Deliverable 9.3: ROUTES - Recommendations for R&D, strategic study and KM activities for future European collaboration

Work Package 9

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°847593.

Document information

Project Acronym	**EURAD**
Project Title	**European Joint Programme on Radioactive Waste Management**
Project Type	**European Joint Programme (EJP)**
EC grant agreement No.	**847593**
Project starting / end date	**1st June 2019 – 30 May 2024**
Work Package No.	**9**
Work Package Title	**Waste management routes in Europe from cradle to grave**
Work Package Acronym	**ROUTES**
Deliverable No.	**9.3**
Deliverable Title	**ROUTES - Recommendations for R&D, strategic study and KM activities for future European collaboration**
Lead Beneficiary	**IRSN**
Contractual Delivery Date	**M58**
Actual Delivery Date	**M60**
Type	**Report**
Dissemination level	**Public**
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To be cited as:

Marsal F., Maître M. (2024): ROUTES - Recommendations for R&D, strategic study and KM activities for future European collaboration. Final version as of 31.05.2024 of deliverable D9.3 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

Disclaimer

Acknowledgement

This document is a deliverable of the European Joint Programme on Radioactive Waste Management (EURAD). EURAD has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

Status of deliverable		
	By	Date
Delivered (Lead Beneficiary)	François Marsal (IRSN), Mélanie Maître (Andra)	11 March 2024
Verified (WP Leader)	François Marsal (IRSN)	11 March 2024
Reviewed (Reviewers)	Stefan Mayer (IAEA), David Ulfbeck (SIS)	20 May 2024
Approved (PMO)	Elisabeth Salat (IRSN)	30 May 2024
Submitted to EC	Andra (Coordinator)	03 June 2024

Executive Summary

The ROUTES Work Package (WP) is one of the two strategic studies being conducted as part of the European Joint Programme on Radioactive Waste Management (EURAD) studying waste management routes, from cradle to grave, in Europe. The objectives of ROUTES are to (1) provide an opportunity to share experience and knowledge on waste management routes between interested organisations (from different countries, with programmes at different stages of development, with different amounts and types of radioactive waste to manage), (2) identify safety-relevant issues and their R&D needs associated with the waste management routes (cradle to grave), including the management routes of legacy and historical waste, considering interdependencies between the routes, (3) describe and compare the different approaches to characterisation, treatment and conditioning and to long-term waste management routes, and identify opportunities for collaboration between Member-States (MS).

This report presents the identified Research and Development (R&D), Strategic Studies (StSt) and Knowledge Management (KM) needs and opportunities for collaboration between Member States, and details the recommendations as a result of the insights and achievements obtained from the deliverables and milestones generated in ROUTES tasks.

ROUTES WP enabled the identification of twenty-two recommendations on research and development (R&D), strategic studies (StSt) and knowledge management (KM) activities for future European collaboration. Most of R&D recommendations regarding radioactive waste characterization have been taken into account in the EURAD Strategic Research Agenda (SRA) update in 2023, and already paved the way for future advancements. Knowledge management issues aiming at enhancing information sharing between Member States have also been highlighted. In addition to these, the ROUTES project has initiated crucial strategic discussions on the prerequisites for implementing shared or tailored solutions, particularly for Small Inventory Member States (SIMS), amidst the emergence of challenges related to the implementation of borehole disposal (development of technical and scientific basis and of a complete safety case) and long-term storage (ageing of waste forms and materials). It has underscored the vital role of international collaboration in radioactive waste management, serving as a catalyst for cooperation among member countries.

Looking ahead, it appears now essential to integrate these recommendations into new multilateral programs, whether through the continuation of the EURAD-2 program or collaboration under multilateral organizations such as the OECD-NEA or the IAEA.

Furthermore, the ROUTES work package has yielded significant results by fostering a comprehensive understanding of predisposal challenges at the European level and promoting knowledge and technology sharing. It has empowered underrepresented voices to address their challenges and explore potential solutions, while also providing civil society representatives with a platform to voice their perspectives. Through networking, valuable connections have been established, highlighting the importance of collaboration between Small Inventory Member States (SIMS) and Large Inventory Member States (LIMS).

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1. Introduction

The ROUTES WP (Waste management routes in Europe from cradle to grave) is one of two strategic studies within the European Joint Programme on Radioactive Waste Management (EURAD). This work package, involving 36 organizations from 21 countries, was designed to deliver 17 deliverables. Its primary goals are to facilitate the exchange of knowledge and experience among various MS, with different developmental stages of their respective programs and radioactive waste types and levels, to identify safety-related R&D needs as well as to promote the comparison of approaches and collaboration. To fulfill these objectives, the project is structured around several tasks, each dedicated to specific aspects within the field of waste management. The ROUTES WP is organized into eight tasks to delve into the diverse challenges and potential solutions, as illustrated in Figure 1:

- Task 1: Coordination, state-of-the-art and training materials.
- Task 2: Identification of challenging wastes to be collaboratively tackled within EURAD.
- Task 3: Description and comparison of radioactive waste characterization approaches.
- Task 4: Identification of Waste Acceptance Criteria (WAC) used in EU Member-States for different disposal alternatives in order to inform development of WAC in countries without WAC disposal facilities.
- Task 5: Radioactive Waste Management (RWM) solutions for small amounts of wastes (focusing on disposal strategies for small-inventory Member-States).
- Task 6: Description of the state-of-the-art of shared solutions in European countries for characterization, treatment, storage and disposal and planned sharing of facilities between Member-States, as well as identification of gaps and R&D requirements.
- Task 7: Interactions with Civil Society.
- Task 8: ROUTES Extension on the evaluation of the possible waste management solutions for Member States without WAC and with small inventories (SIMS).

Within Task1, subtask 1.3 consists in integrating the recommendations for future RD&D, strategic study and KM activities arising in other tasks. Indeed, work performed in Tasks 2 to 8 led to the identification of twenty-two recommendations related to potential KM, R&D and Strategic Study StSt issues.

This integration work is mainly based on a dedicated workshop aiming to present ROUTES recommendations for future European collaboration, convened in December 2022 (MS337). This workshop served as an input to the update in March 2023 of EURAD Strategic Research Agenda (EURAD SRA 2023, D1.9).

This report presents the methodology carried out within ROUTES to identify these recommendations and details the rationale and the perspectives given by each of these recommendations. It should be considered as a global synthesis of the work carried out within ROUTES work package.

