Deliverable 9.9: Suggestions for the management of challenging wastes while maintaining compatibility with options for disposal

ROUTES Task 4 Final Report

Work Package 9

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Executive summary

Well-established waste acceptance criteria (WAC) or related systems for both pre-disposal and disposal steps help to define a radioactive waste management strategy and are an important requirement for a management route to be effective.

"Waste management routes in Europe from cradle to grave" (ROUTES) is one of two strategic study work packages being conducted as part of the European Joint Programme on Radioactive Waste Management (EURAD).

Task 4 of ROUTES aimed to identify WAC used in European Union (EU) Member States for different waste management strategies in order to inform development of WAC in countries without WAC or facilities. More specifically, Task 4 had the following objectives:

- To provide an overview of the current application in Member States of WAC at different stages in the waste lifecycle[1] and to describe mechanisms to implement them.
- To offer a structured approach to support decision-taking of so-called 'no regret' waste management measures, i.e., decisions that do not lead to problems later on.
- To identify R&D needs and opportunities for collaboration between Member States.

These three objectives have been delivered via the following three subtasks:

- **Subtask 4.1:** *Current use of waste acceptance criteria* – this subtask involved the production of an up-to-date overview per country on the use of WAC in Member States and some Associated Countries, focusing on the use of WAC as a management tool across the waste lifecycle.
- **Subtask 4.2:** *Sharing of experience on waste management with and without WAC being available* – this subtask offered a structured approach to support decision taking of 'no regret' waste management measures. This was achieved by examining case studies of waste management activities without WAC, disposal solutions or other technical facilities being available, as well as a series of cross-cutting topics relating to WAC. These informed a gap analysis and a series of observations and recommendations on progressing waste management whilst maintaining compatibility with a range of options for subsequent waste lifecycle stages.
- **Subtask 4.3:** *R&D needs and opportunities for collaboration* – this subtask identified and prioritised commonly held R&D needs related to the management of challenging wastes, as well as opportunities for collaboration between Member States and Associated Countries. Recommendations identified in Task 4 were integrated with those emerging from other ROUTES tasks and fed into the 2023 edition of the EURAD Strategic Research Agenda (SRA).

The present report is the sole deliverable documenting the work performed under ROUTES Task 4. It summarises the outcomes of ROUTES Subtasks 4.1, 4.2 and 4.3, namely:

- Current use of WAC in Member States and some Associated Countries.
- Key discussion points from the Subtask 4.2 workshop titled "*Sharing experience on waste management with / without WAC available*" held on 14-15 June 2021.
- The results of a gap analysis performed following the workshop including a series of observations and recommendations aimed at supporting the progression of waste management

[1] The waste lifecycle (sometimes referred to as the waste cycle or waste management lifecycle) encompasses collection / retrieval and pre-treatment of raw waste (e.g., sorting, drying); waste treatment (e.g., thermal treatment); waste conditioning and packaging, storage, transport (which may take place at multiple stages) and disposal.

activities when uncertainties remain regarding future stages in the waste lifecycle, particularly disposal end points, and/or when associated WAC are absent.

- Key discussion points from the Subtask 4.3 workshop titled "*R&D needs and opportunities for collaboration*" held on 10 May 2022.
- The process for identifying, screening and prioritising commonly held WAC-related R&D needs and the opportunities for potential future collaboration between Member States and Associated Countries on this topic.

The current use of WAC in Member States and some Associated Countries, examined in Subtask 4.1, was presented in a report published in February 2021. This report contains a detailed investigation of the following topics for twenty-one European countries, with five more covered at a high level:

- The nature and scope of WAC.
- Development and application of generic WAC.
- Approaches to develop and update WAC.
- A comparison of detailed requirements set out in WAC.
- Approaches to check compliance with WAC and for managing non-compliances.

It is noted that the current status of WAC has also been considered within ROUTES Task 5, as reflected in ROUTES Deliverable D9.10. This more recent report places a greater focus on Small Inventory Member States (SIMS) than the Subtask 4.1 report, and also includes some further clarifications and updates to national WAC since 2021.

The Subtask 4.2 workshop and the subsequent gap analysis were documented in an internal memorandum (EURAD Milestone 144). The resulting observations and recommendations regarding 'no regret' waste management measures can be summarised as follows:

With regard to **characterisation**:

- Waste characterisation is essential to understanding the inventory. The waste inventory informs all subsequent management steps and has a major influence on measures that could be applied for waste minimisation, materials recycling and reuse.
- Characterisation at the time of waste generation is essential to minimise the need for more extensive characterisation downstream, which is often more challenging.
- An adequate records management process to store, and facilitate reference to, waste characterisation data needs to be implemented at an early stage, and to endure throughout the waste lifecycle.

With regard to **treatment**:

- Where possible (and relevant), treatment techniques should be flexible, to enable adaptations to be made in response to the particular characteristics of individual waste streams or site-specific constraints, thereby ensuring that processing criteria and WAC for storage and/or disposal of the resulting product can be met wherever a technique is applied.

With regard to **conditioning**:

- Conditioning waste into a matrix reduces flexibility for further management (without reconditioning) and may require the design and operation of a disposal facility to be tailored around conditioned waste characteristics, rather than optimising the waste conditioning approach against disposal conditions. Careful consideration is therefore needed before deploying such an approach to a given waste when its disposal route, and associated requirements, are not yet known.
- It may be preferable to apply interim waste management measures that are more easily reversible, such as repackaging waste in new containers and/or transfer to new storage facilities to facilitate decommissioning of older facilities. However, this can result in increased costs over the full waste lifecycle.
- On the other hand, arguments in support of early conditioning into a matrix include the promotion of safe, standardised storage through conversion of raw waste to a passively safe form. Early conditioning into a matrix can also facilitate a period of extended storage prior to disposal, buying time for additional research to underpin safe disposal. However, such an approach could lead to reducing the political urgency for finding a permanent waste management solution.
- Generic WAC can enable waste packaging to progress in the absence of a disposal route. However, they are typically more constraining than site- or facility-specific WAC since they require conservative assumptions to be made about disposal conditions, which can place a more onerous burden on those responsible for waste treatment and conditioning.

With regard to **storage**:

- Storage conditions should be designed to promote package longevity, thereby reducing the risk that already conditioned waste packages will require reconditioning. Storage arrangements should also enable package performance to be checked through monitoring. If these aspects are difficult to ensure, it may be preferable to minimise the extent of treatment and conditioning conducted (whilst still ensuring that the waste can be stored safely).

With regard to **disposal**:

- Where disposal WAC are available, uncertainty shifts towards characterisation to determine compliance (or otherwise), and/or the selection and qualification of treatment and conditioning methods that will result in a disposable waste form.
- A dual-track disposal strategy (i.e., planning for a national repository and pursuing opportunities for a multinational shared facility in parallel), can help to keep options open and increase the likelihood of identifying a suitable disposal route. Choosing to follow such an approach would be a political decision (at a national level) and might not be considered feasible or desirable in all cases.
- Where a shared solution for disposal is pursued, international political consensus on the basis for implementing the shared solution is essential between all those countries consigning and receiving waste. This may strengthen a desire for harmonisation of waste management arrangements (potentially including WAC) across affected countries.
- Where disposal WAC are subject to change, such changes can be more easily accommodated by implementing flexible treatment and conditioning techniques coupled with in-depth waste characterisation.

With regard to **WAC definition**:

- Waste generators and treatment / conditioning facility operators should be involved in the process for defining WAC as early as possible, to minimise the potential for it being impractical to implement.
- 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 wider principles for waste management, 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.
- The responsibilities of different stakeholders for defining and applying WAC and for checking compliance need to be clearly defined and actioned, to ensure that waste acceptance systems are fit for purpose and to build confidence in their use.
- WAC could provide a tool for confidence building amongst civil society, for example by:
  - Using them to communicate factors that are important to the safety case.
  - Inviting civil society to influence their scope (this might be done indirectly, via inputs to the wider strategy development for a facility).
  - Utilising independent citizen science to check compliance against WAC.
- There is widespread interest in harmonisation of WAC across Member States and Associated Countries, primarily focusing on harmonisation of the methodology for their 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 programmes, could give confidence, including amongst civil society, that a suite of WAC is fit for purpose and applies 'best practice'.

A key overarching observation is the value of **approaches that impart flexibility** to adapt future waste management practices as new information becomes available (e.g., new waste characterisation data), as new technologies are developed (e.g., emerging treatment techniques), or as strategic decisions are made (e.g., progress identifying a disposal site).

The Subtask 4.3 workshop and the identification and screening of commonly held WAC-related R&D needs and opportunities for future collaboration between Member States and Associated Countries, were documented in an internal memorandum (EURAD Milestone 192). The present report reiterates the 25 recommendations resulting from this work. For inclusion in the updated EURAD SRA, five recommendations, considered to have the highest priority based on expert judgement, were selected from the list of 25. These recommendations were integrated with related recommendations emerging from other ROUTES tasks in a workshop held in December 2022.

The final five WAC-related recommendations distilled for inclusion in the updated EURAD SRA as either strategic studies (StSt) or R&D studies (R&D) were:

- **StSt-4:** Common analysis on disposal strategy for wastes that do not meet the WAC for existing or planned facilities.
- **StSt-9:** Comparison and standardisation of radionuclides (and their speciation) to account for in waste characterisation and WAC.
- **StSt-10:** Benchmarking exercises for the process of WAC development.

- **R&D-2:** Development of characterisation methods to determine compliance of particular wastes with WAC.
- **R&D-5:** Development of methodologies for representative sampling of challenging waste types.

These recommendations were communicated in the form of presentation slides, setting each recommendation into context by identifying relevant EURAD roadmap themes; SRA drivers; expected outcomes and impacts of work in each area; and related initiatives.

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Glossary

BWR – Boiling Water Reactor

CHANCE – Characterization of conditioned nuclear waste for its safe disposal in Europe

CISF – Central Interim Storage Facility (Slovenia)

CS – Civil Society

CSO – Civil Society Organisation

DCIC – Ductile Cast Iron Containers

DU – depleted Uranium

EC – European Commission

EGOS – Expert Group on Operational Safety

ENSDF – Engineered Near Surface Disposal Facility (Ukraine)

ERDO – European Repository Development Organisation

EU – European Union

EURAD – European Joint Programme on Radioactive Waste Management

FAFNIR – Waste conditioning plant for nodular resins (Germany)

FAVORIT® – Concentrate drying facilities (Germany)

FEPs – Features, Events and Processes

GDF – Geological Disposal Facility

HAW – Higher Activity Waste (UK)

HHGW – High Heat Generating Waste (UK)

HLW – High-Level Waste

IAEA – International Atomic Energy Agency

ICS – Interaction with Civil Society

IER – Ion exchange resin

IGSC – Integration Group for the Safety Case

ILW – Intermediate-Level Waste

IWMP – Integrated Waste Management Programme (UK)

KM – Knowledge Management

LILW – Low and Intermediate Level Waste

LIMS – Large Inventory Member States

LLW – Low-Level Waste

LLWR – Low-Level Waste Repository

LoC – Letter of Compliance (UK)

LOG – Laag- en middelradioactief afval Opslag Gebouw (COVRA's storage building for LILW) (the Netherlands)

LWC – Legacy Waste Characterisation

MKG – Miljöorganisationernas kärnavfallsgranskning (Swedish NGO Office for Nuclear Waste Review)

NEA – Nuclear Energy Agency

NEWA – (Modular) De-Watering Facility (Germany)

NGO – Non-Governmental Organisation

NPP – Nuclear Power Plant

NTW – Nuclear Transparency Watch

PMO – Programme Management Office

PREDIS – Pre-disposal management of radioactive waste

PUSA – Powder Resin Transfer Facility (Germany)

PWR – Pressurised Water Reactor

REs –Research Entities

R&D – Research and Development

Radwaste – Radioactive Waste

RD&D – Research, development and demonstration

ROUTES – Waste management routes in Europe from cradle to grave

RWM – Radioactive Waste Management

SIMS – Small Inventory Member States[2]

SF – Spent Fuel

SRA – Strategic Research Agenda

SSB – Self-Shielded Box

THERAMIN – Thermal treatment for radioactive waste minimization and hazard reduction

TSOs – Technical Support Organisations

UMAN – Uncertainty Management in a multi-Actor Network

VLLW – Very Low-Level Waste

WAC – Waste Acceptance Criteria

WMOs – Waste Management Organisations

WP – Work Package

[2] The countries considered to be SIMS are identified in ROUTES Task 5 Deliverable D9.10 [1].

1 Introduction

1.1 Background to ROUTES

"Waste management routes in Europe from cradle to grave" (ROUTES) is one of two strategic studies being conducted as part 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). EURAD commenced in June 2019 and draws participants from over 20 European countries, with an overall budget of nearly €60M [2].

The objectives of the ROUTES work package (WP) 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 research and development (R&D) needs associated with the waste management routes (from cradle to grave), including the management routes of legacy and historical waste, considering interdependencies between the routes.
- Describe and compare the different approaches to characterisation, treatment and conditioning and to long-term waste management routes, and identify opportunities for collaboration between European Union (EU) Member States.

Over the course of its work programme, ROUTES is integrating relevant experience from completed and on-going EU projects, such as PREDIS (Pre-disposal management of radioactive waste) [3], THERAMIN (Thermal treatment for radioactive waste minimization and hazard reduction) [4], CHANCE (Characterization of conditioned nuclear waste for its safe disposal in Europe) [5] and other international initiatives (e.g., IAEA / NEA projects).

Activities within the ROUTES work programme are organised under eight tasks:

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 radwaste characterisation 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 solutions for small amounts of wastes, focusing on disposal strategies for small-inventory Member States (SIMS).

Task 6: Description of the state-of-the-art of 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.

Task 8: Further evaluation of possible waste management solutions for Member States without WAC and with small inventories (SIMS).

1.2 ROUTES Task 4 objectives and breakdown

Well-established WAC or related systems for both pre-disposal and disposal steps help to define a waste management strategy and are a fundamental requirement for a management route to be effective. Task 4 of ROUTES aims to identify and examine WAC used in Member States for different waste management strategies in order to inform development of WAC in countries without WAC / facilities.

More specifically, Task 4 has the following objectives:

- To provide an overview of the current application in Member States of WAC at different stages in the waste lifecycle[3] and to describe mechanisms to implement them.
- To offer a structured approach to support decision-taking of so-called 'no regret' waste management measures, i.e., decisions that do not lead to problems later on.
- To identify R&D needs and opportunities for collaboration between Member States.

These objectives have been delivered via three Subtasks:

- **Subtask 4.1:** *Current use of waste acceptance criteria* – this subtask ran for 15 months from June 2019 and involved production of an up-to-date overview per country on the use of WAC in Member States and some Associated Countries[4], focusing on the use of WAC as a management tool across the waste lifecycle. The resulting report (EURAD Milestone 88) was published on the EURAD website in February 2021 [6].
- **Subtask 4.2:** *Sharing of experience on waste management with and without WAC being available* – this subtask ran from November 2019 until December 2021. It offered a structured approach to support decision taking of 'no regret' waste management measures. This was achieved by examining case studies of waste management activities without WAC, disposal solutions or other technical facilities being available, as well as a series of cross-cutting topics relating to WAC. These informed a gap analysis and a series of observations and recommendations on progressing waste management whilst maintaining compatibility with a range of options for subsequent waste lifecycle stages. An internal memorandum (EURAD Milestone 144) presents the task outputs [7].
- **Subtask 4.3:** *R&D needs and opportunities for collaboration* – this subtask was initiated in January 2022, once other Task 4 activities were complete. It identified and prioritised common R&D needs related to the management of challenging wastes, as well as opportunities for collaboration between Member States and Associated Countries. Subtask 4.3 activities also involved integration of the resulting Task 4 recommendations with those emerging from other ROUTES tasks, for input into the 2023 edition of the EURAD Strategic Research Agenda (SRA), as well as documenting the overall results of Task 4 in the present deliverable report (ROUTES Deliverable D9.9).

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[3] The waste lifecycle (sometimes referred to as the waste cycle or waste management lifecycle) encompasses collection / retrieval and pre-treatment of raw waste (e.g., sorting, drying); waste treatment (e.g., thermal treatment); waste conditioning and packaging, storage, transport (which may take place at multiple stages) and disposal.

[4] Associated Countries are non-EU countries that contribute financially to EU initiatives such as Horizon Europe in order to participate and be treated equally to Member States for the purposes of the programme. Current lists of Associated Countries can be found on the web pages of the European Commission (EC).

1.3 Objectives of this report

This report is the sole deliverable produced under ROUTES Task 4. It summarises the outcomes of ROUTES Subtasks 4.1, 4.2 and 4.3, namely:

- Current use of WAC in Member States and some Associated Countries.
- Key discussion points from the Subtask 4.2 workshop titled "*Sharing experience on waste management with / without WAC available*" held on 14-15 June 2021.
- The results of the gap analysis performed following the workshop including a series of observations and recommendations aimed at supporting the progression of waste management activities when uncertainties remain regarding future stages in the waste lifecycle, particularly disposal end points, and/or when associated WAC are absent.
- Key discussion points from the Subtask 4.3 workshop titled "*R&D needs and opportunities for collaboration*" held on 10 May 2022 via Microsoft Teams (Milestone 163).
- The process for identifying, screening and prioritising commonly held WAC-related R&D needs and the opportunities for potential future collaboration between Member States and Associated Countries on this topic.

In doing so, it responds (alongside other forward-looking ROUTES activities) to the underlying basis for establishing ROUTES, as set out in the 2019 initial EURAD SRA [8, Page. 11], i.e.:

> *"With the purpose of sharing 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, a strategic study (EURAD WP9-ROUTES) has been initiated to look holistically at waste management routes in Europe from cradle to grave. Specifically this will look across the spectrum of challenging wastes, characterisation approaches and waste acceptance criteria established across Europe, and **identify areas of focus for the EURAD in the future**."*

It also underlines the role that strategic studies play in informing the course of future EU collaborative R&D studies.

The present synthesis of R&D needs and opportunities for collaboration is timely, noting that:

- Efforts to develop the proposed scope of EURAD-2 are currently in-flight, including engagement with programme / project partners and update of the EURAD and PREDIS SRAs [9], [10].
- Various WAC-related tasks are also underway within the parallel-running EC PREDIS project on the pre-disposal management of radioactive waste, including examination of waste acceptance systems [11] and the link to waste form characterisation and waste form qualification [12], [13], as well as the development of guidance for formulating generic WAC. Cooperation and collaboration between ROUTES and PREDIS on the topic of WAC has been a guiding principle for both initiatives in order to facilitate wider information exchange and to ensure that they deliver consistent and complementary outputs that progress understanding in the field of WAC development and application [7, §1.4], as summarised in Figure 1. This has been promoted through organisation of several joint webinars, e.g., [14], [15] and joint discussion sessions, e.g., [16], widening participation in both ROUTES and PREDIS workshops, as well as through presentation of the synergies between the two programmes at the 2022 EURADWASTE conference [17], and organisation of a joint EURAD-PREDIS summer school on WAC.

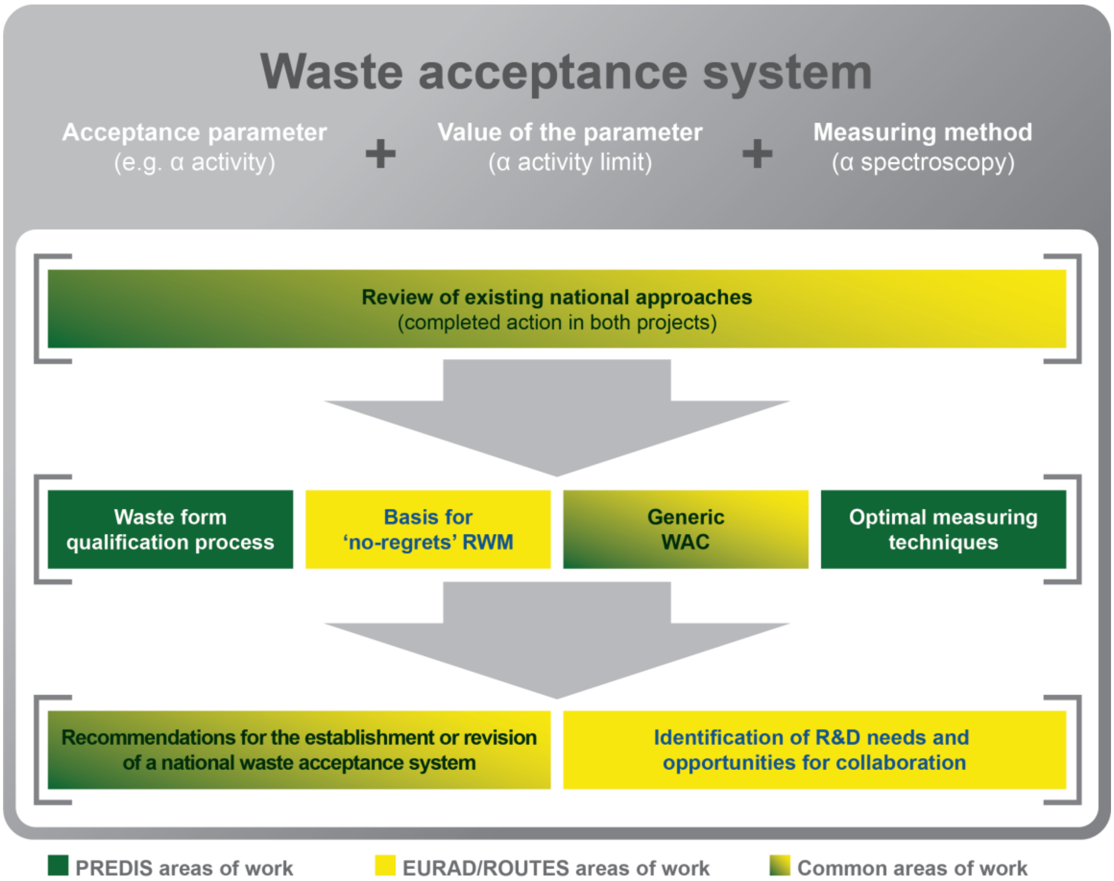

Figure 1 – Collective scope and approach to delivery of complementary WAC-related outputs by the EURAD ROUTES WP and PREDIS project.

- An EC project on harmonisation of practices, regulations and standards in waste management and decommissioning (HARPERS) started in June 2022 [18]. HARPERS aims to:
    - Establish and clarify the benefits and added-value of more aligned and harmonised regulations and standards for prioritised topics related to decommissioning and initial phases of radioactive waste handling.
    - Identify the relevant regulatory differences across Member States and Associated Countries, assess the rationale for the identified regulatory differences and establish the potential for their harmonisation relative to cross border services / facilities for radioactive waste management (RWM), moving to a circular economy in RWM and implementation of advanced technologies in RWM.

  The first twelve months of HARPERS was devoted to identifying recommendations and needs relating to harmonisation and sharing across all aspects of radioactive waste management activities between Member States and Associated Countries for more detailed study later in the project; it can therefore take cognisance of recommendations emerging from ROUTES Subtask 4, which may be highly relevant to the project aims.

1.4 Related initiatives on WAC

Besides the work of ROUTES Task 4 and the PREDIS Project, as mentioned above, there are a number of other recently completed or ongoing international initiatives looking at aspects of WAC development and application. In particular:

- The ERDO working group, which was established to support the development of shared radioactive waste management and disposal solutions for small inventory countries, recently conducted a task to identify 'minimum WAC' for near-surface disposal of very low-level waste (VLLW) and low-level waste (LLW), as part of its Legacy Waste Characterisation (LWC) project [19].
- The NEA's Expert Group on Operational Safety (EGOS), which is a sub-group of the Integration Group for the Safety Case (IGSC) is preparing a report on the role and development of WAC relating to operational safety [20].
- The IAEA also has a range of ongoing activities relating to WAC [21]. These include "*Development of Waste Acceptance Criteria for Low and Intermediate Level Waste*", a Nuclear Energy (NE) Series publication in the final stage of development, as well as several support activities provided to Member States under the Technical Cooperation Programme (e.g., review of existing WAC; assistance in establishing WAC for pre-disposal and disposal; establishing conceptual or preliminary WAC).
- The EC CHANCE project considered WAC in the context of waste characterisation and quality control schemes for conditioned radioactive waste. An important conclusion from this work was that basic assumptions for safety studies or identification of parameters evaluated through WAC could be harmonised across different implementation contexts, but that specific safety relevant parameter values could not, owing to their dependence on the varying national contexts for waste management [22].
- The EC THERAMIN project included proposal of a set of generic criteria for evaluating the disposability[5] of thermally treated wastes. These criteria could be used to evaluate any form of waste product, from any form of thermal treatment, for disposal in any type of facility [23], [24].
- The EC is interested in promoting cross-border collaboration between Member States on sharing technical and licensing practices on final disposal solutions and creating opportunities for the EU-wide market in these areas. An EC study on radioactive waste classification schemes in the EU was recently completed [25] and other initiatives are also ongoing, aiming to promote an aligned, harmonized application of the international regulatory framework in waste management and decommissioning.

[5] The term 'disposability' refers to whether a particular waste can be consigned for disposal (and accepted for disposal at a particular facility).

1.5 Report structure

The rest of this report has the following structure:

- Section 2 summarises the current use of WAC for pre-disposal and disposal steps in Member States and some Associated Countries.
- Section 3 provides an overview of Subtask 4.2 including the outcomes of the Subtask 4.2 workshop and the subsequent gap analysis and recommendations.
- Section 4 provides an overview of Subtask 4.3 including the outcomes of the Subtask 4.3 workshop and the screening and prioritisation of national needs and opportunities for collaboration. Further details on the origin of these needs and opportunities, and the basis for screening decisions are recorded in Appendix A.
- Section 5 presents the methodology used to distil Task 4 recommendations for discussion in a cross-task ROUTES workshop held in December 2022, and the resulting summary of recommendations for subsequent integration into the updated EURAD SRA, published in 2023 [26].
- Section 6 captures the conclusions from ROUTES Task 4.

2 Summary of the current use of WAC

This section recapitulates the findings of the analysis that was performed in Subtask 4.1, conducted in 2019-2020, which reviewed the current use of WAC, as recorded in the EURAD Milestone 88 report [6]. Since this report has already been published, the details are not reiterated here. Nevertheless, notable aspects associated with the following topics are highlighted below for the different Member States and some Associated Countries that were considered within the subtask: the availability of WAC at different stages in the waste life cycle; the development and updating of WAC; commonalities between the requirements contained within WAC; and the actors involved in developing and implementing WAC.

It is noted that the current status of WAC has also been considered within ROUTES Task 5 on "*Radioactive waste management solutions for small amounts of wastes, focusing on disposal strategies for SIMS"*, as reflected in ROUTES Deliverable D9.10 on the "*collection and analysis of actual existing knowledge about disposal options for SIMS*" [1, §3.4]. D9.10 includes some further clarifications on national WAC and how they are applied. It also reflects updates to national WAC made since the completion of the ROUTES Task 4, Milestone 88 report. The analysis and discussion of WAC in D9.10 places a greater focus on SIMS and the differences in WAC availability between SIMS and LIMS, in line with the objectives of Task 5.

2.1 Availability of WAC at the different stages in the waste life cycle

With regard to pre-treatment, treatment and conditioning, and storage, most countries have finalised WAC that are in use for one or more facilities and are applicable to various waste classifications, reflecting the widespread nature of such radioactive waste management practices and the value of WAC as a management tool.

In countries where there are no WAC available for certain waste classifications or life cycle stages, there are various reasons why this is the case, e.g.:

- Waste management programmes are still at an early stage and/or certain waste classifications have only recently been introduced in national legislation. It may also be that a given waste class is not defined within the national radioactive waste programme or through national legislation (this often applies to VLLW).
- WAC are not relevant for the lifecycle stage in question, because no pre-treatment / treatment / conditioning / storage is carried out for certain waste classifications.
- WAC are generally not defined for facilities that accept all waste / material regardless of its characteristics, since the term 'acceptance' criteria implies the potential to also reject consignments to a facility, as well as to require that non-compliances are remediated. This is particularly the case where only one facility exists in a country for handling certain classes of material / waste (e.g., for centralised storage of spent nuclear fuel).
- WAC may not always be present for management activities conducted outside of the country (e.g., Danish combustible waste is sent to Studsvik in Sweden for pyrolysis, SF from Dutch NPPs is reprocessed in France, spent fuel (SF) from research reactors in Austria, Greece, Portugal, Romania was repatriated to the USA and in case of Romania also to Russia).
- Treatment, conditioning, packaging and storage requirements may be incorporated into WAC covering multiple lifecycle stages, but primarily focused on storage and/or disposal.
- WAC are not always defined for lifecycle stages where there is no transfer in the ownership or liability for the waste.

There is much more variation in the status of WAC for disposal, including considerable variation for different waste classifications within individual countries, largely depending on the status of existing and planned disposal routes for different waste classes. For VLLW and LLW, most countries have preliminary or final WAC (for planned or operational repositories, respectively), although some countries are at an early stage of developing waste management / disposal arrangements and do not yet have plans on which to base disposal WAC. In contrast, for intermediate-level waste (ILW) and high-level waste (HLW), most countries do not have any disposal WAC because planning for geological disposal is still at an early stage.

