Deliverable 9.5: Overview of issues related to challenging wastes

Work Package 9 - ROUTES

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Executive Summary

Within the ROUTES Work Package, Task 2 aims to identify challenging waste to be collaboratively tackled within the Joint Programme. More specifically, this task aims to provide an overview of issues and difficulties experienced by the different EURAD Member States regarding the management and disposal of challenging waste, in order to identify Research and Development (R&D) needs and possible topics for future research programmes.

Divided into two main subtasks, the first (Subtask 2.1) helped to define what is meant by challenging waste, i.e., waste for which there are no current or applicable solution for their safe management, including difficulties or the absence of at least one step in the waste lifecycle. Waste can also be considered challenging even when the site for disposal itself is missing. Based on this definition, 11 types of challenging waste have been identified by the Member States: *sludges, spent ion exchange resins, organic waste, bituminized waste, graphite waste, decommissioning waste, disused sealed radioactive sources, Ra/Th/U bearing wastes, particular spent fuel, waste containing reactive metals and waste containing chemotoxic substances*.

An initial overview of the main difficulties faced during the management of the challenging waste in this list was detailed within Deliverable 9.4. Based on this work, technical meetings about each challenging waste were held as part of Subtask 2.2 in order to gather feedback from the Member States to better understand their good practices, main difficulties, or implemented solutions. These technical discussions allowed for the collection of detailed descriptions of particular problems that need to be solved, as well as common gaps amongst Member States.

The categorisation into generic groups used in the present deliverable is based on the main commonalities in the waste stream properties and composition. Nevertheless, the radioactivity levels and chemical composition within a group of waste can broadly differ from country to country and a group of waste can include waste streams often different in composition.

So, the objective of the work conducted under ROUTES Task 2.2 was to highlight commonalities in the management of the selected waste streams, to identify the main related issues and plans to overcome these difficulties.

Finally, these exchanges promoted discussion about the R&D needs for improved management of these types of waste in the future.

This deliverable presents the main outcomes of the ROUTES Subtask 2.2 meetings, detailing the major difficulties at stake for each challenging waste and initiatives that have been implemented by some Member States.

A first identification of R&D needs and possible topics for future research programmes raised during the technical exchanges is also suggested at the end of this deliverable.

To summarise this report, the following paragraphs provide an overview of the main issues associated with each challenging waste, focusing on future needs and potential R&D research topics.

It is worth noticing that some challenges in the management of radioactive waste (RAW), identified in ROUTES Task 2, had already been identified and specific EC projects had already been conducted on these topics. In such case, references to the appropriate project and reports of interest will be provided.

1. Management of Sludge

Sludge defines a broad class of challenging waste, which mainly comes from treatment of effluents. For most of the Member States, difficulties relating to the management of sludge lie in the characterization step, as well as the treatment and conditioning steps.

Regarding the characterization step, Member States have to deal with different types of sludge containing very diverse chemical and radiological compositions. However, their heterogeneous nature makes it difficult to obtain representative samples and, therefore, to obtain accurate inventories. This issue is particularly problematic for legacy waste, which have high variability, whether by the different

production processes implemented over time, or by the heterogeneity of the sludge. In addition, it should be mentioned that uncertainties in the characterization process itself lead to further complexity, notably in obtaining a clear identification of chemicals. These difficulties often prevent a clear understanding of the behaviour of waste packages under disposal conditions. This observation has direct consequences for the treatment and conditioning steps, for which Member States are experiencing various challenges with no ideal solutions.

Various treatments and conditioning approaches have been tested by the Member States, such as drying and high-pressure compaction, development of geopolymers for sludge immobilisation, cementation, co-precipitation followed by incorporation in geomatrices, etc. Currently, treatment and conditioning of sludge into stable forms remain challenging, although different initiatives have been implemented in various Member States.

As sludges can vary significantly from one country to another, the implementation of a dedicated R&D programme would not be universally relevant. However, continued sharing of best practices and innovative technologies among the community is highly encouraged.