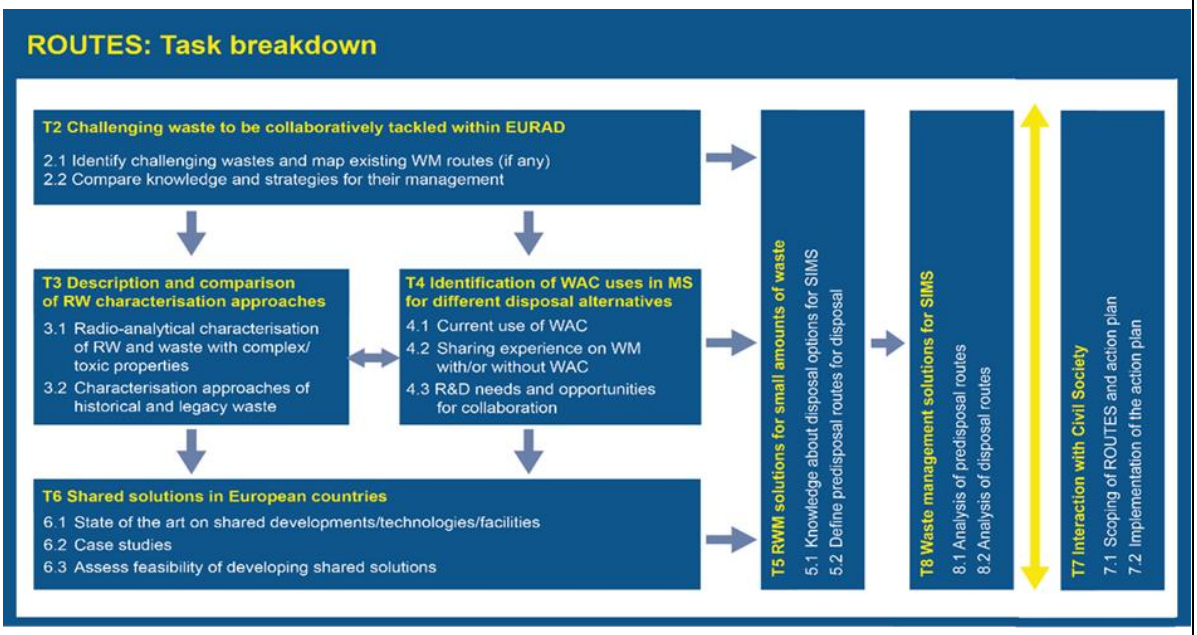

Figure 1 – Task breakdown

2. Methodology

The formulation of recommendations within the ROUTES project was driven by a methodology that encompasses a series of structured steps, from initial data gathering to collaborative workshops and detailed analysis.

The essence of the methodology lies in the adoption of an inclusive workshop approach, facilitating robust collaboration among a diverse array of stakeholders. These workshops served as pivotal forums for engaging partners representing various backgrounds, including participants from large and small inventory Member States (LIMS and SIMS). By fostering an environment favorable to the exchange of experiences, knowledge, and perspectives on radioactive waste management (RWM), these workshops ensured a holistic understanding of challenges and opportunities across different contexts. Integral to this methodology is the deliberate engagement of usually underrepresented voices, including civil society representatives, in ROUTES recommendations development process. This inclusive approach ensured that diverse perspectives are comprehensively considered, contributing to the development of holistic and inclusive recommendations that reflect the broader societal context.

The global methodology of ROUTES initiated with a comprehensive data gathering and analysis phase within all ROUTES tasks. This phase entailed surveys, workshops, and case studies to collect pertinent information on national waste classification, inventory, practices regarding predisposal steps and disposal facilities, and related aspects, that were then compiled within milestones and deliverables. This collated data forms the foundational basis for identifying key issues and R&D needs associated with waste management routes. The collaborative efforts were then concentrated on identifying and prioritizing common R&D needs pertinent to the management of challenging wastes. Through thorough analysis and extensive discussions among partners, recommendations were considered and prioritised based on their alignment with the evolving needs of the European radioactive waste management landscape.

A dedicated workshop, convened in December 2022, served as a focal point for deliberating and refining recommendations generated within the project (milestone 337). This workshop brought together a spectrum of stakeholders, including ROUTES participants, end-users, Project Management Office

(PMO) representatives, European Commission (EC) project officer, and other relevant entities, to prioritize recommendations and harmonize their wording for clarity and coherence. Recommendations presented during this workshop and detailed thereafter were grounded in deliverables and milestones generated throughout the project's lifecycle, that provide the foundational framework for synthesizing insights, contextualizing recommendations, and highlighting anticipated outcomes and impacts.

The recommendations, picked from collaborative analysis, were systematically structured around key thematic areas identified within the project

- Interactions with civil society and safety culture.
- International cooperation.
- Global strategies
- Concept selection.
- Waste acceptance criteria
- Characterization
- Treatment and conditioning.

These areas are not necessarily directly tied to ROUTES tasks, as some recommendations stem from different tasks. Additionally, Task 3 led to a significant number of R&D recommendations, which were divided into two areas: Characterization and Treatment and Conditioning. They were classified into three groups, depending on the objective associated: R&D, KM, and StSt. KM encompasses the development of guidance, SotA and training whereas StSt encompasses networking on methodologies and common challenges.

Following the workshop, recommendations underwent refinement based on discussions, feedback, and insights gleaned from stakeholders. The finalized recommendations are documented in the following chapter regarding a specific nomenclature. R&D-X, StSt-X and KM-X.

3. Proposed recommendations by ROUTES to improve European radioactive waste management

This chapter details the rationale and perspectives linked to each recommendation proposed by ROUTES WP and is organized around the key thematic areas presented above (Interactions with civil society and safety culture, International cooperation, Global strategies, Concept selection, Waste Acceptance criteria, Characterization, Treatment and conditioning).

3.1 Interactions with civil society & Safety culture

Task 7 of the ROUTES WP, overseen by CS experts, aimed to translate scientific/technical findings for effective interaction with the Civil Society (CS), facilitate expression of CS expectations/views on ROUTES WP topics; and enhance mutual understanding on R&D for safe radioactive waste processing and disposal solutions. Task 7 collaborated with other ROUTES tasks and engaged with the broader CS group, resulting in the delivery of 5 deliverables (D9.15, D9.16, D9.17, D9.18 and D9.19). This work notably highlighted needs regarding the implementation of the Aarhus Convention and the persistence of safety culture over generations.

3.1.1 Needs regarding the implementation of the Aarhus Convention

Context

In the context of implementing the Aarhus Convention, two complex questions arise, necessitating a comparison of approaches adopted across the European Union to enhance governance in radioactive waste management (RWM):

- Access to resources and expertise for civil society actors, along with considerations of funding and sustainability, often proves insufficient. It is then crucial to examine the outcomes of models currently in place in various countries, such as France, Slovenia, Belgium, the UK, Sweden, and Denmark, to determine if any of them could be deemed suitable for different stakeholders and recommended for widespread use within the EU. European funding could assist in promoting and harmonizing these independent, citizen-focused local committees, facilitating the transfer of knowledge across generations and strengthening societal engagement (see Deliverable D9.17).
- The integration of inclusivity in RWM activities, in accordance with the provisions of the Aarhus Convention and other legal EU frameworks, also varies from one Member State to another (legislative framework, responsibilities). There is a significant information imbalance between the public, on one hand, and project proposers/operators, on the other (see Deliverable D9.17).

Due to constraints related to time, expertise, and financial resources, the public relies primarily on information provided by project proposers/operators. Public access to consultations with independent experts is insufficient, primarily due to financial limitations, a lack of independent nuclear experts, and short procedural deadlines.

This disparity in information and expertise access between the public and radioactive waste sector stakeholders underscores the need for action to improve transparency, citizen participation, and the consistent implementation of the Aarhus Convention within the European Union.

ROUTES Recommendations

StSt-1 - Comparison of approaches regarding implementation of access to resources and inclusivity

The proposed recommendation, "Comparison of approaches regarding the implementation of access to resources and inclusivity," carries the potential for profound transformation of CS involvement in the field of radioactive waste management. Guided by representative national case studies already

elaborated on in EURAD 1, including from countries where access to resources and inclusivity have been provided to a higher or lesser degree, as well as LIMS and SIMS, it could serve as a catalyst for heightened collaboration among stakeholders involved in radioactive waste management (RWM), while emphasizing the imperative of effective communication and shared knowledge. By creating a legislative model for improved public access to RWM resources, it would lay the groundwork for stakeholders to collaborate more effectively. This approach would foster greater transparency and inclusivity, leading to more informed discussions and cooperative efforts among diverse actors, thereby strengthening RWM practices.

