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REVIEW ARTICLE

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EURAD EC project – overview of the routes work package: identified key issues and open questions about waste management routes in Europe, from cradle to grave

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Abstract. 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). ROUTES' objectives are (i) to provide a framework for European Union's member states (MS) to share methodologies, experiences, and knowledge in situations in which a waste management strategy is difficult to define as well as to (ii) to compare national approaches and strategies of waste management. The work considers national programmes at different stages of their development and deals with different amounts and types of radioactive waste. The expected output is identifying Research & Development (R&D) needs and opportunities for collaboration between MS, which need not be confined to ROUTES or EURAD frameworks. This work has enabled ROUTES partners to identify key issues such as retrieving poorly characterised legacy waste from a predisposal or disposal facility, implementing specific waste management solutions in the absence of well-defined WAC or developing innovative or shared solutions for MS that have only limited amounts of waste to manage. Discussion of these questions is illustrated through some of the case studies identified and analysed under the ROUTES WP.

1 Introduction

The ROUTES WP has been implemented in response to the Strategic Research Agenda (SRA) of the European Joint Programme on Radioactive Waste Management (EURAD), a five-year initiative which aims to coordinate activities on agreed priorities of common interest between European Waste Management Organisations (WMOs), Technical Support Organisations (TSOs) and Research Entities (REs), based on the conclusions of EC JOPRAD project [1].

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The ROUTES WP is a strategic study whose objectives are to:

- 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 and with different amounts and types of radioactive waste to manage.
- Identify safety-relevant issues, and their R&D needs associated with the waste management routes from the cradle to the grave, including the management routes for legacy waste, considering interdependencies between the routes.

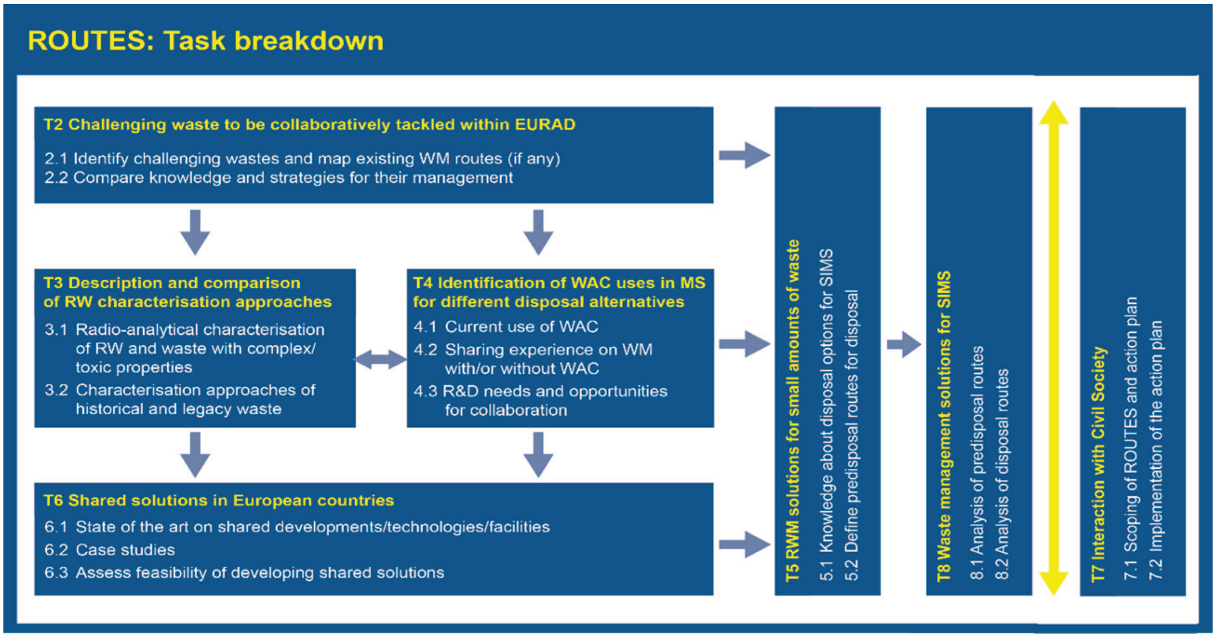

Fig. 1. ROUTES task breakdown.