SF management is one of the least developed areas in terms of WAC. Reasons for this may be country-dependent, e.g., the absence of SF in the country, repatriation of SNF to the country of origin, the absence of appropriate disposal facilities for SF, or SF isn't categorised and classified as radioactive waste.

For transport between nuclear licensed sites / users, most countries simply apply IAEA transport regulations / requirements and international agreements concerning the carriage of dangerous goods as WAC for transport (most notably the agreement on the international carriage of dangerous goods by road (ADR), which is mandatory in the EU), without specifying additional requirements. Elsewhere, transport WAC are heavily based on these international regulations and requirements, with extensions to reflect the national context. Transport between facilities on the same site is often not subject to formalised WAC, although there may still be requirements relating to the transfer of waste between facilities or installations.

2.2 Development and updating of WAC

In countries with long-standing nuclear programmes, historic acceptance limits or specifications were typically formalised as WAC to comply with some general rules / norms imposed by the regulator. In contrast, for facilities that are planned / in development, or became operational in the last few years, the WAC were developed during the licensing process of the particular facility (either for treatment & conditioning or for storage / disposal), based on the safety assessment. Often, WAC form part of the safety case or Safety Assessment Report.

Usually, WAC are developed by the WMO or facility operator (which is sometimes the same entity) in consultation with other parties and agreed / approved by the regulator, but in some cases, WAC have been established by the regulator itself. In a small number of cases (for example, in Germany and the Netherlands), the regulator appears not to have had direct involvement in the development of WAC (or related requirements) [6, Table 6].

Most countries have provisions for periodic review and update of WAC, but the frequency varies and is not always explicitly set out. Often, WAC are updated, if necessary, as part of periodic or step-wise relicensing activities for a facility (conditioning / packaging, storage or disposal facilities) and the indicated frequency is related to the periodicity of licence revision / renewal.

Preliminary WAC (for disposal facilities that are planned / in development) are continuously reviewed, and updated from time to time, typically at each major milestone of the development programme.

Other opportunities for updating WAC may be: changes to the legal and regulatory framework, the introduction of new waste types, containers or waste forms, and the desire to integrate the experience accumulated from past operations.

2.3 Commonalities between requirements contained in WAC

Observed commonalities are that WAC (for LLW) devote a lot of attention to radiological characteristics (nuclide activities) and properties (dose rate, surface contamination), but less to physical, chemical, biochemical and biological characteristics or properties. Nevertheless, the WAC of most countries address physical hazards (explosion, fire, …), putrescible materials (i.e., organic matter that is subject to decay through the action of bacteria and/or fungi), waste form stability, voidage, free liquids and prescribe the use of a certain type of container (or containers). Organic and reactive wastes that have the potential to produce gas, complexants and/or free liquids as they degrade generally require treatment to convert them to a more passively safe form prior to conditioning and packaging, particularly where WAC preclude their acceptance for storage and/or disposal.

For geological disposal, long-term safety mainly relies on the host rock as a barrier. Nevertheless, WAC for HLW and ILW disposal still set out specific requirements and/or values for the integrity of the waste package, container and waste form under disposal conditions, reflecting the assignment of safety functions to engineered barriers as well, during both the operational phase and for long-term safety. The applicable WAC are currently preliminary (e.g., France) or generic (e.g., UK) and are therefore expected to be developed further before geological disposal is implemented.

Generic WAC represent a special approach to defining requirements. The development and application of generic WAC is only conducted in a limited number of European countries and within these countries, the interpretation of what 'generic WAC' constitute varies widely:

- Only the UK has developed and applied an extensive system of generic 'WAC' that is integral to its national approach to radioactive waste management (these apply to waste destined for geological disposal).
- Elsewhere, generic WAC are not necessarily a precursor to site- or facility-specific WAC to be developed at a later date, but can also be final requirements. Examples of this are: the generic WAC for storage and discharge of radioactive waste in Cyprus, and the French CSA disposal facility, where both specific and generic criteria are adopted and used at the same time.
- Generic WAC / disposability criteria have also been defined by the IAEA and through collaborative international programmes (e.g., THERAMIN), as a starting point for the development of tailored WAC that are specific to a particular national context and facility.

2.4 Actors involved in WAC

The detailed roles of different parties during application of WAC and compliance verification vary from country to country, with distinct nuances in the responsibilities applicable in each country. In some countries, a single organisation fulfils several roles. Often, several organisations (or representatives of different divisions within a single organisation) are responsible for specific compliance activities. Such cross-over can help to ensure that any non-compliances are identified.

The safety authority (regulator) is generally responsible for approving the framework within which waste management activities are carried out. However, this does not always explicitly include a role in the development and/or application of WAC, nor in the selection or qualification of approaches to determine compliance.

Non-compliances can be detected by a range of different stakeholders including the WMO, waste generators, facility operator or the regulator. The status of a non-compliance, once identified, is often tracked until it is resolved to all parties' satisfaction. In particularly serious cases, the regulatory body may withdraw the license and thus stop operation of a nuclear installation.

The methods used to verify compliance with WAC are quite different among EU countries: from simple radiometric measurements (such as dose rate measurements, often complemented with specific nuclide vector / scaling factors) to more involved methods such as chemical analysis and chromatography for detection of gas generation and identification of the gas. Both non-destructive methods, such as physical inspection, radiometric measurements, or gamma spectrometry, and destructive methods, such as radiochemical analysis, are used to check waste package compliance with WAC either for storage or for disposal.

3 Sharing experience on waste management with and without WAC available

3.1 Overview of Subtask 4.2 and use of case studies

A key activity within ROUTES Subtask 4.2 was an online workshop titled "*Sharing experience on waste management with / without WAC available*" held via Microsoft Teams on 14-15 June 2021 (EURAD Milestone 132). The agenda for the workshop was structured around:

- The presentation and discussion of five case studies of waste management activities in the absence of WAC, a disposal solution and/or some other technical facility (see Section 3.1.1).
- Three cross-cutting topics relating to WAC; their scope and derivation is described in Section 3.1.2.

Participation in this workshop was extended beyond EURAD Partners and End Users to include representatives from PREDIS, ERDO, the IAEA and the NEA, as part of ongoing efforts to promote collaboration and exchange of experiences relating to WAC between all interested parties and initiatives. This has allowed ROUTES to build on discussions at the joint WAC webinars mentioned in Section 1.3. PowerPoint presentations and other workshop materials are available on the EURAD website here.

3.1.1 Case studies

A central theme of the case studies considered under Subtask 4.2 is the dilemma of when to implement final conditioning of radioactive waste in the absence of an established disposal route, as requirements for safe disposal (and associated WAC) are still being determined. This is illustrated in Figure 2.

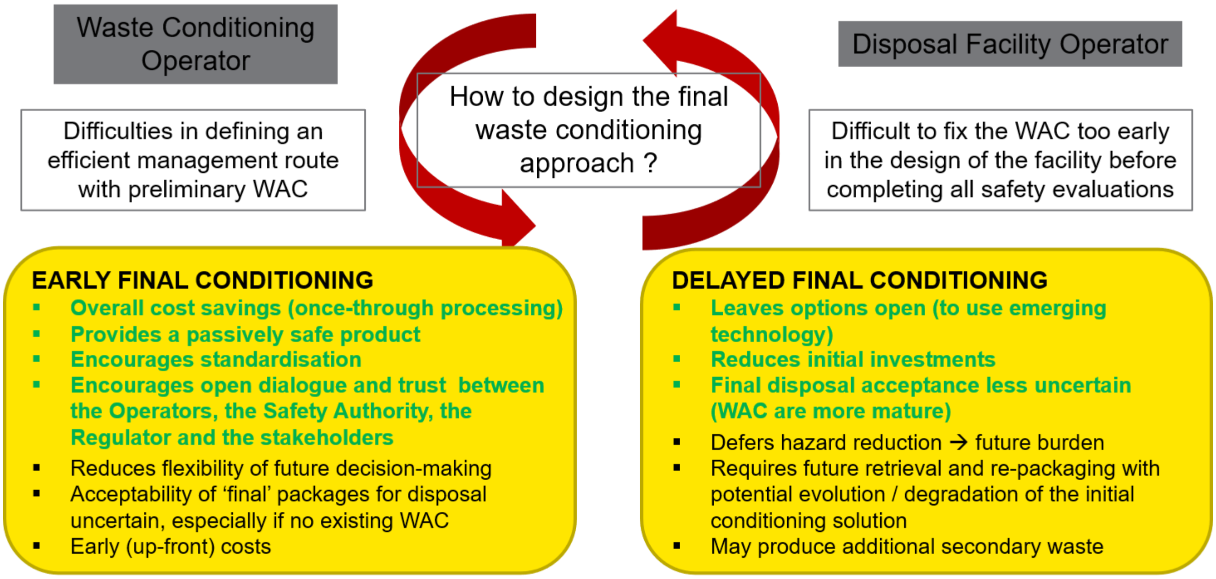

Figure 2 – Summary of the pros and cons of early versus delayed final conditioning of radioactive waste from the perspective of developing WAC for disposal (adapted from a figure originally developed by Orano).

Case studies of waste management experiences were initially identified in national responses to Section 5 of the ROUTES questionnaire [27], [28]. A long-list was drawn up and six were selected by ROUTES Task 4 partners for more detailed study and discussion based on the following considerations:

- Cases that were of the most widespread interest and where detailed information was available.
- Drawing on experiences and perspectives from the different partners and countries involved in Subtask 4.2, including both LIMS and SIMS.
- Allowing comparison of different degrees of waste management (e.g., treatment and conditioning) deployed in the absence of WAC / disposal solutions / facilities.
- Capturing both shallow (i.e., surface or near-surface) and deep geological repositories as waste management end points.

Four case studies (from Ukraine, Greece, the Netherlands and Spain) were considered in detail during the workshop. A fifth case study (from Germany) was shared via email in July 2021; feedback on this case study was integrated into the Subtask 4.2 memorandum. A further case study (from Slovenia) was presented as part of introductory material for one of the cross-cutting topics. The selected case studies are summarised in Table 1.

Table 1 – Summary of case studies considered in ROUTES Subtask 4.2.

Case study	An example of:	Relevant steps in waste lifecycle	Disposal Route	
			Shallow	Geological
Ukraine: Production and management of bituminized waste with varying levels of WAC available at different stages	Treatment and conditioning of waste in the absence of disposal WAC	**Conditioning** for storage – further conditioning for disposal is planned	X	
Greece: Cement solidification of sludges from the liquid waste evaporator (conditioned four decades ago)	Conditioning prior to availability of a disposal facility	**Conditioning** for storage – may require reconditioning	X	
The Netherlands: Storage and processing of a variety of wastes at COVRA	Conditioning prior to availability of a deep geological repository	**Conditioning** (immobilisation / encapsulation) ready for disposal		X
Spain: Management of irradiated reactor graphite to enhance disposability to El Cabril	Treating waste in order to establish a disposal route	**Treatment and conditioning** for ongoing storage and disposal	X	
Germany: Development of different management solutions for spent ion exchange resins at individual NPP sites	Alternative waste management solutions for a common waste	**Variable** (e.g., drying, incineration, regeneration, packaging, etc.)		X
Slovenia: Development of WAC for a specific storage facility without a nuclear licence or legal requirements, and initially without knowledge of the disposal route	Methodology for storage and disposal WAC development, initially in the absence of a disposal site and without the disposal facility design / type being known	**Storage and disposal**	X	

Presentations were made for each case study, followed by group discussion based around the following questions:

1) How do you see the link between current waste management activities and final disposal WAC in your country?
   - What gaps persist between current activities and achieving disposal with respect to WAC? How might these be addressed?
2) Where the disposal route and/or WAC are not yet known, how is waste management being implemented to keep options open?
3) What extent of waste processing is appropriate while this is the case?
   - What are the most important considerations? E.g.:
     - Early processing to improve passive safety / storage arrangements / others? Combined with monitoring?
     - Flexibility (i.e., deferred processing), combined with ongoing research?
     - Conservatism / stringency of requirements for storage?
     - Provision for reconditioning?

3.1.2 Cross-cutting topics

Various topics of interest were identified by ROUTES partners during development of the first Task 4 memorandum [4]. Their scope was refined through planning discussions with Subtask 4.2 partners and three topics were selected for further consideration:

- Generic WAC and the UK disposability assessment process, noting that:
  - Interest had been expressed by some partners in the potential for wider application of generic WAC.
  - Interpretations of what 'generic WAC' constitute vary considerably from country to country.
- The involvement of stakeholders in the development and application of WAC, including:
  - The link between safety assessment and derivation of WAC.
  - Other factors influencing the scope of defined WAC.
  - The role of checking compliance with WAC in providing reassurance to civil society.
- Managing the potential for non-compliances to arise as WAC are iterated, and in particular:
  - What happens if more restrictive limits on waste acceptance are imposed based on e.g., development of the safety assessment for a planned disposal facility?

Introductory presentations were made for each topic, followed by group discussion based around a series of topic-specific questions.

3.2 Subtask 4.2 workshop discussion

This section summarises the key discussion points from the ROUTES Subtask 4.2 workshop. These are presented for each case study and cross-cutting topic and are based on summing-up presentations made by the secretaries for each morning and afternoon session of the workshop.

3.2.1 Session 1 (Monday 14th June, morning)

3.2.1.1 Introduction to session

The following presentations were made during Session 1 of the ROUTES Subtask 4.2 workshop (see slides on the EURAD website here):

- An introduction from the workshop chair.
- Links to wider ROUTES activities.
- Reflections from joint WAC webinars.
- Case study 1: Bituminization of evaporated concentrate at the Rivne NPP in Ukraine: An example of conditioning waste without disposal WAC being available.
- Case study 2: Cement solidification of sludges from the liquid waste evaporator in Greece: An example of conditioning prior to availability of a disposal route.

3.2.1.2 Discussion of joint WAC webinars and other joint initiatives on WAC

Links between the goals and expected outcomes of ROUTES Task 4 and other related initiatives considering WAC were discussed. Two particular outputs from the WAC webinars jointly organised by PREDIS, ERDO and ROUTES [14], [15] were highlighted by workshop participants as areas that would benefit from additional focus in future:

- **Harmonisation of WAC across different countries**, to the extent that this is achievable, would facilitate future waste management. This point is discussed further below.
- The uncertainties and constraints surrounding legacy waste management call **for development of sampling and characterisation methods**. This need arises for various reasons (as discussed in ROUTES Deliverable D9.5 [29]), including to determine compliance with relevant WAC as part of identifying suitable management routes for challenging wastes. ROUTES Task 3, which focuses on waste characterisation approaches, is expected to further explore sampling and characterisation issues currently obstructing the better management of legacy and other challenging wastes.

Methodologies for development and application of WAC are viewed as one area where harmonisation could be possible; harmonisation of criteria themselves may be more challenging (particularly quantitative criteria and criteria for disposal) since these are aligned to national frameworks for radioactive waste management and/or the requirements of the process/facility in question. A coordinated approach in EC, IAEA and NEA projects would be helpful to realise enhanced harmonisation.

It was noted by an IAEA participant that even for the methodologies related to WAC development, some approaches may need to remain country specific. Before thinking about joint WAC, it would help to **harmonise across countries the regulatory frameworks related to management of radioactive wastes**: e.g., dose limits, waste classifications, clearances thresholds, etc.

Regarding harmonisation, experience from ERDO activities has indicated that many WAC are not specifically linked to the safety assessment of a particular repository or facility; such WAC may be shared to ensure that assessments of disposability take account of common factors [19].

The case of **sharing**, whether in terms of common WAC or joint storage/disposal facilities, is a topic that needs to be further explored. **This is a difficult but not unrealistic option**; some sharing is already a reality, and there is widespread support for doing so (for example, 50% of Member States are considering the possibility of shared solutions for disposal according to feedback received on EC Directive 2011/70) [30], [31, Pages 8-9].

Participants noted that finding shared solutions (whether knowledge management, pre-disposal or disposal) depends on the effort put in by different countries, and that small countries will not be able to develop dedicated disposal facilities (particularly geological repositories) to only receive small quantities of radioactive waste. Some participants suggested that sharing experience on the development and application of WAC can be seen as a precursor or enabling step to more extensive shared waste management and disposal activities in future; others felt that it would be desirable to first envisage harmonisation of treatment and conditioning processes and wider use of mobile dedicated facilities for treating common wastes, before thinking about common and harmonised WAC across Member States and Associated Countries.

It was noted that shared facilities need to:

- Demonstrably operate under the framework of relevant EU legislation and IAEA recommendations with all appropriate safety and security arrangements in place to meet national and international obligations.
- Have a shared funding base linked to the amounts and characteristics of wastes being handled from different consigners.
- (In the case of treatment / conditioning facilities) have clear provisions for the repatriation of treated / conditioned waste to the country of origin.

Outcomes from polling of participants in the two joint WAC webinars were discussed, particularly participant opinions on the appropriate extent of pre-disposal activities in the absence of disposal solutions and/or WAC (see Figure 3). As indicated by the figure, opinions on this point are wide-ranging. It was suggested that management strategies for existing challenging wastes should be complemented by consideration of how to minimise future waste generation. For example, activities relating to the licensing of nuclear facilities should seek to prevent the generation of further waste with characteristics that are known to be particularly challenging to manage. It was also noted that the appropriate extent and timing of predisposal activities may vary for waste streams with differing characteristics, depending on the level of uncertainty over likely compliance with future WAC.

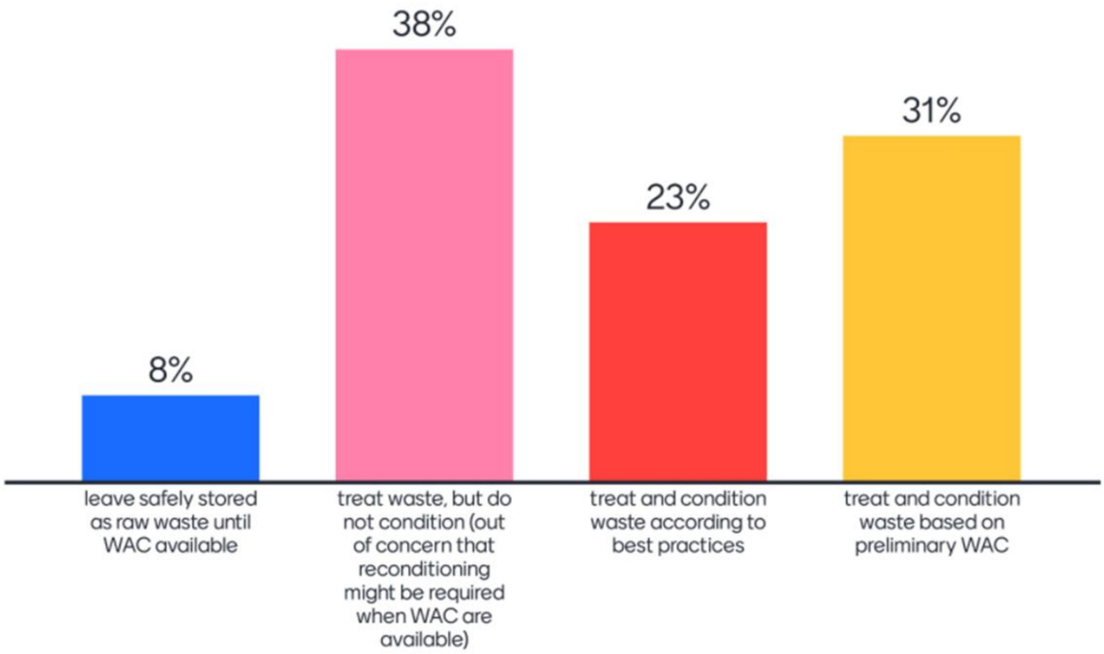

Figure 3 – Responses to a poll of participants in the first joint PREDIS / ROUTES / ERDO WAC webinar held on 21 April 2021, asking "In the absence of disposal solutions and/or WAC, what should be the approach to pre-disposal?". 65 participants responded to this polling question [14].

3.2.1.3 Discussion of Ukrainian and Greek case studies

Two case studies were presented, relating to (i) the reconditioning of bituminized wastes produced without available WAC in Ukraine and (ii) the characterisation of historical cemented sludges in Greece. These presentations highlighted various initiatives taken to **better characterise these legacy wastes** for which information and detailed characteristics have been lost. The Ukrainian case also explores approaches to manage waste packages that are not compliant with new WAC, or whose compliance cannot be verified based on existing characterisation data.

The bituminized evaporated concentrates covered in the Ukrainian case were produced between 1995-2002, prior to disposal WAC being established for the envisaged disposal route (the Engineered Near-Surface Disposal Facility (ENSDF)) in 2008. 739 drums of bituminized waste (148 m^3) were produced. Some non-bituminized conditioned waste has also been produced, including containers of salt cake and dehydrated sludge. The bituminized waste poses a challenge to acceptance against the WAC for ENSDF for the reasons highlighted in Figure 4.

In contrast to bituminized waste in storage elsewhere (e.g., in Belgium), swelling / volume expansion of the wasteform is not of particular concern for the bituminized concentrates that are the subject of the Ukrainian case study. One of the reasons for this is that the waste packages (thick-walled steel drums designed to provide structural integrity during storage) are hermetically sealed and are not 100% filled, which provides some space for expansion of the bitumen compound. This has been confirmed by the experience of storing these drums at the Rivne NPP for more than 20 years.

Radiological	Chemical		Physical
Radionuclide inventory list and activity	Chemical composition	**Complexing and chelating reagents**	Permeability and porosity
Max activity values	**Toxicity**	**Fire resistance**	Structural stability
Radiation resistance	**Free liquid**	**Gassing**	Cavities
Homogeneity	**Explosiveness**	Corrosion resistance of RW packages	Mechanical strength of RW packages
Critical safety	Compatibility	Biological stability	Heat
Dose rate	Leaching		Thermal stability

Figure 4 – List of WAC for ENSDF, coloured according to whether these are met by bituminized evaporated concentrates from the Rivne NPP. Green = met; orange = partially met; red = not met; grey = not yet determined [32].

With regard to the Ukrainian case study, chemical properties as well as physical ones such as explosiveness were thoroughly analysed to prepare for additional packaging (anticipated to involve immobilisation in pre-cast reinforced concrete containers backfilled with additional concrete). The decision to implement this additional conditioning was made because the drums in which the waste is currently packaged do not, on their own, provide a sufficient barrier to the spreading of radioactivity over the long-term following disposal. The additional conditioning will also help to ensure that new containers meet the WAC for the envisaged storage and disposal route, including those related to the structural stability and mechanical strength of the waste packages. The fact that the waste will be enclosed in reinforced concrete containers ensures sufficient thermal stability and fire safety under operational conditions. Further steps are under consideration to maximise fire safety over the long term for example, by placing this waste in the lower layers of the ENSDF; this would make it difficult for an external fire to reach the bituminised waste.

Safety assessments informed by recent waste characterisation activities have allowed some criteria to be revised to remove conservatisms that are not considered necessary in light of the more detailed understanding of waste characteristics that has been gained and the relatively small volume of the waste compared to the ENSDF disposal capacity. For example, free liquids have been determined to be well-distributed at low levels (small volumes) across the waste, rather than concentrated in small areas. As such, they are not expected to contribute significantly to radionuclide mobility.

Cemented sludges discussed in the Greek case were generated from evaporation of liquid waste arising from various sources. 60 drums of various sizes are stored in a surface facility with no climate control or monitoring arrangement. The drum contents are expected to be variable with activities classified as either exempt waste or VLLW. However, there is no information regarding their origin, date of production, initial characteristics, cement specifications or cementation boundary conditions. Both destructive and non-destructive methods are under consideration to generate samples that will be used to identify the radiological characteristics of the waste and prepare it for reconditioning. Destructive methods (including mechanical breakdown into smaller pieces and coring) are preferred because of the anticipated heterogeneity in radionuclide distribution; suitable implementation approaches are being investigated. It is envisaged that the cemented sludge waste will be removed from its drums, mechanically broken down into smaller pieces and, in the cases where it is deemed necessary, reconditioned in a cementitious matrix to meet the WAC for disposal.

Following these two presentations, discussion highlighted the following points:

- Development of sampling and characterisation methods requires **consequent means** implying financial and human resources. It is notable that for the Greek case, the characterisation of cemented sludges has not progressed further because of a lack of financial resources.
- The Greek destructive characterisation method is **not transferable to all countries** where larger volumes of cemented sludges might be at stake. Particulate production during crushing would require active management, but in any case, may not be acceptable within other national regulatory frameworks.
- Criteria on which waste acceptance are based **need to be coherent and careful translation between languages is required**. Some confusion has arisen between clearance and exemption levels in the Greek translation of Directive 2013/59/EURATOM of 3 December 2013.
- The Ukrainian case study demonstrates that the **chemical and physical characteristics are equally important as radiological characteristics from a waste acceptance perspective**. For the particular case of bituminized wastes, the real challenges lie in identifying suitable **treatment methodologies** that should be further developed.

3.2.2 Session 2 (Monday 14th June, afternoon)

3.2.2.1 Introduction to session

The following items were covered during Session 2 of the ROUTES Subtask 4.2 workshop (see slides on the EURAD website here):

- Case study 3: Storage and processing of wastes at COVRA's facilities in the Netherlands: An example of conditioning waste prior to availability of a geological repository.
- Cross-cutting Topic 1: Generic WAC and the UK Disposability Assessment Process.

Subsequent discussion of Topic 1 was based around the following questions:

1) How might generic WAC provide a tool to facilitate waste management (conditioning, packaging, storage and/or evaluation of disposability) for wastes where no disposal route is currently available?
2) Do you see an opportunity / benefit of drawing on generic WAC (or equivalent) in the development of waste management arrangements for countries that do not yet have a disposal facility / WAC? How would you like to see that implemented?
    - Conversely, are there any risks of applying generic WAC?
3) Interpretations of what 'generic WAC' constitute may vary considerably. What interpretations do you consider to be most useful (if any)?

3.2.2.2 Discussion of Dutch case study

The presentation described the implementation of the Dutch radioactive waste management policy, i.e., the consolidation and processing of all radioactive waste at COVRA's facilities into conditioned packages suitable for storage above ground for at least 100 years, followed by disposal in a single deep geological repository. A dual-track disposal strategy is currently being progressed, which involves planning for a national repository and pursuing opportunities for a multinational shared facility in parallel, with a decision on the disposal approach to be made around 2100. A new long-term research programme on geological disposal started in 2020 and will cover a period of at least 30 years, with reviews every five years. Periodic monitoring and inspection of stored packages is conducted in the meantime.

The presentation described COVRA's waste acceptance arrangements, focusing on the receipt of compacted Low and Intermediate Level Waste (LILW) in 200 litre drums for storage in the Low and Medium Radioactive Waste Storage Building (LOG). It was noted that sub-categories of LILW assigned for transport, processing and storage purposes (and used as the basis for established WAC) have limited relevance for disposal, since all these sub-categories could include long-lived radionuclides. Instead, for long-term disposal safety assessment, wastes are grouped into families based on their anticipated behaviour in a disposal environment in order to estimate radionuclide source terms. This grouping considers waste inventories (particularly of long-lived mobile radionuclides) as well as the origin, and physical / chemical properties of the waste.

Waste management strategy in the Netherlands involves the early conditioning of waste, before the nature of the disposal site and design of the disposal facility are known. Various approaches are applied to manage this uncertainty:

- Consolidating all waste in one place for management by a single organisation increases the safety and security of storage, pending disposal. This allows time for ongoing research into safe disposal, as well as the provision of funding for disposal.
- The dual-track disposal strategy means that the Netherlands is not dependent only on a shared (international) disposal solution being realised. The value of this strategy is that both solutions can be promoted, monitored, developed and compared in parallel, whilst retaining flexibility to change track and place an emphasis on one or other approach as and when necessary.
- Regular monitoring of waste package performance during storage is conducted, with provision for reconditioning of packages, if necessary. Inspections are conducted every 15-20 years; effectively this coincides with the rolling stewardship of the waste, each time by a new generation of the workforce at COVRA over the course of the long storage period. Monitoring and inspection of waste is facilitated by the storage approaches implemented (e.g., no lids on packages). In discussion it was noted that there also need to be sufficient provisions for knowledge management over 100(+) years of storage.
- Established waste acceptance requirements for storage are expected to be at least as stringent as those for disposal.
- Ongoing research into disposability is supporting continued improvements in WAC.
- Simple assumptions about the nature of the disposal system underpin the safety assessment for geological disposal whilst the site is not yet known.
- Conservative assumptions are made in disposal safety assessment calculations.

It is noted that monitoring of waste packages during long-term storage is under consideration in WP7 of the EC PREDIS project (focusing on cemented waste packages) and the current State of the Art of strategies, methods and procedures for monitoring during long-term storage was captured in a 2021 report [33]. Exchanges between ROUTES and PREDIS partners could enable the link between monitoring approaches and WAC to be further explored. Also of relevance is the work of the EURAD MODATS WP which, although focused on repository monitoring, will include examination of methods to measure, treat, analyse and manage monitoring data in a consistent manner [34].

It was pointed out in discussion that the long storage timescale applied in the Netherlands may give the impression that nothing needs to be done now. This could result in a lack of political urgency, particularly considering the fluidity and short timescales of national government. It was emphasised that lead times for implementing disposal are long (many decades), and that implementing a disposal solution should therefore not wait until 2100.

Small volumes of unusual wastes are known to challenge existing WAC. Targeted, cost-effective conditioning solutions may be required for these wastes, potentially including thermal treatment.