A central point of this recommendation is also the establishment of a comprehensive framework that could promote inclusivity within RWM. It envisions an inclusive model that ensures the voices of civil society experts, and the public are not only heard but also respected throughout the entire RWM process. This blueprint sets the stage for equitable participation and shared responsibility. By implementing a model for public consultations with independent experts, the recommendation might lead to an enrichment of decision-making by infusing it with expert insights, reinforcing inclusivity as a cornerstone of RWM practices. In a best-case scenario and depending on the circumstances, this model could be implemented at the European, national, regional and/or local levels.

In summation, the implementation of the recommendation "Comparison of approaches regarding the implementation of access to resources and inclusivity" is poised to nurture trust, empower the development of tailored governance solutions, and foster knowledge exchange among diverse stakeholders. Ultimately, this endeavor promises to usher in more sustainable and inclusive practices in RWM, benefiting both the present and future generations.

KM-1 – Development of guidance for effective public access to information

The recommendation "Development of Guidance for Effective Public Access to Information" would represent a critical advancement in helping to bolster transparency, inclusivity, and overall efficiency within RWM processes, as well as constitute a precondition for public participation in these processes at various levels. During the work of Task 7, significant differences were identified in several case studies between the level of effective access to information among various EU Member States, which call for better implementation of already existing provisions and - in some respects - even specification of further provisions.

A primary expected outcome would be the development of a legislative model designed to ensure that the public has effective access to information related to RWM. This model could serve as a legal framework, imparting clear standards and requirements, thereby enhancing transparency and accountability within the RWM sphere. By defining, when needed, mandatory legal parameters and ample institutional mechanisms to facilitate their implementation, it paves the way for a more open and accessible RWM landscape.

In parallel, the recommendation strives to institute a model for public consultations, responding, e.g., to regional and local preferences, while at the same time meeting the overall requirements of the Aarhus Convention, featuring impartial experts. This innovative approach facilitates well-informed decision-making by integrating expert perspectives into the process. By doing so, it would address public concerns with a level of expertise that enhances the quality of RWM practices. The inclusion of independent experts is indeed considered as a way to elevate the credibility and effectiveness of RWM decision-making.

By implementing these measures, a substantial increase in transparency throughout RWM activities might be anticipated. Transparency acts as the cornerstone of informed participation. This heightened transparency not only makes RWM information more accessible to the public but also encourages more active public involvement in the decision-making process. The collective result would be a more robust and comprehensive consideration of diverse perspectives, which ultimately leads to better decisions.

In summary, the recommendation "Development of Guidance for Effective Public Access to Information" is poised to establish clear legislative standards, elevate transparency, encourage broader public participation, enhance decision quality through expert input, and strengthen trust. Furthermore, it offers avenues for cost optimization, early issue identification, and the preservation of valuable information for the benefit of future generations.

3.1.2 Needs regarding the persistence of safety culture

Context

The imperative to maintain a robust culture of safety across generations presents multiple challenges. First and foremost, due to the long lifetime of the radioactive waste, there is a critical need to explore and establish an intergenerational management concept, which would imply preservation of knowledge and maintaining the possibility of including civil society in the RWM decision-making process. Such inclusion could improve conditions for preservation of knowledge by maintaining public interest in the matters at hand. This concept envisions the perpetual monitoring and maintenance of radioactive waste, with the responsibility seamlessly transitioning from one generation to the next. The ultimate goal is to preserve the possibility of retrieving, recharacterizing, and repackaging the waste if such actions become necessary over time. This demands meticulous planning and coordination to ensure that the custodianship of radioactive waste remains intact and effective, even as generations evolve, and mechanisms that ensure that future generations are not allowed to forget about the radioactive waste.

Concurrently, the quest for effective safety culture preservation necessitates the investigation of mechanisms for continuous knowledge management. Beyond simply cataloging information about radioactive waste, these mechanisms must facilitate the transmission of a safety culture across generations. Such an approach ensures that the awareness of the need for resource allocation and the commitment to taking timely corrective actions are upheld, if this is deemed necessary and proportional, e.g., as a consequence of new knowledge or development of new technology in a given area. This is essential to safeguard not only the present but also the future, as it empowers successive generations with the knowledge, values, and practices required for maintaining the highest safety and security standards in radioactive waste management.

In terms of human aspects, an expanded safety culture notably appears as crucial for long-term multistakeholder governance of geological disposal. Socio-technical uncertainties, alongside technical ones, affect safety-related activities. For effective intergenerational governance, CS involvement from the outset and thorough discussion time are essential, emphasizing transparency in decision-making and reporting. Public support relies on trust built through engagement. Safety culture fosters trustworthy interactions amid complexities in long-term radioactive waste management, but flexibility is needed for adapting to progress and errors. CS participation is vital at international, national, and local levels, aligning with the Aarhus Convention for long-term safety case development and could be a driver to ensure a sustained safety culture (see D9.18).

ROUTES Recommendation

StSt-2 – Identification of challenges related to long-term / rolling stewardship

The adoption of this recommendation would help to clarify the issues associated with long-term planning and schedules underpinned by a stepwise decision-making process. This evolution would ensure that RWM activities are meticulously thought out and strategically executed, ultimately fortifying safety and effectiveness.

Dealing with RWM in the long-term would not necessarily imply a new definition of the public, which, according to the Aarhus Convention, constitutes one or more natural or legal persons, and, in accordance with national legislation or practice, their associations, organizations or groups. However,

the decision-making in the RWM processes affecting the public would have to be able to strike a balance between a strong implementation of the precautionary principle, not putting undue burdens on future generations and the requirement to take interdependencies in the steps of RWM into consideration – also in the long term.

Central to this recommendation is the commitment to support long-term safety, due to extended disposal periods, as safety would not be merely a short-term consideration but an enduring commitment woven into the fabric of long-term stewardship.

Transparency, public engagement, and knowledge preservation are also critical aspects, which could be addressed by providing clarity on the dissemination of public information in the long term and establishing robust public participation processes, fostering trust among stakeholders. Moreover, this approach would ensure the perpetual utilization of past knowledge and experiences to inform future RWM practices, thus providing additional assurance that knowledge is preserved for the benefit of the decision-making process.

In particular, the concept of rolling stewardship is characterized by a flexible interpretation of safety standards and the management of uncertainties over time. By considering practical challenges that can be addressed in the short term while maintaining a broader perspective on future needs, rolling stewardship offers a dynamic framework for intergenerational stewardship, supported by institutional control mechanisms addressing legal, technical, financial, administrative, and research and development (R&D) issues. These mechanisms include the development of overarching principles guiding stewardship activities, determining guidelines for their implementation, dissemination of information, promotion of adaptability, and addressing funding concerns.

3.2 International cooperation

3.2.1 Needs for sharing of knowledge and best practices

Context

The coexistence of Large Inventory Member States (LIMS) and advanced programs that have accumulated substantial expertise and a rich history in waste management with Small Inventory Member States (SIMS) represents for the latter an opportunity to benefit from experiences and best practices of LIMS. Indeed, these experiences and practices are invaluable not only for their successes but also for the lessons learned from challenges and pitfalls. This reservoir of knowledge already serves as a guide for SIMS on their RWM, offering them practical examples to emulate and potential pitfalls to avoid, as regularly shown within ROUTES.

Recognizing the transformative potential of this knowledge transfer, there is a pressing need for the development and implementation of tools and mechanisms. These tools encompass dedicated platforms, organizational structures, and mobility programs that facilitate the sharing of experiences and best practices among Member States. Through these means, the collective knowledge and expertise of LIMS and advanced programs can be disseminated effectively to encourage the capabilities of SIMS.

In essence, the recommendations presented in this chapter underscores the necessity of fostering knowledge and practice sharing in RWM, emphasizing the importance of drawing from the experiences of those who have blazed the trail. By bridging the knowledge gap between LIMS and SIMS and promoting collaborative learning, Member States can collectively advance towards safer, more efficient, and sustainable radioactive waste management practices.