2. Management of Spent Ion Exchange Resins (SIERs)

Spent Ion Exchange Resins (SIERs) represent a widespread class of challenging waste that result from water treatment and filtration processes. Major difficulties related to the management of SIERs are similar to those faced for the management of sludge, and relate to the characterization, treatment and conditioning steps.

For operational waste, Member States typically have access to clear radiological inventories and chemical compositions, and the presence of additives and corrosive products can sometimes be specified. However, challenges surrounding legacy waste include difficulties in obtaining representative samples, which can prevent accurate radiological and chemical characterization.

As is the case for sludge, the Member States are studying various treatment and conditioning processes for SIERs. These processes aim to obtain stable waste packages and thus avoid the early degradation of conditioning matrices as well as the production and release of complexing substances that can have major consequences for the safety provided by deep disposal (by increasing the mobility of radionuclides). Some countries have opted for a cementation process. Some specific matrix formulations and pre-treatment steps are sometimes needed in order to obtain a stable waste form. Therefore, new innovative technologies and tailored conditioning matrix are being tested in some Member States. Moreover, ion exchange resins are widespread waste, so mobile solutions able to treat and condition operational SIERs where they are produced would be of great interest. For example, France has developed a mobile installation for conditioning resins using an epoxy matrix that allows management of the resins produced by the various nuclear power plants. The possibility of sharing mobile treatment installations among the European countries raised some interest among the Member States. Apart from this, Member States concluded that, as for sludge, no common R&D programme particularly needs to be implemented. However, continued sharing of innovative technologies among countries is highly encouraged.

3. Management of Organic Waste

Organic waste include a wide variety of waste that can exist in solid or liquid form. For the management of organic waste, Member States are facing major difficulties regarding characterization, treatment, and conditioning steps.

Regarding characterization, cocktails of sub-products such as chelating and complexing substances are very difficult to identify. However, accurate concentrations of these are needed to determine the behaviour of the waste packages in the disposal facilities. The particular case of organic oils requires further development to get appropriate inventories. In addition, legacy waste represent a clear challenge in terms of characterization, as they often exist as large volumes of varied waste that are temporarily stored in different geographic places with no reliable inventories.

For treatment and conditioning, the case of liquid organic waste is the focus of many much attention, as physical form and chemical components reduce the available options. Indeed, if some Member States opt for incineration routes, this will still not be suitable for some particular liquid organic waste partly because of the incompatibility of their chemical composition and activity with specific waste acceptance criteria of incineration facilities. For this reason, other processes, which use polymers or mineral binders, or specific thermal/chemical destruction processes are under review. Past and ongoing European research projects (e.g., THERAMIN, CORI and PREDIS projects) are partly dedicated to this particular theme. Thus, Member States requested further links between these different projects. Future R&D programmes could then be set up, seeking to go beyond the laboratory scale by developing industrial processes. Other R&D programmes could also be dedicated to the long-term behaviour of the innovative conditioning matrices.

4. Management of Bituminized Waste

Bituminized waste relate to the conditioning of spent resins and effluent sludges, often associated with fuel reprocessing plants, as bitumen was a matrix commonly used from the 1960s to stabilize these reactive waste. In terms of bituminized waste management, Member States are facing difficulties for each step in the waste lifecycle: characterization, treatment and conditioning, storage and disposal. More precisely, one of the major issues reported by the Member States relates to the case of historical drums, for which clear inventories are often unknown, and swelling or corrosion of some drums are observed, leading to reconditioning operations. The particular case of Lithuania, where bituminized waste have been stored in large canyons without further treatment or conditioning, should also be mentioned, as the retrieval of this large quantity of waste is not currently planned.

Nowadays, Member States have launched various R&D programmes, not only to cope with characterization and reconditioning issues, but also to tackle particular issues such as prevention of fire hazards, or possible leakage of chemical cocktails influencing the mobility of radionuclides in deep disposal facilities. In this sense, no additional research programmes appear to be particularly needed now. However, it has to be recognised that for bituminized waste resulting from reprocessing processes, the presence of salts raises issues for the long-term evolution of drums. Consequently, one possible R&D topic could aim to address the implementation of treatment processes allowing the destruction of certain chemical species, thus ensuring the production of stable waste packages. However, it is worth mentioning that the question of treatment is directly related to each national context and the willingness of different safety authorities. Therefore, this research topic should be further investigated and may require support at a higher level than the ROUTES project.