3.2.2.3 Discussion of cross-cutting topic 1 (on generic WAC)

A representative of Nuclear Waste Services (NWS)[6], outlined the UK Disposability Assessment process, which is used to assess the compatibility of higher activity waste (HAW[7]) packaging proposals with requirements for safe disposal at a UK Geological Disposal Facility (GDF). Since the UK currently does not have a site for geological disposal no formal disposal WAC exist, as yet. In order to allow packaging of waste for disposal in a future UK GDF to progress, the UK has developed generic specifications for three types of host rock: higher strength rock, lower strength sedimentary rock and evaporites.

Waste owners submit proposals for waste packaging to NWS, which uses the most constraining parameters applicable to these three geological environments to evaluate disposability (e.g., the maximum envisaged waste package stack height). Proposals assessed to be compatible are endorsed via a Letter of Compliance (LoC). NWS assures the continued endorsement of packaging proposals (and produced packages) via the Package Assurance function, which uses various activities (periodic review; cross-cutting reviews; technical audits; updates to disposability assessments) to ascertain and/or maintain the validity of endorsements.

Scotland has a different policy for the disposal of HAW located in Scotland than that applicable to the rest of the UK, namely disposal in near-surface facilities, as near to the site where the waste is produced as possible. However, since Scotland has not developed an analogue or alternative to the Disposability Assessment process, it is still used to assess the compatibility of Scottish waste packaging proposals with near-surface disposal.

In the subsequent discussion, approaches to defining WAC and to assessing proposals for geological disposal adopted in France, Italy and Sweden were discussed and the following points were noted:

- The approach to develop WAC and ensure that waste packages are compliant with WAC is broadly the same in France as in the UK. The main difference is that in France, preliminary WAC are associated with a particular site and facility proposed for geological disposal, whereas in the UK, preliminary 'WAC' are generic in nature, i.e., not linked to a particular site or facility.
- Italy applies a similar disposability assessment approach to the UK. Flexibility for future waste management is imparted by postponing the conditioning of solid ILW and packaging this waste in high integrity ductile cast iron containers with no matrix.
- SKB (Sweden) has set out a range of predefined processes for conditioning and packaging waste. Waste packagers should make use of one of these. If something else is required that is not pre-approved, packagers need to submit appropriate arguments to the repository operator justifying the proposed approach. A similar approach is followed at the Low Level Waste Repository (LLWR) in the UK.

Uses of high integrity containers in the UK were discussed, citing the current use of Ductile Cast Iron Containers (DCICs) to package dried spent ion exchange resins for disposal as an example. It was noted that there are concerns around the amount of voidage present in some of these waste packages. LoCs for high-voidage waste packages incorporate a caveat stating that acceptable levels of in-package

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[6] Nuclear Waste Services (NWS) was created in January 2022 as the single organisation responsible for radioactive waste management and disposal in the UK. It brings together expertise from LLW Repository Ltd (responsible for operating the LLWR since the mid-1950s), Radioactive Waste Management Ltd (responsible for implementing a GDF) and the Integrated Waste Management Programme (IWMP) (responsible for exploring the potential for innovative, streamlined and risk-informed approaches to management across the whole UK radioactive waste inventory).

[7] The term applied in the UK to radioactive waste destined for geological disposal.

voidage for disposal are uncertain and requiring that provisions are made to infill the voidage with suitable material if deemed necessary in future.

A common issue identified by several workshop participants was that interim waste management measures may be required if a long period of surface storage is foreseen prior to disposal. An example from the UK makes use of another type of high integrity container, the Self-Shielded Box (SSB). This thick-walled, ductile cast-iron container is being used at Sellafield for interim storage of spent fuel in order to facilitate emptying and decommissioning of legacy facilities. NWS is currently undertaking work to assess the disposability of SSBs to the GDF; if this is not feasible then repackaging for disposal would be required.

The packaging of High Heat Generating Waste (HHGW) was discussed. The UK does not yet have final designs for waste packages for HHGW disposal, since their design will be driven by the geological environment of the GDF, which is yet to be determined. A range of interim specifications and precursor designs are currently being developed. These are bounded by certain requirements for safe storage and disposal, but retain flexibility to be adapted once the conditions at the disposal site are known. These interim specifications will inform development of WAC for disposal of HHGW.

There was discussion around moving from generic specifications to WAC for a specific disposal facility, particularly concerning the relative scope of generic specifications versus WAC. The presenter from NWS noted that whilst WAC will need to be consistent with generic specifications, facility specific WAC are expected to be less constraining than these specifications, which are intended to be bounding of any of the disposal concepts currently under consideration by NWS. When a specific disposal concept / design is selected, some of the generic specifications that don't apply to this concept could be relaxed. For example, if disposal in an evaporite were pursued, limits on heat output from the waste could potentially be relaxed, since concerns over thermal impacts on cementitious or clay barriers are of limited relevance to the generic disposal concepts applicable in this geological environment.

When asked whether generic specifications could lead to unreasonably conservative criteria, the presenter from NWS responded that one would likely continue to use the same waste packages in a site- / facility-specific context but might have different demands on proof of performance of those packages when going from generic specifications to WAC. Margins / tolerances will, in any case, be factored into package performance so that any relaxation of requirements may not make a pronounced difference to the package designs. Over-engineering packaging approaches is considered preferable to the risk of needing to repackage waste if it is not done appropriately the first time around.

3.2.3 Session 3 (Tuesday 15th June, morning)

3.2.3.1 Introduction to session

The following presentations were made during Session 3 of the ROUTES Subtask 4.2 workshop (see slides on the EURAD website here):

- Case study 4: Graphite management in Spain: An example of treating waste in order to establish a disposal route.
- Topic 2: Role of civil society and other stakeholders in the development and application of WAC.

Subsequent discussion of Topic 2 was based around the following questions:

1) Should WAC have a role beyond ensuring that the requirements of the safety case are met?
2) Does the role of WAC as a demonstration of fulfilling the safety case have implications for who should be involved in checking compliance?

3.2.3.2 Discussion of Spanish case study

Presentation:

The presentation provided details about challenges related to the management of graphite waste in Spain from two origins:

- Graphite from the JEN-1 research reactor (material testing reactor).
- Graphite from the Vandellòs I NPP (gas-cooled reactor), consisting of:
  - 18,000 graphite sleeves (mass of ±1,000 tons)
  - Graphite moderator pile (mass of ±2,600 tons)

The graphite of JEN-1, after its dismantling, was characterised at the CIEMAT research centre. The radiological inventory of the graphite allowed for its disposal without treatment. A large proportion of this graphite was managed as VLLW. It was conditioned in cubic containers, to form six monoliths of the types C2-a and C2-b. These monoliths met WAC for their specific type and were consequently disposed at the El Cabril near-surface repository.

The graphite of Vandellòs I is still kept on the site of the now dismantled NPP. The graphite pile is in a safe enclosure (for 25 years) located inside the reactor building. The graphite sleeves have been removed from the reactor; they were initially stored in silos and were then pre-treated (crushed) and packaged in 240 cubic containers (boxes) of the type CME.

Unlike the graphite from JEN-1, the graphite from the sleeves is "challenging" waste. Its radiological inventory surpasses the maximum allowable C-14 content of El Cabril. Additional specific challenges are:

- Characterisation (how to take samples of graphite from its current location, find nuclide vector, avoid producing secondary waste).
- Treatment (reduction of the C-14 content to make the waste compatible with El Cabril disposal WAC, as far as possible).
- Conditioning (resulting in a wasteform with long-term stability).

The case study presentation then focused on the crushed graphite from the sleeves.

The main challenge of the characterisation work conducted by CIEMAT has been to define a methodology to determine C-14 and H-3 in the absence of a suitable correlation nuclide vector and that also takes account of volatile nuclides. This work was presented in the workshop (see Slides 8-11).

The ultimate aim of ongoing R&D is to define a suitable management route for the graphite from the sleeves in which retrieval, treatment and conditioning are performed on site. Appropriate techniques and methodologies are being investigated for:

- Retrieval (conformity of the graphite powder with the applicable WAC).
- Treatment (C-14 reduction by chemical treatment, thermal treatment and electrochemical treatment in molten salt are being investigated).
- Conditioning (cement-based, geopolymeric, and glass matrices are being investigated).

Ideally, C-14 could be removed to such an extent that all graphite waste is compatible with disposal WAC for the El Cabril near-surface disposal facility, which accepts VLLW, LLW and some ILW. For any remaining graphite waste that fails to meet these WAC, the alternative solution is geological disposal in an intermediate depth repository.

Questions and discussion:

The question was raised by the audience whether on the basis of the performed tests, there is confidence that treated and conditioned graphite will be able to meet the radiological WAC of El Cabril.

The presenter confirmed that the only radionuclide of concern from this perspective is C-14. He noted that leaching tests have shown that the migration of this nuclide out of the graphite matrix itself is very slow, and C-14 retention is further improved by immobilising the waste in a surrounding matrix. This was observed for cement-based, geopolymeric, and glass matrices. No volatile C-14 was observed and graphite waste is not susceptible to any degradation processes facilitated by microorganisms.

As such, the tests performed provide confidence that treated and conditioned graphite will be suitable for disposal at El Cabril. Moreover, the test results provide support for alternative conditioning solutions. This case study is especially interesting for other countries that also have irradiated graphite in their radioactive waste inventory[8].

3.2.3.3 Discussion of cross-cutting topic 2 (on stakeholder involvement).

Presentation:

The presentation focused on the topics of transparency, Civil Society as a stakeholder, citizen science[9], whistleblowers, and the independence of WMOs. Key points for each topic are noted below.

Transparency: This is highly important. It is a key element to ensure accountability and public involvement.

WAC link the different radioactive waste management processes. As such, they are not stand-alone requirements, but play a central role in waste management. Public access to how WAC are defined and implemented is therefore crucial for the transparency of radioactive waste management.

The establishment of WAC at an early stage, and as part of public procedures (such as Environmental Impact Assessments), would contribute significantly to the justification of the production of the associated wastes (amounts, forms, even existence). If a given technology produces a waste that will be difficult to manage, the selection of that technology should be considered carefully before its implementation (see also discussion in Section 3.2.1.2).

Civil society as a stakeholder: The presenter expressed his regret that Civil Society representatives are generally not invited to workshops organised by e.g., the IAEA or NEA, even if they are mentioned in associated publications.

Civil Society is not everybody. It encompasses only those people who want to be involved (with a direct interest) and those who have to be involved (with crucial knowledge or an important point of view). It includes the following groups:

- People for whom a waste management facility will have a direct impact on their life (living around the facility or with transport to / from the facility passing by).
- Non-governmental organisations (NGOs), representing certain groups of citizens and having expertise.

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[8] This topic is of particular interest for many IAEA Member States. Therefore, the IAEA has, over the last few years, conducted several projects focused on the management of graphite from research reactors and NPPs. A dedicated IAEA document on characterisation and conditioning of graphite waste is close to being published and another one, addressing disposal aspects is under development.

[9] Citizen science is any activity that involves the public in scientific research and thus has the potential to bring together science, policy makers, and society as a whole in an impactful way [35].

- Academic experts (being a source of knowledge, but also offering an independent second opinion).

Citizen science: As part of stakeholder involvement, citizens and NGOs can take measurements and/or samples and make use of citizens' laboratories (e.g., ACRO, CRIIRAD, Umweltinstitut München) or academic laboratories. Thus, an alternative source of primary data can be established to support an independent second opinion.

Whistleblowers: It generally takes some time before a whistleblower seeks wider (external) attention in relation to an identified concern. Before that, he / she usually tries to send warnings within his / her own organisation. Only if he / she is met with defensive reactions internally, the whistleblower may approach an NGO.

The first step carried out by an NGO is to check the quality of the information and ask for external expertise. If the information is verified, then the NGO can bring the problem to public attention, while at the same time trying to protect the whistleblower.

The presenter observed that experience has shown that nuclear stakeholders do not react constructively to whistleblowing within their own organisations.

Independence of WMOs: According to the presenter, WMOs are not independent actors, because:

1) A WMO is not legally required to be independent, unlike e.g., Safety Authorities.
2) People working for the WMO have a 'professional bias' (high degree of technical involvement making it difficult or impossible to have a neutral, objective viewpoint).
3) A WMO can undergo pressure from other primary stakeholders. Examples suggested by the presenter are:
   - SKB (owned by nuclear operators) not being critical about copper corrosion issues, as indicated in discussion of corrosion studies and associated reference materials on MKG's website (see, for example [36]).
   - COVRA (independent state-owned organisation, but having 'revolving doors' in terms of staff exchange with governance and operators in the Netherlands) avoids debate on disposal after storage.
   - JAVYS (independent state organisation, but a solid part of the 'nuclear bubble') use of generic WAC could degrade quality control over international waste processing in Bohunice.

The presenter stressed the importance of securing the highest possible level of independence for a WMO. This makes interaction with all other stakeholders easier (because of higher WMO credibility), although more labour-intensive (more questions and viewpoints to be taken into account).

Equally important is to secure credible and accepted independent feedback mechanisms. Existing examples are:

- Sweden: independent Civil Society secretariats (MKG and MILKAS) and an environmental court.
- France: independent Local Information Committees (CLIs in French).
- Germany: an independent oversight group formed by Civil Society and other stakeholders.

The presenter also noted historic examples exist in which these and similar mechanisms were unfortunately overruled by the WMO (e.g., in the UK, Czechia, Slovenia, Germany, France, Sweden).

Presenter's conclusions: In general:

- Transparency is a vital issue; in the case of WAC development and implementation, it is a key element to ensure accountability and public involvement.
- Civil Society is still under-represented in the decision process and the implementation work.
- Whistleblowing is not perceived as a constructive tool for improvement, and is often not at all appreciated by nuclear stakeholders.
- WMOs are not considered, in practice, to be independent. They have to become more independent to increase the perceived integrity of their work.

Questions and discussion:

An NEA representative asked what the presenter means by 'overruling' (in the context of the above discussion on independence of WMOs). The presenter replied that, for example, in Czechia, a public participation process on waste management, modelled on a Swedish precedent, was set up in which citizens, NGOs and other Civil Society representatives took part. The aim was to come up with recommendations for the WMO. However, during this process SURAO became discouraged, was not receptive anymore and halted the initiative. Another example from the UK was cited, where for the fourth time a public participation process was set up, with the aim to come up with recommendations for GDF siting and technological choices. The WMO and officials found previous engagement processes brought too much complexity to planning discussions, and this was felt by the presenter to be a contributing factor in their failure. In France, officials reportedly tried to silence several CLIs.

A ROUTES participant asked how to interpret the term 'nuclear bubble' (again, in the context of the above discussion). The presenter replied that in small countries or in SIMS, the number of people working in the field of nuclear science and technology is relatively small and that this can be regarded as a bubble of expertise in the wider community. This can be overcome in two ways: (1) by facilitating international exchange of experts, and (2) by building-in mechanisms to decrease the possibility of a conflict of loyalty when somebody starts to work for another organisation (e.g., mandated time spent working outside the nuclear industry).

A representative from the PREDIS project remarked that he was surprised to find out that in some countries WAC are not made public. The presenter responded by pointing out that the justification for waste management and the production of waste cannot be separated and that parties involved in a public participation process should be aware of this. There is also an industrial aspect to waste management. On the other hand, the nuclear industry should realise the complexity of managing radioactive waste and the wider interests this engenders. In the Czech case mentioned earlier, this mutual understanding was lacking, which ultimately led to SURAO stopping the process.

3.2.4 Session 4 (Tuesday 15th June, afternoon)

3.2.4.1 Introduction to session

The following presentations were made during Session 4 of the ROUTES Subtask 4.2 workshop, which focused on cross-cutting topic 3, i.e., managing the potential for non-compliances to arise as WAC are iterated:

- Managing new criteria and more restrictive limits imposed by the safety report of the planned near-surface repository in Belgium.
- Experience in Slovenia with operating the Central Interim Storage Facility (CISF) for small generators, initially without WAC and later on with imposition of criteria for storage and for disposal.

Subsequent discussion of Topic 3 was based around the following questions:

1) How can the potential for retrospective non-compliances resulting from WAC updates be managed?
   - Is early awareness / monitoring key?
2) What experiences are there from elsewhere (not just Slovenia and Belgium)?
   - Note the relevant experience from the UK presented during Topic 1 discussions (see Section 3.2.2.3).

Slides are available on the EURAD website here.

3.2.4.2 Discussion of cross-cutting topic 3 (on managing potential future non-compliances)

Presentation 1 (Belgium):

Certain new criteria introduced in the WAC for the near-surface disposal facility to be constructed in Belgium are, in practice, difficult to meet by waste generators. The concerned 'critical' criteria are related to the insensitivity of the cemented waste to the alkali-silica reaction or delayed ettringite formation, and to the content of mineral chloride ions, sulphate and cellulose materials in the waste. As such, these criteria are threatening to disrupt the industrial process of waste removal from the sites of the generators.

The solution proposed by ONDRAF / NIRAS consists of three elements:

1) Future modifications to the safety report. R&D is continued, to support future relaxation of 'critical' criteria.
2) Guidance to waste generators on sorting of raw waste. The aim of this is to make waste fluxes 'mono-problematic', so as to simplify the future demonstration of the compliance of specific waste fluxes to the WAC.
3) Modification of the acceptance system. Under certain conditions, non-conditioned mono-problematic waste may be accepted for treatment and conditioning and for storage. The conditioned mono-problematic waste then has to stay in storage for at least as long as until R&D has shown the acceptability of the associated waste family for disposal and the safety report has been modified accordingly.

Presentation 2 (Slovenia):

The CISF facility in Brinje was used in the 1980's and 1990's for storing low and medium activity waste from medical, industrial and research applications. It was operated by the Jozef Stefan Institute (JSI) but in 1999 this responsibility was transferred to ARAO, in the context of a legislation reform.

ARAO was faced with the challenge of bringing the existing storage situation in line with new requirements. Alongside refurbishing and expanding the storage facility in Brinje, they also developed new WAC. The aim was for ARAO to be able to take over all waste from small generators and to prepare it for future transport, while at the same time making sure that waste generators assess the acceptability of their waste with respect to certain criteria.

The initial WAC produced in 2001 were basic, following international practice and without detailed requirements. Subsequent versions gradually became more detailed, but did not yet take account of disposal. Preliminary WAC for disposal in the LILW near-surface (silo) repository were only developed from 2008 onwards.

Questions and discussion (Belgium):

A ROUTES participant asked what will happen with already-conditioned waste that is not compliant with the more restrictive criteria put in place, if based on the Safety Report the criteria for final disposal may not be relaxed. The presenter answered that this is a calculated risk, but from the ongoing discussions with the safety authorities the WMO is confident that the criteria can be further relaxed.

A related question concerned how easy it would be to recondition waste that does not meet the more restrictive criteria. The presenter specified that waste reconditioning will be considered only if the criteria may not be relaxed. As an alternative, the disposal route could be changed and non-compliant waste that has already been conditioned could be disposed of in the geological repository. The presenter also pointed out that in Belgium up to now, a disposal facility for radioactive waste has never been licensed. So, the safety authority tends to be very conservative and this sometimes leads to restrictive criteria that are not feasible to meet. Ongoing liaison with waste generators would help to ensure that developing WAC are practicable.

An NEA representative asked about the management of alpha-bearing waste. The presenter answered that in Belgium this waste category is not planned for disposal in the near-surface disposal facility but, rather, in the geological repository.

The NEA representative also asked about the implementation of WAC where conditioning is carried out by the waste generator. The presenter responded that the conditioning processes applied by waste generators need to be ‘qualified’ by the WMO. This means that ONDRAF / NIRAS supervises the methods applied by the generator to ensure that they can produce waste that meets the applicable acceptance criteria. Also, all WAC applicable across the waste life cycle, including those for conditioned waste, have been developed by the WMO in consultation with the waste generators. In the near future, legislation will take effect that will also give the safety authorities a role in new WAC development, which will be to check whether the proposed WAC comply with certain general rules.

An example was cited of experience in France with waste conditioned prior to commissioning of the surface disposal facility Centre de l’Aube. For those waste packages, a long-term collaborative programme of re-characterisation, re-categorisation and reconditioning has been performed (and is still ongoing).

A ROUTES participant elaborated on a related example of alpha-bearing waste destined for geological disposal in France. France has a large inventory of this waste, dating back as far as the 1990’s (or earlier) that is not compliant with the current safety case for the geological repository. The general approach is for the repository design to be adapted (if possible) if the waste is already conditioned, and for the envisaged conditioning process to be adapted, if the waste is not yet conditioned. Nevertheless, finding an appropriate solution and the right balance between reconditioning versus geological disposal is an iterative process requiring discussion between waste generators, WMOs and regulators.

Questions and discussion (Slovenia):

A participant asked about the philosophy for developing WAC for the storage facility and if they had been carried out with future waste management activities in mind. The presenter responded that WAC development in 2001 had been urgent and the WAC had been kept as simple as possible, with a view to keeping all options for future waste treatment and conditioning open. It was also noted that these WAC for the storage facility were developed without knowing the future criteria for final disposal.

An NEA representative asked about the management of alpha-bearing waste. The presenter indicated that calculations will be made in order to decide if the alpha-bearing waste can be accepted in the silo-type repository to be implemented in Slovenia.

The NEA representative also asked about the implementation of WAC where conditioning is carried out by the waste generator and, in particular, what controls are in place to verify compliance with WAC (and with the principles for establishing WAC) in such cases. In the context of the Slovenian case study, the presenter mentioned that the nuclear regulatory authority checks fulfilment of WAC and noted that regular inspections are performed by them to check the process documentation.

3.2.5 Feedback on case study distributed after the workshop

A PowerPoint presentation exploring a further case study: development of different management solutions for spent ion exchange resins at individual NPP sites in Germany (an example of alternative waste management solutions for a common waste) was distributed by email after the workshop. This is available on the EURAD website here. Acronyms used in the presentation are defined in the list at the front of this report.

Workshop participants were invited to comment on this case study, giving consideration to the following aspects:

- The link with final disposal WAC (to the extent that this is known).
- Keeping waste management options open.
- Specific boundary conditions (e.g., storage requirements, the need for passive safety, monitoring, ongoing research, provisions for reconditioning, …).

Presentation:

Ion exchange resins (IER) are used to remove activity from cooling water at various NPP sites in Germany, including boiling water reactors (BWRs) and pressurised water reactors (PWRs). Both powdered and nodular resins are used. The spent IER are packaged in 200 litre drums for storage at the NPP sites.

Disposal to the Schacht Konrad facility for non-heat-generating waste is planned (this is expected to become operational in 2027). However, the raw waste poses challenges to compliance with associated WAC, owing to its residual water content (typically ~40-55 % by mass) and flammability.

Various modular, mobile facilities have been developed for transferring the waste to robust shielded containers (MOSAIK® II drums or Gusscontainer Type VI cubic containers) followed by in-container vacuum drying (PUSA / FAFNIR facilities for vacuum transfer; NEWA and FAVORIT® facilities for dewatering / drying). These facilities can be adapted to meet the needs of different NPP sites. This combination of conditioning and packaging allows disposal WAC to be met without the need for cementation of the waste.

Feedback:

The following observations were made in relation to this case study:

- Management of spent ion exchange resins is described comprehensively.
- In Czechia, the NPPs are of Russian type reactors. The activities of spent ion exchange resins are less than those associated with Western reactor designs. Nevertheless, the ion exchange treatment activities described in the presentation correspond to those conducted in Czechia.

3.3 Gap analysis and recommendations for 'no regret' waste management decisions

This section provides a high-level gap analysis of knowledge gaps, considering 'ideal' situations where final WAC for disposal are available during upstream waste management activities, as well as situations where only preliminary, draft or even no WAC for disposal are available.

The gap analysis has been performed with reference to the various case studies and cross-cutting topics that were discussed during the Subtask 4.2 workshop, as described in Section 3.2. It distinguishes between routes leading to surface (or near-surface) disposal and routes leading to geological disposal.

The intention of the gap analysis is not to be critical of non-ideal waste management approaches but rather, to consider how historic and current experiences can inform the planning of future pre-disposal activities (characterisation, treatment, conditioning and storage)[10] that have to proceed in the face of ongoing uncertainties relating to disposal conditions and/or disposal WAC. Some of the gaps highlighted in the analysis have already been, or are in the process of being, addressed.

The gap analysis feeds into Section 3.3.2, which provides a series of recommendations for 'no regret' waste management measures and decision making. It will also inform activities under Subtask 4.3 to identify R&D needs and opportunities for collaboration relating to the management of challenging wastes, particularly in relation to maintaining compatibility with options(s) for disposal.

3.3.1 Gap analysis

Table 2 documents the principal knowledge gaps in waste management activities associated with the different case studies and cross-cutting topics that were discussed during the Subtask 4.2 workshop, and maps these against applicable stages in the waste lifecycle: **Ch** = characterisation (noting that this can be conducted at multiple stages); **Tr** = treatment; **Co** = conditioning; **St** = storage; **Di** = disposal. Stages where knowledge gaps are located are shown in dark green; other affected stages are shown in pale green.

Cross-cutting topic 2 on the role of stakeholders in the development and application of WAC (Section 3.2.2.3) is not included in Table 2 because associated knowledge gaps are primarily applicable to the methodology for WAC development, rather than specific stages in the waste lifecycle. Associated observations and recommendations for so-called 'no regret' waste management decisions are discussed in Section 3.3.2.6.

[10] No experiences pertaining to radioactive waste transport have been identified that have an influence on the ability to make 'no regret' waste management decisions.

Table 2 – Knowledge gaps associated with case studies and cross-cutting topics discussed at the ROUTES Subtask 4.2 workshop. Ch = characterisation; Tr = treatment; Co = conditioning; St = storage; Di = disposal. Stages where the knowledge gaps are located are shown in dark grey; other affected stages are shown in pale grey; unaffected stages are without colour.

Source / Reference	**Relevant stages in waste lifecycle**					**Description of gap(s)**
	Ch	**Tr**	**Co**	**St**	**Di**	
Ukrainian case study: Reconditioning of bituminized wastes produced without WAC being available (see Section 3.2.1.3)	dark grey	pale grey	pale grey		dark grey	Disposal WAC were not available at the time the waste (evaporated concentrates from Rivne NPP) was conditioned (in a bitumen matrix). The disposal route (near-surface disposal at the ENSDF) and disposal WAC are now defined. The bituminized waste is now known to be unsuitable for direct disposal to the ENSDF and requires reconditioning. The waste needs to be (re-)characterised in detail (including physically and chemically) so that a suitable reconditioning method can be established. A related benefit is that the additional characterisation is allowing the disposal WAC to be fine-tuned taking account of the significance of the waste stream for the disposal safety assessment.
Greek case study: Cement solidification of sludges from liquid waste evaporator (see Section 3.2.1.3)	dark grey	pale grey	pale grey	dark grey	pale grey	Sludges were conditioned (in a cement matrix) without knowledge of the disposal route. No records have been kept from when the wastes were conditioned and they have been stored for around 40 years in poor conditions, such that the packages require reconditioning prior to disposal. The wastes continue to be stored in the same facility. The waste needs to be characterised, in this case, potentially using destructive techniques, so that a suitable reconditioning method can be established. A decision has not yet been taken on the characterisation approach to be deployed. The disposal route and associated disposal WAC remain unknown.
Dutch case study: Storage and processing of wastes pending availability of a deep geological repository (see Section 3.2.2.2)	pale grey	pale grey	pale grey	pale grey	dark grey	Government policy is for above-ground storage for at least 100 years, followed by geological disposal. The waste management strategy is based on early conditioning (for LILW, this is in a cement matrix), in combination with measures for optimised storage (centralised location, extensive monitoring and inspection) and a long-term research programme into geological disposal. The disposal route and associated disposal WAC remain unknown. The long storage timescale may give rise to a lack of political urgency for finding a permanent solution (disposal), and consequently, for understanding the requirements for safe disposal at a particular site and for developing disposal WAC. Moreover, the waste categories assigned for transport, processing and storage (and used as the basis for established WAC) have limited relevance for disposal, so an alternative system may be needed.

Source / Reference	**Relevant stages in waste lifecycle**					**Description of gap(s)**
	Ch	**Tr**	**Co**	**St**	**Di**	
Spanish case study: Management of irradiated reactor graphite to enhance disposability to El Cabril (see Section 3.2.3.2)						The disposal WAC (for the El Cabril near-surface repository) are known. Treatment and conditioning of a challenging waste (graphite sleeves from Vandellòs I NPP) is under investigation. This is partly because of a knowledge gap in the characterisation of the waste: the characterisation methodology was missing a suitable correlation nuclide vector. In addition, the C-14 inventory exceeds acceptance criteria and the waste was crushed during pre-treatment, such that its current physical form may not be acceptable. Various treatment and conditioning methods have been investigated and demonstrated to yield a durable conditioned wasteform suitable for disposal at El Cabril. No method has been selected for application as yet.
German case study: Development of management solutions for spent ion exchange resins at individual NPP sites (see Section 3.2.5)						The disposal WAC (for the Konrad geological repository) are known. However, the water content and flammability of the raw waste (spent ion exchange resins) are not compliant with these WAC. The waste is generated at different locations (German NPPs), resulting in small variations in waste characteristics and storage arrangements, and therefore in processing requirements. Various modular, mobile facilities have been deployed; these provide a flexible approach for treating and packaging the waste to generate a product that is compatible with disposal WAC, even without the need for conditioning in a matrix. Consequently, the knowledge gap relating to the need for treatment to generate a disposable wasteform has been addressed.
Cross-cutting topic 3: Managing potential future non-compliances; Slovenian example: Experience operating centralised storage for small generators, initially without WAC (see Section 3.2.4.2)						The disposal route and associated WAC were not known at the time the Brinje storage facility (for medical, industrial and research waste) was originally operated, nor when it was upgraded in line with modern standards. Prior to the transfer of responsibility for management, and refurbishment activities, much of the waste was poorly characterised and storage conditions did not conform to modern standards. Pre-disposal WAC for storage and future transport were developed, and progressively updated to be more detailed. Later on, preliminary disposal WAC (for the Vrbina near-surface repository) were developed. These impacted on the requirements for characterisation, treatment and conditioning of the waste destined for the Brinje facility, and on the methods applied during these lifecycle stages.