ROUTES Recommendation

KM-2 – Development of a forum for communities of practice between LIMS and SIMS

The recommendation to establish a knowledge-sharing forum holds the potential to improve the feedback on RWM practices.

It would help the development of comprehensive guidance for navigating the complexities of challenging waste predisposal routes, which encompass every aspect of waste management, from initial inventory to characterization, treatment, conditioning methods, and disposal options. Of particular significance are the intricate challenges posed by chemotoxic and legacy waste. By elaborating on these hurdles and providing practical guidance, Member States gain a compass to navigate these complexities effectively, steering their RWM efforts toward safer and more sustainable outcomes.

Another important asset would be to empower Member States with guidance on topics such as waste characterization methods or development of (generic) waste acceptance criteria, with the essential tools and insights required. The collaborative spirit of such a forum would extend beyond guidance alone. It could encompass a commitment to enhancing competences within the RWM field, fostering a skilled and knowledgeable workforce. In particular, it could include the dissemination of developments in the application or validation of scaling factors and the sharing of best practices. These contributions would serve to enhance efficiency, cost-effectiveness, and safety in radioactive waste management, benefiting all Member States involved in these critical endeavors.

3.2.2 Needs of shared solutions

Context

The transportation of radioactive waste across national borders necessitates permits, and the processes for obtaining these permits can vary significantly based on the countries involved and the waste type. This variation often results in resource-intensive and time-consuming phases within the waste management process. Moreover, public concerns regarding the risks associated with waste transportation further complicate matters. However, a paradigm shift is possible by employing mobile facilities that move to the waste rather than the reverse. This approach alleviates the challenges associated with cross-border waste transport, reducing resource consumption and mitigating public apprehensions.

Furthermore, the exploration of shared waste management solutions within ROUTES, and more specifically in Task 6 (see Deliverable D9.14), provided a comprehensive assessment of the feasibility of developing further European shared solutions for waste management from cradle to grave, on the basis of the collective experience and lessons learned by Member States. Considering insights from ROUTES and ERDO, this report identifies promising topics and waste streams that could lead to opportunities for collaborative solutions between Member States.

Several challenging waste streams have been identified, including sludges, graphite, particular spent fuel, disused sealed radioactive sources, reactive metals, chemotoxic substances, spent radioactive ion-exchange resins, and organic waste (both solid and liquid). The challenges associated with these waste streams often lie in the lack of comprehensive characterization, treatment, and disposal routes. The relatively small volumes linked to these waste streams make them suitable for shared solutions, notably relative to the development of mobile facilities for characterization, treatment or conditioning.

Even though several topics of common interest and suitable for shared solutions were identified, practical bottlenecks were also recognized: standard procedures, common understanding of WACs, and harmonized regulations were highlighted as topics that needed further development to achieve effective shared solutions. It is notably evident that sharing predisposal and disposal facilities needs important work in regulatory and WM procedures harmonization (see Deliverable D9.16 and D9.18). While technical research is needed, the advancement of shared solutions relies heavily on political decisions.

In this societal-political context, it is finally important to keep in mind Task 7 input to achieve a level playing field for the collaborators and lessons learned from case studies showing the importance of public consultation.

ROUTES Recommendations

R&D-1 – Development of mobile facilities for RAW characterization, treatment or conditioning

A particular interest emerged in the potential sharing of mobile treatment facilities, particularly for addressing challenges related to the treatment of sludges and resins. Representative sampling was also identified as a significant obstacle for successful waste characterization. Member States with small inventories (SIMS) indicated resource constraints, notably to implement the characterization of their radioactive waste for decommissioning, due to the need for heavy infrastructures and specific skills. Consequently, the possibility of setting up an R&D programme on radiological characterization equipment that can be shared and transported between countries was discussed.

The concept of developing mobile facilities, especially concerning the characterization and treatment of sludges and resins, could indeed improve the flexibility in selecting treatment approaches, help Member States to explore the possibility of using commercial treatment facilities beyond their national borders and significantly expand the options available for efficiently managing radioactive waste. By reducing reliance on a single national facility, Member States can optimize their waste management strategies, enhance treatment capabilities, and potentially reduce costs.

Another significant impact of mobile facilities is their potential to decrease the time radioactive waste spends in storage. Indeed, radioactive waste is often stored for extended periods while awaiting treatment or conditioning. This not only aligns with safety principles but also mitigates potential risks associated with long-term storage.

StSt-3 – Harmonization of procedures to facilitate collaborations between MS

This recommendation to "harmonize procedures to facilitate collaboration between Member States" aims at clarifying the complexities associated with determining the necessary procedures and permits, which can be both time-consuming and resource intensive. Simplifying this process requires harmonizing the various steps needed to enhance the possibility of operating commercial treatment facilities outside national borders, help reduce storage periods and improve safety, and encourage the possibility of using shared storage or disposal facilities through harmonized procedures.

One of the primary objectives of harmonizing procedures is to facilitate the operation of commercial treatment facilities outside national borders. Currently, variations in regulatory frameworks and procedural requirements hinder the establishment and operation of such facilities, leading to delays and inefficiencies. Harmonizing procedures would create a unified framework that allows for smoother coordination and operation of treatment facilities, thereby enhancing the overall effectiveness of RWM practices.

Additionally, harmonization of procedures can contribute to reducing storage periods for radioactive waste. Lengthy storage periods not only pose risks to safety and security but also increase the financial burden on Member States. By streamlining regulatory processes and permitting requirements, harmonization can expedite the transportation and treatment of radioactive waste, ultimately reducing the need for prolonged storage.

Finally, harmonized procedures can significantly improve safety standards in RWM practices. Inconsistencies in regulations and procedures across borders can create loopholes and vulnerabilities in safety measures, compromising the overall integrity of waste management systems. Through harmonization, Member States can establish uniform safety protocols and standards, ensuring robust protection against potential risks and hazards associated with radioactive waste.

3.3 Global strategies

3.3.1 Needs overview on disposal strategies of "challenging waste"

Context

Among the different tasks of the ROUTES work package, Task 2 and Task 4 particularly highlighted gaps in terms of disposal strategies for so-called "challenging waste". The term "challenging waste" can be defined as waste for which there are no current or applicable solution for their safe management, including difficulties or the absence of at least one step in the waste lifecycle. Based on this definition, 11 challenging waste have been identified[1] and various reasons have led to them being considered as challenging. Among those reasons, two recurring ones are related to the fact that the considered "challenging waste" either (i) **do not meet WAC for existing or planned facilities** or (ii) **do not have any disposal solution.**

Based on this observation, ROUTES Task 2 focused on predisposal and disposal needs for improved management of challenging waste. Deliverable D9.5[2] details the main outcomes related to the work of ROUTES Task 2. It notably highlights two challenging wastes for which disposal strategies have to be found in the near future. First, it concerns **Radium, Thorium and Uranium (Ra/Th/U) bearing waste**, which arise from various economic sectors (e.g., industrial, medicine, research) and include a diverse range of waste, sometimes with large waste volumes. Given their diversity, Member States experience different issues for their management, beginning with the lack of appropriate disposal routes. In fact, a large proportion of Member States remain without disposal solutions, in this case, notably waiting for national policies or safety regulations to be developed. Some others are studying shallow depth disposals routes for these wastes; such strategies could potentially be shared among all the interested Member States.