- Describe and compare the different approaches to characterisation, treatment and conditioning, and long-term waste management routes, and identify opportunities for collaboration between European Union (EU) Member-States (MS).

The scope of the ROUTES WP is limited to so-called "challenging waste". This encompasses those waste streams considered challenging or problematic, for which MS are encountering difficulties in defining appropriate management routes due to intrinsic properties of the waste (e.g. specific hazard), an unknown or uncertain inventory (e.g. legacy waste) or uncertainties related to their behaviour in different waste management life-cycle steps (e.g. treatment and conditioning issues, long-term behaviour in disposal situations).

Activities within the ROUTES WP have been organised under seven tasks in order to explore the different challenges and potential solutions (Fig. 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 characterisation approach.
- Task 4: identification of Waste Acceptance Criteria (WAC) used in EU Member-States for different disposal alternatives in order to inform the development of WAC in countries without WAC disposal facilities.
- Task 5: radioactive waste management solutions for small amounts of waste (focusing on disposal strategies for small-inventory Member-States).
- Task 6: description of the state-of-the-art shared solutions in European countries for characterisation, 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.

In addition, an eighth task has been included in the ROUTES' work within EURAD second wave WPs selection process in Year 2 with the objective to strengthen collaboration between Small Inventory Member States (SIMS) and Large Inventory Member States (LIMS) and to ensure knowledge transfer with respect to the SIMS needs. The resulting Task 8 evaluates the possible waste management solutions for member states without WAC and with small inventories (SIMS).

The task breakdown covers the technical and non-technical key factors that must be considered when choosing a radioactive waste management route. Broad factors influencing technology selection notably include the availability of a final disposal site and well-established WAC, regulatory considerations and, finally, public involvement. Waste-related aspects mainly include the type of waste, volume, radioactivity level, intrinsic physicochemical properties, chemical and physical interaction between waste and the conditioning matrix and availability of suitable waste treatment technology.

Differences in the management route can also arise from the overall volume of radioactive waste a country has to manage. One of the major differences between SIMS and LIMS is that the latter may have access to existing facilities, infrastructures and knowledge and can also distribute fixed costs over a broader range of waste. For SIMS, moving forward with programmes for treatment and conditioning wastes in the absence of a disposal strategy and facilities is risky. The small volume to be managed makes the development of specific treatment capabilities disproportionately expensive. For this reason, specific attention is paid within ROUTES to knowledge transfer between SIMS and LIMS and to the conditions for developing shared solutions which could be a valuable alternative for SIMS to move forward.

2 Methodology

The ROUTES' work is primarily based on inputs from partners. The initial work (in year 1, i.e. 2019–2020) was devoted to gathering the data necessary for all tasks. A significant amount of data and information was gathered via a questionnaire disseminated to all ROUTES participants, covering all important aspects of managing challenging waste. One reply per country was requested to receive consistent information and strengthen the exchange between the main actors involved in the national RWM programme (WMO, TSO, RE).

The respondents to this questionnaire were asked about general information on the RWM programme in their country, such as national waste classification, waste inventory, disposal facilities and stakeholders' involvement. The questionnaire also addressed more specific issues concerning WAC, data relating to inventories of challenging waste and management routes, including uncertainties associated with the waste streams. With respect to this, the respondents also provided information concerning characterisation methods for each challenging waste they identified. To acquire knowledge about waste-related and broader issues for the management of challenging waste streams, the respondents were also asked whether a management strategy for each challenging waste stream had already been identified in their respective country and, if not, how the waste is managed safely in the meantime. Finally, to assess the feasibility of developing further shared solutions at a European level, respondents were asked to provide information on technologies, facilities and possible structures for such shared solutions and to present relevant case studies. Following the subsequent analyses of the answers, findings and results were published in already developed ROUTES deliverables.