Source / Reference	Relevant stages in waste lifecycle					Description of gap(s)
	Ch	Tr	Co	St	Di	
Cross-cutting topic 3: Managing potential future non-compliances; Belgian example: Managing new criteria for the planned near-surface disposal facility (see Section 3.2.4.2)						Pre-disposal criteria were developed in the presence of preliminary disposal WAC (for the planned near-surface repository in Dessel). Now that the repository is approaching licensing and the disposal WAC are more mature, it turns out that the pre-disposal criteria used for treatment and conditioning are not conservative with respect to certain waste characteristics. An R&D programme has been launched with the aim of relaxing the relevant disposal WAC (where this can be done without undermining safety). At the same time, the waste acceptance system is being reformed, to facilitate production of 'mono-problematic' waste streams (through prevention and sorting) and to use the storage capacity as a time buffer in the waste cycle (until the affected disposal WAC are relaxed).
Cross-cutting topic 1: generic WAC; UK example: The UK Disposability Assessment process (see Section 3.2.2.3)						The site for a UK GDF (for disposal of HAW) is not yet known and associated disposal WAC are therefore not available. In the meantime, generic waste packaging specifications have been established, against which the suitability of plans to package waste for geological disposal can be assessed. This enables wastes to be conditioned (including application of a suitable wasteform matrix, where relevant), ready for geological disposal without further processing. Several thousand disposal waste packages have already been produced in this manner. The generic specifications and assessment approach are conservative to account for ongoing uncertainties associated with the disposal site and GDF design.

3.3.2 Recommendations for 'no regret' waste management decisions

This section aims to highlight approaches to support the progression of waste management activities when uncertainties remain regarding future stages in the waste lifecycle, particularly disposal end points and/or when associated WAC are absent. In doing so, it addresses the Subtask 4.2 objective of offering a structured approach to support decision-taking of 'no regret' waste management measures, i.e., decisions that do not lead to problems later on.

A series of observations and recommendations are presented below. These are worded to be universally applicable, regardless of the size of Member State / Associated Country, waste inventory, disposal route(s), and other aspects of national- or facility-specific context against which they might be applied. The observations and recommendations are drawn from various sources, including:

- The discussion of waste management case studies in the presence / absence of WAC and of cross-cutting topics relating to WAC during the Subtask 4.2 workshop, as recorded in Section 3.2.
- The gap analysis presented in Section 3.3.1.

- Analysis and conclusions presented in the EURAD Milestone 88 report on the current use of waste acceptance criteria, produced under ROUTES Subtask 4.1 [6] and presented in several subsequent meetings, workshops and conferences.
- Outputs from the two webinars on WAC jointly organised by PREDIS, ROUTES and ERDO in April and May 2021 [14], [15], in which representatives of ROUTES participated.
- Discussion in Section 3.4 of ROUTES Deliverable D9.10 ("*Collection and Analysis of Actual Existing Knowledge about Disposal Options for SIMS"*), which examines the differences in WAC availability between SIMS and LIMS [1] [11].

In doing so, they reflect lessons learned from previous waste management experiences, which can aid planning of future activities.

Observations and recommendations are organised by lifecycle stage (characterisation; treatment; conditioning; storage and disposal); a series of recommendations relating to the methodology for defining WAC, including considerations relating to stakeholder involvement, is also presented. The basis for, and origin of, each recommendation is provided by cross-referencing the source of discussion or the experience (e.g., the relevant case study) that led to its identification.

A key overarching principle is the identification of approaches that impart flexibility to adapt future waste management practices as new information becomes available (e.g., new waste characterisation data) or as strategic decisions are made (e.g., progress identifying a disposal site). Any applicable drawbacks or limitations are also acknowledged.

3.3.2.1 No regret approaches applicable to waste characterisation

Waste characterisation is essential to understanding the inventory. The waste inventory informs all subsequent management steps and has a major influence on measures that could be applied for waste minimisation, materials recycling and reuse.

Characterisation of raw waste at the time it is generated (or as soon after as is practicable), is essential to minimise the extent of downstream characterisation that is necessary to facilitate treatment, conditioning, storage, transport or disposal. If not undertaken at the time of waste generation, it may prove significantly more challenging to obtain equivalent data on waste characteristics at a later date owing to, e.g., waste or storage facility degradation, transfers of ownership decreasing traceability, waste accessibility and/or subsequent treatment / conditioning operations. This is borne out by current challenges relating to the need for better characterisation of legacy wastes, as discussed in Section 3.2.1.2 and in ROUTES Deliverable D9.5 [29].

It is also essential to plan ahead to ensure that an adequate records management process is in place to store, and facilitate reference to, waste characterisation data so that it is available for the duration of the applicable waste lifecycle. This can avoid a need to repeat waste characterisation activities as a result of records being lost.

Both of these recommendations are supported by the discussion of the Greek case study on the characterisation of historical cemented sludges (Section 3.2.1.3), where there is no information on the origin or initial characteristics of the waste, and where destructive methods (followed by reconditioning) may be required to adequately characterise the waste for onward management. Similarly, the poor documentation of the waste inventory and historical storage conditions at the Brinje facility in Slovenia (discussed in Section 3.2.4.2) meant that demanding waste characterisation and repackaging campaigns were required after responsibility for the facility was transferred to ARAO. The Spanish case study (see Section 3.2.3.2) also highlights the importance of conducting thorough characterisation at an

[11] Draft Version 2.0 of D9.10 (dated October 2021) was consulted when preparing these recommendations.

early stage to reduce associated requirements downstream. Meanwhile, the Ukrainian case study (also discussed in Section 3.2.1.3) illustrates how a more detailed understanding of waste characteristics can sometimes allow conservatisms built into WAC to be relaxed.

3.3.2.2 No regret approaches applicable to waste treatment

Flexible treatment techniques enable adaptations to be made in response to the particular characteristics of individual waste streams or site-specific constraints, whilst ensuring that processing criteria and WAC for storage and/or disposal of the resulting product can be met wherever a technique is applied.

This can be seen with reference to the German case study on the application and adaptation of different management solutions for conditioning and packaging spent ion exchange resins at individual NPP sites, as discussed in Section 3.2.5.

3.3.2.3 No regret approaches applicable to waste conditioning[12]

Whilst conditioning waste into a matrix increases the level of passive safety provided, it significantly reduces flexibility for further management (without reconditioning), as indicated in

Figure *2*. 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, e.g., if a matrix is selected without adequate knowledge of the local environment / host geology and properties of the wider multi-barrier system underlying safe disposal. It is crucial to strike a balance between these factors, taking account of applicable boundary conditions.

This observation is illustrated in the Ukrainian case study discussed in Section 3.2.1.3, where reconditioning of bituminized evaporated concentrates (by placement of the existing drums in reinforced concrete containers and filling of the surrounding void spaces with concrete) is anticipated to be necessary in order to meet WAC for disposal at the ENSDF. With this in mind, it might be considered preferable to avoid conditioning waste in a matrix until the disposal route is known.

Nonetheless, there are circumstances where early conditioning of waste into a matrix (i.e., immobilisation) may be desirable, for example, to facilitate safe, standardised long-term storage, as in the Dutch case study of waste processing and consolidated storage of LILW at COVRA's facilities for as long as up to 100 years (see Section 3.2.2.2). Immobilisation converts raw waste to a passively safe form, reducing associated hazards and readying the waste for disposal once a suitable facility is available. Early conditioning in a matrix also 'buys time' for an extended period of research to underpin safe disposal although, as noted in Table 2, this could lead to reducing the political urgency for finding a permanent solution (disposal) to manage the waste. The performance of conditioned waste packages during any periods of extended storage needs to be confirmed through monitoring, in preparation for subsequent management and disposal.

Although it can increase the safety, security and efficiency of waste storage pending disposal, early conditioning in a matrix comes at the expense of reducing future flexibility to tailor the waste conditioning approach to disposal conditions at a repository once these are known. Indeed, the reverse may be true: the design of the disposal facility, its operation, and perhaps even its capacity, may be constrained by the properties of waste that has already been conditioned. This is expected to be the case to enable the geological disposal of French alpha-bearing waste that has already been conditioned, as noted in the discussion of cross-cutting topic 3 (Section 3.2.4.2).

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12 In accordance with the IAEA safety glossary, conditioning can include conversion of the waste to a solid wasteform, enclosure of the waste in containers and, if necessary, provision of an overpack [37].

Generic WAC (or analogous requirements / specifications) are one mechanism that enables waste conditioning (including conversion to a solid wasteform and placement of waste in suitable containers for disposal) to progress in the absence of a disposal route, facility or site. As noted in Section 3.2.2.3 and Table 2, such an approach is used to evaluate the disposability of all packaging proposals for HAW destined for geological disposal in the UK, and several thousand disposal waste packages have already been produced via this process. A disadvantage of this mechanism is that it requires conservative assumptions to be made about disposal conditions, and potentially more stringent criteria to be specified than would be the case for site-specific WAC. Consequently, generic WAC are typically more constraining than facility-specific WAC and can therefore place a more onerous burden on waste conditioning requirements than might be the case where disposal conditions are known at the time of processing.

Sometimes, there are strong drivers to deploy interim waste management measures (i.e., early treatment, conditioning and/or transfer to a new storage facility) to reduce near-term risks associated with ongoing storage of raw wastes, rather than waiting until disposal conditions are known, even though this may lead to additional waste processing requirements over the long term. An example from the UK, discussed in Section 3.2.2.3, concerns current work to retrieve spent fuel from ageing storage facilities and transfer it into thick-walled SSBs, which may or may not be suitable for direct disposal to the GDF without further conditioning or repackaging. Another example of deploying interim waste management measures is the Dutch case study.

Notably, the UK's use of SSBs highlights that repackaging waste in new containers without matrix conditioning can provide a flexible and crucially, reversible, 'middle ground' whereby a limited amount of waste processing facilitates emptying and decommissioning of ageing facilities whilst retaining the waste in a form that can still be further treated or conditioned in many different ways before its eventual disposal. However, a disadvantage of such an approach is that it may increase full lifecycle costs. It is noted that there is variable acceptance of the disposability of wastes without conditioning into a matrix across different Member States and Associated Countries, and that this also varies within individual countries depending on the activity and other properties of specific waste streams and the envisaged disposal route.

3.3.2.4 No regret approaches applicable to storage

Conditions during storage, pending disposal, should be designed to promote package longevity, thereby reducing the risk that already conditioned waste packages will need to be re-conditioned as a result of degradation during interim storage. Storage arrangements should also enable package performance to be checked through monitoring. If these aspects are difficult to ensure, it may be preferable to minimise the extent of treatment and conditioning carried out (whilst still ensuring that the waste can be stored safely) in order to avoid the need to repeat waste processing steps.

Waste management experiences that provide the basis for this recommendation include the storage of cemented sludges in Greece, as discussed in Section 3.2.1.3 and experiences in Slovenia relating to the refurbishment of the Brinje storage facility and associated repackaging and rearrangement of the waste stored there, as discussed in Section 3.2.4.2 and Table 2. In the former case, degradation of waste packages during storage has taken place and reconditioning is anticipated to be required; in the latter case, some reconditioning is being implemented (alongside improved waste characterisation), partly due to poor storage conditions, and the opportunity to being taken to ensure that the reconditioned waste meets WAC for disposal at Vrbina.

3.3.2.5 No regret approaches applicable to disposal

Relatively few recommendations applicable to disposal have been identified. This is not surprising given that reaching this stage and being able to meet applicable WAC would imply that suitable strategies have already been deployed to enable progression through upstream stages in the waste lifecycle.

The Spanish and German case studies discussed in Sections 3.2.3.2 and 3.2.5 respectively reflect a more 'ideal' situation from a waste management perspective compared to the other case studies considered during the Subtask 4.2 workshop, where disposal WAC were available prior to waste conditioning being implemented. Where disposal WAC are available (e.g., in the case of WAC for disposal at El Cabril in Spain), uncertainty shifts towards characterisation to determine compliance (or otherwise), and/or the selection and qualification of treatment and conditioning methods that will result in a disposable wasteform.

Regarding geological disposal, deploying a dual-track disposal strategy (i.e., planning for a national repository and pursuing opportunities for a multinational shared facility in parallel), as applied in the Netherlands (see Section 3.2.2.2), can help to keep options open and increase the likelihood of identifying a suitable disposal route. Choosing to follow such an approach would be a political decision, rather than a technical strategy relating to WAC that can be implemented by the WMO. Moreover, although it is being implemented in the Netherlands, a dual-track strategy may not be realistic for some SIMS since developing a national repository may be considered to represent a disproportionate cost and technical / socio-political challenge compared to the size of the inventory requiring disposal. Pursuit of a shared disposal solution is preferred by some SIMS for this reason.

The Belgian case study discussed in Section 3.2.4.2 illustrates a situation where disposal WAC are something of a 'moving target' (as is often encountered in the progression from preliminary to 'final' WAC in use at a disposal facility). In this case, new criteria have been introduced as the repository approaches licensing, followed by exploration of possibilities for relaxing certain of these WAC where this can be done without undermining safety. A lesson learned from this experience is that changes in disposal WAC can be more easily accommodated by implementing:

- Flexible treatment and conditioning techniques that are easy to adapt to evolving requirements.
- In-depth characterisation of the waste, so that the implications of changes to WAC can be readily determined.

3.3.2.6 No regret approaches to WAC definition

It is recommended that waste generators and treatment / conditioning facility operators should be involved in the process for defining WAC as early as possible, to minimise the potential for WAC being impractical to implement. Difficulties have been encountered in e.g., Belgium, where such involvement was limited during the specification of new criteria within the WAC for near-surface disposal (as discussed in Section 3.2.4.2).

The link between WAC and the safety assessment for a facility is important. However, for existing WAC it is not always apparent. This observation was made in the conclusions of PREDIS Deliverable D2.4 [11, §8], which states that:

"*Although safety assessment is widely considered as a condition or precursor for the formulation of certain WAC, the actual relation of WAC to the safety assessment of storage/disposal facilities (i.e., the method for their derivation) has not often been clearly identified. The relationship should be specified for generic criteria, if relevant, and for site specific criteria, if possible. Simple examples of using existing procedures (e.g., those specified in national documents and/or IAEA recommendations) will be helpful and could be demonstrated during the project implementation.*"

Clear demonstration of this link (as far as it is applicable) is an important aspect of communicating the basis for, and justification of, WAC to be applied, and therefore contributes to confidence building in the suitability of processes established to ensure safe waste management.

This observation clearly indicates that the scope of WAC does not necessarily have to depend entirely on the safety assessment of a facility. It can also be linked with wider principles for waste management, 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.

Regarding stakeholder involvement, different countries have very different combinations of responsibilities amongst nuclear stakeholders for defining and applying WAC and checking compliance, linked to the national context for waste management and disposal. This can be seen with reference to Tables 5 and 11 in the EURAD Milestone 88 report on the current use of waste acceptance criteria [6], which respectively summarise organisations responsible for developing WAC and organisations responsible for the various aspects of WAC application. These differences should not pose a concern and would, in any case, be challenging to harmonise without first harmonising the overarching framework for waste management across different countries. What is important (as discussed in the Milestone 88 report) is to ensure that responsibilities are clearly defined and actioned.

The role of WAC as a tool available for confidence building amongst civil society was discussed under cross-cutting topic 2 (Section 3.2.3.3). The potential value of WAC for communicating factors important to the safety case was highlighted. It was also suggested that civil society involvement in WAC development and/or implementation (either by somehow influencing their scope, or through involvement in their application) could support public acceptance of their use. Regarding the demonstration of compliance with WAC, citizen science was identified as a source of additional primary data and independent analysis available to support evaluation and build confidence in findings across a wide stakeholder base.

As noted in Section 3.2.1.2, there is widespread interest in harmonisation of WAC across Member States and Associated Countries, primarily focusing on harmonisation of the methodology for their definition. Boundary conditions such as the environmental conditions of a disposal site, the size of the waste inventory, and national legislation / regulations differ considerably from one country to another and such factors present an insurmountable difficulty for comprehensive harmonisation of WAC, particularly numerical criteria, as noted above. Nevertheless, 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 programmes would give confidence that a suite of WAC is fit for purpose.

4 WAC-related needs and opportunities for collaboration

4.1 Overview of Subtask 4.3 and approach to identify WAC-related recommendations

4.1.1 Request for national inputs

In preparation for the Subtask 4.3 workshop on "*R&D needs and opportunities for collaboration*" held on 10 May 2022, ROUTES partners were asked to identify R&D needs and opportunities for collaboration relating to issues that are still outstanding in their country with respect to the management of challenging wastes, particularly in relation to the conditioning of waste while maintaining compatibility with options for disposal. The resulting national responses comprised the main input to Subtask 4.3.

No template for responses was provided, to allow national inputs to be tailored to the situation in different countries. However, the following guidance questions were developed during the period of response:

1) What are your national R&D priorities with respect to WAC development and the management of challenging wastes?
2) How do you foresee these R&D needs being addressed?
   - As part of a national waste management programme (possibly bringing in expert support from external / international sources)?
   - Through collaborative projects (e.g., EC research)?
   - Other? A combination?
3) Are there any areas where you consider that a joint / collaborative approach to address a common issue would be particularly welcome? How would you like to see this implemented?
4) Are there gaps in the discussion / programme of work relating to WAC under ROUTES, PREDIS and other current international initiatives that you consider are not being adequately addressed?

4.1.2 National inputs received and workshop organisation

Feedback was received prior to the workshop from Belgium, Bulgaria, Czechia, France, Germany, Poland and Slovenia. Responses were received in a variety of formats, ranging from single recommendations to long lists of suggestions. Some national inputs were highly focused on WAC, whilst other countries' recommendations were much broader in scope. This has been factored into the subsequent screening of recommendations, as described in Section 4.3.3.

The agenda for the Subtask 4.3 workshop was structured in two parts:

- The morning, and early afternoon, were devoted to the presentation and discussion of national recommendations for R&D needs and opportunities for collaboration. Inputs received from the above countries were discussed, as recorded in Sections 4.2.1 to 4.2.7. Feedback on the status of WAC-related activities under the PREDIS project and early reflections on associated R&D needs and opportunities for collaboration were also presented during this session; associated discussion is recorded in Section 4.2.8.

- The rest of the workshop involved presentation and discussion of how R&D needs have been collated, rationalised and screened to produce a 'shortlist' of commonly held, WAC-related R&D needs. This was followed by a polling exercise to identified indicative priorities associated with these R&D needs (based on the perspectives of workshop participants).

PowerPoint presentations and other workshop materials, including video recordings, have been collated on Project Place here. Presentation slides are also integrated throughout this report, where relevant.

Additional national inputs from Romania and Ukraine were received after the workshop; these are captured in Section 4.2.9 and have been integrated into the conclusions set out in Sections 4.3.6 and 5.1.

4.1.3 Inputs from other sources

Besides the national inputs described above, various other potential sources of recommendations were also reviewed. These included:

- Discussion points identified earlier in Task 4, as recorded in the memoranda for Subtasks 4.1 and 4.2 [6], [7].
- National responses to the ROUTES questionnaire (particularly Questions 18-22, which consider waste management experiences and R&D programmes to address difficulties encountered) [27], [28].
- Memoranda of the two joint PREDIS / ROUTES / ERDO webinars on WAC held in April and May 2021 [14], [15]. In particular, the second of these webinars focused on WAC-related needs, challenges and opportunities.
- The PREDIS gap analysis [38].

Associated recommendations were collated and analysed alongside national inputs, and were discussed at the Subtask 4.3 workshop.

4.2 Presentation and discussion of R&D needs and opportunities for collaboration

Sections 4.2.1 to 4.2.8 describe inputs presented and discussed at the Subtask 4.3 workshop. Sections 4.2.1 to 4.2.7 describe national inputs and section 4.2.8 describes the feedback received from PREDIS. Section 4.2.9 describes additional national inputs from Romania and Ukraine received after the workshop.

4.2.1 Presentation and discussion of Slovenian inputs at the workshop

4.2.1.1 Inputs presented at the workshop

The speaker on behalf of Slovenia (a representative of Elektroinštitut Milan Vidmar (EIMV)) presented a summary of the relevant national R&D needs as indicated in the slide shown in Figure 5.

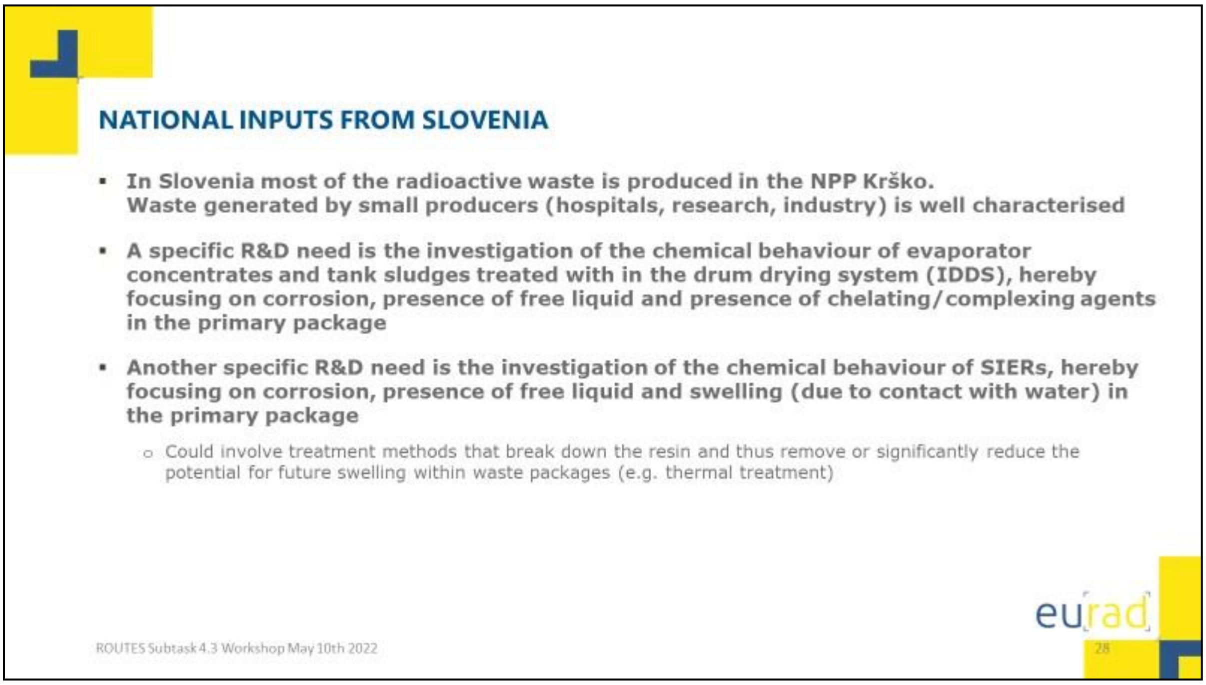


Figure 5 – Summary of R&D needs and opportunities for collaboration identified for Slovenia.

In Slovenia, most radioactive waste is produced at the Krško nuclear power plant (NPP). Radioactive waste streams generated by small generators (hospitals, research, and industry) are generally well characterised (via several campaigns) and are stored in the Central Interim Storage Facility (CISF) operated by the Agency for Radwaste Management (ARAO). Some have not yet undergone final treatment and conditioning, pending confirmation of their disposal route and applicable WAC.

Nevertheless, Slovenia's prime R&D needs at present are linked with certain waste streams from the Krško NPP, notably evaporator concentrates and tank sludges that have been treated using an in-drum drying system, and spent ion exchange resins (SIERs). In both cases, there is a need to better understand the chemical behaviour of the wastes during storage and disposal, noting the presence of free liquid and chelating / complexing agents, the propensity for swelling of SIERs in contact with water and the potential for waste package corrosion, coupled with high dose rates in the case of evaporator concentrates. ARAO and the Krško NPP operator plan a joint research programme from 2022-2025 to investigate the chemical behaviour of these wastes and associated waste treatment requirements.

The presented inputs can be summarised and rephrased as R&D needs relating to the:

- Chemical behaviour of evaporator concentrates and tank sludges.
- Chemical behaviour of SIERs.

4.2.1.2 Discussion points

A workshop participant asked for clarification on whether it is planned to investigate the chemical behaviour of these waste as part of the Slovenian national programme or whether this is still a gap that needs to be addressed elsewhere. The presenter clarified that this chemical behaviour will be investigated first as part of the national programme and that it has a high priority within this programme. However, it is envisaged that the results of these studies will be verified and underpinned by comparing them with international experience on this subject.

Another listener asked whether any medium-active SIERs coming from the dismantling of nuclear power plants are among the SIERs mentioned in the third bullet of the slide. The presenter replied that, at present in Slovenia, SIERs requiring treatment for storage and disposal are all (long-lived) operational wastes; SIERs originating from NPP dismantling have not yet arisen. Consequently, the treatment and conditioning of SIERs from the dismantling of NPPs is an R&D need of low priority in Slovenia.

4.2.2 Presentation and discussion of Belgian inputs at the workshop

4.2.2.1 Inputs presented at the workshop

The speaker on behalf of Belgium (a representative of ONDRAF / NIRAS) presented a summary of the relevant national R&D needs in the slide shown in Figure 6.

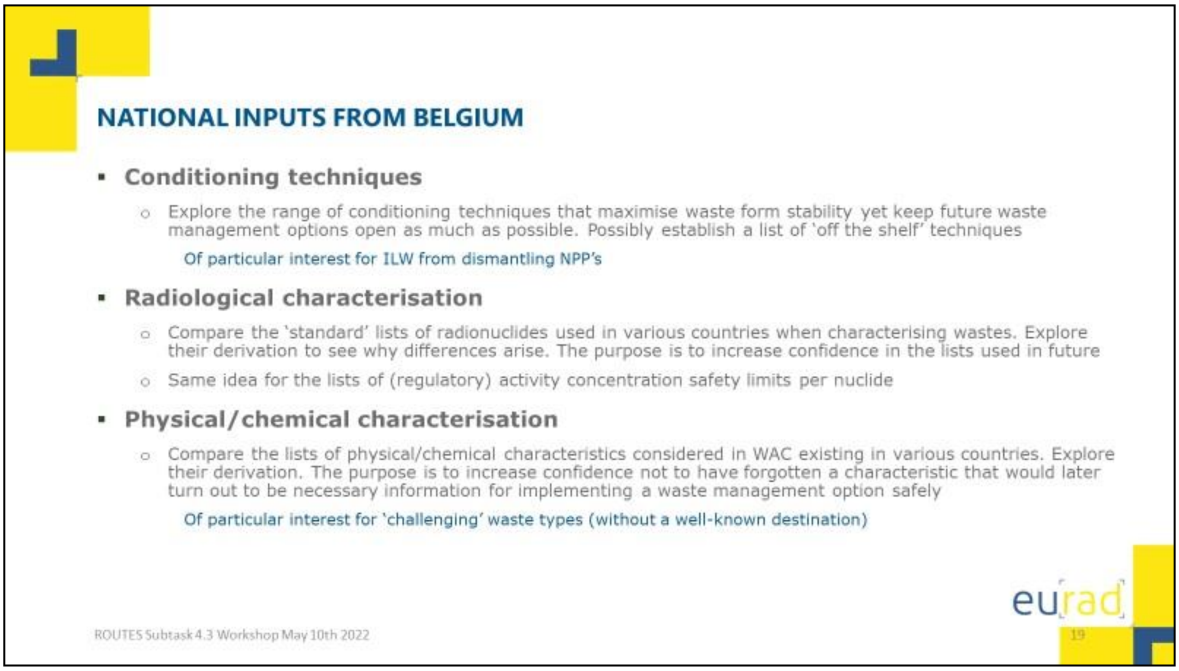


Figure 6 – Summary of R&D needs and opportunities for collaboration identified for Belgium.

In Belgium, the licensing process for the surface disposal facility in Dessel is nearing its final stage. The low and medium active short-lived wastes destined for disposal at this facility have been the prime focus of study in recent years. The focus of national research is now expected to gradually shift towards those waste streams requiring geological disposal, i.e., long-lived wastes, and those short-lived wastes that fail to meet WAC for surface disposal. Consequently, Belgium's prime R&D needs at present are linked to known issues related to the management of these wastes.

The objective of the item 'conditioning techniques' is to establish a list of 'off the shelf' techniques that could provide a solution to the dilemma of choosing between early and late conditioning in a matrix. This item is especially linked with medium activity waste that will arise from the dismantling of NPPs (e.g., reactor pressure vessel internals).