The case of **particular spent fuel and depleted uranium** can also raise concerns as no suitable disposal solutions are available. Particular spent fuels (PSFs) include all non-uranium oxide spent fuels, which includes Magnox spent fuels, aluminium cladding, spent fuel used in former Natural Uranium Graphite Gaz reactors and even particular spent fuel developed for R&D activities. For now, the management of PSFs or depleted uranium does not represent a difficulty as such since they are still considered as reusable resources and are not yet declared as waste[3]. However, Member States have stressed that disposal strategies remain an open question and could represent a challenge in the coming years if PSFs or depleted uranium are reclassified as waste. Therefore, sharing future strategies about disposal of those particular wastes has been expressed as a need for different Member States.

ROUTES Task 4 focused on the current use of WAC and sharing experiences on waste management with and without WAC. Deliverable D9.9[4] provides a detailed overview of all the main outcomes related to the work conducted with ROUTES Task 4. Among the discussions, Member States often highlighted the fact that in their national framework, they have to manage challenging waste which do not meet WAC for existing or planned facilities, because of their inventory or properties.

This is for instance the case of evaporation concentrates in Bulgaria, as well as wastes from "old" treatment techniques in Germany. Moreover, managing wastes that do not meet existing WAC was also selected as a priority during the works carried out in Task 4.

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[1] sludges, spent ion exchange resins, organic waste, bituminized waste, graphite waste, decommissioning waste, disused sealed radioactive sources, Ra/Th/U bearing waste, particular spent fuel, waste containing reactive metals and waste containing chemotoxic substances.

[2] Wasselin V., Maître M., Kutina I., (2022). *Overview of issues related to challenging wastes.* Final version as of 18.08.2022 of deliverable D9.5 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

[3] Similarly, Ra/Th/U bearing wastes designated as naturally occurring radioactive material (NORM) may not be subject to the same provisions in all EU member states. Some Member States do not consider NORM waste as radioactive waste.

[4] De Bock C., Harvey E., Harrison T., (2023). *Suggestions for the management of challenging caste while maintaining compatibility with options for disposal: ROUTES Task 4 Final Report*, Final version as of xxxx of deliverable D9.9 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

Based on this context, two major recommendations have been suggested by the ROUTES WP and are detailed in the paragraphs below.

ROUTES Recommendations

StSt-4 – Common analysis on disposal strategy for waste that do not meet WAC for existing/planned facilities

According to the needs highlighted within Tasks 2 and 4, the recommendation StSt4 aims to provide a *common analysis on disposal strategy for waste that do not meet WAC for existing or planned facilities*.

A *disposal strategy* for a given waste sets out the vision for safe disposal and how this will be achieved. For wastes not meeting WAC, the disposal strategy might involve:

- Implementing alternative treatment and conditioning of a challenging waste, such that the resulting product meets the WAC for an available disposal facility.
- Reviewing the WAC to understand reasons for non-compliance, and whether there is a basis for adapting the WAC to allow the challenging waste to be consigned, whilst still ensuring that the requirements of the safety case will be met. Such an approach may be particularly appropriate if the WAC are 'preliminary' or 'generic', [as discussed in PREDIS Deliverable 2.7] and therefore incorporating a high degree of conservatism.
- Finding an alternative disposal route.
- Hold points to assess available options and opportunities (e.g. immobilisation of the waste in a matrix or delay of this immobilisation).

Practically, this recommendation will focus on challenging waste for which no disposal routes can be found now, either because no disposal solution exists, or because of their non-compliance with WAC. Sharing common issues on this subject among interested Member States through, for example, establishing a Community of Practice (CoP) could, with time, help to identify new options and potential alternatives, and consequently, reduce the number and range of challenging wastes with no clear disposal routes. This work will also allow a broader application of experience and best practice, and result in better insight into available treatment and conditioning options, and disposal routes.

The case of Ra/Th/U bearing waste, with currently no disposal routes, is also tackled by this recommendation. Specifically, the aim would be to identify the needs and expectations of interested Member States in terms of disposal solutions for these particular wastes. European Member States are already required to develop such solutions and strategies (national programmes) to achieve them. Therefore, the idea would be to provide an overview of national contexts and current strategies that would be a basis for identifying common issues and challenges. This will make it possible to propose common strategies for the elimination of waste containing Ra/Th/U, which will ultimately be adapted to national contexts. For instance, it should be acknowledged, that Ra/Th/U bearing wastes designated as NORM may not be subject to the same provisions in all EU member states. Some member states do not consider NORM waste as radioactive waste.

In terms of cooperation with current projects and national contexts, it should be noticed that this recommendation also reflects discussions with the EC PREDIS project. Regarding national concerns, some Member States are already working on these challenging wastes. For instance, in the UK, management of challenging wastes is considered via the problematic waste integrated project team (PW-IPT), led by NWS, and in France, which is currently focusing on a shallow disposal concept, which can host Ra/Th/U bearing waste.

StSt-5 – Common analysis on disposal strategies for particular spent fuel and depleted uranium

Based on the results of Task 2, pointing out that disposal of particular spent fuel (PSFs) and depleted uranium (DU) remains an open question and could represent a challenge in the coming years, ROUTES WP recommended a *common analysis on disposal strategies for particular spent fuel and depleted uranium*. In line with the previous recommendation, the work aims to identify the needs and expectations of interested Member States in terms of disposal of PSFs and DU. This would help to obtain an overview of current national contexts and potential strategies, and would help to define, among Member States, common needs that could lead to common actions in the future. Note that the two topics (PSFs and depleted uranium) will call for separate studies as their radiological inventories are completely different.

At this stage, no particular cooperation with existing projects have been identified.

3.3.2 Needs related to the management of SMR waste

Context

Small Modular Reactors (SMRs) and advanced reactor concepts are considered as crucial options to meet global energy demands. However, their deployment brings forth significant challenges, with one of the most prominent being the management of spent fuel and radioactive waste generated during operation and decommissioning. This challenge encompasses not only disposal but also pre-disposal considerations and the potential reprocessing of spent fuels from advanced reactor concepts.

The landscape of SMRs and advanced reactors is diverse, featuring various designs, technologies, and applications that impact waste management strategies and technical solutions for both pre-disposal and disposal phases. These impacts must be comprehensively integrated into the decision-making processes for incorporating these reactors. Furthermore, the socio-technical aspects of public engagement and technology acceptance play a pivotal role in optimizing the outcomes of technical endeavours within this context.

The challenges include expanding databases to cover modern fuels, assessing new legislative and administrative requirements, understanding inert matrix and dispersion fuels, developing suitable transport and storage containers, and evaluating the impact of new waste types on storage facility design.

ROUTES Recommendation

StSt-6 – Develop strategies for SMR waste management

The introduction of Small Modular Reactors (SMRs) with advanced reactor concepts presents a unique opportunity to deal with waste management before their effective implementation.

The comprehensive evaluation of the impact of SMR implementation on potential pre-disposal and disposal strategies could be anticipated into a proactive approach that would allow to adapt waste management strategies accordingly, ensuring that they align with the requirements imposed by these innovative reactor technologies.

Identifying and evaluating the needs for introducing new legislative requirements and administrative controls for the disposal of radioactive waste and spent nuclear fuel in relevant repositories would also be essential. It would ensure that the regulatory framework aligns with the evolving landscape of SMR-generated waste.

Additionally, understanding inert matrix fuels and dispersion fuels becomes imperative, examining their properties, stability as waste forms, and suitability for long-term storage and disposal. This knowledge would aid in making informed decisions regarding the management of these unique fuel types.

Moreover, the development or selection of suitable transportation and storage and disposal containers would be crucial for the safe and efficient handling of SMR-generated radioactive waste and spent nuclear fuel of advanced reactor concepts.

Lastly, evaluating the impact of emerging types of radioactive waste from SMRs on the conceptual solution and design of disposal facilities would also help to ensure that repositories can accommodate and safely manage these waste streams.