5. Management of Graphite Waste

Graphite waste come from both former nuclear research reactors and nuclear power plants. Depending on their position within the reactor, these waste could have been in contact with the fuel and could therefore be highly activated. Member States acknowledge the fact that the management of graphite waste raises various difficulties, as obtaining reliable characterization information for graphite is often complicated by the heterogeneous distribution and activation of impurities, which means that realistic inventories cannot be obtained. The implementation of conditioning and treatment processes also presents challenges in terms of safety, for instance, to neutralize Wigner effect, although some countries such as Austria have healed out its effects using heat treatment. Finally, issues related to the presence of highly mobile radionuclides such as C-14 or Cl-36 limit viable solutions for final disposal routes.

In this context, various R&D programmes have been launched by the different Member States, and common European research programmes do not seem particularly needed for now, especially since former European research projects such as GRAPA, CAST and CARBOWASTE were dedicated to the management of graphite waste. Therefore, Member States are encouraged to further investigateon the main outcomes of these past projects, in order to focus more on practical applications.

6. Management of Decommissioning Waste

Member States agreed that Decommissioning Waste represents a widespread class of challenging waste that can comprise construction materials, soils, scrap metal, wood, tools and safety equipment and even contaminated liquids. Major challenges associated with the management of these waste relate to the variety of the waste involved and the large volumes that will be produced in the coming decades that will need specific management strategies. For these reasons, Member States insist on the need to develop models to determine in advance the amount of waste produced that could be managed either by radioactive waste storage facilities or by conventional ones.. In addition, the characterization of reliable chemical inventories aiming to prevent the production of sub-products in the long-term is another issue relating to the management of decommissioning waste. That would help to apply a risk-informed approach to their management (e.g. less active components to landfill disposal sites), thereby minimising waste requiring near-surface or geological disposal. Given the large volumes involved, thermal treatment could be an interesting solution for volume reduction, but it is not applied to all types of waste, such as concrete or rubble. Therefore, alternatives for treatment and conditioning are under review, beginning with metals recycling, low- or high-pressure compaction, etc.

Finally, even if it remains dependant of the regulatory framework of each country, Member States are willing to share good practices in terms of minimisation and valorisation. Links with the European SHARE project are also strongly encouraged.

7. Management of Disused Sealed Radioactive Sources (DSRS)

Disused sealed radioactive sources (DSRS) arise from various economic sectors (e.g., industrial, medicine, research) and are present in a wide variety of different types (e.g., disused measurement devices, smoke detectors, calibration sources, lightning rods, medical sources, etc). The major difficulties faced by the Member States relate to the characterization and disposal phases.

Regarding the characterization phase, Member States stress that radiological and chemical inventories can be diverse and are often unknown, as reliable documentation and certificates proving the accurate activity are often lost, not to mention the wide distribution of sources within each country. This is particularly the case for orphan and legacy sources. In order to fill in the missing information, measurement techniques are implemented to identify the main radionuclides inside the sources. However, the identification of particular radionuclides, such as Sr-90, is difficult. In addition, in some countries, such as Hungary, Lithuania or Ukraine, DSRS have been stored for decades in RADON-type facilities, without any proper characterization or separation from other waste.

Disposal of DSRS leads to particular issues, insofar as many of the affected Member States have no final repositories and are, for now, dealing with DSRS by storing them in temporary facilities, some of which are reaching their capacity limits. Therefore, some options have been implemented to manage DSRS via radioactive decay and clearance options.

Based on this context, Member States encourage the development of research projects dedicated to characterization issues, aiming notably to develop methodologies for radiological characterization of orphan sources or identification techniques of particular radionuclides.