The background behind the item 'radiological characterisation' is that there is currently considerable variation in what countries regard as radionuclides relevant for operational and long-term safety, and thus for determining a management route for wastes with a particular radionuclide inventory. There are 'standard' lists of radionuclides being used in various countries, with some radionuclides appearing in all lists, but other nuclides not. Of course, this is somehow linked to the applicable levels of radioactivity and the proposed disposal route, and this may be specific to the national context. Nevertheless, it would be useful to make a comparison and to understand how relevant radionuclides are determined in each country and why such differences arise. The results of a common R&D effort on this topic could provide a means to confirm to countries that they are taking account of all relevant radionuclides.

The objective of the item ‘physical / chemical characterisation’ is to establish a ‘standard’ list of waste characteristics that should be determined in order to have confidence that information potentially necessary for implementing subsequent management activities is not overlooked.

The presented inputs can be summarised and rephrased as the following R&D needs:

- Explore conditioning techniques that maximise wasteform stability, but keep future waste management options open.
- Comparison and standardisation of radionuclides (and speciation) to account for in waste characterisation and WAC.
- Work on inventories and speciation of particular radionuclides.
- Comparison and standardisation of physical / chemical waste characteristics to account for in waste characterisation and WAC.

4.2.2.2 Discussion points

Clarity was requested on the approach envisaged to establish a list of ‘off the shelf’ conditioning techniques that would maximise wasteform stability whilst keeping future management options as open as possible. For example, would each technique be evaluated to identify a corresponding list of advantages and disadvantages? The presenter clarified that the focus would ideally be on acquiring technological information, in order to gain a better understanding of the applicability of each technique, depending on the waste type and the circumstances.

4.2.3 Presentation and discussion of Bulgarian inputs at the workshop

4.2.3.1 Inputs presented at the workshop

The speaker on behalf of Bulgaria (a representative of the Technical University of Sofia) presented a summary of the relevant national R&D needs in the slide shown in Figure 7.

In Bulgaria, R&D needs with respect to challenging wastes are driven by national legislation (i.e., the ‘Strategy for Managing the Spent Nuclear Fuel and Radioactive Waste until 2030’, issued in 2015 by the Bulgarian Council of Ministers), which requires the development of a management strategy for all types of radioactive waste.

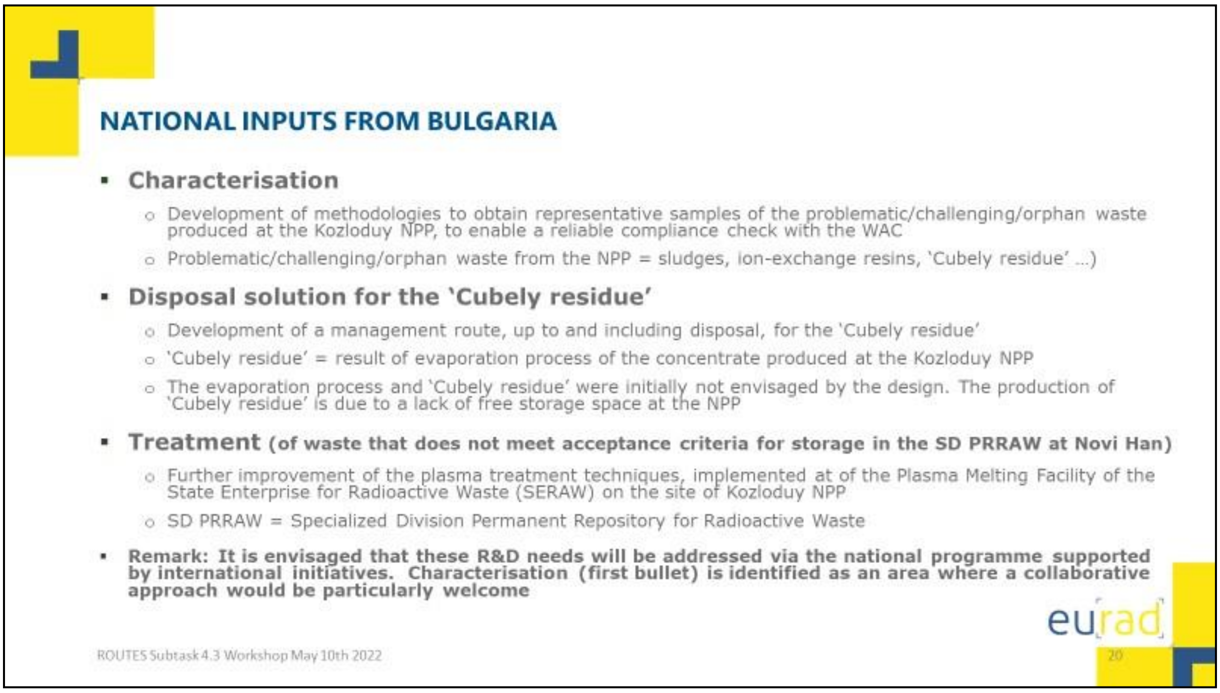


Figure 7 – Summary of R&D needs and opportunities for collaboration identified for Bulgaria.

An important new source of information became available at the end 2018, namely the radioactive waste inventories from the State Enterprise for Radioactive Waste (covering the Kozloduy NPP) and from the Specialized Division Permanent Repository for Radioactive Waste (covering the Novi Han repository).

Wastes produced by the Kozloduy NPP that are considered to be 'challenging' include sludges, SIERs and the so-called 'Cubely residue', arising from evaporation of concentrates. There is also a particular interest in developing treatment techniques for wastes which do not meet applicable disposal WAC, including developing the capabilities of the Plasma Melting Facility (operating at the Kozloduy site).

The presented inputs can be summarised and rephrased as the following R&D needs:

- Characterisation methodologies to obtain representative samples.
- Management routes for particular challenging wastes.
- Approach to treat wastes that do not meet WAC for existing / planned facility.
- Chemical behaviour of evaporator concentrates and tank sludges.

4.2.3.2 Discussion points

The following clarifications were provided in response to questions asked by workshop participants:

- It is not clear whether the plasma treatment facility at the Kozloduy NPP will be used to treat the 'Cubely residue', since the management route for this waste stream is not yet fully established.
- If the 'Cubely residue' *were* processed via this route then it would first need to undergo a specific pre-treatment to convert it into a suitable form for processing in the plasma treatment facility, which was originally designed to receive solid waste (including some SIERs and organic waste) originating from both NPPs and wider industrial activities.
- The primary goal of the characterisation needs set out in Figure 7 is to inform decision making on the management route for the 'Cubely residue'.

4.2.4 Presentation and discussion of Czech inputs at the workshop

4.2.4.1 Inputs presented at the workshop

A representative of SURAO presented a proposal on behalf of ROUTES participants from Czechia for a benchmarking exercise that could support the development of disposal WAC for countries / facilities where these are not yet available. Key points of this exercise are summarised in Figure 8.

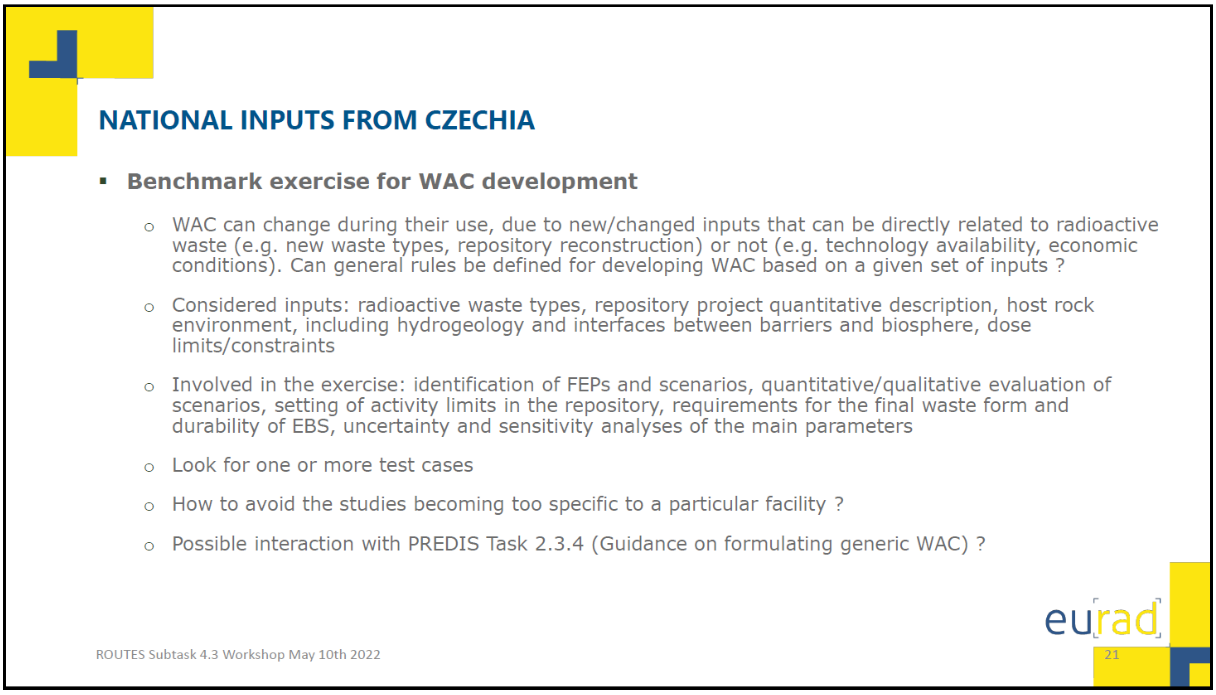


Figure 8 – Summary of R&D needs and opportunities for collaboration identified for Czechia.

The overall goal is to define a series of general rules and approaches for developing WAC based on a given set of inputs. Such rules would also ideally be useable to adapt established WAC in response to changed inputs (e.g., new waste types, repository redesign or new technologies becoming available). The suggested approach would make use of one or more test cases for particular wastes and facilities, and develop a generalised methodology with reference to approaches that have been successfully applied elsewhere (e.g., to generate WAC for existing facilities).

The proposed benchmarking study was captured for subsequent analysis as the following R&D need:

- Benchmarking exercise for WAC development.

4.2.4.2 Discussion points

It was observed that a factor motivating this proposal was that a benchmarking activity of this nature could help to provide a well-underpinned methodology for WAC development (and robust WAC themselves) for countries that don't have WAC for certain facilities. The process of developing the methodology by considering test cases would also facilitate the transfer of experience in this field from more advanced to less advanced waste management programmes. However, in order to maximise the value of the work across Member States (and beyond), it would be important to ensure that the outputs of such a study were not overly waste- or facility-specific.

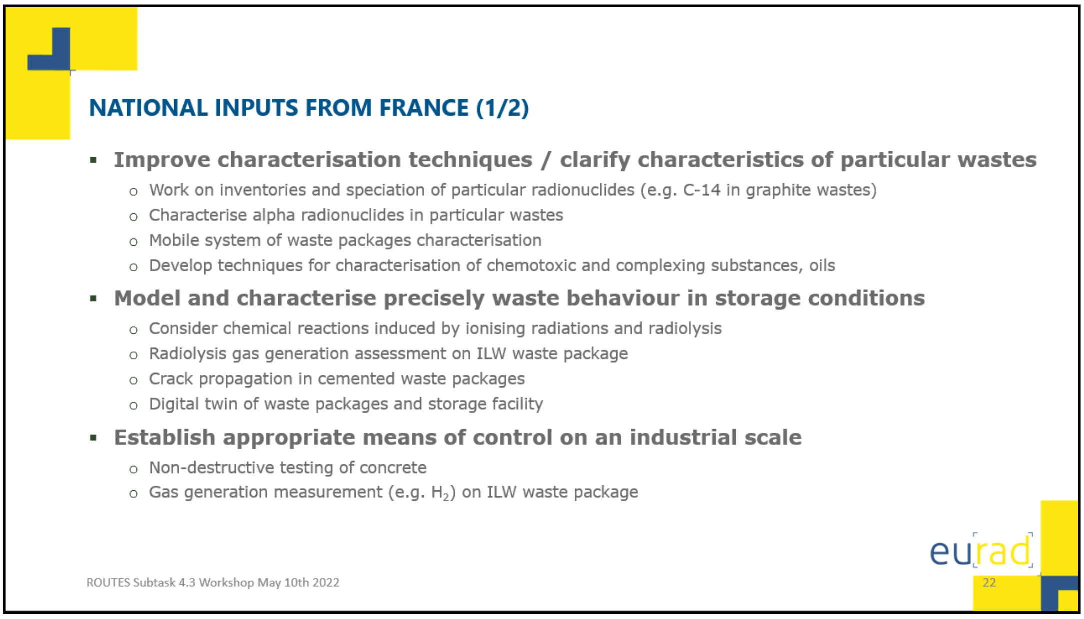
A representative of the PREDIS project commented that different countries adopt widely varying approaches to derive WAC, which could make it difficult to apply a benchmarking process to establish a single, universally applicable methodology. He also noted the need to avoid repeating work already conducted elsewhere, for example, earlier in ROUTES and in the ongoing PREDIS work programme on WAC (PREDIS Task 2.3). Both projects have already collated information on different national approaches to develop WAC and an ongoing PREDIS task (Task 2.3.4) involves the production of guidance on formulating generic WAC. Moreover, the IAEA has been preparing a document on WAC generation for several years, and this is nearing publication. The representative suggested that it would be preferable to focus on the provision of more practical advice that is tailored to the needs of specific countries based on their waste management programmes. Sufficient background information should have already been collected to enable such advice to be provided.

Clarification was sought on the proposed approach to utilise FEPs and scenarios to manage uncertainties within the benchmarking activity. The representatives proposing this approach were not available to respond in the workshop but this was noted as an area of interest for further discussion.

4.2.5 Presentation and discussion of French inputs at the workshop

4.2.5.1 Inputs presented at the workshop

The speaker on behalf of France (a representative of Orano) presented a summary of the relevant national R&D needs in the two slides shown in Figure 9.



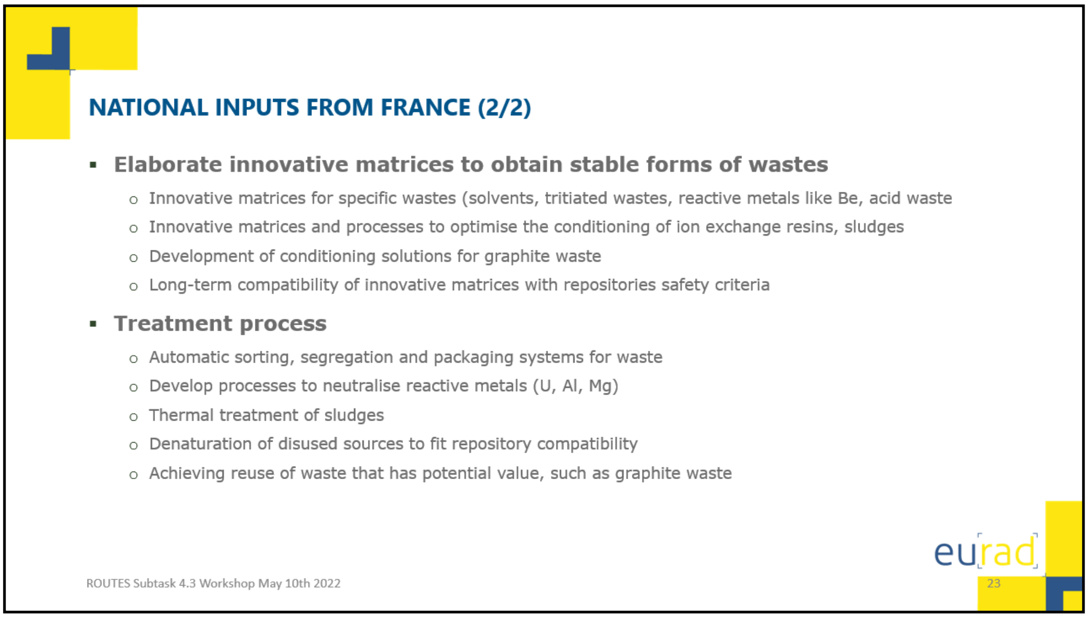


Figure 9 – Summary of R&D needs and opportunities for collaboration identified for France.

France has a large and mature nuclear industry with various near-surface disposal facilities (Centre de stockage de l'Aube (CSA) – in operation; Centre de stockage de la Manche – in closure; and the CIRES repository for VLLW – in operation) as well as a geological disposal programme in development. Consequently, France's research needs are wide-ranging in scope. Only those which would benefit from a collaborative approach have been put forward for discussion in ROUTES Subtask 4.3. Joint efforts responding to these needs would help to reinforce the waste management programme in France, and elsewhere.

The presented R&D needs fall into five broad categories, each of which encompasses several, more specific recommendations:

- Improvement of characterisation techniques.
- Modelling and characterisation of waste behaviour under storage conditions.

- Establishing appropriate means of control on an industrial scale.
- Researching innovative matrices to stabilise wastes.
- Developing treatment processes.

(For brevity, the individual recommendations are not listed here, but can be inspected in the Subtask 4.3 memo [39]).

R&D to improve characterisation techniques is linked to the need for developing inventories and speciation information for particular radionuclides (e.g., C-14 in graphite), as well as techniques for characterisation of chemotoxic and complexing substances and oils, and alpha radionuclides. Developing mobile systems for waste package characterisation was also mentioned as a need.

Work to model and characterise waste behaviour in storage conditions is needed to develop a more precise understanding, considering crack propagation in cemented wastes, chemical reactions induced by ionising radiation and radiolysis, and gas generation caused by radiolysis. Development of digital twins of waste packages and storage facilities was also mentioned as a need.

Establishing appropriate means of control on an industrial scale concerns the need for increasing confidence in testing conducted at a larger scale. This includes the need for further development of concrete non-destructive testing and ILW package gas generation measurement techniques.

A need was identified to develop innovative matrices to obtain stable wasteforms for certain challenging wastes (including solvents, tritiated wastes, reactive metals like beryllium, acid wastes, SIERs, sludges and graphite wastes). The importance of ensuring that wastes conditioned using these matrices would meet repository safety criteria was emphasised. The approach to conduct research in this field in France was contrasted with that followed in Czechia and Slovakia; in France, an emphasis has been placed on developing robust wasteform matrices, whereas Czechia and Slovakia first established criteria that the matrices would need to fulfil. The possibility for successful collaboration between these countries was recognised because of the synergies that these differing approaches could promote.

Recommendations relating to the development of treatment processes were quite wide-reaching, encompassing automated sorting, segregation and packaging systems; processes to neutralise reactive metals (including uranium, aluminium and magnesium); thermal treatment of sludges; denaturation of disused sources to meet repository acceptance criteria; and enabling reuse of wastes that have potential value, such as graphite wastes.

4.2.5.2 Discussion points

It was acknowledged by the presenter that many of the French recommendations were not strongly linked to WAC, so would also benefit from consideration by the wider ROUTES WP, outside of Task 4. Such recommendations should therefore be fed into the identification of future R&D needs and opportunities for collaboration under e.g., WP6 (Shared Solutions) and WP1 (Coordination).

Additional context was provided by a PREDIS representative on the Czechian / Slovakian approach to the development of wasteform matrices, with reference to a case study. SÚRAO, the operator of the Dukovany repository, was approached with a proposal that geopolymer matrices be used for conditioning certain wastes to be consigned to the repository. The organisation making this proposal was required to prove that the new waste form would meet existing limits and conditions of the repository operation, including WAC. A variety of different techniques were used to measure performance against established parameters and, hence, to confirm acceptance. This is considered to be an excellent case study of a new wasteform being successfully integrated into operating practices at an existing repository. A report documenting this case study is being prepared in the PREDIS project and will be shared with ROUTES participants once available. The presenter observed that this experience contrasted with difficulties encountered in France when trying to apply standards established for concrete wasteform matrices to geopolymers, and expressed an interest in learning more about the details of the criteria being applied, and how they ensure long-term safety.

4.2.6 Presentation and discussion of German inputs at the workshop

4.2.6.1 Inputs presented at the workshop

The speaker on behalf of Germany (a representative of GRS) presented a summary of the relevant national R&D needs in the two slides shown in Figure 10.

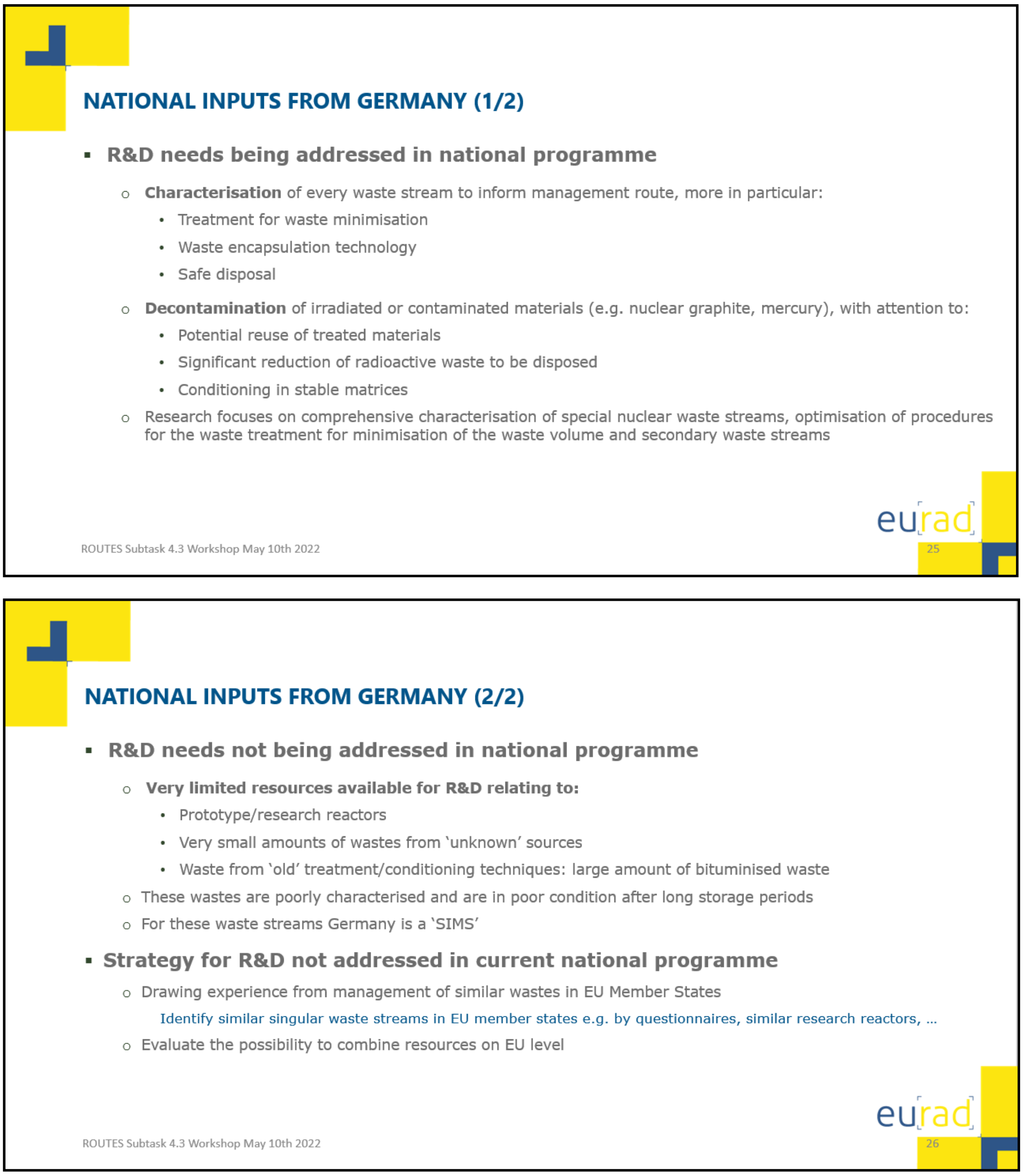


Figure 10 – Summary of R&D needs and opportunities for collaboration identified for Germany.

The only permissible disposal route in Germany for all radioactive waste is deep geological disposal. The location for a repository for HLW and other wastes unsuitable for disposal at the Konrad repository is currently in the early stages of a site selection process, with operation not expected to commence until 2050. Consequently, much of the effort in Germany associated with managing these wastes is currently focused towards their long-term interim storage. Storage and disposal activities are conducted by separate WMOs, each with its own strategic research agenda.

There is currently significant effort within German research programmes on improving the characterisation of waste streams to inform decisions on management routes, including the need for treatment, appropriate encapsulation techniques and methods for safe disposal. National efforts are also examining options for decontamination of irradiated or contaminated materials with a view to facilitating their reuse and reducing the volume of waste requiring long-term storage and disposal. Nevertheless, some R&D needs are not currently being addressed in the national programme so there is much potential for collaborative research.

Topics where collaboration would be of interest relate to wastes from prototype / research reactors (which tend to give rise to small-volume waste streams with unusual or distinctly challenging characteristics); orphaned wastes of unknown origin; and wastes dating back as far as the 1960s that were treated using techniques that are now considered to be sub-optimal in Germany (e.g., bituminisation). These wastes are poorly characterised and have often undergone chemical degradation since they were generated or conditioned. Gas generation and associated pressurisation in waste packages was noted as a particular issue. For these wastes, Germany has a small inventory and thus, it is considered desirable to combine resources for research into these topics, and to be able to draw on experience from the management of similar wastes in other countries.

National inputs from Germany can be summarised and rephrased as the following R&D needs:

- Characterisation methodologies to obtain representative samples.
- Non-destructive analysis of conditioned waste, e.g., testing of concrete, including industrial implementation for small inventories.
- Decontamination of irradiated or contaminated materials.
- Achieving reuse of waste that has potential value, e.g., graphite.
- Long-term compatibility of innovative matrices with repository safety criteria.
- Development of innovative matrices and processes to optimise the conditioning of specific wastes e.g., SIERs, sludges, and spent fuel.
- Development of conditioning solutions for graphite waste.
- Management routes for particular challenging wastes.
- Approach to treat wastes that do not meet WAC for existing or planned facilities.
- Behaviour of spent fuel and high-level waste under storage or disposal conditions.
- Radionuclide mobility and retention under disposal conditions.

4.2.6.2 Discussion points

Workshop participants discussed which countries currently face similar waste management challenges to those highlighted in the national inputs from Germany. The presenter noted that Norway and Italy are known to have similar research reactor waste streams, and also that one of the German research reactors is of the same design as a British reactor. It was noted that spent fuel from research reactors is generally repatriated to the country of origin (typically Russia or the USA), as noted in the ROUTES Subtask 4.1 report [6], and that waste management challenges in the countries where research reactors are based are therefore concerned with LLW and ILW. The potential for collaboration with Belgium was also recognised as Belgium has encountered issues with the disposability of uranium metal from reactors, owing to its reactivity.

Participants remarked that future collaborative work in this area would need to start by identifying the commonalities (and differences) in specific problematic waste streams as a basis for developing associated waste management solutions.

4.2.7 Presentation and discussion of Polish inputs at the workshop

4.2.7.1 Inputs presented at the workshop

The speaker on behalf of the Polish Institute of Nuclear Chemistry and Technology (ICHTJ) presented a summary of relevant national R&D needs in the slide shown in Figure 11.

The Polish National Programme of Radioactive Waste and Spent Fuel Management adopted by the Council of Ministers in 2015 and updated in 2020 sets goals in the field of spent fuel and radioactive waste management. It includes an inventory and estimates quantities of radioactive waste expected to arise in future. At present, Poland only has institutional wastes in its inventory. However, a significant increase in the volume of radioactive waste is expected following commencement of a new nuclear power programme that is foreseen to meet the country's energy needs and environmental commitments.

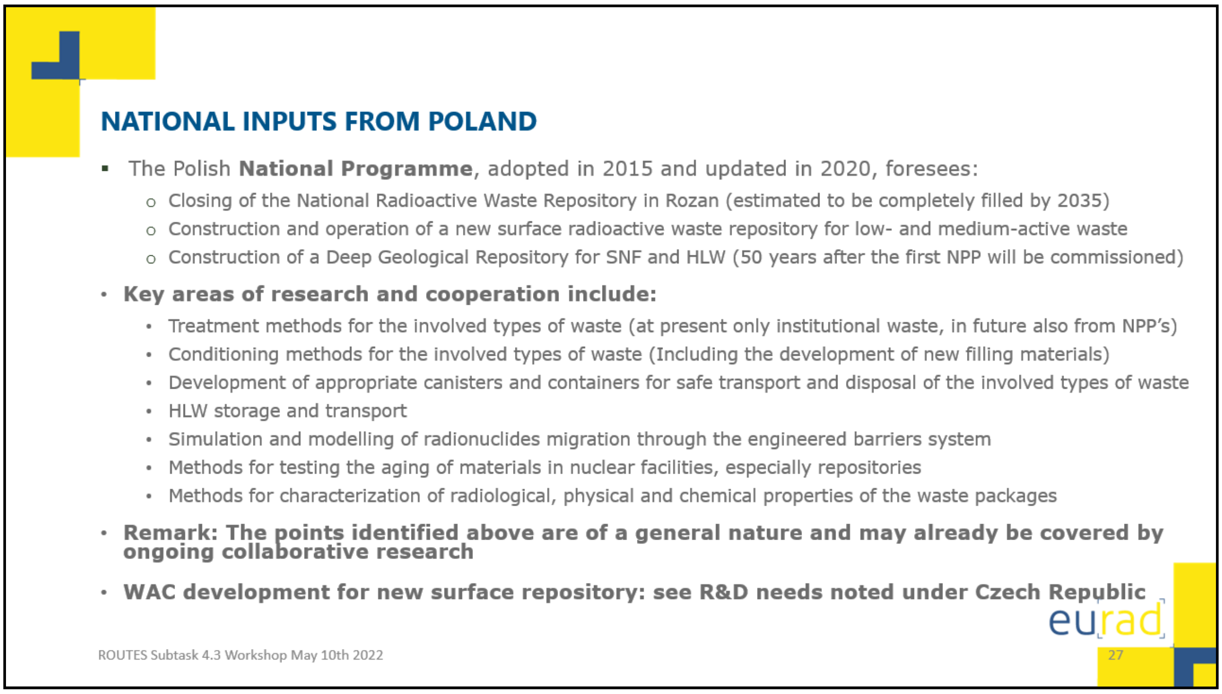


Figure 11 – Summary of R&D needs and opportunities for collaboration identified for Poland.