Year 2 (2020–2021) activities focused on comparing approaches and strategies adopted by MS to cope with issues related to waste management. This was mainly achieved through analysis of case studies, including both successful and unsuccessful experiences. This methodology has been chosen based on the belief that lessons learnt by experience are often more relevant and representative than information gained by looking at collated inventories or a too high-level approach.

Based on the data acquired and the analysis resulting from case studies, upcoming work to be carried out for each task in years 3 to 5 (2021 to 2024) will be focused on the definition of R&D needs related to the management of challenging wastes. These needs will be identified and prioritised, and potential collaboration between the Member States and recommendations for future R&D projects will be proposed. Finally, the knowledge generated in ROUTES through knowledge/know-how sharing and discussions of common challenging issues will be consolidated and integrated as input to EURAD KM activities.

In addition to the work performed within the framework of the ROUTES WP, interactions are also organised with other EURAD work packages (e.g. joint session during the first EURAD Annual Meeting on "Influence of organics and other wastes on redox and RN transport processes in geological disposal facilities in different programmes" in cooperation with CORI, FUTURE and KM work packages, dissemination of outcomes related to organic waste to CORI WP) and with other EU-projects, such as PREDIS (organization of joint webinars, participation of PREDIS and SHARE representatives to ROUTES workshops and vice versa). These interactions will be reinforced in years 3 to 5 (Fig. 2).

3 Outcomes

This section presents the main outcomes of the ROUTES WP at this stage. In the following, the identified challenging waste is presented, and some overarching topics will be illustrated by means of case studies collected.

3.1 Challenging waste

In order to compare strategies and experiences in the management of challenging waste streams, preliminary work to compare the classification and categorisation schemes in each participating country was deemed necessary to constitute a baseline. Indeed, even if the IAEA approach to classification is applied in most participating countries, the terminology used does not always correspond strictly to the classes of "low-level waste" and "intermediate-level waste" as defined in the IAEA General Safety Guide for the Classification of Radioactive Waste (GSG-1) [2], that corresponds to waste suitable or not suitable for near-surface disposal respectively. Indeed, some countries (e.g. Bulgaria, Lithuania, Netherlands) combine low and intermediate-level waste into one class (LILW), which, in turn, can be subdivided into short-lived and long-lived RW. Generally, short-lived LILW could be associated with LLW within the meaning of GSG-1, whereas long-lived LILW could be associated with ILW within the meaning of GSG-1. This has proved crucial in analysing the inventory of challenging waste to compare the management route and strategy for waste streams of similar composition but different activities. A comprehensive description of this work, which also offered the opportunity to identify a preliminary list of challenging waste and the difficulties related to its management, has been published in [3].

Challenging wastes are defined as those for which no complete solution for their safe management is available, mainly because one of the predisposal steps (including characterisation, treatment and conditioning) is missing, or the disposal strategy is not yet defined. The reasons for this can be either technical or organisational. As a first analysis, the main difficulties faced by the member states that participated in the ROUTES questionnaire are the lack of disposal route (31%), characterisation (22%), and conditioning or treatment issues (20%). Regarding disposal route aspects, it turns out that the end state of

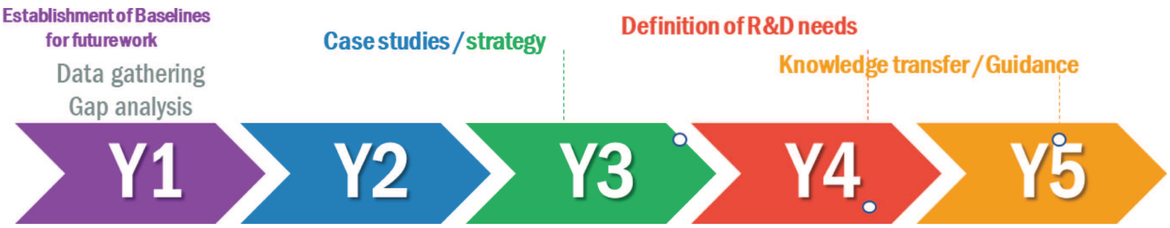

Fig. 2. ROUTES yearly priorities.

