches.

[1] The other seven countries who hold DU either did not provide a clear definition or stated there is no specific definition for DU within their country.

Contribution from civil society experts

Management strategies for small amounts of waste

SIMS but also some LIMS often do not have sufficient resources for RWM, particularly for challenging waste streams. CS is interested in the transparent and safe management of all types of RW, including legacy wastes. Transparency, CS participation in the decision-making process and a participation and a shared culture for safety and security are needed also in predisposal issues.

Developing **intergenerational stewardship** models is one topic of interest for CS. The main legal and ethical principle to be applied during the long-term engagement of CS is the precautionary principle. One of the management models that has attracted considerable interest is rolling stewardship, which is an intergenerational management concept requiring monitoring and maintenance of RW for, in theory, an indefinite period, with responsibility being passed on from one generation to the next, preserving all necessary information and ensuring resources for the next generation. Such a stewardship process could last until a final safe solution is found which would no longer require constant care, cost and memory.

Shared solutions in radioactive waste management

Findings from the EURAD ROUTES project, particularly task 7 on Interaction with Civil Society (ICS), show that key concerns of CS are ambiguities around responsibility in a shared solution: who bears long-term liability, manages oversight, and ensures safety when multiple countries are involved? These unsolved issues can undermine public trust and raise fears about accountability. Civil society experts also express concern that less influential countries or local communities could be pressured into accepting disproportionate environmental burdens. Addressing these issues needs good quality public participation at local, national and transboundary levels. Creating a level playing field between stakeholders by applying the highest standards and independent oversight is essential.

5. Debate and summary, conclusions and outlook

Further analysis of technology readiness, feasibility and implementation challenges for alternative RWM solutions are needed by many countries, in particular SIMS, to safely manage and dispose of their waste. These alternative RWM strategies are especially relevant for waste types that currently lack WM routes, or where WM routes could be optimised for challenging waste forms, or where the originally proposed/considered national concept have evolved and previously proposed solutions require revision. Alternative RWM strategies may include storage lifetime extension, DBD and internationally shared waste management solutions. Regarding the management of waste bearing naturally occurring long-lived radionuclides (Depleted Uranium-DU, U, Th, Ra), a variety of strategies also exist. These alternative strategies can be considered by countries at different stages of programmes and with different volumes of waste, offering flexible and context-sensitive options for improving long-term safety and sustainability.

ASTRA is contributing to identification of R&D needs, optimisation and innovation of national waste management programmes by identifying methods and processes which enable early-stage programmes to progress based on lessons learned in advanced programmes. ASTRA has provided an effective platform/forum for a community of practice between LIMS and SIMS to share thinking on alternative future disposal strategies and to discuss the associated difficulties, to support the development of cost-effective RWM solutions, and to discuss risks for humans and environment with CS participants. A RD&D proposal for EURAD-2 2nd wave is in preparation proposing the setup of a knowledge exchange platform for waste characterisation, conditioning methods, end-of-life considerations of storage facilities and waste packages, decision support for related problems etc. as direct exchange and support in between SIMS and LIMS countries, which will include a demonstrator partnership of SIMS and LIMS partners to show how such knowledge exchange could be setup and run properly. It is obvious that this proposed knowledge exchange may have some overlap with WP2 KM (Knowledge Management).

DBD has been identified as a credible alternative disposal option for specific waste groups, providing reduced probability for human intrusion, but still with knowledge gaps related to e.g., the development of a safety case and the lack of large-scale demonstration. As part of an RD&D proposal for EURAD-2 2nd wave, the development of a guidance framework for a DBD safety case is proposed. The safety concept for DBD will be complemented by a generic safety case methodology to allow the definition of safety functions. This methodology should be applicable to specific sites, accounting for differences in the strategic context that exist between countries, such as regulatory requirement for waste retrievability.

With respect to NORM waste, a StSt has been initiated to be proposed for EURAD-2 2nd wave by TSO college, because the management of NORM and DU waste across Europe remains fragmented, with significant variations between MS in definitions, practices, and long-term planning: the conditioning is common, but methodologies are not systematically shared; reuse and recycling face uneven progress; and disposal safety cases are at very different stages.

Enabling participation of civil society assures structured interactions between actors, including CS and help to foster mutual understanding and trust about how the RWM is selected and implemented. In ASTRA, mutual understanding is not only in between the colleges WMO, TSO, RE and CS, but also in between participants from the same colleges but coming from different countries with different RWM programmes and at different programme phases.