National activities in the field of radioactive waste management are relatively immature, so there is interest in all potential avenues for research and cooperation. Key areas were identified to include:

- Methods for treating different wastes, noting the anticipated diversification in waste types arising from a nuclear power programme being established.
- Conditioning methods relevant to different waste streams and the development of new encapsulation materials.
- Development of canisters and containers for packaging, transport and disposal of waste.
- HLW storage and transport.
- Development of methods for the simulation and modelling of radionuclide transport through the systems of protective barriers in repositories.
- Development of methods for testing the aging of materials in nuclear facilities, especially repositories.

- Development of methods for conditioned waste characterisation, including radiological and chemical properties, as well as physical properties of the waste packages.

At present, it is unclear which areas have the greatest priority in Poland, but an emphasis is placed on activities linked to the development and performance of waste repositories, noting that the current repository in Rozan is expected to be full by 2035 and that its operating duration has already been extended. It was also noted that WAC will need to be developed for future near-surface and geological repositories and that Poland has an ongoing interest in participating in collaborative projects in this field to ensure that these WAC will take account of international best practice.

The presented inputs can be summarised and rephrased as the following R&D needs:

- Non-destructive analysis of conditioned waste, e.g., testing of concrete, including industrial implementation for small inventories.
- Behaviour of spent fuel and high-level waste under storage / disposal conditions.
- Radionuclide mobility and retention under disposal conditions.
- Benchmarking exercise for WAC development.

4.2.7.2 Discussion points

Clarification was requested on methods currently deployed for treating radioactive waste in Poland. The presenter responded that around 50% of the current waste inventory is organic, and a significant amount of this waste is incinerated. Workshop participants noted that there could be scope for further collaborative research focused on this treatment approach and the resulting waste products, building on the conclusions of the EC THERAMIN project. This is already being considered within the Polish national programme.

The presenter observed that the suggested collaboration between France, Czechia and Slovakia to develop novel wasteform matrices (as discussed in Section 4.2.5.2) would also be of interest to Poland, since national activities are currently exploring options for waste stabilisation including vitrification and the use of geopolymers. A further area of interest for collaboration was noted to be future work on graphite waste management.

4.2.8 Feedback from PREDIS

4.2.8.1 Inputs presented at the workshop

A representative of CV Řež participated in the workshop on behalf of the PREDIS project, as part of ongoing collaboration and knowledge exchange between EURAD and PREDIS and, more specifically between ROUTES and PREDIS, on activities relating to WAC (as discussed in Section 1.3). He presented the status of WAC-related activities within the PREDIS project and provided some early reflections on WAC-related R&D needs and opportunities for collaboration emerging from the project. He also highlighted upcoming cooperative activities between PREDIS and other EC projects on WAC; these include a joint poster presented at the EURADWASTE conference in early June 2022 [17] and an upcoming webinar on the status of WAC activities in PREDIS, to be held in October 2022, which ROUTES participants are invited to attend. Further information is available on the PREDIS website.

The full presentation is included in the Subtask 4.3 memorandum [39]. This sub-section summarises emerging recommendations and associated discussion.

The overall goal of PREDIS activities on WAC is to provide advice and guidance on selected issues relating to the development of waste acceptance systems, in particular, on wasteform characterisation, the wasteform qualification process[13], and on the development and use of generic WAC.

Inputs from PREDIS can be summarised and rephrased as the following R&D needs:

- In relation to **characterisation**:
    - Sampling and characterisation methodologies to obtain representative samples, particularly for legacy wastes.
    - Shared development of methodologies for quantifying parameters linked to WAC.
    - Improving the link between characterisation and the definition of WAC.
- In relation to **treatment and conditioning**:
    - Further exploring trade-offs between early versus postponed conditioning, as well as options for multi-step conditioning versus potential requirements for reconditioning.
    - Further exploring the timing of conditioning for storage and disposal, taking account of the maturity of associated WAC.
- In relation to **WAC development**:
    - Recognising the importance of non-radiological WAC.
    - Improving record keeping, including archiving representative waste samples.
    - Shared identification of appropriate levels of conservatism in limits on e.g., radionuclide release, to avoid over-conservatism, particularly in preliminary WAC.
    - Harmonisation of preliminary and/or generic WAC across different countries, which is viewed as beneficial and feasible (whereas harmonising final WAC for specific disposal systems is viewed as challenging, if not impossible).
    - Pursuing opportunities to share both technologies and, potentially, regulatory activities, particularly between SIMS.

4.2.8.2 Discussion points

A participant asked for clarification on what is meant in relation to the harmonisation of generic WAC among different countries. The presenter responded that generic WAC are not linked to any particular facility or disposal system. They are developed and applied in some countries as a precursor to facility-specific WAC. It follows that a common set of generic WAC (developed collaboratively) could potentially be applied across many different facilities (in different countries) to promote consistent waste management activities (by setting out consistent expectations for waste characterisation and description). These generic WAC would then be 'upgraded' to facility-specific WAC at an appropriate time, when sufficient information is available on a particular disposal route and approach.

The workshop co-chair added that the exact interpretation of the terms 'generic WAC' and 'preliminary WAC' varies between different countries and programmes. In particular, 'preliminary WAC' is sometimes regarded as a synonym for generic WAC (i.e., having the same meaning), but may alternatively refer to facility-specific WAC that are at an early stage of development (i.e., not yet finalised and in use). The interpretation of these terms is being explored in PREDIS activities to develop guidance on the use of generic WAC. Cooperative discussions between ROUTES and PREDIS on this point will help to establish a consensus on the use of such terminology going forwards.

[13] The term 'wasteform qualification' is used in PREDIS to refer to the process of demonstrating that a selected wasteform is compatible with its designated disposal system.

In relation to harmonisation, the presenter commented that harmonisation of approaches to WAC development (and of generic WAC) is considered achievable, and a beneficial area for further discussion and collaboration. However, harmonisation of detailed WAC applicable to specific facilities and particularly, harmonisation of numerical criteria, is viewed as challenging if not impossible, owing to variation in the factors governing waste management at different facilities (e.g., waste classification; national regulations; facility design; safety functions; etc.). It was noted that harmonisation of WAC may be discussed more extensively in the upcoming HARPERS project.

4.2.9 National inputs received after the workshop

As noted in Section 4.1.2, additional national inputs from Romania and Ukraine were received after the workshop, based on partners' review of the amalgamated recommendations described in Section 4.3.2. These inputs are summarised below. Their impacts on the screened-in recommendations that form the main outputs from Subtask 4.3 are discussed in Section 4.3.6.

4.2.9.1 Romania

Inputs received indicate interest in the following R&D needs:

- Sampling and characterisation methodologies to obtain representative data (particularly for challenging / legacy wastes).
- Characterisation methods to determine compliance of particular wastes (conditioned and non-conditioned) with WAC, including:
  - Chemotoxics.
  - Complexants, chelating agents and other liquid organics.
  - Wastes with high alpha-emitting radionuclide inventory.
- Non-destructive analysis of conditioned waste, e.g., testing of concrete, including industrial implementation for small inventories.
- Destructive characterisation techniques for conditioned waste.
- Gas generation measurement (H_2, etc.) on ILW waste packages, including implementation on an industrial scale.
- Decontamination of irradiated or contaminated materials to facilitate reuse of materials with potential 'value', free release or optimised waste management (e.g., reduced waste volumes requiring geological disposal).
- Develop processes to neutralise reactive metals (e.g., U, Al, Mg).
- Develop innovative matrices (e.g., geopolymers?) for specific wastes and evaluate their compatibility with repository safety criteria. Wastes of interest include:
  - Solvents and acids.
  - Tritiated wastes.
  - Wastes containing reactive metals.
  - SIERs.
  - Sludges.
  - Spent fuel.
- Chemical behaviour of specific wastes under storage and disposal conditions, including radiation-induced processes and impacts on gas generation and radionuclide mobility and retention. Wastes of interest include:
  - SIERs.
  - Evaporator concentrates and tank sludges.
  - Cemented waste packages (particularly with respect to crack propagation).
  - Spent fuel and HLW.
- Benchmarking exercise for WAC development.

- Comparison and standardisation of radionuclides (and their speciation) to account for in waste characterisation and WAC, including ^{14}C.
- Comparison and standardisation of physical / chemical waste characteristics to account for in waste characterisation and WAC.
- Collaboration with other Member States on legal aspects of waste management.
- Collaboration with other Member States on societal aspects of waste management.
- Collaboration with other Member States to provide training and sustain competences in the field of radioactive waste management.

4.2.9.2 Ukraine

Inputs received indicate interest in the following R&D needs:

- Characterisation methods to determine compliance of particular wastes (conditioned and non-conditioned) with WAC, including:
    - Chemotoxics.
    - Complexants, chelating agents and other liquid organics.
    - Wastes with high alpha-emitting radionuclide inventory.
- Mobile systems and other shared approaches to waste characterisation.
- Gas generation measurement (H_2, etc.) on ILW waste packages, including implementation on an industrial scale.
- Decontamination of irradiated or contaminated materials to facilitate reuse of materials with potential 'value', free release or optimised waste management (e.g., reduced waste volumes requiring geological disposal).
- Develop innovative matrices (e.g., geopolymers?) for specific wastes and evaluate their compatibility with repository safety criteria. Wastes of interest include:
    - Solvents and acids.
    - Tritiated wastes.
    - Wastes containing reactive metals.
    - SIERs.
    - Sludges.
    - Spent fuel.
- Treatment and conditioning solutions to enhance the disposability of graphite wastes.
- Approach to manage challenging wastes with inventories or properties that do not meet WAC for existing or planned facilities.
- Chemical behaviour of specific wastes under storage and disposal conditions, including radiation-induced processes and impacts on gas generation and radionuclide mobility and retention. Wastes of interest include:
    - SIERs.
    - Evaporator concentrates and tank sludges.
    - Cemented waste packages (particularly with respect to crack propagation).
    - Spent fuel and HLW.
- Benchmarking exercise for WAC development.

4.3 Screening and prioritisation of recommendations

This section describes how the identified R&D needs and opportunities for collaboration[14] originating from the various sources described in Section 4.2 have been collated, rationalised, screened, and prioritised to arrive at a short list for onward consideration in ROUTES and more widely.

Cross-references are made throughout this section to Appendix C of the Subtask 4.3 memo [39], which reproduces the various components of an Excel spreadsheet considered during the Subtask 4.3 workshop, and to Appendix E of the Subtask 4.3 memo, which reproduces some of the associated worksheets, updated to incorporate inputs received from Romania and Ukraine after the workshop (as discussed in Section 4.2.9). Appendix A of the present report is a copy of Appendix E from the Subtask 4.3 memo [39].

4.3.1 Collation of inputs

National inputs received from each country were recorded in their 'raw' form in a worksheet entitled *"R&D needs – full list".* This was included in the Subtask 4.3 memo as Appendix C.1.

Most of the recommendations identified in the national inputs were listed separately, without considering whether this gave rise to duplicates of similar recommendations made elsewhere. The originating country was noted with an 'X'. Recommendations were organised into the following groups:

- Characterisation (including recommendations with an emphasis on <u>*how*</u> to characterise).
- Treatment.
- Conditioning.
- Storage and/or disposal strategy.
- Storage and/or disposal behaviour.
- WAC development (including recommendations with an emphasis on <u>*what*</u> to characterise).

These groups are aligned with stages in the waste lifecycle, and also with the groupings applied in ROUTES Subtask 4.2 to present observations and recommendations regarding 'no regret' waste management measures [7, §4 and Executive Summary].

Recommendations from other sources, as discussed in Section 4.1.3 were then integrated. The same groups were assigned to new recommendations identified at this point. However, at this stage, any recommendations that had already been recorded were not listed again – instead the additional countries making the recommendation were recorded with an additional 'X'. For this reason, the interests expressed in recommendations by some countries, as recorded in Appendix C of the Subtask 4.3 memo [39], are not always apparent from the national inputs presented in Section 4.2.

This process gave rise to 63 'raw' WAC-related recommendations. It is observed that the duplication of recommendations arising from ROUTES and PREDIS indicates consistency in the R&D needs being identified across the two projects, as well as highlighting commonly held needs between countries.

4.3.2 Rationalisation and initial review

A second worksheet was prepared, entitled "*Amalgamation of R&D needs*" (see Appendix C.2 of Subtask 4.3 memo). In this worksheet, recommendations from the first worksheet with a similar scope were combined (with some rephrasing) into a single overarching recommendation to remove overlaps

[14] For brevity, R&D needs and opportunities for collaboration are referred to simply as 'recommendations' throughout the rest of this report.

and duplication. For traceability, the original recommendations were retained as hidden rows within the spreadsheet, and were marked up with comments to record how and why they had been amalgamated.

The combined recommendations were then assigned unique reference numbers linked to the groups above as follows:

- Characterisation = **CH** (eight recommendations).
- Treatment = **TR** (six recommendations).
- Conditioning = **CO** (five recommendations).
- Storage and/or disposal strategy = **SS** (one recommendation).
- Storage and/or disposal behaviour = **SB** (three recommendations).
- WAC development = **WAC** (twelve recommendations)

The amalgamated recommendations were circulated for initial review and cross-checking before the workshop. Some partners indicated their countries' interest in recommendations supplied by other partners by adding an additional 'X' where relevant. Again, this highlights commonalities in R&D needs between countries, but results in interests being expressed by some countries that are not immediately apparent from their national inputs presented in Section 4.2.

This rationalisation gave rise to 35 'amalgamated' recommendations for WAC-related R&D needs and opportunities for collaboration. At this stage, the pre-existing duplication of various recommendations had been resolved.

4.3.3 Screening of recommendations

The amalgamated recommendations (incorporating updates from the initial partner review) were then screened against various criteria to generate a final worksheet entitled "*Screening updated 06_05_22*" (see Appendix C.3 of Subtask 4.3 memo). The purpose of this screening was to identify recommendations for further work of a novel scope (i.e., not already conducted elsewhere) and clearly linked to WAC (in line with the objectives of ROUTES Task 4) that address needs identified in multiple countries.

The criteria applied were as follows:

1) Recommendations that are not obviously common to more than one partner, or that are only identified in the PREDIS project, were screened out[15].
2) Recommendations that are not clearly linked to the development or application of WAC, or where the consideration of WAC is only peripheral, were screened out.
3) Recommendations that have already been addressed (or that will shortly be addressed) as part of ongoing and planned collaborative work programmes (e.g., in PREDIS), were screened out[16].

These criteria were reviewed and discussed during the workshop; no amendments or additional criteria were proposed.

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[15] With one or two exceptions, where there appeared to be a compelling reason for not doing so – where relevant, these reasons are recorded in Appendix C.3 of [39].

[16] The HARPERS project was also considered in relation to this criterion, and links to Subtask 4.3 recommendations are highlighted. However, since the detailed Phase 2 work programme for HARPERS had not yet been finalised when this exercise was conducted, related recommendations have not been screened out based on its potential scope.

Criterion 1) had by far the greatest impact on screening and resulted in 13 of the 'amalgamated' recommendations being screened out. Three other recommendations (TR2, TR3 and CO2) could have been screened out against this criterion but were retained because interest in these topics is believed to be more widespread (based on wider ROUTES and PREDIS discussions) than the evidence analysed in Subtask 4.3 suggests.

Criterion 2) was identified as being applicable to three recommendations. However, these had all already been screened out against Criterion 1). Three further recommendations were identified as *potentially* requiring screening against Criterion 2) (CO3, SB1 and WAC12). However, for the time being, it was decided to retain all of these recommendations because they all have a degree of linkage to WAC. It was also decided to feed these recommendations into the overarching discussions of outputs and recommendations from the ROUTES WP conducted under Tasks 1 and 6, since they are clearly also of wider relevance.

One recommendation (WAC9) was screened out against Criterion 3) on the basis that it has already been addressed in ROUTES Subtask 4.2 [7] and is being further explored in PREDIS Task 2.3.4, which is formulating guidance for developing generic WAC. A further recommendation (WAC6) could arguably be screened out against Criterion 3) but the extent to which this recommendation will be taken forward in e.g., the HARPERS project is not yet clear. Therefore, it was decided to retain this recommendation so that it can be factored into ongoing discussions.

The process described above gave rise to 21 'screened-in' recommendations for WAC-related R&D needs and opportunities for collaboration. Each of these recommendations is supported by multiple ROUTES partners.

4.3.4 Summary of inputs to the Subtask 4.3 workshop

Figure 12 summarises the method followed for collating, rationalising and screening recommendations prior to the Subtask 4.3 workshop and described in Sections 4.3.1 to 4.3.3 of this report. Table 3 lists the screened-in recommendations, as discussed at the workshop.

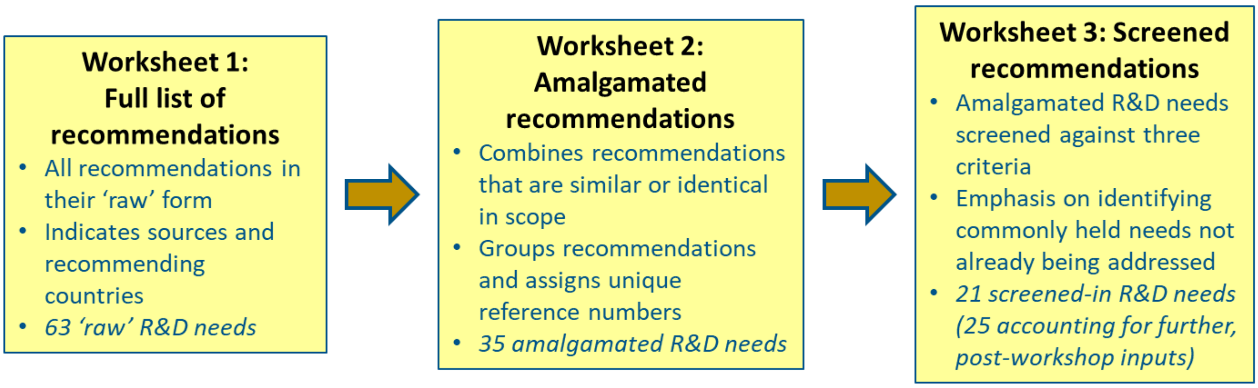


Figure 12 – Summary of methodology for identifying WAC-related R&D needs and opportunities for collaboration.

4.3.4.1 Discussion points

The overall process to collate, rationalise and screen recommendations was supported by workshop participants. Some minor updates to the wording of screened-in recommendations (e.g., WAC6) were proposed and are captured in Table 3.

Table 3 – Screened-in recommendations (pre-workshop).

<table>
<tr><th>Group</th><th>Recommendation</th></tr>
<tr><td rowspan="5">Characterisation

Including recommendations with an emphasis on <u>how</u> to characterise</td><td>CH1: Sampling and characterisation methodologies to obtain representative data (particularly for challenging / legacy wastes)</td></tr>
<tr><td>CH2: Characterisation methods to determine compliance of particular wastes (conditioned and non-conditioned) with WAC, including:
• Chemotoxics
• Complexants, chelating agents and other liquid organics
• Wastes with high alpha-emitting radionuclide inventory</td></tr>
<tr><td>CH3: Non-destructive analysis of conditioned waste, e.g., testing of concrete, including industrial implementation for small inventories</td></tr>
<tr><td>CH4: Destructive characterisation techniques for conditioned waste</td></tr>
<tr><td>CH5: Mobile systems and other shared approaches to waste characterisation</td></tr>
<tr><td rowspan="3">Treatment</td><td>TR1: Decontamination of irradiated or contaminated materials to facilitate reuse of materials with potential 'value', free release or optimised waste management (e.g., reduced waste volumes requiring geological disposal)</td></tr>
<tr><td>TR2: Automated sorting, segregation and packaging systems for waste</td></tr>
<tr><td>TR3: Sharing of waste management facilities (fixed, modular or mobile options)</td></tr>
<tr><td rowspan="4">Conditioning</td><td>CO1: Explore conditioning approaches and establish off-the-shelf list of techniques that maximise wasteform stability, but keep future waste management options open</td></tr>
<tr><td>CO2: Further evaluation of the trade-offs between early and postponed conditioning, including:
• Timing of conditioning for storage and disposal versus maturity of disposal WAC
• The need for flexibility of approach to be proportional to uncertainty in disposal route
• Options for 'multi-step' conditioning versus requirements for reconditioning (and further characterisation)</td></tr>
<tr><td>CO3: Develop innovative matrices (e.g., geopolymers?) for specific wastes and evaluate their compatibility with repository safety criteria. Wastes of interest include:
• Solvents and acids
• Tritiated wastes
• Wastes containing reactive metals
• SIERs
• Sludges
• Spent fuel</td></tr>
<tr><td>CO4: Treatment and conditioning solutions to enhance the disposability of graphite wastes</td></tr>
<tr><td>Storage / disposal strategy</td><td>SS1: Approach to manage challenging wastes with inventories or properties that do not meet WAC for existing or planned facilities</td></tr>
</table>

Group	Recommendation
Storage / disposal behaviour	**SB1:** Chemical behaviour of specific wastes under storage and disposal conditions, including radiation-induced processes and impacts on gas generation and radionuclide mobility and retention. Wastes of interest include: • SIERs • Evaporator concentrates and tank sludges • Cemented waste packages (particularly with respect to crack propagation) • Spent fuel and HLW
WAC development *Including recommendations with an emphasis on what to characterise*	**WAC1:** Benchmarking exercise for WAC development
	WAC2: Comparison and standardisation of radionuclides (and their speciation) to account for in waste characterisation and WAC, including ^{14}C
	WAC4: Improve the link between scientific characterisation activities and WAC establishment / measurements to check compliance - alignment of characterisation to planned waste management and associated safety assessments
	WAC5: Explore the role of WAC in designing a national policy for waste management and in supporting geological repository development
	WAC6: Shared / harmonised approaches to regulation and/or WAC (definition and/or application) across different countries (to the extent that this is achievable), also accounting for applicable non-radiological regulations (e.g., for hazardous / toxic wastes)
	WAC8: Develop a common method for quantifying parameters for the important features of WAC and identifying appropriate levels of conservatism in limits on e.g., radionuclide release
	WAC12: Collaboration with other Member States to provide training and sustain competences in the field of radioactive waste management

4.3.5 Prioritisation of recommendations

Online polling was conducted using Mentimeter in order to sample the views of workshop participants on which of the 21 recommendations they considered to have the highest priority. Owing to the number of recommendations, it was necessary to split them between two polls, which covered:

- Poll 1: Recommendations relating to characterisation, treatment and conditioning.
- Poll 2: Recommendations relating to storage / disposal and WAC development.

Workshop participants were asked to select their top three priorities for each poll (from a list presented to each individual in a randomised order). There were 15 responses to each poll. The outcomes (weighted by the software according to the first, second and third priorities assigned by participants) are presented in Figure 13 for Poll 1, and Figure 14 for Poll 2.

Figure 13 – Results of polling on the relative priority of screened-in recommendations in the Characterisation, Treatment and Conditioning groups.

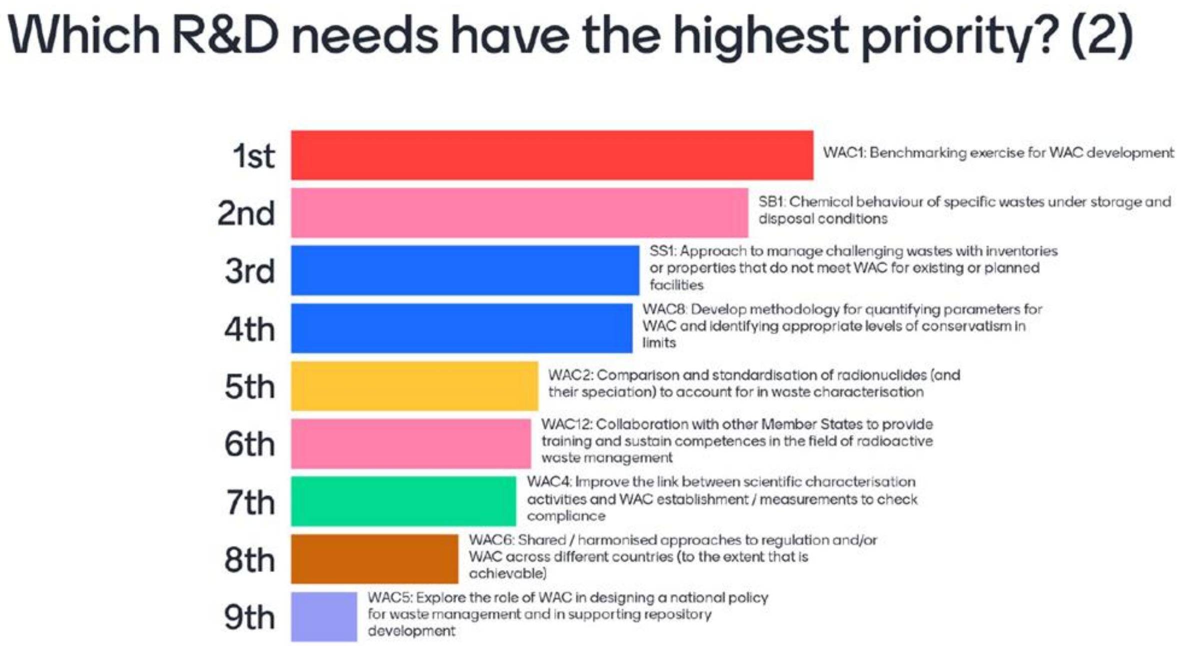


Figure 14 – Results of polling on the relative priority of screened-in recommendations in the Storage / disposal strategy, Storage / disposal behaviour, and WAC development groups.

It can be seen from these figures that the three recommendations assigned the highest priority by workshop participants are CO3 (*Develop innovative matrices (e.g., geopolymers?) for specific wastes and evaluate their compatibility with repository safety criteria*), WAC1 (*Benchmarking exercise for WAC development*) and SB1 (*Chemical behaviour of specific wastes under storage and disposal conditions*).

A number of caveats should be borne in mind when inspecting these polling results:

- Firstly, the number of responses (15) is relatively small and the number of options polled (21) is relatively large. This could have the effect of magnifying relatively small differences in the priorities assigned to recommendations.
- Secondly, the outcomes of the polling are heavily dependent on those participating in the workshop and their perspectives. For example, it is noted that not all Member States and Associated Countries participating in ROUTES and EURAD were represented in the workshop and, on the other hand, that there were multiple participants from some countries, thereby lending a potential bias to certain national perspectives. Differences in e.g., WMO, TSO, RE and Civil Society perspectives could also affect the outcomes of the polling exercise and these groups were not equally represented.
- Thirdly, the polling does not capture feedback on five recommendations that were screened back in as a result of national inputs received following the Subtask 4.3 workshop, as discussed in Sections 4.2.9 and 4.3.6.
- Finally, due to the capabilities of the polling software, it was necessary to split the screened-in recommendations between two separate polls. This approach prevents a direct comparison of the outcomes from the two polls and therefore prevents overall top priorities from being identified.

Taken together, these caveats mean that the polling results can be regarded as giving indications of priority recommendations, but one should avoid placing too much emphasis on them in isolation.

4.3.6 Updated screening of recommendations

As noted in Section 4.2.9, additional inputs were received from Romania and Ukraine after the Subtask 4.3 workshop. These were based on associated partners' reviews of the amalgamated recommendations described in Section 4.3.2. No further recommendations were identified at this stage.

These inputs have a bearing on the outcomes from the screening process described in Section 4.3.3, since they reinforce support for, and interest in, several recommendations that had, hitherto, only been expressed by one country, and which were therefore screened out against Criterion 1).

Appendix A presents the final worksheet developed under Subtask 4.3 (Appendix E of the Subtask 4.3 memo [39]) incorporating these inputs and recording associated changes in screening decisions. Table 4 presents the additional recommendations not listed in Table 3 that are now screened in.

Table 4 – Additional screened-in recommendations based on feedback following the workshop.

Group	Recommendation
Characterisation *Including recommendations with an emphasis on how to characterise*	**CH6:** Gas generation measurement (H_2, etc.) on ILW waste packages, including implementation on an industrial scale.
WAC development *Including recommendations with an emphasis on what to characterise*	**WAC3:** Comparison and standardisation of physical / chemical waste characteristics to account for in waste characterisation and WAC.
	WAC10: Collaboration with other Member States on legal aspects of waste management.
	WAC11: Collaboration with other Member States on societal aspects of waste management.