the waste management strategy is not clearly defined in many countries, which leads to difficulties in developing treatment and conditioning techniques, as the packages produced may not be suitable for the Waste Acceptance Criteria (WAC) of future facilities. For characterisation issues, a vicious circle has been pointed out, consisting of saying that not having a management route prevents prioritising the characterisation of waste, and the lack of characterisation prevents the identification of management routes.

Eleven types of challenging waste have been identified by the ROUTES' partners: sludges, spent ion exchange resins (SIER), organic waste, bituminised waste, graphite waste, decommissioning waste, disused sealed radioactive sources, Ra/Th/U bearing wastes, spent fuel, wastes containing reactive metals and wastes containing chemotoxic substances. Experiences and difficulties encountered by the member states to define management routes and strategies to manage these waste streams have been compared and analysed in the framework of task 2.

For some, precise technical or technological challenges related to the absence of or immature technical solutions have been identified. This is the case with, for example, the management of graphite waste, reactive metals (Be, Mg, Na etc.), liquid organic waste, and sludges for which dedicated conditioning matrices are not available yet, or specific characterisation issues are at stake (i.e. determination of 14C content in graphite waste). The challenges identified for each waste stream at the different steps of the waste management life-cycle and the preliminary R&D needs are summarised in [4]. Although some questions are still open, these challenges are usually quite well identified and efficiently addressed in the framework of national and international (EC-funded) R&D Projects [5–7]. For example, new matrices for the conditioning of some of the mentioned challenging waste are being studied and tested in the framework of the PREDIS Project (WP 4, 5, 6). Although extensive work is still needed in terms of R&D (durability, compatibility with the different waste streams), development work is also necessary to implement them at the industrial level and ensure that this innovation will finally be implemented.

3.2 Issues related to characterisation of legacy waste

Several member states are facing difficulties in managing legacy waste, including both unconditioned and conditioned wastes. Difficulties are mainly related to characterisation uncertainties, as most countries need to manage legacy radioactive waste without adequate information about their origin and radionuclide content, and in some cases, waste streams have been mixed.

Such uncertainties may be related to the quantification of some specific radionuclides estimated with indirect methods (i.e. 14C in graphite waste) or to techniques for detecting particular species such as activation products or complexing substances, but one of the major overarching topics concerns the strategy to put in place for the retrieval of unconditioned waste when their characterisation is uncertain. Two experiences managing legacy sludge in the UK and France highlighted difficulties that might be encountered due to characterisation uncertainties.

In the UK, storage of Magnox spent fuel in ponds for several decades has given rise to a large inventory of sludge streams (around 90 sludge waste streams). This case study notably highlights that implementation of sampling allowing a better knowledge of radiological and chemical inventories is very complicated, as sludge stored in tanks and ponds tends to settle. This results in different stratifications that make it challenging to obtain representative samples. Concerning sludge that has already been conditioned, some drums have corroded, which implies reconditioning and transfer to new containers may be required. Therefore, further sampling and establishing a new analysis regime would be possible at this stage of the waste life cycle.

In France, the same difficulties as those mentioned by the UK have been reported concerning 9000 m^3 of LL-ILW (according to French classification) sludges generated in La Hague by spent fuel reprocessing and liquid effluent treatment, placed into seven adjoining tanks and considered as legacy waste. This sludge presents high variability due notably to different production processes implemented over time. The lack of characterisation has led to the current difficulties in identifying a safe management route for this sludge. Extensive work was needed to determine their radiological and chemical composition (see Focus 1 on the French case study provided in [4]), which has been conducted on the basis of both historical records and 6 characterisation campaigns with sampling at different depths.