8. Management of Particular Spent Fuel and Depleted Uranium

Particular spent fuels (PSFs) include all non-UOX (uranium oxide) spent fuels and can concern Magnox spent fuel, aluminium cladding, spent fuel used in former Natural Uranium Graphite Gaz (UNGG) reactors, or even particular spent fuel developed for R&D activities. In general, the management of PSFs raises no difficulties as such since particular spent fuels are generally still considered as reusable resources and are not yet declared as waste. In this context, no particular characterization is conducted and PSFs are often stored in cooling pools, without any special treatment or conditioning following removal from the reactor. It is interesting to mention the particular case of the UK, where Magnox spent fuel is reprocessed at the Magnox Reprocessing Plant at Sellafield. The plant was originallyscheduled to close in 2020, but after a period of "controlled shutdown" in 2020 due to the Covid-19 pandemic, will now cease operations at the end of 2021. Any residual Magnox spent fuel will then be placed into interim storage pending geological disposal.

Member States also stress that the case of disposal remains an open question and could represent a challenge in the coming years, as PSFs are not part of the current inventory to be disposed of. Therefore, if PSFs are reclassified as waste, Member States acknowledge the need to review disposal strategies and to share information about possible long-term solutions.

Regarding the case of depleted uranium, as it is about to be considered as waste in some Member States, its disposal route will be a major challenge in the years to come, given the large volumes involved. Therefore, Member States agreed to share their future strategies and to discuss about the associated difficulties of long-term disposal.

9. Management of Ra/Th/U bearing waste

Ra/Th/U bearing waste comes from various economic sectors (e.g., industrial, medicine, research) and involves diverse and large waste volumes. The management of these waste lead to different difficulties beginning with characterization aspects and the lack of long-term disposals. Regarding the characterization step, either because of their heterogeneous nature, or because of the legacy of non-characterized historic waste, Member States are facing poor radiological and chemical inventories. Some initiatives are sometimes deployed in order to obtain a global identification, as is the case for Belgium, which has set up a system for mapping the distribution of radioactivity in some of its contaminated soils.

For treatment and conditioning processes, as well as for final disposal, a large proportion of Member States remain without solutions, and are waiting for safety regulations to be developed that will allow management routes to be determined. Nevertheless, some countries are studying shallow depth disposal that could be used to manage Ra/Th/U bearing waste. In any case, all agreed on the need to share future disposal strategies and to discuss the associated difficulties.

10. Management of waste containing reactive metals

Waste containing reactive metals often originates from the nuclear power production cycle during decommissioning activities. Those waste can include a wide range of metals such as Aluminium, Beryllium or Magnesium. The main difficulties faced during the management of these waste are related to the characterization, treatment & conditioning and disposal steps.

Regarding the characterization step, major challenges relate to obtaining a precise and reliable inventory and, more specifically, an exact list of activation products. As a result, countries struggle to determine how much of the metal content has been activated within the reactor and the related volumes involved. To cope with these difficulties, calculations using Monte Carlo methods have been carried out by some Member States.

For the treatment and conditioning of these waste, the main challenge is to limit corrosion reactions and ensure stable waste containers in disposal conditions. To do so, various initiatives and R&D actions have been implemented, and a work package within the European Research Project PREDIS is dedicated to the development of matrices adapted to reactive metals.

In terms of future needs, Member States have noted that research programmes have been already launched regarding the management of particular metals such as Al or Mg. On this basis, it is commonly agreed that sharing among Member States of good practices regarding the management of waste containing reactive metals would be valuable in the first instance. Similarly, learning from the main outcomes of the PREDIS work package and making links between this and the management of reactive metals is highly encouraged.

11. Management of waste containing chemotoxic substances

Waste containing chemotoxic substances often result from operation or decommissioning activities and can contain a wide range of substances (e.g., Cd, Hg, Be, etc.), with difficulties encountered in terms of characterization, treatment and conditioning, and disposal.

Member States acknowledge the needed tools to be developed to allow for the precise characterization of chemicals, keeping in mind the issues of heterogeneity and representativeness of sampling. Treatment and conditioning of waste containing chemotoxic substances also lead to some difficulties in stabilizing reactive substances into suitable forms for disposal. In the UK, different commercial services have been developed to treat asbestos, either by using thermal treatment or by chemical deconversion. In this context, for the majority of Member States, only temporary storage solutions are implemented whilst waiting for appropriate means to carry out the characterization, treatment and conditioning steps.