It can be seen that a further four recommendations are now screened in. Note that Recommendation TR4 (*Develop processes to neutralise reactive metals (e.g., U, Al, Mg)*) is no longer screened out against Criterion 1, but remains screened out against Criterion 2 on the basis that it is focused more on technology development than on WAC development and application.

These four recommendations should be taken forward for further consideration alongside those listed in Table 3. They have not been subject to additional polling to determine associated prioritisation.

5 Distillation of ROUTES WAC-related recommendations

Section 5.1 summarises the process followed in Subtask 4.3 to derive WAC-related needs and opportunities for future collaboration (“recommendations”). Section 5.2 describes how the five highest priority recommendations were identified from this list and taken for wider consideration with recommendations emerging from elsewhere in ROUTES. Section 5.3 presents the details of these recommendations that were considered in a cross-ROUTES workshop in December 2022 and subsequently incorporated in the updated EURAD SRA.

5.1 Summary of outcomes from Subtask 4.3

Subtask 4.3 of ROUTES followed a stepwise approach to identify, rationalise, screen and prioritise WAC-related R&D needs and opportunities for collaboration in Europe, as described in Section 4. The first step consisted of establishing a broad list of associated recommendations. The following sources of information were studied to do this:

- Dedicated national inputs to ROUTES Subtask 4.3:
    - Nine countries identified their R&D needs and desired areas for collaboration with respect to the management of challenging wastes, particularly in relation to the conditioning of waste while maintaining compatibility with option(s) for disposal.
- Feedback from PREDIS:
    - Memoranda of two joint PREDIS / ROUTES / ERDO webinars on WAC, held in April 2021 [14] and May 2021 [15].
    - The PREDIS gap analysis outputs [38].
- Other inputs:
    - Review of the national responses to the ROUTES Questionnaire (particularly Q18-22) [27], [28].
    - Discussion points identified earlier in Task 4, as identified by cross-checking the memoranda prepared for Subtasks 4.1 [6] and 4.2 [7].

The resulting “long-list” of 63 recommendations was organised according to the stage in the waste lifecycle that each recommendation pertains to, as well as overarching recommendations relating to WAC development, as follows:

- Characterisation (including recommendations with an emphasis on <u>how</u> to characterise) (CH).
- Treatment (TR).
- Conditioning (CO).
- Storage or disposal strategy (SS).
- Storage and/or disposal behaviour (SB).
- WAC development (including recommendations emphasising <u>what</u> to characterise) (WAC).

The second step consisted of rationalising the initial long list of recommendations by amalgamating those that bear some degree of similarity or overlap in scope. A reference code, linked to the above lifecycle groups, was assigned to each recommendation at this stage. This process reduced the long list of recommendations from 63 to 35.

The third step consisted of screening out those recommendations that are not commonly held between participating countries, are not strongly related to WAC, and/or are already being addressed (or will be addressed) in ongoing or planned collaborative work programmes. It is noted that there is a strong element of subjectivity in the screening applied. This is particularly true when deciding how to delineate the boundary between activities relating to WAC and those relating to wider waste management and/or safety case development. The project team therefore took a cautious approach to screening out recommendations that appear to be of limited relevance from the perspective of developing and applying WAC, in order to avoid ruling out areas for further work that could, nevertheless, be of widespread interest. A degree of judgement was also applied in a few instances where the number of countries interested in a recommendation appeared to be limited, but where it is believed that interest has actually been expressed more widely in other forums (such as discussions in other collaborative projects).

Taking account of all national inputs received over the course of the subtask, this screening resulted in a final list of 25 recommendations, which are presented in Table 5.

Table 5 – All screened-in recommendations.

Group	Recommendation
Characterisation *Including recommendations with an emphasis on how to characterise*	**CH1:** Sampling and characterisation methodologies to obtain representative data (particularly for challenging / legacy wastes)
	CH2: Characterisation methods to determine compliance of particular wastes (conditioned and non-conditioned) with WAC, including: • Chemotoxics • Complexants, chelating agents and other liquid organics • Wastes with high alpha-emitting radionuclide inventory
	CH3: Non-destructive analysis of conditioned waste, e.g., testing of concrete, including industrial implementation for small inventories
	CH4: Destructive characterisation techniques for conditioned waste
	CH5: Mobile systems and other shared approaches to waste characterisation
	CH6: Gas generation measurement (H_2, etc.) on ILW waste packages, including implementation on an industrial scale.
Treatment	**TR1:** Decontamination of irradiated or contaminated materials to facilitate reuse of materials with potential 'value', free release or optimised waste management (e.g., reduced waste volumes requiring geological disposal)
	TR2: Automated sorting, segregation and packaging systems for waste
	TR3: Sharing of waste management facilities (fixed, modular or mobile options)
Conditioning	**CO1:** Explore conditioning approaches and establish off-the-shelf list of techniques that maximise wasteform stability, but keep future waste management options open
	CO2: Further evaluation of the trade-offs between early and postponed conditioning, including: • Timing of conditioning for storage and disposal versus maturity of disposal WAC • The need for flexibility of approach to be proportional to uncertainty in disposal route • Options for 'multi-step' conditioning versus requirements for reconditioning (and further characterisation)

Group	Recommendation
	CO3: Develop innovative matrices (e.g., geopolymers?) for specific wastes and evaluate their compatibility with repository safety criteria. Wastes of interest include: • Solvents and acids • Tritiated wastes • Wastes containing reactive metals • SIERs • Sludges • Spent fuel
	CO4: Treatment and conditioning solutions to enhance the disposability of graphite wastes
Storage / disposal strategy	**SS1:** Approach to manage challenging wastes with inventories or properties that do not meet WAC for existing or planned facilities
Storage / disposal behaviour	**SB1:** Chemical behaviour of specific wastes under storage and disposal conditions, including radiation-induced processes and impacts on gas generation and radionuclide mobility and retention. Wastes of interest include: • SIERs • Evaporator concentrates and tank sludges • Cemented waste packages (particularly with respect to crack propagation) • Spent fuel and HLW
WAC development *Including recommendations with an emphasis on what to characterise*	**WAC1:** Benchmarking exercise for WAC development
	WAC2: Comparison and standardisation of radionuclides (and their speciation) to account for in waste characterisation and WAC, including ^{14}C
	WAC3: Comparison and standardisation of physical / chemical waste characteristics to account for in waste characterisation and WAC.
	WAC4: Improve the link between scientific characterisation activities and WAC establishment / measurements to check compliance - alignment of characterisation to planned waste management and associated safety assessments
	WAC5: Explore the role of WAC in designing a national policy for waste management and in supporting geological repository development
	WAC6: Shared / harmonised approaches to regulation and/or WAC (definition and/or application) across different countries (to the extent that this is achievable), also accounting for applicable non-radiological regulations (e.g., for hazardous / toxic wastes)
	WAC8: Develop a common method for quantifying parameters for the important features of WAC and identifying appropriate levels of conservatism in limits on e.g., radionuclide release
	WAC10: Collaboration with other Member States on legal aspects of waste management
	WAC11: Collaboration with other Member States on societal aspects of waste management
	WAC12: Collaboration with other Member States to provide training and sustain competences in the field of radioactive waste management

The final step consisted of exploring opinions on the relative priority of screened-in recommendations. This was achieved by conducting an online polling exercise during the Subtask 4.3 workshop held in May 2022. The results of this poll indicate that the three highest priority recommendations to take forward are:

- CO3: Development of innovative matrices for specific wastes and evaluation of their compatibility with repository safety criteria.
- WAC1: Benchmarking of WAC development.
- SB1: Study the chemical behaviour of specific wastes under storage and/or disposal conditions.

The polling gives a helpful indication of important recommendations for future work. However, the outcomes are strongly dependent on aspects of how the polling was conducted. The number of responses was relatively small and was limited to individuals participating in the Subtask 4.3 workshop. Different Member States and Associated Countries were not represented with equal numbers of participants in this workshop and some were not represented at all. Nor was a balance sought between the different perspectives associated with the nature of the represented organisations (WMO, TSO, RE or CSO). Also, for practical reasons the poll was conducted in two parts, which prevents direct comparison of all recommendations against each other. Finally, four recommendations were not included in the polling, since they were screened out before the workshop and only reinstated following the subsequent receipt of additional national inputs. Great care should therefore be taken to avoid placing too much emphasis on the polling outcomes in isolation. It is also observed that two of the three 'top priority' recommendations have only limited relevance to WAC development and application, but were retained for further consideration by the cautious approach to screening described previously.

A stronger indication of recommendations worth pursuing in future collaborative work can be drawn by inspecting the polling results in conjunction with the number of countries indicating an interest in each of the 25 screened-in recommendations. For the top priority recommendations according to the polling, the number of countries (out of fifteen) expressing an interest are five for CO3; three for WAC1 and seven for SB1. Thus, according to the poll, SB1 would be the recommendation in which most countries are interested. The level and spread of interest in other screened-in recommendations can be inspected with reference to Appendix A.

An important principle regarding recommendations relating to WAC development is that further collaborative work in this area should focus on addressing specific, targeted needs rather than conducting general reviews on the status of existing WAC or producing general guidance. Both of these aspects, while useful, have been, and continue to be, the subject of recent and ongoing work. Indeed, in recent years several reviews on WAC have been conducted, notably the ROUTES Subtask 4.1 report [6] and PREDIS Deliverable 2.4 [11]. And several guidance reports have been produced, such as the ROUTES Subtask 4.2 report [7] or are being produced, including guidance on the formulation of generic WAC under PREDIS Task 2.3.4, and an upcoming IAEA technical document on the approach to the development of WAC for LILW. Taking this consideration into account, the present report, and the subsequent Task 4 deliverable, should serve as a source of information to identify specific needs in the area of WAC development that could be tackled in future collaborative work.

5.2 Methodology for distilling Task 4 recommendations for the updated EURAD SRA

In late 2022, WAC-related recommendations identified during Subtask 4.3 were fed into a workshop aiming to share and disseminate wider recommendations for R&D activities, strategic studies and work on knowledge management that had been identified across the ROUTES WP [40]. This workshop was held online on 6th December 2022, and was attended by ROUTES partners and end users; PMO representatives, including the EURAD Coordinator and Chief Scientific Officer; other WP leads; the EC Project Officer; and representatives from the EC PREDIS and HARPERS projects and from the NEA.

Inputs to this workshop from across all ROUTES tasks were prepared in a common format, as shown in Figure 15. This enabled all relevant information to be captured in a manner that would facilitate the direct incorporation of each recommendation into the EURAD SRA, an updated version of which was prepared in late 2022 and published in early 2023 [26]. The updated SRA provides the principal basis around which proposals for the EURAD-2 work programme have been developed [41].

The template for inputs included space for recording:

- The title and scope of the recommendation, including identification of whether it was new to the EURAD SRA or required adaptation / expansion of existing wording.
- The nature of the study(ies) proposed to address the need, i.e., R&D, a strategic study, or work relating to knowledge management.
- The origin of the recommendation (i.e., the ROUTES task(s) in which the need was identified), including an indication of whether the recommendation was shared across multiple ROUTES work areas / tasks.
- The relevant theme(s) from the EURAD roadmap [42].
- Drivers that justify the need (to be selected from a common list used across the EURAD SRA) [26, § 4.1].
- A contextual description of the recommendation, which needed to be consistent with the selected driver(s).
- The expected outcomes and impacts of work responding to the recommendation.
- Relevant past projects and possible opportunities for cooperation.

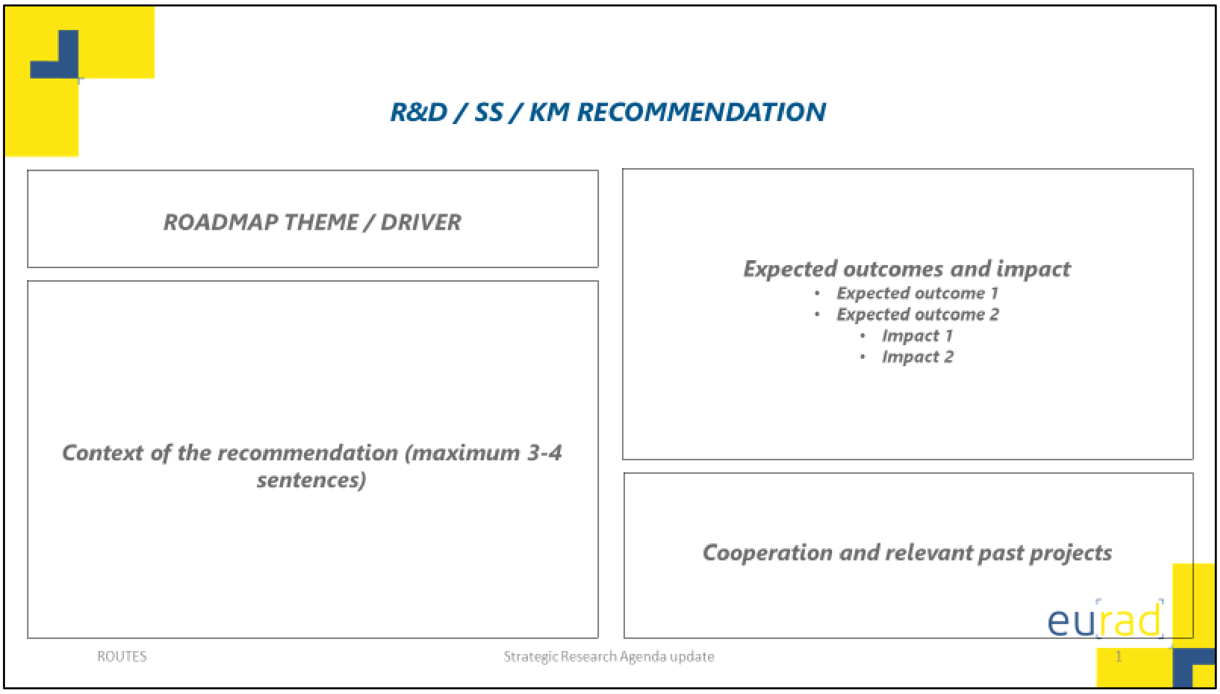


Figure 15 – Template used for the preparation of inputs to the ROUTES recommendations workshop held in December 2022.

For reasons of pragmatism, it was not possible to feed all 25 of the Subtask 4.3 recommendations into the cross-ROUTES workshop and the updated EURAD SRA. Therefore, expert judgement was used to down-select the five highest priority WAC-related recommendations from the list set out in Table 5, taking consideration of the following:

- Multiple Member States and Associated Countries indicating an interest in the recommendation (ideally a minimum of five), as indicated in Appendix A.
- A high interest being expressed in the recommendation during the polling exercise conducted during the Subtask 4.3 workshop, as indicated in Figure 13 and Figure 14 (Section 4.3.5).
- Other indicators of the topic being of widespread interest, for example, the identification of a similar topic, idea or recommendation within other initiatives, such as development of the PREDIS SRA; EURAD lunch and learn webinars; or with responses to surveys / questionnaires.
- The recommendation having a clear focus on the development and application of WAC, rather than being primarily concerned with a wider topic, where consideration of WAC would be only a peripheral element of associated studies.
- The recommendation being sufficiently well scoped out to allow a future work programme to be visualised.

Based on these considerations, the following five recommendations from Subtask 4.3 were selected for discussion in the ROUTES recommendation workshop, and for inclusion in the updated EURAD SRA:

- **CH1:** Sampling and characterisation methodologies to obtain representative data (*five countries supporting this recommendation*).
- **CH2:** Characterisation methods to determine compliance of particular wastes with WAC (*seven countries supporting this recommendation*).

- **SS1:** Approach to manage challenging wastes with inventories or properties that do not meet WAC for existing or planned facilities (*six countries supporting this recommendation*).
- **WAC1:** Benchmarking exercise for WAC development (*three countries supporting this recommendation and a top priority, as identified in* Figure 14*; strongly linked to WAC development and application*).
- **WAC2:** Comparison and standardisation of radionuclides (and their speciation) to account for in waste characterisation and WAC (*five countries supporting this recommendation*).

Several other recommendations from Table 5, such as CH3, CH5, TR1, CO3, SB1, and WAC12 are also widely supported, but were not amongst the top five priorities identified from Task 4 because they did not fulfil all of the other considerations described above. For example, CH3 (Non-destructive analysis of conditioned waste); CH5 (Mobile systems and other shared approaches to waste characterisation); CO3 (Develop innovative matrices for specific wastes); and SB1 (Chemical behaviour of specific wastes under storage and disposal conditions) were all supported by at least five Member States and Associated Countries and some performed well in polling of priorities, as described in Section 4.3.5. However, it was felt that consideration of WAC would likely be a peripheral element of work on these topics, rather than a central tenet. The same was true for TR1 (Decontamination of irradiated or contaminated materials to facilitate reuse, free release or optimised waste management; supported by four Member States and Associated Countries). Moreover, this topic was already expected to be studied within the EC HARPERS project (as part of WP4, which focuses on circular economies). Finally, WAC12 (Collaboration with other Member States to provide training and sustain competences in the field of radioactive waste management; also supported by four Member States and Associated Countries) was recognised as a core principle that is crucial to the success and value of collaborative EC work, but was not considered to be a well-defined topic for study in its own right. Instead, this principle should be reflected in the working methodologies of future WPs.

Despite these outcomes for the decision-making process described above which, because of the scope of Task 4, was necessarily focused on WAC, many of the other recommendations discussed in Subtask 4.3 were still factored into ROUTES inputs to the updated EURAD SRA because they had *also* been identified as high priority recommendations under other ROUTES tasks.

The five highest priority Task 4 recommendations, as identified above, were integrated with wider ROUTES recommendations into a cross-cutting presentation for discussion in the workshop on 6th December 2022 [43]. Consistent with this integration, a common numbering / colour-coding scheme was adopted for designating recommendations identified across all ROUTES tasks according to the type of further study that was considered necessary. As such, recommendations for R&D studies were coloured **blue**; recommendations for strategic studies (StSt) were coloured **mustard**; and recommendations for knowledge management (KM) activities were coloured **green**. Within each of these three groups, recommendations were numbered sequentially.

This workshop presentation and associated discussion was organised around the following themes:

- Interactions with civil society and safety culture.
- International cooperation.
- Disposal strategies, which included consideration of SS1 from Table 5 (now renumbered **StSt-4**).
- Concept selection.
- WAC, which included consideration of WAC1 and WAC2 from Table 5 (now renumbered **StSt-10** and **StSt-9** respectively).

- Characterisation, which included consideration of CH1 and CH2 from Table 5 (now renumbered **R&D-5** and **R&D-2** respectively).
- Treatment and conditioning.

Following the workshop, minor updates were made to the integrated ROUTES recommendations to reflect changes agreed during discussions, as recorded in a PowerPoint presentation, which constitutes EURAD Milestone 337 [44].

5.3 Summary of WAC-related recommendations and associated discussion

Task 4 inputs to the ROUTES recommendations workshop, prepared according to the methodology described in Section 5.2, are reproduced in Figure 16, Figure 17 and Figure 18 [43].

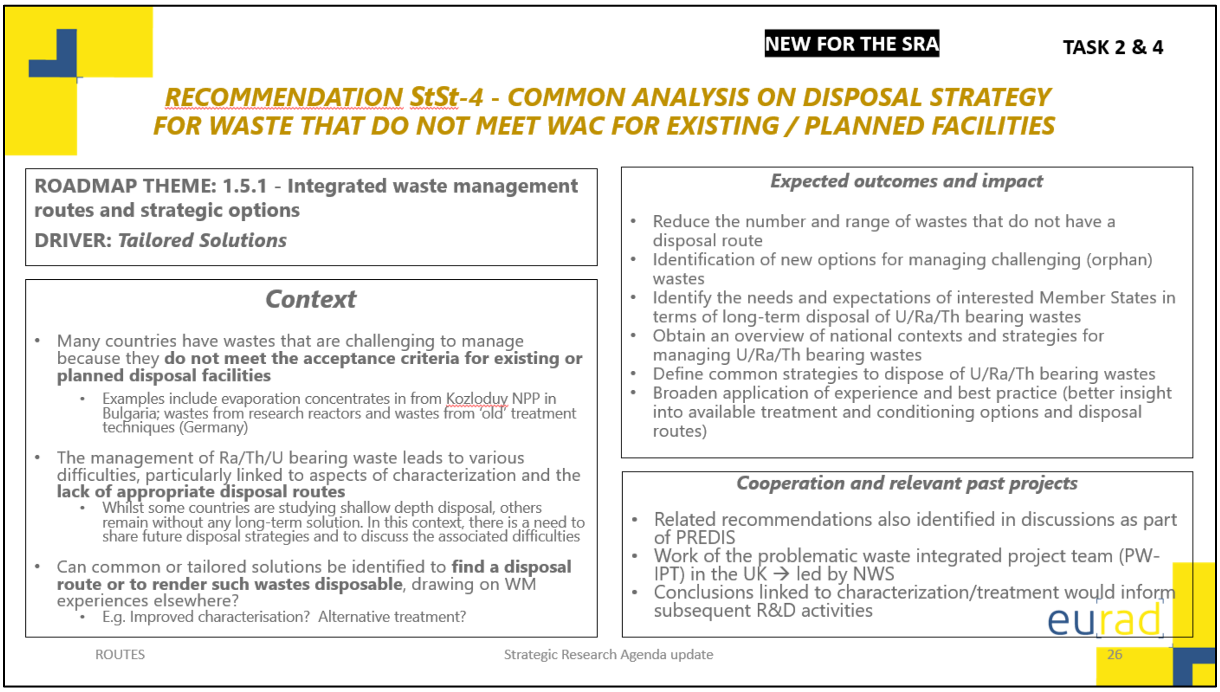
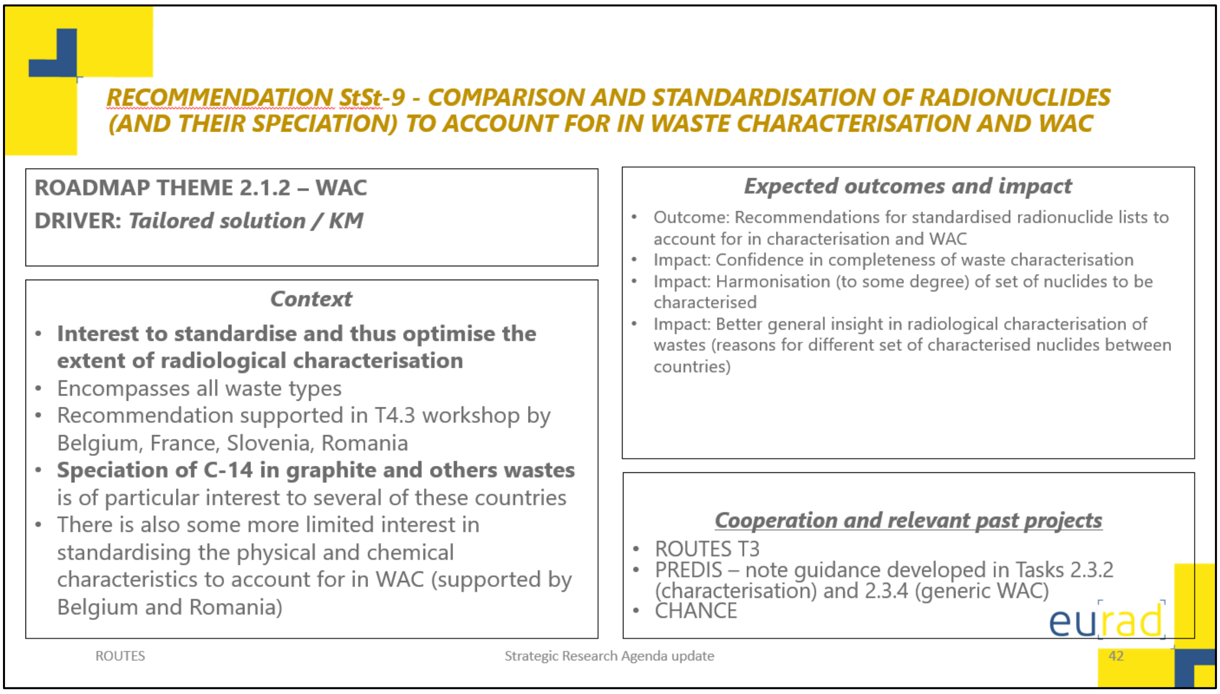


Figure 16 – WAC-related recommendation discussed under the disposal strategies theme at the ROUTES recommendations workshop. (This recommendation was previously numbered SS1).



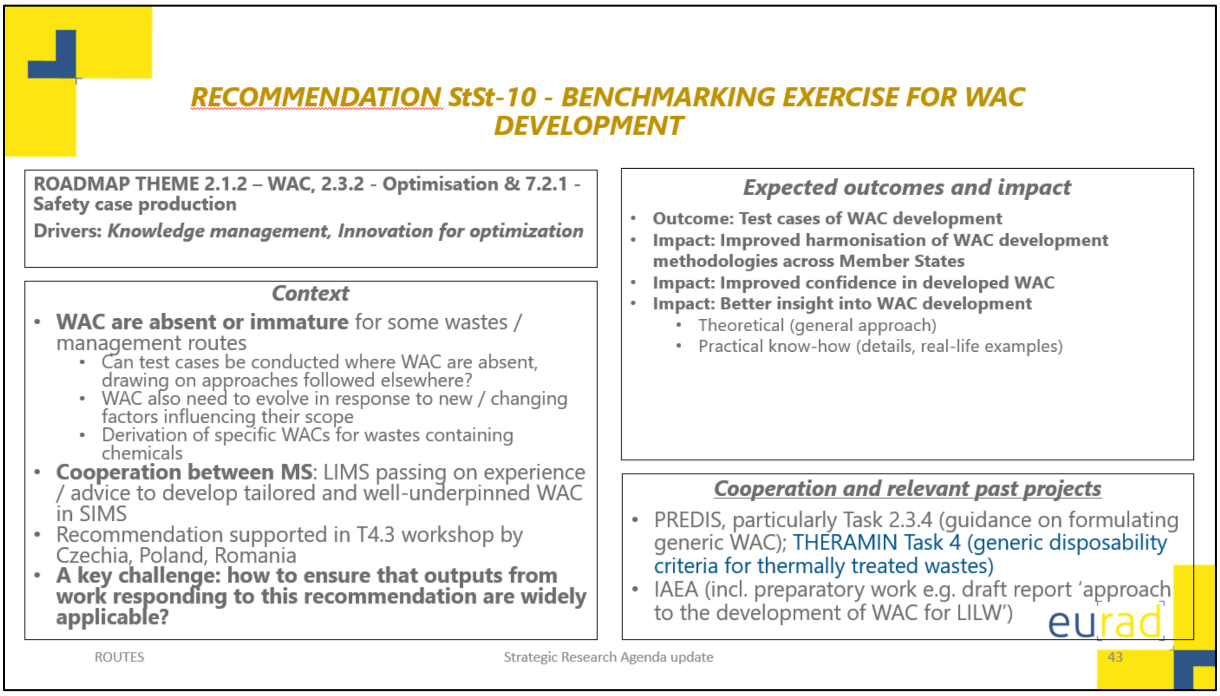
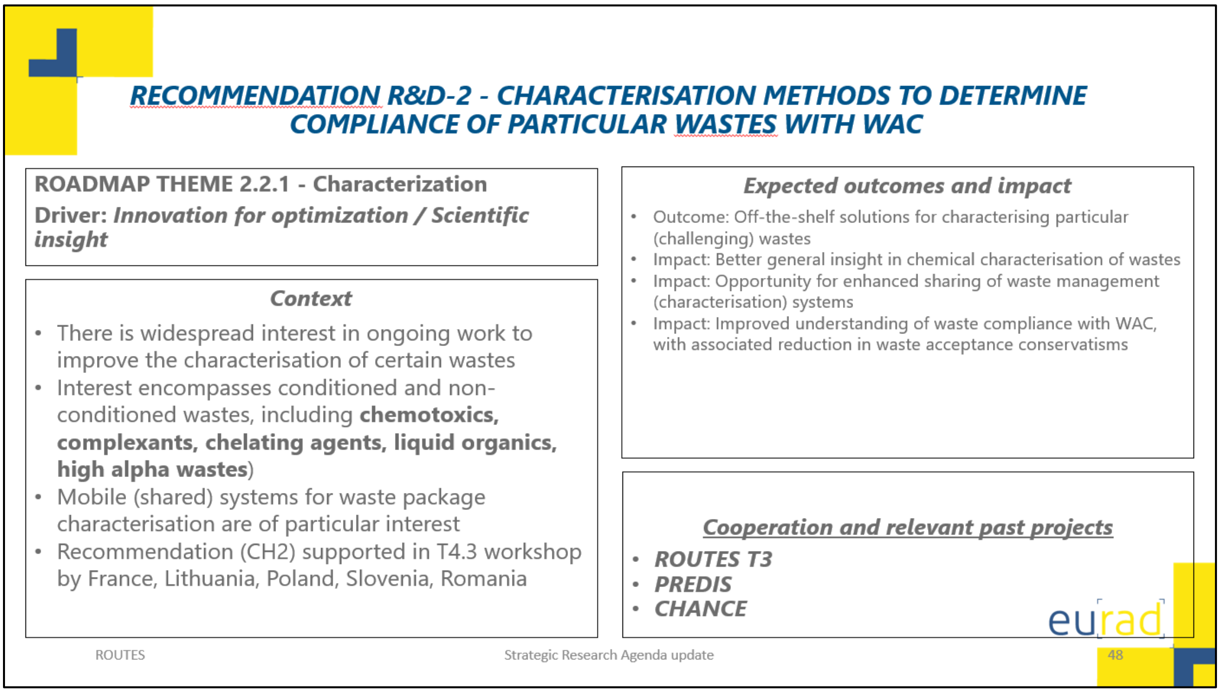


Figure 17 – WAC-related recommendations discussed under the WAC theme at the ROUTES recommendations workshop. (These recommendations were previously numbered WAC2 and WAC1 respectively).