The UK and French experiences illustrate two "vicious circles" related to characterisation of legacy waste: (i) on the one hand, not having a management route prevents prioritising the characterisation of waste, and the lack of characterisation prevents the identification of management routes and, (ii) on the other hand, waste needs to be retrieved to be characterised, but in order to be retrieved, a detailed inventory is required that needs to be characterised first. To address this situation, France has chosen to conduct extensive characterisation campaigns based on samples in order to be able to retrieve and condition certain wastes. Examples of similar situations were also shared by SIMS, and this presents an opportunity to learn from LIMS's experience. This is the case for cemented sludge in Greece, which characterisation has been presented in the ROUTES workshop about Sharing Experience on Waste Management with or without WAC [8]. The Greek case notably highlighted that characterisation of cemented sludge was hindered because of a lack of financial resources. This lack of characterisation has led to current difficulties in identifying a safe management route for this sludge. This highlights a crucial point: sampling and characterisation require consequent means implying financial and human resources, which are not always available for SIMS. For this reason, an EC-wide approach and EC support in terms of technology and safety doctrine from LIMS to SIMS are highly beneficial.

More generally, future progress in terms of non-destructive characterisation may provide significant improvements to solve the challenge of characterising legacy waste. However, the implementation of any solution should be analysed regarding a strategic question: which level of uncertainty should be considered acceptable in order to implement operations on legacy waste? The Chance Project [9], specifically devoted to characterisation methods and approaches to conditioned waste, analysed the impact of these uncertainties and how to deal with them. While the importance of uncertainties was considered critical, suggestions for dealing with them are too general and not clear enough to be easily implemented (creation of new standards and regulations, need to upgrade the system of characterisation, need to improve skills and techniques applied in characterisation). In view of the elements presented above, an outcome of ROUTES WP is that a specific project dedicated to the characterisation issues and techniques related to legacy waste management might be considered a priority for future EC-funded projects.

3.3 Issues due to early or delayed conditioning

Several member states have had to deal with wastes conditioned decades ago which are since then undergoing a degradation process. Early conditioning offers the advantage of a final solution and encourages standardisation contributing to cost minimisation, but it requires a close dialogue between all the stakeholders, especially the waste producers, the waste management organisation and the regulatory body, as well as stability in waste acceptance criteria. In turn, delayed conditioning has the advantage of leaving options open and reducing the initial investments when no disposal solution is under development, but it inevitably requires future retrieval and re-packaging with potential degradation of the initial waste form and the potential risk of producing additional secondary waste. In the absence of an established disposal route, all member states face the dilemma of when to implement the final conditioning of radioactive waste while requirements for safe disposal and associated WAC are still being determined. This theme has been extensively analysed in the framework of the ROUTES workshop about Sharing Experience on Waste Management with or without WAC [8], notably through the Belgian, Dutch and UK cases cited thereafter.

Again, the lack of disposal WAC and/or available disposal routes prevents member states from developing or using the appropriate treatment and conditioning techniques since the packages produced may not be in line with future WAC. An obstacle to early conditioning is that conditioning waste into a matrix significantly reduces flexibility for further management (without reconditioning). It also strongly influences the behaviour and performance of the waste over the long term, potentially giving rise to properties that may be undesirable in a disposal facility if a matrix is selected without adequate knowledge of the disposal environment and properties of the wider multi-barrier system underlying safe disposal. Finally, early conditioning might reduce flexibility and then limit the implementation of innovative techniques. This observation is apparent from the Belgian case. In this case, a yellow gel-like material was found on drums conditioned in a cementitious matrix containing evaporator concentrates or ion exchange resins from waste packages produced by NPPs until 20 years before. A research programme found that the gel most likely results from alkali-silica reactions between the highly alkaline pore solution and the reactive siliceous aggregates of the matrix, which might have consequences in terms of the long-term safety of future near-surface disposal. This finding led to a suspension of the cementation processes of concentrates and ion exchange resins produced by the NPPs.