Given that chemicals will have to be increasingly integrated into safety assessments in the coming years, Member States all agreed on the need to anticipate the management of those particular substances and to define an appropriate regulatory framework. Development of research programmes to achieve improved characterization of chemotoxic substances within radioactive waste have been encouraged. The case of beryllium, which is considered to be a radiological hazard, a chemically toxic and a reactive metal could be the subject of a research topic. Member States also encourage sharing of the different initiatives implemented for particular chemicals such as asbestos or mercury.

12. First needs and future R&D actions for a better management of challenging wastes

The work meetings dedicated to each challenging waste allowed the different needs for better management of these waste to be identified.

First, all Member States highly encourage the sharing of experiences between interested countries, good practices, and different initiatives that can be implemented. Among the mentioned topics of shared interest that were mentioned, the following ones are highlighted in particular:

- Cases of innovative treatment and conditioning for sludges, SIERs and organic waste,
- Minimisation and recycling processes of dismantling waste,
- Disposal strategy for PSFs
- Disposal strategy of depleted uranium,
- Treatment initiatives for asbestos and mercury.

In addition to the sharing of information, maintaining strong links with ROUTES Task 3, which is dedicated to characterization aspects, was also stressed. According to the Member States, ROUTES Task 3 could indeed take on the task of investigating some blocking points preventing the better management of challenging waste, such as:

- Sampling representativeness strategy especially for legacy waste;
- Identification of chemotoxic and complexing substances;
- Chemical and radiological characterization of oils;
- Radiological characterization of graphites.

Strong links with former research projects (e.g., THERAMIN, GRAPA, CAST and CARBOWASTE) have also been encouraged, so as to benefit from their results and progress, and to see what can be either directly implemented or completed by new research programmes. Links with current research programmes exploring some issues of interest for the management of challenging wastes are also encouraged, such as the CORI work package of the EURAD EJP, or PREDIS and SHARE European Research Projects.

Finally, possible topics for future R&D programmes have been identified and could help to improve the management of some challenging wastes. The list of possible topics is as follows:

- Explore the long-term behaviour of innovative matrices notably developed to manage SIERs, sludge and organic waste;
- Develop treatment processes dedicated to bituminized waste coming from reprocessing;
- Investigate characterization methodologies and identification techniques for orphan sources, with focus on particular radionuclide like Sr-90 or Ra-226;
- Identify possible strategies for the management of waste containing beryllium.

Table of content

List of figures

List of Tables

List of acronyms and abbreviations

AGR	Advanced Gas-cooled Reactor
BWSF	Bituminized Waste Storage Facility (located in Lithuania)
CARBOWASTE	Treatment and Disposal of Irradiated Graphite and Other Carbonaceous Waste
CAST	CArbon-14 Source Term
CHANCE	Characterization of conditioned nuclear waste for its safe disposal in Europe
CILVA	Centralised Treatment/Conditioning Facility (located in Belgium)
CIRES	Industrial Centre for collection, storage and disposal (located in France)
CORI	Cement-organic-radionuclide interactions
DSRS	Disused Sealed Radioactive Sources
EC	European Commission
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
GRAPA	Irradiated Graphite Processing Approaches
GDF	Geological Disposal Facility
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
LILW	Low and Intermediate Level Waste
LIMS	Large Inventory Member States
LLWR	Low Level Waste Repository
LLW	Low Level Waste
LRW	Liquid Radioactive Waste
MS	Member States
NDA	Nuclear Decommissioning Authority (UK)
NOL	NOL is a new upgraded storage facility (in Danish: Nyt Opgraderet Lager) which is currently under planning/design by Danish Decommissioning.
NORM	Naturally Occurring Radioactive Material
NPP	Nuclear Power Plant
PREDIS	Pre-disposal management of radioactive waste
PSFs	Particular Spent Fuels