3.3.3 Needs related to EU Green Deal

Context

The European Green Deal, with its focus on sustainability and environmental responsibility, has significant implications for the management of radioactive waste (RAW) and spent nuclear fuel (SNF) in European Member States. A strategic study has to be undertaken to evaluate the effects of the Green Deal, particularly the EU taxonomy or "green taxonomy," on radioactive waste management (RWM) programs.

One of the primary considerations is the need for potential legislative changes, adjustments in RWM policies, and strategic shifts to align with the Green Deal's sustainability goals. The Green Deal's emphasis on circular economy principles necessitates a re-evaluation of how RAW and SNF are managed. This includes exploring opportunities for recycling, reusing, and reducing waste within the nuclear industry.

Harmonization of requirements across individual Member States and at the EU level is an important aspect of implementing circular economy principles in RAW and SNF management. Achieving consistency in regulations and standards will facilitate the development of sustainable waste management strategies while ensuring compliance with the Green Deal's objectives.

The financial impact of the Green Deal on the nuclear industry and its RAW/SNF management programs cannot be overlooked. This includes considerations for investment in new disposal facility development, as well as the broader implications for the nuclear sector's development and sustainability within the context of the Green Deal.

ROUTES Recommendation

StSt-7 – Impact of the EU Green Deal on radioactive waste management

A comprehensive study on the impact of the EU Green Deal on the national radioactive waste management in Europe may offer significant contributions to the development of this field. Operational disposal facilities, as a prerequisite of financial benefits of the EU Green Deal application, will need to undergo an accelerated implementation in order to fulfil the requirements of the EU Green Deal and this study would enhance our understanding on short-term and intermediate turn effects on construction of disposal solutions for current and future waste streams. Insights gathered from the scientific community and stakeholders of new nuclear power plants of the 4th generation would provide a robust foundation for informed decision-making in radioactive waste management.

Moreover, the study should not stop at analysis but should go further by providing actionable recommendations for future research on adaptation of disposal solutions. It could assess regulatory frameworks, hazards, and risk assessment methodologies. These recommendations would guide future research directions, enriching the knowledge base and informing policy decisions.

Furthermore, the study could align radioactive waste management practices with the European Green Deal, promoting sustainability and environmental responsibility in the nuclear industry. It would foster stakeholder cooperation at both national and international levels, facilitating the exchange of best practices and shared knowledge. Additionally, the study could offer practical guidance for Member

States on adapting to Green Deal requirements, ensuring their preparedness to meet sustainability commitments while effectively managing radioactive waste.

3.4 Concept selection

3.4.1 Needs regarding deep borehole disposal

Context

Small Inventory Member States (SIMS) face unique challenges regarding radioactive waste management. While SIMS typically have small quantities of high-level radioactive waste (HLW) and spent nuclear fuel, they encounter obstacles in effectively managing these materials. Another issue are highly concentrated activities, such as in DSRS.

SIMS such as the Netherlands, Poland, and Slovenia find themselves in a distinctive position. They possess relatively small quantities of HLW and spent fuel, which makes the traditional disposal concept of Direct Geological Disposal (DGD) economically unfeasible. The costs associated with establishing and operating a dedicated disposal facility for such limited amounts of radioactive waste are often prohibitively high (see Deliverable D9.10).

Moreover, SIMS often lack the necessary expertise and human resources to develop a robust safety case for a disposal facility, particularly for a DGD facility. As a result, SIMS face significant challenges in navigating the complex regulatory landscape and building a compelling case for the safe disposal of their radioactive waste. Some SIMS have implemented a dual track approach. The first track is a multinational disposal solution, this is investigated inter alia by ERDO association. The second track is a small-sized national disposal solution, for which deep borehole disposal might be a suitable solution.

To address the challenge of a large-scale disposal solution for a small inventory, there is growing support for the concept of Deep Borehole Disposal (DBD). DBD proposes a more flexible and economically viable approach to managing small quantities of HLW and spent fuel. Additionally, due to the relocatability of drilling equipment, DBD solutions facilitate shared solutions among SIMS and potentially LIMS. This concept aligns with the goal of optimizing resources and expertise across borders.

However, even if the DBD concept might offer a promising path forward, the development of complete safety cases is still needed, as well as a comprehensive guidance to help the implementation of this solution.

ROUTES Recommendation

KM-3 – Development of guidance for the implementation of deep borehole disposal, including their safety case development

The implementation of a recommendation for the development of a comprehensive guidance framework for the safety case of deep borehole disposal would play a pivotal role in ensuring the safety and effectiveness of DBD solutions. By drawing comparisons with the well-established concept of Geological Disposal Facilities (GDF), the guidance for DBD safety cases would provide a roadmap for addressing key safety and regulatory aspects. This aspect is critical, as the safety case is fundamental in gaining regulatory approval and public confidence in DBD as a viable waste disposal solution. Additionally, this comparison would highlight potentially existing gaps of the safety case for DBD and enhance target-oriented RD&D.

The specific issues that arise when implementing DBD, especially in the context of emplacing waste, packaging, and establishing safety barriers, require tailored solutions and careful consideration. Developing guidance that addresses these aspects is thus essential for the successful implementation of DBD. It would ensure that challenges associated with deep borehole disposal are adequately managed and mitigated, contributing to the overall safety and feasibility of the approach.

3.4.2 Needs regarding long-term storage

Context

Long-term storage is both a strategic concept in radioactive waste management (RWM) practices across the globe, as well as a necessity emerged from the disposal site development timelines. Notably, countries like the Netherlands have adopted this approach as a viable strategy while waiting for the development of a solution for HLW.

The adoption of long-term storage introduces a host of socio-technical challenges that must be diligently addressed. These challenges encompass various aspects of waste management, including the emplacement of waste, maintenance of waste packages, ensuring accessibility and handling over extended periods, and establishing safety barriers. Furthermore, interaction with the public and compliance with legal requirements, such as those outlined in the Aarhus Convention, might play pivotal roles in the successful implementation of long-term storage facilities.

One of the noteworthy complexities associated with long-term storage is the safety case that underpins these facilities. Often, this safety case is not universally comprehended by all stakeholders involved in RWM. A key aspect that warrants particular attention is the interplay between the social and technical challenges inherent to long-term storage. Factors like protection against malevolent attacks and the implications for planning and implementing final disposal facilities are of utmost significance.

In essence, long-term storage needs to be included in the RWM strategy, catering to the needs of countries with varying degrees of advancement in their programs. It is imperative to foster a comprehensive understanding of the socio-technical intricacies, enabling effective and sustainable solutions in the realm of radioactive waste management.

ROUTES Recommendation

StSt-8 – Identification of social and technical interrelated challenges related to long-term storage

The implementation of this recommendation would foster a more comprehensive understanding of the safety and risk management aspects associated with long-term storage facilities. By identifying the social and technical challenges linked to extended storage periods (such as the burden imposed to future generations, the transmission of a safety culture and access to information for the public over generations or ageing of materials and waste forms), RWM stakeholders could develop more robust strategies to mitigate potential hazards.

It would also encourage better collaboration among various stakeholders, including regulatory bodies, technical experts, and civil society. By addressing both social and technical dimensions, it would pave the way for constructive dialogues and shared decision-making processes. This improved stakeholder engagement would be of primary interest for building trust, transparency, and consensus.

A key outcome of this recommendation would be to enhance the overall state of storage solutions. By identifying and addressing the interrelated challenges in long-term storage, RWM programs could fine-tune their strategies to align with evolving societal, environmental, and technical requirements. This optimization would contribute to more efficient and sustainable waste management practices.