However, early conditioning might be seen as preferable in order to reduce early hazard and consolidate the safety of storage facilities, even if the uncertainties over the disposal route persists. This point is illustrated by the Dutch case study of waste processing and consolidated storage of LILW at COVRA's facilities for as long as 100 years. Indeed, geological disposal is planned for both LILW and HLW in the Netherlands, but the final decision for disposal is to be made around 2100. Currently, waste treatment and conditioning depend mostly on the safety of the storage facility in which the waste will be stored and the corresponding WAC. This strategy relies on the assumption that requirements for waste to be accepted for storage are similar or higher to those still to be defined for future geological disposal, as key considerations include degradation of the waste forms and packaged waste during these long timespans and the resulting impacts on the safety of the storage facility. This would enable the direct transfer of waste packages to the DGR, once available, without further processing (such that all stored waste is ready for final disposal). It is worth noting that some resin waste streams are stored for short periods (~5 years) in packages that do not meet the dose rate WAC for the storage facility. This allows time for COVRA to identify and deploy suitable conditioning solutions. In the meantime, "smart packaging and stacking" is employed to ensure safe storage, such as adding an extra concrete shielding package placed around some waste packages for a period of time, thereby enabling dose rate criteria to be met.

A “middle ground” approach has also been presented by the UK [4], consisting of packaging waste in new containers without matrix conditioning. This can provide a flexible and, crucially, reversible solution whereby a limited amount of waste processing facilitates the emptying and decommissioning of ageing facilities while retaining the waste in a form that can still be further treated or conditioned in many different ways before its eventual disposal. This point is particularly well illustrated by the case of non-reprocessed spent fuel currently stored in cooling ponds on the Sellafield site in the UK. This spent fuel will be transferred to a geological disposal facility in the future, but the process of identifying a suitable site is still at an early stage. During decades of storage, corrosion of the fuel and surrounding Magnox cladding has occurred. In the meantime, legacy storage facilities for non-reprocessed Magnox spent fuel are ageing, and there is a pressing need to empty them so that they can be decommissioned. With this in mind, work is underway to transfer Magnox spent fuel into high-integrity containers called Self-Shielded Boxes (SSBs). These thick-walled, vented, ductile cast-iron containers will be used for ongoing storage of the spent fuel at Sellafield in a new waste and spent fuel store so as to enable decommissioning of the ageing storage facilities to proceed. Work is currently being undertaken to assess whether the filled SSBs would be suitable for direct disposal to the geological disposal facility; if this is not feasible, then further conditioning or re-packaging would be required.

3.4 Conditions and main issues for development of shared solutions or facilities

Some programmes across Europe are considering or have considered the feasibility of shared solutions or facilities, including multinational repositories, which can provide infrastructure for all, or part, of the waste management route for a specific waste type.

Shared solutions have been researched over the last 20 years, and much of the knowledge base lies within the ERDO Association [10]. The founding feasibility studies for sharing disposal solutions in Europe were carried out by ERDO members in the European Commission SAPIERR projects [11,12]. This led to the establishment of the ERDO Working Group in 2009. Over the following decade, the fundamental concepts and practical aspects of multinational waste management solutions were researched and promoted by the IAEA, with the central involvement of ERDO members [13]. The ERDO Association (Association for Multinational Radioactive Waste Solutions) was founded in 2021 by some ERDO WG members, it is an association of national organisations with a mission to work together to address the common challenges of safely managing the long-lived radioactive wastes in their countries. A multinational disposal facility is of particular interest to countries with relatively small inventories of radioactive waste. The development of shared solutions for disposal is still in its feasibility phase, though, as only one agreement for the disposal of small amounts of institutional waste (from Luxemburg to Belgium) has been notified.