Ongoing discussion in LDFs, bilateral task meetings, exchange with other EURAD-2 WPs (ANCHORS, CLIMATE, FORSAFF; OPTI, ICARUS) and WSs with partners, CS and the large end-user community will detail the EURAD-2 2nd wave proposals from ASTRA (RD&D and StSt WPs).

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7. Appendix A – Organisations participating in the biannual ASTRA workshop (12 March 2025).

ALARA, Estonia	NDA, UK
AMPHOS21, Spain	NES, Austria
ANDRA, France	NIPNE, Romania
ARAO, Slovenia	NTW, France
ASNR, France	NWS, UK
Atkins Realis, UK	PNNL, USA
BASE, Germany	POLYECO, Greece
Cavendish Nuclear, UK	PSI, Switzerland
COVRA, The Netherlands	SOGIN, Italy
Democritos, Greece	SSTC NRS, Ukraine
EC (RTD), Belgium	SURO, Czech Republic
EGIS, France	TUS, Bulgaria
EIMV, Slovenia	ULISBOA, Portugal
Energorisk, Ukraine	UTARTU, Estonia
FUND, Croatia	VTT, Finland
GSL, UK	Westinghouse, USA
IAEA, Austria	ZWILAG, Switzerland
ICHTJ, Poland	
Isotoptech, USA	
KORAD, South Korea	

8. Appendix B – ASTRA Stakeholders and End Users from official EURAD-2 list

Organisation	Nature	Country	End-User / Stakeholder
Sogin	WMO	Italy	EUG
Cyclife Germany GmbH	Other (Supply chain)	Germany	Stakeholder
FANC	Regulator	Belgium	Stakeholder
IAEA	Other (international organisation)	Austria	Stakeholder
Lucideon Ltd	Other (Material development and validation organisation)	UK	Stakeholder
NNL	Research institute/university	UK	Stakeholder
PNNL	Research institute/university	USA	Stakeholder
Remondis	Other	Switzerland	Stakeholder
PNNL	Research institute/university	USA	Stakeholder
Sogin SpA	WMO	Italy	Stakeholder
U.S. Nuclear Waste Technical Review Board	Other (Independent advisory agency to implementer)	USA	Stakeholder
Ray of Sunshine Energy	Other (Borehole Disposal Consultant)	Australia	Stakeholder
McCombie Consulting	Other (Consultant)	Switzerland	Stakeholder
KAERI	Research institute/university	South Korea	Stakeholder
Independent Consultant	Other (Consultant to IAEA, research institutes, waste management organizations - focus on deep borehole disposal)	USA	Stakeholder
Platom Oy	Other	Finland	Stakeholder
IAEA	Other (international organisation)	Austria	Stakeholder
Cyclife engineering	Other (nuclear decommissioning)	France	Stakeholder
AtkinsRéalis	Nuclear Waste Management Consultant	UK	Stakeholder
CNL	Waste producer	Canada	Stakeholder
ISOTOPTECH ZRT	TSO	Hungary	EUG
IFIN-HH	WMO	Romania	EUG
EEAE	Regulator	Greece	EUG
Environment Agency	Regulator	UK	EUG
Zwilag	WMO	Switzerland	EUG
Westinghouse	WMO	Spain	EUG
DSA	Regulator	Norway	EUG
Polyeco	WMO	Greece	EUG
NDA	WMO	UK	Stakeholder
Cavendish	WMO	UK	EUG
ALARA	WMO	Estonia	EUG
AB SVAFO	Waste owner	Sweden	EUG

KORAD	WMO	South Korea	EUG
FOND NEK	WMO	Croatia	EUG
LUT University	Research institute/university	Finland	Stakeholder
BGE Technology	Other	Germany	Stakeholder
Deep Borehole Demonstration Center	NGO	USA	Stakeholder
BASE	Regulator	Germany	EUG
ISIN	Regulator	Italy	Stakeholder
University of Sheffield	Research institute/university	UK	Stakeholder
East China University of Technology (ECUT)	Research institute/university	China	Stakeholder
Marriott Well Engineering and Management Services Limited (MWEMS)	Other (consultant)	UK	Stakeholder
US Nuclear Waste Technical Review Board	TSO	USA	Stakeholder
Neil Chapman Consulting Ltd	Other (Consultant)	Ireland	Stakeholder
School of Chemical, Materials & Biological Engineering, The University of Sheffield	Research institute/university	UK	Stakeholder
Frazer-Nash Consultancy Ltd	Technical Safety Organisation	UK	Stakeholder
ANVS	Regulator	The Netherlands	EUG
Veolia Nuclear Solutions	WMO	USA	EUG
Uniper Nuclear	Waste producer	Sweden	EUG
ARWA	WMO	Australia	EUG