Finally, this recommendation would promote knowledge sharing and capacity building among different RWM actors. By facilitating discussions on the implications, consequences, and trade-offs associated with long-term storage, it would foster a culture of learning and continuous improvement. This knowledge sharing would ensure that RWM practices remain up-to-date and adaptive to changing circumstances.

3.5 Needs regarding development of Waste Acceptance Criteria

3.5.1 Context

Well-established WAC or related systems for both pre-disposal and disposal steps help to define a comprehensive waste management strategy and are an important requirement for a chosen management route to be effective. However, discussions among ROUTES partners and more particularly within ROUTES Task 4 have highlighted the fact that WAC are still absent or immature for some stages in the waste lifecycle, particularly disposal end points. This is how ROUTES deliverable D9.9 recognized different key considerations regarding WAC definition:

- An accurate characterization of waste when generated is fundamental. More precisely, the identification of specific radionuclides and their standardized speciation would allow for a more comprehensive understanding of the nature of radioactive waste, providing a basis for precise treatment strategies and disposal considerations including WAC definition. This consideration encompasses all waste types.
- The link between WAC and the safety assessment for a facility is of primary importance. However, the scope of WAC does not necessarily have to depend entirely on the safety assessment of a facility. It can also be linked with sound principles for waste management taken in the round, and supported by experience from waste operations. Regardless of their scope and the basis for their derivation, there must be a clear justification for how a suite of WAC has been developed and why each criterion is necessary.
- There is widespread interest in harmonization of WAC across Member-States, primarily focusing on harmonization of the methodology for WAC definition. Adoption of common approaches to define the broad scope of WAC, combined with cross-checking the completeness of WAC through reference to other waste management programs, could give confidence, including amongst the civil society, that a suite of WAC is fit for purpose and applies ‘best practice’.
- The intricate interplay between stakeholders, including waste producers, treatment and conditioning facility operators, and civil society is a strong argument for the involvement of these stakeholders at an early stage of WAC definition. This engagement fosters a collaborative approach, ensuring that WAC development is practical, effective, and aligned with the safety assessments of facilities.
- WAC are absent or immature for some waste types or management routes.

Based on these considerations, two main recommendations have been suggested and are detailed below.

3.5.2 ROUTES Recommendations

StSt-9 – Comparison and standardization of radionuclides and their speciation to account for in characterization and WAC

According to the needs highlighted within ROUTES Task 4, the recommendation StSt9 *“Comparison and standardization of radionuclides (and their speciation) to account for in waste characterization and WAC”* aims at responding to the interest of standardizing and thus optimizing the extent of radiological characterization. Practically, the expected outcome is to provide recommendations for standardized radionuclide lists to account for in characterization and WAC. This recommendation will have various impacts, beginning with the confidence in completeness of waste characterization. In some ways, it will also help to harmonize set of radionuclides to be characterized. Finally, this recommendation can improve overall understanding of radiological characterization of wastes, elucidating reasons for variations in the sets of characterized nuclides across countries.

In terms of cooperation with other European projects, it should be noticed that this recommendation is also part of discussions within PREDIS and CHANCE projects.

StSt-10- A benchmarking exercise for WAC-development

The recommendation StSt10 *"Benchmarking Exercise for WAC Development"* aims at testing cases of WAC development's processes/applications in order to improve the harmonization and confidence of WAC implementation methodologies across MS. Additionally, this benchmark exercise could be of benefit for SIMS, giving access to the knowledge and experience of LIMS and provide better insight into WAC development. Practically, this work can provide useful know-how on WAC development's processes (e.g., real-life examples, details, etc.). A particular attention will also be given on the fact that output should be widely applicable, whatever the national context. This recommendation was put forward in a dedicated Task 4 workshop. It should be noted that this recommendation has also been suggested by PREDIS project and the former THERAMIN project. In terms of international context, the work conducted by IAEA and aiming to develop an "approach to the development of WAC for LILW" should be mentioned.

3.6 Characterization

3.6.1 Needs regarding development of characterization methods

Context

Several Member States face a significant challenge in dealing with legacy wastes, primarily due to uncertainties related to their inventory and origin, often as a result of a lack or loss of historical documents. These uncertainties extend to the anticipated behavior of the wastes once retrieved for subsequent management. The key to addressing this challenge lies in the supplementary characterization of these legacy wastes. However, it has been clearly emphasized within ROUTES Tasks 2, 3 and 4 that implementing such characterization can be difficult for various reasons, including limited accessibility within legacy storage facilities and heterogeneity across the stored waste [cf. D9.5, D9.8 and D9.9 under review]. ROUTES has identified two so-called "vicious circles" that contribute to the complexities associated with characterizing legacy wastes, underscoring the pivotal role of identification of characterization issues as the primary reason for considering wastes challenging to manage [Euradwaste paper]. On one hand, the lack of adequate characterization hinders the identification of a suitable management route. Conversely, the absence of a defined management route can impede the prioritization of waste characterization, particularly in preparation for retrieval and management. Furthermore, a common dilemma arises where the retrieval of waste from a legacy facility is necessary for adequate characterization. However, ensuring the safe retrieval of this waste requires a prior understanding of its characteristics. This interdependence underscores the need for a comprehensive and integrated approach to address the challenges associated with legacy waste management. Several actions have been identified to address the characterization challenge, including characterization campaigns examining material sampled at different depths, historical records examination, and requirements to recondition drums containing corroded waste offer the chance for further sampling and characterization. There exists a real necessity to enhance characterization methods.

In addition to this, ROUTES' work helped identifying knowledge gaps in characterization of other waste forms [D9.5, D9.7]. For graphite waste for instance, unresolved issues include defining a Wigner energy threshold for safe disposal and enhancing scaling factors' validation. Characterizing large sludge amounts highlighted the need of methodologies for non-equilibrium radionuclides, improved gamma-spectrometry correction factors, and techniques for re-characterizing solidified SIERs. Moreover, U/Ra/Th-bearing wastes pose challenges in gamma-spectrometry correction factors and representative sampling. The particular case of disused sealed radioactive sources (DSRS) also shows that the characterization of some radionuclides remains difficult and that it would be advisable to improve identification techniques to better manage particular radionuclides or simply characterize orphan

sources. Finally, decommissioning wastes present hurdles in representative sampling, in-situ measurements, and scaling factor validation.

Based on all these observations, 6 recommendations have been suggested by ROUTES Tasks 2, 3 and 4. They have been classified according two main goals: (i) needs for development of characterisation approaches and (ii) needs for development of sampling methods. The 6 recommendations are detailed in the paragraphs below.

ROUTES Recommendations

R&D-2 - Characterization methods to determine compliance of particular wastes with WAC

Discussions among ROUTES Tasks 2, 3 and 4 lead to the elaboration of recommendation R&D 2 *"Characterization Methods to Determine Compliance of Particular Wastes with WAC"* which aims to provide 'off-the-shelf' solutions for characterizing particular waste both conditioned and non-conditioned. This work will lead to technics allowing a better general insight in chemical characterisation of wastes, including chemotoxics, complexants, chelating agents or liquid organics. This project would also be an opportunity to enhance sharing of waste characterization systems. It is worth noting that shared mobile systems for waste package characterization are of particular interest for several European countries. It should also be noted that PREDIS and CHANCE projects have also underlined the needs of characterization methods in their respective work.

R&D-3 - Research on Wigner energy threshold for WAC

When speaking about graphite waste, conclusions from ROUTES Tasks 2 and 3 lead to R&D3, aiming to better characterize the energy stored within graphite waste, known as Wigner energy. More precisely, the challenge lies in the absence of a Wigner energy threshold for the final disposal of graphite, a critical parameter that needs to be defined in WAC. Consequently, implementing this recommendation would facilitate the development of an up-to-date WAC for graphite, coupled with a safety assessment for final disposal sites incorporating graphite. This, in turn, would enhance the operational and long-term safety of disposal facilities. Regarding international context, it should be mentioned that CARBOWASTE European project as well as GRAPA IAEA project and other IAEA activities related to the development on an international overview of current status towards disposal considerations for irradiated graphite, have brought significant outcomes on this issue and will be useful to target the future work.