To our knowledge, no shared facilities have been implemented in Europe up to now. For this reason, the ROUTES WP enlarged the frame of situations considered as a shared solution in its work, including some hybrid situations which cannot be considered, strictly speaking, as shared solutions but which present some analogies or mechanisms of interest for their implementation. For these reasons, some commercial solutions treating or having treated foreign waste have been included in the analysis. This choice is driven by the observation that hundreds of transboundary shipments of spent fuel and nuclear waste are authorised each year in member states with available capacities for processing or reprocessing in Europe, notably in Sweden and Germany. The development of shared solutions or facilities, notably mobile treatment or conditioning facilities, would represent an alternative option for transboundary shipments.

The development of shared treatment and conditioning facilities could be of interest in at least two situations: for countries with small or medium-sized inventories or some categories of problematic radioactive waste of quite small amounts. In these two situations, most waste producers have a fairly small volume of waste to manage (e.g. batteries, solvents or pyrochemical waste), which would make the development of treatment capability at each site disproportionately expensive per volume unit. Individual member states may not be able to afford a solution, but an EC-wide approach could potentially be utilised to develop effective processes. This would avoid having to construct a treatment or conditioning facility for only a very small amount of radioactive waste. Shared solutions for RW management could provide the best-added value, especially for small inventory countries which do not have the infrastructure and know-how to deal with the waste, financial and other resources required for the exercise. This specific theme was identified as a high priority in the SRA.

Nevertheless, planning such facilities encompasses important and innovative developments (including the legal framework), which have been considered in work under the auspices of the EC or IAEA. The mechanisms to implement shared solutions depend both on the type of multilateral options and on the type of chosen technical solution, as a shared mobile facility jointly developed would probably be implemented more easily and raise fewer concerns about acceptability than a facility thermally treating nuclear waste. The establishment of the legal framework for shared solutions was broadly analysed under task 7 [14], which proposed the following definition of a shared solution behind the mere technical definition: “*Shared solutions encompass all the elements, be they tangible or intangible, that are developed and used in concert between entities in different countries, or between the countries themselves at various levels in any phase of the nuclear fuel cycle. In the frame of RWM, it includes the research carried out, the knowledge used, the technology developed, and transferred and the facilities constructed* *and operated through all the phases of the RWM, the legal and institutional arrangements established to run things smoothly and safely, and the process of interaction among the stakeholders, including safety culture and governance issues*". The work performed within ROUTES task 7 also identifies the public concerns related to shared solutions and notably stresses the necessity of a common safety culture and a level playing field as prerequisites to develop such solutions. In particular, if such a playing field is not in place, the development and localisation of shared facilities might gravitate towards countries with the lowest environmental and social standards, causing environmental and social dumping. Finally, three cases of different shared situations have been analysed with the contribution of the ICS larger group and some general findings derived:

- shared solutions for RW management would provide best-added value for small inventory countries that do not have the infrastructure, but their implementation raises critical issues.
- Good transparency (public access to information, evidence-based decision-making, effective public participation and access to justice) must be established.
- A specific deliberative process should be developed, with proper representation from local, national and multinational actors besides officials.

4 Conclusion

The initial work carried out in the framework of the ROUTES WP has been devoted to gathering data on radioactive waste management, especially related to waste identified as challenging, as well as to comparing approaches and strategies adopted by member states to cope with issues related to these challenging wastes through the comparison of case studies. This has enabled ROUTES partners to identify issues which will be further analysed, notably related to the retrieval of poorly characterised legacy waste from a predisposal or disposal facility, the implementation of specific waste management solutions in the absence of well-defined WAC or the development of innovative or shared solutions for member states that have only limited amounts of waste to manage. Future work will be focused on the identification and prioritisation of (i) common R&D needs related to the management of challenging wastes and (ii) opportunities for collaboration between member states. A particular focus will be made on the harmonisation of WAC or treatment and conditioning processes as potential precursors to more extensive shared waste management and disposal activities in future.

Conflict of interests

The authors declare that they have no competing interests to report.

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Conceptualisation, E.L, F.M; methodology, all authors; validation, all authors; investigation, all authors; resources, all authors; writing – original draft preparation, E.L; writing – review and editing, F.M; visualization, all authors. All authors have read and agreed to the published version of the manuscript.

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