PWR	Pressurised water reactor
R&D	Research and development
Radwaste/RW	Radioactive waste
ROUTES	Waste management routes in Europe from cradle to grave
SIERS	Spent Ion Exchange Resins
THERAMIN	Thermal treatment for radioactive waste minimization and hazard reduction
WAC	Waste acceptance criteria
WMO	Waste management organisation
WP	Work package

1. General Introduction

1.1 Some reminders about the ROUTES project

"Waste management routes in Europe from cradle to grave" (ROUTES) is one work package (WP) of the EURAD European joint programme dedicated to Radioactive Waste Management. Started in June 2019, the main objectives of the ROUTES 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, with different amounts and types of radioactive waste to manage);

- Identify safety-relevant issues and their R&D needs associated with the waste management routes (cradle to grave), including the management routes of legacy and historical waste, considering interdependencies between the routes;

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

The work conducted within the ROUTES WP is divided into eight tasks, beginning with Task 1, which is devoted to the WP management and coordination. Then, technical topics are addressed by the following tasks:

- Task 2: Identify challenging waste streams;
- Task 3: Describe/compare characterization approaches;
- Task 4: Identify WAC used in MS;
- Task 5: Solutions for small amounts of waste;
- Task 6: Shared solutions for MS;
- Task 7: Interaction with Civil Society.
- Task 8: ROUTES Extension on the evaluation of the possible disposal solutions for MS without WAC and with small inventories.

In addition, note that at the beginning of the ROUTES project, a general questionnaire was sent to all partners, in which different questions were asked to address the challenges of each task. Therefore, the responses to this questionnaire served as important work material for the launch of each task, and in particular for ROUTES Task 2.

1.2 Overall objectives of the ROUTES Task 2

The ROUTES Task 2 aims to identify challenging waste and related difficult issues to be collaboratively tackled within EURAD. More precisely, the idea of this task is to map and share understanding at EU level of the practical issues on waste management routes, taking into account specific issues of challenging waste and small inventory programmes. To achieve this goal, ROUTES Task 2 is divided into 2 main subtasks:

- Based on the responses to the ROUTES questionnaire, Subtask 2.1 aimed to review the existing work on categorization and classification of radioactive waste by analysing what is at stake in each MS. Waste for which there is not yet a complete management plan has also been identified among the MS and allow us to have a first picture of the main challenging waste to be dealt within ROUTES WP.

- Subtask 2.2 is seeking to better understand at EU level the practical issues on radioactive waste management routes for challenging waste. More particularly, this subtask relies on mapping and sharing knowledge on challenging waste inventories at each pre-disposal steps in order to get a clear overview of issues related to management and disposal of these particular waste. On this basis, R&D needs can be deduced and then considered as part of future activities of EURAD.

1.3 Main outcomes from ROUTES Subtask 2.1 and deliverable D9.4 regarding the management of challenging waste

The deliverable 9.4 *'Overview of existing work on categorization/classification of radioactive waste in participating states'* (May 2021) provides details on the work conducted within subtask 2.1 and gives notably a first overview of the challenging waste for which the MS are facing difficulties. Precisely, the deliverable suggests a definition of what can be considered as challenging waste by focusing on all waste for which there is no available solutions for their safe management, inducing notably that at least one step in the waste lifecycle is missing (even the site disposal itself). In that sense, various reasons can lead to consider waste as a challenging one, and the *Figure 1* suggests some examples.