R&D-4 - Investigate characterization methodologies and identification techniques for DSRS and orphan sources

For many countries, in addition to orphan sources, part of their source inventory is not well documented and characterization techniques are often not sufficient or adequate to obtain radiological and chemical detailed inventory or to identify particular radionuclides such as Strontium-90. In this context, discussions among ROUTES Tasks 2 and 3 reveal that important volume of DSRS remains in storage awaiting better characterization in order to foresee long-term management solutions. To cope with this situation, Recommendation R&D4 *"Investigate Characterization Methodologies and Identification Techniques for DSRS and Orphan Sources"* aims to develop methodologies and techniques dedicated to sources, in order to provide accurate radiological and chemical inventories. In term, this recommendation would clearly help to define treatment and conditioning processes and ultimately enabling the anticipation of suitable final disposal for characterized DSRS.

R&D-6 - Development of innovative non-destructive methods

The recommendation R&D6 *"Development of Innovative Non-Destructive Methods"* comes from the need to establish a methodology for non-destructive measurements, with minimal uncertainty, to provide a precise estimation of the activity in the waste packages. It would improve the sorting and minimizing waste from decommissioning due to the possibility to clear larger amounts of material from decommissioning. In addition, it would increase the measurement reliability and the determination of scaling factors by addressing the challenges within radioanalytical characterization, specifically the

difficult-to-measure radionuclides often associated with SIERs. Regarding current research projects, it should be noted that PREDIS WP 4 also insists in the need to develop innovative non-destructive methods.

R&D-7 - Development of innovative methods for scaling factors validation

Application of the scaling factor methodology is a well-known and commonly applied approach for the determination of difficult-to-measure radionuclides. However, this methodology is heavily dependent on the application of validated scaling factors. Therefore, ROUTES Task 3 suggested recommendation R&D 7 dedicated on *"Development of Innovative Methods for Scaling Factors Validation"*. More precisely, this recommendation aims to enhance the reliability of characterization results by improving the reliability of scaling factors.

3.6.2 Needs regarding development of sampling methods

R&D 5 - Development of methodology for representative sampling of challenging waste types

Work conducted in ROUTES Tasks 2, 3 and 4 have clearly shown that the reliability of characterization results utilizing destructive methods is heavily dependent on representative samples. However, many challenging wastes are highly heterogeneous in character (e.g., legacy waste, SIERs, etc.). Consequently, to be adequately identified, challenging waste would need accurate sampling strategies which would take into account variation among each waste packages as well as among waste stream itself. It should be noted that these sampling strategies would also be effective for waste involving large volumes (e.g. originating from decommissioning activities) where systematic characterization is not possible but could benefit from being targeted and representative. This is how recommendation R&D-5 *"Development of Methodology for Representative Sampling of Challenging Waste Types"* have been suggested. This would allow to provide new characterization strategies for heterogeneous waste streams and consequently, imply less uncertainties and over-conservatism in impact assessments and WAC definition. Those representative sampling strategies would also make possible national and international comparison among waste characterization, due to identical, repeatable and reliable sampling methodology. Regarding national and international contexts, it should be noted that CHANCE research project also highlights the need to develop such approaches. Moreover, in the UK, NWS is also leading research work on this aspect. Finally, it should be kept in mind that technology is available in this area in the supply chain, for instance, Veolia Nuclear Solutions will implement a new solution on the market. That could be a good opportunity to share good practices.

3.7 Treatment and conditioning

3.7.1 Needs regarding innovative matrices

Context

The management of reactive waste like SIERs, sludges, organic waste raises difficulties in terms of long-term behavior under disposal conditions. For several year, some MS have explored innovative matrices (e.g., ceramic, geopolymeric matrices, alkali activated cement, magnesium brucite-based cement) combined with various treatment processes to stabilize such complex waste. Note that ROUTES deliverable D9.5 provides some details about such research conducted in some MS. However, D9.5 also emphasizes that the long-term behavior of these matrices in disposal conditions remains unknown, necessitating further exploration before contemplating large-scale development. To answer this challenge, the recommendation R&D-8 have been suggested.

ROUTES Recommendation

R&D-8 - Explore long-term behavior of innovative matrices

The recommendation R&D-8 *"Explore Long-Term Behavior of Innovative Matrices"* aims to provide a better understanding of the degradation mechanisms of innovative matrices in disposal conditions. This work will help to anticipate potential interactions with disposal components and collect valuable inputs to define WAC associated with these innovative waste packages.

3.7.2 Needs regarding treatment of bitumen waste

Context

As bitumen was a matrix commonly used from the 1960s to stabilize reactive waste, it turns out that nowadays bituminized waste often relates to the conditioning of spent resins and effluent sludges. For several years, MS have faced difficulties for the management of the bituminized waste, starting from the characterization step to disposal. Nowadays, Member States have launched various R&D programs, not only to cope with characterization and reconditioning issues, but also to tackle particular issues such as prevention of fire hazards, or possible leakage of chemical cocktails influencing the mobility of radionuclides in deep disposal facilities. In this sense, no additional research programs appear to be particularly needed now. However, it has to be recognized that for bituminized waste resulting from reprocessing processes, the presence of salts raises issues for the long-term evolution of drums. Consequently, ROUTES deliverable D9.5 brings to the fore on one remaining R&D topic aiming to address the implementation of treatment processes allowing the destruction of certain chemical species, thus ensuring the production of stable waste packages. This is the scope of the recommendation R&D-9 detailed below.

ROUTES recommendation

R&D-9 - Investigate particular needs on treatment processes for bituminized wastes coming from reprocessing

R&D-9 *"Investigate Particular Needs on Treatment Processes for Bituminized Wastes coming from Reprocessing However"* aims to identify the needs and expectations of interested Member States in terms of treatment processes for bituminized wastes. In time, it will possibly lead to define the framework for a future common research program dedicated to this topic. It is worthy to mention that this recommendation can be linked to the outcomes of the past THERAMIN project, and has also been highlighted by the current CORI European project.

4. Conclusion

ROUTES WP enabled the identification of twenty-two recommendations on Research and Development, strategic studies and knowledge management activities for future European collaboration. R&D recommendations regarding radioactive waste characterization have been integrated into EURAD Strategic Research Agenda (SRA) and paved the way for future advancements, and “knowledge management” initiatives aiming at enhancing information sharing between Member States have also been highlighted. In addition to these, the ROUTES project has initiated crucial discussions on the prerequisites for implementing shared or tailored solutions, particularly for Small Inventory Member States (SIMS), amidst the emergence of challenges like borehole disposal and long-term storage. It has underscored the vital role of international collaboration in radioactive waste management, serving as a catalyst for cooperation among member countries.

Looking ahead, it appears now essential to integrate these recommendations into new multilateral programs, whether through the continuation of the EURAD-2 program or collaboration under multilateral organizations such as the OCED-NEA or the IAEA.

Furthermore, the ROUTES work package has yielded significant results by fostering a comprehensive understanding of predisposal challenges at the European level and promoting knowledge and technology sharing. It has empowered underrepresented voices to address their challenges and explore potential solutions, while also providing civil society representatives with a platform to voice their perspectives. Through networking, valuable connections have been established, highlighting the importance of collaboration between Small Inventory Member States (SIMS) and Large Inventory Member States (LIMS).

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