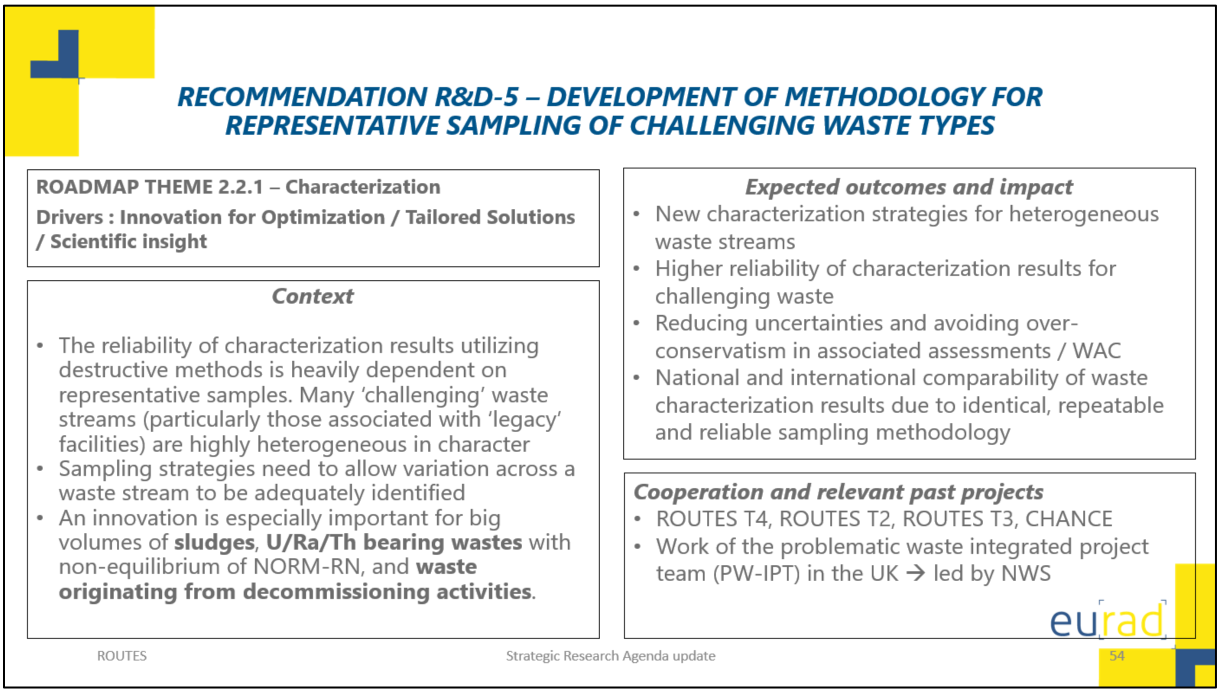


Figure 18 – WAC-related recommendations discussed under the characterisation theme at the ROUTES recommendations workshop. (These recommendations were previously numbered CH2 and CH1 respectively).

The following minor, but notable, changes to WAC-related recommendations were agreed during workshop discussions and reflected in the final ROUTES inputs to update of the EURAD SRA [44]:

- The title of Recommendation StSt-10 was updated to read: "Benchmarking exercise for *the process of* WAC development", in order to emphasise that associated work would need to focus on methodologies for WAC development, albeit with reference to test cases focusing on specific waste management facilities.
- The title of Recommendation R&D-2 was updated to read: "*Development of* characterisation methods to determine compliance of particular wastes with WAC", in order to emphasise that work responding to this recommendation should place a greater emphasis on the progression of characterisation techniques towards real-world applications, rather than research of novel approaches that have limited prospects, or long timescales, for application.

Other notable discussion points linked to WAC-related recommendations were as follows:

- For **StSt-4** (corresponding with Task 4 recommendation SS1), the possibility exists to combine certain topics proposed for future strategic studies, in order to achieve best value from future EC joint programming, as well as the value of involving non-EC countries to be able to draw on wider waste management experiences.
- For **StSt-9** (corresponding with Task 4 recommendation WAC2), the value of an integrated consideration of radiological and chemotoxic hazards posed by radioactive wastes, and a desire to improve harmonisation of associated national and international regulations. Relevance for the ongoing work of the HARPERS project was acknowledged.
- For **StSt-10** (corresponding with Task 4 recommendation WAC1), the importance of understanding, through benchmarking activities, why different WAC or WAC development approaches can be appropriate for particular facilities or when considered against different national contexts.
- For **R&D-2** (corresponding with Task 4 recommendation CH2), the suggestion to progress this topic initially through a short (six-month) strategic study that would seek to specify what collaborative development activities would be most beneficial to conduct in this area.
- For **R&D-5** (corresponding with Task 4 recommendation CH1), the high relevance and value of developing representative sampling approaches for both LIMS and SIMS, and the particular interest of some countries on approaches to sample large numbers of small volume waste streams, such as bottled samples, as well as the need to improve shared supply chains for waste characterisation expertise.

Wider outputs from the ROUTES recommendations workshop are recorded in the workshop minutes.

The above WAC-related recommendations are captured in the updated EURAD SRA [26] within the following needs:

- Under EURAD Theme 1 (National Programme Management):
  - *Domain 1.3.3 (International collaboration):* A newly formulated need for development of a forum for a community of practice between LIMS and SIMS (**StSt-10**; **R&D-2**; **R&D-5**, corresponding with Task 4 recommendations WAC1, CH2 and CH1 respectively).
  - *Domain 1.3.3 (International collaboration):* A newly formulated need for identification of possible shared (and possibly mobile) solutions for radioactive waste characterisation, treatment or conditioning (**R&D-2**, corresponding with Task 4 recommendation CH2; also other Task 4 recommendations, e.g., **CH-5**).

  - *Domain 1.5.1 (Integrated waste management routes and strategic options):* A newly formulated need for a common analysis on management strategies for waste types (e.g., particular spent fuels or large volumes of low active, long-lived waste) and small amounts of waste in SIMS (**StSt-4**; **R&D-2**, corresponding with Task 4 recommendations SS1 and CH2 respectively).
- Under EURAD Theme 2 (Pre-disposal):
  - *Domain 2.1.1 (Inventory):* A newly formulated need for knowledge management regarding existing studies on legacy and problematic waste inventories and capturing good practice in the management of inventory data and uncertainty treatment (**StSt-9**, corresponding with Task 4 recommendation WAC2).
  - *Domain 2.1.2 (Waste acceptance criteria):* An updated need for the development of guidance for the derivation of WAC and benchmarking exercises for the process of WAC development (**StSt-10**, corresponding with Task 4 recommendation WAC1).
  - *Domain 2.1.2 (Waste acceptance criteria):* A newly formulated need for dealing with non-compliant and challenging waste streams by developing methodologies for demonstrating compliance with WAC (linked to **StSt-10**, corresponding with Task 4 recommendation WAC1).
  - *Domain 2.2.1 (Characterisation):* A newly formulated need to develop characterisation methods and techniques for (conditioned and non-conditioned) radioactive waste (and packages) (**R&D-2**, corresponding with Task 4 recommendation CH2).
  - *Domain 2.2.1 (Characterisation):* A newly formulated need for development of innovative methods for scaling factors validation (linked to **StSt-9**, **R&D-2** and **R&D-5**, corresponding with Task 4 recommendations WAC2, CH2 and CH1 respectively).
  - *Domain 2.2.1 (Characterisation):* A newly formulated need for development of methodologies for uncertainty and data management during characterisation (**R&D-5**, corresponding with Task 4 recommendation CH1).

6 ROUTES Task 4 conclusions

6.1 ROUTES Task 4 objectives and structure

ROUTES Task 4 aimed to identify and examine WAC used in Member States for different waste management strategies in order to inform development of WAC in countries without WAC / facilities. More specifically, Task 4 had the following objectives:

- To provide an overview of the current application in Member States of WAC at different stages in the waste lifecycle and to describe mechanisms to implement them.
- To offer a structured approach to support decision-taking of so-called 'no regret' waste management measures, i.e., decisions that do not lead to problems later on.
- To identify R&D needs and opportunities for collaboration between Member States[17].

These objectives have been delivered via three successive subtasks:

- **Subtask 4.1:** *Current use of waste acceptance criteria* – this subtask involved the production of an up-to-date overview per country on the use of WAC in Member States and some Associated Countries, focusing on the use of WAC as a management tool across the waste lifecycle. The work in Subtask 4.1 was presented in a report published in February 2021 [6]. The results of Subtask 4.1 are summarised in Section 2 of this report. It is noted that the current status of WAC has also been considered within ROUTES Task 5, as reflected in ROUTES Deliverable D9.10 [1, §3.4]. Compared to the Milestone 88 report, D9.10 includes some further clarifications and reflects updates to national WAC since 2021. It also places a greater focus on SIMS.
- **Subtask 4.2:** *Sharing of experience on waste management with and without WAC being available* – this subtask offered a structured approach to support decision taking of 'no regret' waste management measures. This was achieved by examining case studies of waste management activities without WAC, disposal solutions or other technical facilities being available, as well as a series of cross-cutting topics relating to WAC. These informed a gap analysis and a series of observations and recommendations on progressing waste management whilst maintaining compatibility with a range of options for subsequent waste lifecycle stages. The work of Subtask 4.2 was documented in an internal memorandum (EURAD Milestone 144) [7]. The results of Subtask 4.2 are summarised in Section 3 of this report and its main conclusions are reiterated in Section 6.2.
- **Subtask 4.3:** *R&D needs and opportunities for collaboration* – this subtask identified and prioritised commonly held R&D needs related to the management of challenging wastes, as well as opportunities for collaboration between Member States and Associated Countries. To achieve this, first a long list of 63 recommendations for future R&D was drawn up, based on already available information and new inputs acquired through a dedicated workshop. Subsequently, this list was shortened to 35 by combining and grouping recommendations that were similar or with the same scope. Finally, the short list was further reduced to 25 recommendations by screening out those that are not shared among partners, not connected to WAC, or that are already being addressed in other collaborative work programmes. In addition, the relative priorities of these recommendations were explored with ROUTES partners. This work was documented in an internal memorandum (EURAD Milestone 192) [39] and is summarised in Section 4 of this report. Five out of these 25 recommendations, considered to have the highest priority based on expert judgement, were selected for discussion alongside

[17] Although this refers to R&D, it should be taken to encompass wider future needs, e.g., further strategic studies.

recommendations emerging from other ROUTES tasks at a workshop in December 2022 and were subsequently fed into the updated EURAD SRA. The five selected WAC-related recommendations were attributed a different code number at this point, for consistency with the numbering scheme used in that wider context. The process of distilling the final five recommendations is described in Section 5 of this report and the main results of Subtask 4.3 are reiterated in Section 6.3.

6.2 Recommendations for 'no regret' waste management measures

The objective of ROUTES Subtask 4.2 was to offer a structured approach to support decision-taking of 'no regret' waste management measures, i.e., decisions that do not lead to problems later on. This has been achieved through the presentation of a series of observations and recommendations on 'no regret' approaches that can be deployed at different stages of the waste lifecycle and also during the definition of WAC. These observations and recommendations draw together learning from discussion and analysis of:

- A series of waste management case studies in the presence / absence of WAC.
- Various cross-cutting topics relating to WAC.
- A gap analysis of the above-mentioned resources.
- Outputs from related activities elsewhere in ROUTES, as well as in other collaborative international projects and initiatives.

The observations and recommendations regarding 'no regret' waste management measures, can be summarised as follows:

With regard to **characterisation**:

- Waste characterisation is essential to understanding the inventory. The waste inventory informs all subsequent management steps and has a major influence on measures that could be applied for waste minimisation, materials recycling and reuse.
- Characterisation at the time of waste generation is essential to minimise the need for more extensive characterisation downstream, which is often more challenging.
- An adequate records management process to store, and facilitate reference to, waste characterisation data needs to be implemented at an early stage, and to endure throughout the waste lifecycle.

With regard to **treatment**:

- Where possible (and relevant), treatment techniques should be flexible, to enable adaptations to be made in response to the particular characteristics of individual waste streams or site-specific constraints, thereby ensuring that processing criteria and WAC for storage and/or disposal of the resulting product can be met wherever a technique is applied.

With regard to **conditioning**:

- Whilst conditioning waste into a matrix increases the level of passive safety provided, it significantly reduces flexibility for further management (without reconditioning) and may require the design and operation of a disposal facility to be tailored around conditioned waste characteristics, rather than optimising the waste conditioning approach against disposal conditions. Careful consideration is therefore needed before deploying such an approach to a given waste when its disposal route, and associated requirements, are not yet known.

- It may be preferable to apply interim waste management measures that are more easily reversible, such as repackaging waste in new containers and/or transfer to new storage facilities to facilitate decommissioning of older facilities. However, this can result in increased costs over the full waste lifecycle.
- On the other hand, arguments in support of early conditioning into a matrix include the promotion of safe, standardised storage through conversion of raw waste to a passively safe form. Early conditioning into a matrix can also facilitate a period of extended storage prior to disposal, buying time for additional research to underpin safe disposal. However, such an approach could lead to reducing the political urgency for finding a permanent waste management solution.
- Generic WAC can enable waste packaging to progress in the absence of a disposal route. However, they are typically more constraining than site- or facility-specific WAC since they require conservative assumptions to be made about disposal conditions, which can place a more onerous burden on those responsible for waste treatment and conditioning.

With regard to **storage**:

- Storage conditions should be designed to promote package longevity, thereby reducing the risk that already conditioned waste packages will require reconditioning. Storage arrangements should also enable package performance to be checked through monitoring. If these aspects are difficult to ensure, it may be preferable to minimise the extent of treatment and conditioning conducted (whilst still ensuring that the waste can be stored safely).

With regard to **disposal**:

- Where disposal WAC are available, uncertainty shifts towards characterisation to determine compliance (or otherwise), and/or the selection and qualification of treatment and conditioning methods that will result in a disposable waste form.
- A dual-track disposal strategy (i.e., planning for a national repository and pursuing opportunities for a multinational shared facility in parallel), can help to keep options open and increase the likelihood of identifying a suitable disposal route. Choosing to follow such an approach would be a political decision (at a national level) and might not be considered feasible or desirable in all cases.
- Where a shared solution for disposal is pursued, international political consensus on the basis for implementing the shared solution is essential between all those countries consigning and receiving waste. This may strengthen a desire for harmonisation of waste management arrangements (potentially including WAC) across affected countries.
- Where disposal WAC are subject to change, such changes can be more easily accommodated by implementing flexible treatment and conditioning techniques coupled with in-depth waste characterisation.

With regard to **WAC definition**:

- Waste generators and treatment / conditioning facility operators should be involved in the process for defining WAC as early as possible, to minimise the potential for WAC being impractical to implement.
- 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 wider principles for waste management, 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.

- The responsibilities of different stakeholders for defining and applying WAC and for checking compliance need to be clearly defined and actioned, to ensure that waste acceptance systems are fit for purpose and to build confidence in their use.
- WAC could provide a tool for confidence building amongst civil society, for example by:
  - Using them to communicate factors that are important to the safety case.
  - Inviting civil society to influence their scope (this might be done indirectly, via inputs to the wider strategy development for a facility).
  - Utilising independent citizen science to check compliance against WAC.
- There is widespread interest in harmonisation of WAC across Member States and Associated Countries, primarily focusing on harmonisation of the methodology for their 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 programmes, could give confidence, including amongst civil society, that a suite of WAC is fit for purpose and applies 'best practice'.

In conclusion, a key overarching observation is the value of **approaches that impart flexibility** to adapt future waste management practices as new information becomes available (e.g., new waste characterisation data), as new technologies are developed (e.g., emerging treatment techniques), or as strategic decisions are made (e.g., progress identifying a disposal site).

6.3 Identification of common R&D needs and opportunities for future collaboration

A stepwise approach has been followed to identify, rationalise, screen and prioritise WAC-related R&D needs and opportunities for collaboration in Europe, drawing on multiple sources of information including materials produced earlier in Task 4, feedback from related work being progressed in the PREDIS project and dedicated national inputs. This process led to the identification of 25 recommendations, which are listed in Table 5 of this report (see Page 77).

For reasons of pragmatism, it was not possible to feed all 25 of the Subtask 4.3 recommendations into the cross-ROUTES workshop and the updated EURAD SRA. Therefore, expert judgement (based on a wide range of considerations, as described in Section 5.2) was used to down-select the five highest priority WAC-related recommendations from the list set out in Table 5. Many of the other recommendations discussed in Subtask 4.3 were still factored into ROUTES inputs to the updated EURAD SRA because they had also been identified as high priority recommendations under other ROUTES tasks.

The five highest priority Task 4 recommendations, as identified above, were integrated with wider ROUTES recommendations into a cross-cutting presentation for discussion in the workshop on 6th December 2022 [43]. Consistent with this integration, a common numbering scheme was adopted for designating recommendations identified across all ROUTES tasks according to the type of further study that was considered necessary.

Based on workshop discussions, the following WAC-related recommendations were communicated by ROUTES for inclusion in the updated EURAD SRA as either strategic studies (StSt) or R&D studies (R&D) [44]:

- **StSt-4** (corresponding with Task 4 recommendation SS1)**:** Common analysis on disposal strategy for wastes that do not meet the WAC for existing or planned facilities

- **StSt-9** (corresponding with Task 4 recommendation WAC2)**:** Comparison and standardisation of radionuclides (and their speciation) to account for in waste characterisation and WAC.
- **StSt-10** (corresponding with Task 4 recommendation WAC1)**:** Benchmarking exercises for the process of WAC development.

- **R&D-2** (corresponding with Task 4 recommendation CH2)**:** Development of characterisation methods to determine compliance of particular wastes with WAC.
- **R&D-5** (corresponding with Task 4 recommendation CH1)**:** Development of methodologies for representative sampling of challenging waste types.

The communication took the form of presentation slides, setting each recommendation into context by identifying relevant EURAD roadmap themes; SRA drivers; expected outcomes and impacts of work in each area; and related initiatives. These slides are depicted in Figure 16, Figure 17, and Figure 18 [18] of the present deliverable report (see Page 83 onwards).

[18] It should be noted that the description of StSt-10 and R&D-2 in these Figures differs slightly from the final description.

7 References

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Appendix A. Screened R&D needs and opportunities for collaboration (post-workshop)

This table provides a finalised version of the screened R&D needs and opportunities, incorporating inputs received from Romania and Ukraine after the Subtask 4.3 workshop, as discussed in Sections 4.2.3 and 4.3.6. Screened-out recommendations are shaded grey and crossed out. Recommendations that were initially screened out but were screened back in based on inputs received from Romaine and Ukraine are highlighted in yellow. The basis for the final screening decisions is recorded.

Ref. Nº.	Recommendations for WAC-related R&D needs	Country / Project making recommendation or highlighting it as being of particular interest																Number of countries / projects expressing an interest	Basis for screening recommendation in / out
		BE	BG	CZ	FR	DE	(GR)	(LT)	PL	(PT)	SL	(ES)	(SK)	(RO)	(UA)	(UK)	PR		
CH1	Sampling and characterisation methodologies to obtain representative data (particularly for challenging / legacy wastes)		X			X					X			X			X	5	No screening criteria apply – RETAIN.
CH2	Characterisation methods to determine compliance of particular wastes (conditioned and non-conditioned) with WAC, including: - Chemotoxics - Complexants, chelating agents and other liquid organics - Wastes with high alpha-emitting radionuclide inventory				X			X	X		X			X	X		X	7	No screening criteria apply – RETAIN.
CH3	Non-destructive analysis of conditioned waste, e.g., testing of concrete, including industrial implementation for small inventories	X			X	X	X		X					X			X	7	No screening criteria apply – RETAIN.
CH4	Destructive characterisation techniques for conditioned waste	X					X							X				3	No screening criteria apply – RETAIN.
CH5	Mobile systems and other shared approaches to waste characterisation				X		X							X	X		X	5	No screening criteria apply – RETAIN.
CH6	Gas generation measurement (H_2, etc.) on ILW waste packages, including implementation on an industrial scale				X									X	X			3	No screening criteria apply – RETAIN.
~~CH7~~	~~Archiving of representative waste samples for further, future characterisation~~																~~X~~	1	Only identified once – not obviously a common (shared) R&D need: SCREEN OUT (Criterion 1).
~~CH8~~	~~Application of new developments in monitoring and characterisation technologies to WAC issues~~																~~X~~	1	Only identified once – not obviously a common (shared) R&D need: SCREEN OUT (Criterion 1). This also appears to be a general principle, rather than a recommendation for new work scope? Nevertheless, it seems important to promote the continual improvement of waste characterisation through application of newly emerging techniques.
TR1	Decontamination of irradiated or contaminated materials to facilitate reuse of materials with potential 'value', free release or optimised waste management (e.g., reduced waste volumes requiring geological disposal)				X	X								X	X			4	No screening criteria apply – RETAIN.
TR2	Automated sorting, segregation and packaging systems for waste				X													1	Could be screened out based on only being identified once (Criterion 1). However, interest in this topic is believed to be more widespread than the evidence analysed in Subtask 4.3 suggests. RETAIN.
TR3	Sharing of waste management facilities (fixed, modular or mobile options)																X	1	Could be screened out based on only being identified once (Criterion 1). However, interest in this topic is believed to be more widespread than the evidence analysed in Subtask 4.3 suggests. RETAIN.
~~TR4~~	~~Develop processes to neutralise reactive metals (U, Al, Mg)~~				~~X~~									~~X~~				2	Focused more on technology development than WAC development and application: SCREEN OUT (Criterion 2).
~~TR5~~	~~Thermal treatment for sludges~~				~~X~~													1	Only identified by one partner - not a common (shared) R&D need. Also focused more on technology development than WAC development and application: SCREEN OUT (Criterion 2).

Ref. Nº.	Recommendations for WAC-related R&D needs			Country / Project making recommendation or highlighting it as being of particular interest														Number of countries / projects expressing an interest	Basis for screening recommendation in / out
		BE	BG	CZ	FR	DE	(GR)	(LT)	PL	(PT)	SL	(ES)	(SK)	(RO)	(UA)	(UK)	PR		
~~TR6~~	~~Denaturation of disused sources to fit repository compatibility~~				~~X~~													1	Only identified by one partner - not a common (shared) R&D need. Also focused more on technology development than WAC development and application: SCREEN OUT (Criteria 1 and 2).
CO1	Explore conditioning approaches and establish off-the-shelf list of techniques that maximise wasteform stability, but keep future waste management options open	X															X	2	No screening criteria apply – RETAIN.
CO2	Further evaluation of the trade-offs between early and postponed conditioning, including: - Timing of conditioning for storage and disposal versus maturity of disposal WAC - The need for flexibility of approach to be proportional to uncertainty in disposal route - Options for 'multi-step' conditioning versus requirements for reconditioning (and further characterisation)																X	1	Could be screened out based on only being identified once (Criterion 1). However, this was an important area of discussion in Subtask 4.2 and there could be benefit in maintaining collective dialogue. Also, CO2 brings together several related R&D needs that were identified in PREDIS. RETAIN.
CO3	Develop innovative matrices (e.g., geopolymers?) for specific wastes and evaluate their compatibility with repository safety criteria. Wastes of interest include: - Solvents and acids - Tritiated wastes - Wastes containing reactive metals - SIERs - Sludges - Spent fuel				X	X								X	X		X	5	The scope of work responding to this recommendation might have only a peripheral link to WAC, which could provide a basis for screening it out (against Criterion 2). Retained for the time being, to facilitate further discussion on this topic: RETAIN.
CO4	Treatment and conditioning solutions to enhance the disposability of graphite wastes				X	X						X			X			4	No screening criteria apply – RETAIN.
~~CO5~~	~~Gather wider experience on the management of raw wastes where there is no option to postpone conditioning~~																~~X~~	1	Only identified once – not obviously a common (shared) R&D need: SCREEN OUT (Criterion 1).
SS1	Approach to manage challenging wastes with inventories or properties that do not meet WAC for existing or planned facilities		X			X		X							X	X	X	6	No screening criteria apply – RETAIN.
SB1	Chemical behaviour of specific wastes under storage and disposal conditions, including radiation-induced processes and impacts on gas generation and radionuclide mobility and retention. Wastes of interest include: - SIERs - Evaporator concentrates and tank sludges - Cemented waste packages (particularly with respect to crack propagation) - Spent fuel and HLW		X		X	X			X		X			X	X			7	The scope of work responding to this recommendation might have only a peripheral link to WAC, which could provide a basis for screening it out (against Criterion 2). Retained for the time being, to facilitate further discussion on this topic: RETAIN.
~~SB2~~	~~Digital twin of waste packages and storage facility, as a method to evaluate compliance with WAC~~				~~X~~													1	Only identified by one partner - not a common (shared) R&D need: SCREEN OUT (Criterion 1). However, if a future work package on digital twins were to progress in response to wider drivers, their role in evaluating compliance with WAC could potentially be integrated into the work programme.
~~SB3~~	~~Analysis of natural analogue evidence for geopolymer conditioned wastes as a basis for demonstrating WAC compliance~~																~~X~~	1	Only identified once – not obviously a common (shared) R&D need: SCREEN OUT (Criterion 1).
WAC1	Benchmarking exercise for WAC development			X					X					X				3	No screening criteria apply – RETAIN.
WAC2	Comparison and standardisation of radionuclides (and their speciation) to account for in waste characterisation and WAC, including ^{14}C	X			X						X			X			X	5	No screening criteria apply – RETAIN.

Ref. Nº.	Recommendations for WAC-related R&D needs			Country / Project making recommendation or highlighting it as being of particular interest														Number of countries / projects expressing an interest	Basis for screening recommendation in / out
		BE	BG	CZ	FR	DE	(GR)	(LT)	PL	(PT)	SL	(ES)	(SK)	(RO)	(UA)	(UK)	PR		
WAC3	Comparison and standardisation of physical / chemical waste characteristics to account for in waste characterisation and WAC	X												X				2	No screening criteria apply – RETAIN.
WAC4	Improve the link between scientific characterisation activities and WAC establishment / measurements to check compliance - alignment of characterisation to planned waste management and associated safety assessments	X									X						X	3	No screening criteria apply – RETAIN.
WAC5	Explore the role of WAC in designing a national policy for waste management and in supporting geological repository development												X				X	2	No screening criteria apply – RETAIN.
WAC6	Shared / harmonised approaches to regulation and/or WAC across different countries (to the extent that this is achievable), also accounting for applicable non-radiological regulations (e.g., for hazardous / toxic wastes)		X														X	2	This was an important area of discussion in ROUTES Subtask 4.2. Moreover, the wider need for harmonisation is underlined by initiation of the EC HARPERS project, which commenced in June 2022. Arguably, this recommendation could be screened out (against Criterion 3) based on its likely consideration in HARPERS. However, the extent to which harmonisation relating to WAC will be taken forward in this project is not yet clear. The recommendation is therefore retained for the time being, to facilitate further discussion: RETAIN.
~~WAC7~~	~~Improve records keeping on properties of known and available waste packages~~																~~X~~	1	Only identified once – not obviously a common (shared) R&D need: SCREEN OUT (Criterion 1). Nevertheless, this recommendation may be of relevance to knowledge management WPs in both ROUTES and PREDIS.
WAC8	Develop a common method for quantifying parameters for the important features of WAC and identifying appropriate levels of conservatism in limits on e.g., radionuclide release	X															X	2	No screening criteria apply – RETAIN.
~~WAC9~~	~~Explore interest in the wider use of generic WAC to facilitate waste management, e.g., as a step toward site-specific WAC, particularly for a deep geological repository~~		~~X~~															1	This recommendation was identified in the ROUTES Subtask 4.1 report [6] and addressed in Subtask 4.2 [7]. The topic is being further explored in PREDIS Task 2.3.4, which is formulating guidance for developing generic WAC. It is therefore considered to be adequately addressed in current and ongoing work: SCREEN OUT (Criterion 3). Note that the screening decision here differs from that for WAC6 because of differences in the current level of certainty over the scope of ongoing and future work.
WAC10	Collaboration with other Member States on legal aspects of waste management	X												X				2	No screening criteria apply – RETAIN.
WAC11	Collaboration with other Member States on societal aspects of waste management	X												X				2	No screening criteria apply – RETAIN.
WAC12	Collaboration with other Member States to provide training and sustain competences in the field of radioactive waste management		X			X				X				X				4	The scope of work responding to this recommendation might have only a peripheral link to WAC, which could provide a basis for screening it out (against Criterion 2). However, this general need was highlighted in the 2nd EURAD annual meeting as an important function of strategic studies that should be continued in the future. The recommendation is therefore retained for the time being, to facilitate further discussion on this topic. RETAIN.