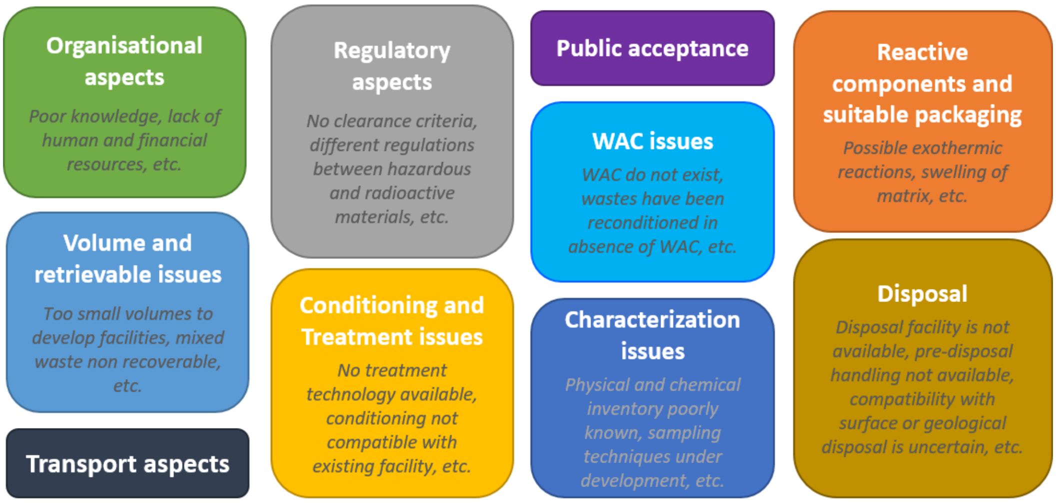

Figure 1: Reasons leading to consider a waste as challenging one

In this context, for the ROUTES WP, the following challenging waste have been identified: sludges, spent ion exchange resins (SIERs), organic waste, bituminized waste, graphite, U/Th/Ra bearing waste, decommissioning waste, particular spent fuel, Disused Sealed Radioactive Sources (DSRS), waste containing reactive metals, and waste containing chemotoxic substances. According to the responses to the ROUTES questionnaire and to further exchanges with some MS, it turns out that the list of the 11 challenging waste is mostly of interest for both nuclear and non-nuclear countries. Indeed, MS faced difficulties in the management of, on average, 6 different challenging waste with the most common being SIERs, DSRS, decommissioning waste and graphite waste (see ***Erreur ! Source du renvoi introuvable.***).

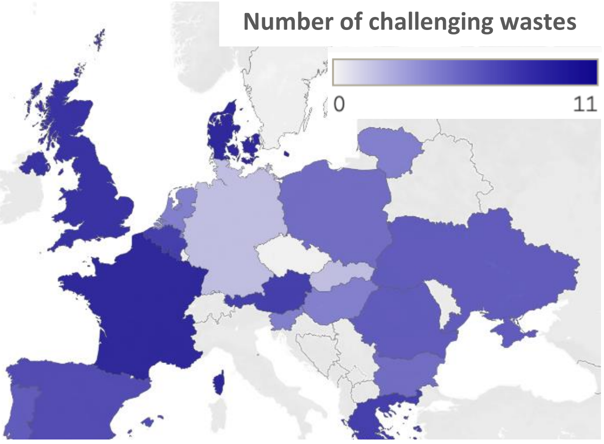

Figure 2: Number of challenging wastes faced by the different Member States involved in ROUTES Task 2

In countries such as Czech Republic or Sweden, it is worth mentioning that some solutions for the management of challenging waste exist, and in that sense they do not face difficulties as such. However, this does not mean that these countries don't have any challenges left for the management of those waste.

As a first analysis of the main difficulties faced by the MS in the management of challenging waste, ROUTES questionnaire's responses have shown that **(i) lack of disposal route (31%), characterization (22%) and Conditioning or Treatment issues (20%) are the main blocking points** (see *Figure 3*).

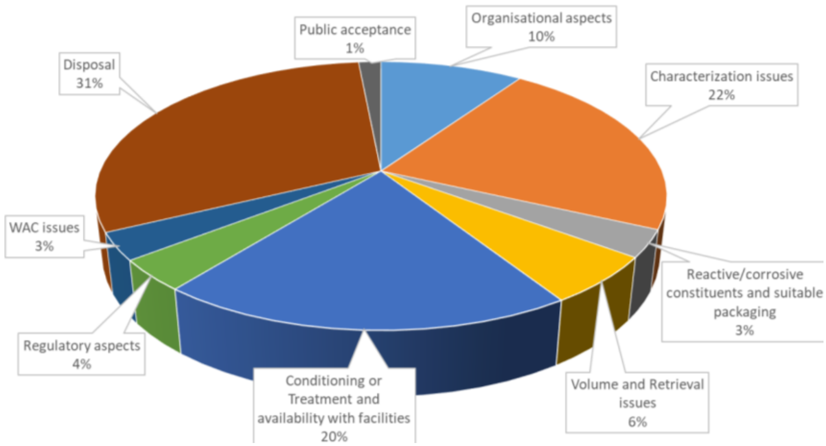

Figure 3: Major issues faced by the Member States in the management of challenging waste.

Regarding disposal route aspects, for many MS, it turns out that the end state of the waste management strategy is not clearly defined, which leads to difficulties in developing treatment and conditioning techniques, as the packages produced may not be suitable for future facilities Waste Acceptance Criteria (WAC). For characterization issues, a vicious circle has been pointed out by the UK and was shared by all the partners, it consists in saying that not having a management route prevents prioritizing the characterization of waste and the lack of characterization prevents the identification of management routes.

1.4 ROUTES Subtask 2.2: objectives and work methodology

Based on the first elements provided by the ROUTES Subtask 2.1, the work of subtask 2.2 aimed to provide a comprehensive list of challenging waste taking into account the situation in participating Member States and describing particular problems to be solved for these waste, whether at the pre-disposal or disposal step. To achieve this goal, the scope of work in subtask 2.2 has been defined in a series of work meetings dedicated to each challenging waste. In particular, these focused on:

- Setting up discussion on technical details of what is at stake in the different MS in terms of feedback experiences, good practices, difficulties, solutions already existing for each step of the RW categorisation scheme-approach (see *Figure 4*);
- Identifying possible R&D needs and common research programmes that could be launched in the future.

Figure 4: Radioactive waste categorisation scheme-approach

From March to June 2021, seven work meetings were organised (see *Table 1*), during which challenging waste were discussed and detailed. The main outcomes of these work meetings are detailed in the following paragraphs. Note that within these paragraphs, concrete examples of difficulties faced by countries or initiatives implemented by them are provided.

	Dates	Challenging Waste
1	March, 24	Sludges + SIERs
2	March, 30	Organic Waste
3	April, 14	Bituminized Waste
4	May, 7	Graphite Waste + Decommissioning Waste
5	May, 18	DSRS
6	May, 25	Ra/Th/U bearing waste + Particular Spent Fuel
7	June, 8	Waste containing reactive metals + chemotoxic substances

Table 1: List of work meetings organised under ROUTES Subtask 2.2

2. Detailed overview of issues related to management and disposal of challenging waste

2.1 The management of sludge

Sludge defines a broad class of waste, which mainly come from treatment of effluents (e.g., precipitation, evaporation, concentration). Sludges have different origins and come from various processes, so their chemical compositions and radioactivity levels are different.

Whether MS have defined a waste management route for some sludge streams, some others are still considered as challenging. The characteristics of challenging sludges provided by the different MS are provided in *Table 2*. Due to the broad variability of the chemical and radiological compositions of sludges, the provided data should not be considered as comprehensive[1] of all types of sludges (especially for very Large inventory Member States). Nevertheless this first list enables to identify commonalities related to their management. Concentrates arising from NPP operations are not addressed in this report.

2.1.1 General context and first insights

As shown in *Figure 5*, 10 MS are experiencing difficulties in the management of sludge. More precisely, these difficulties are mainly related to characterization (39%) and conditioning or treatment issues (26%) (See *Figure 6*).

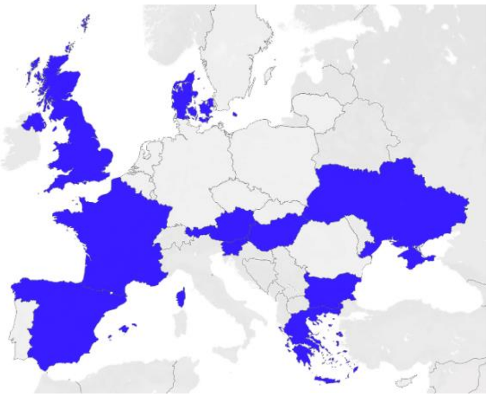

Figure 5: Member States experiencing difficulties in the management of sludge

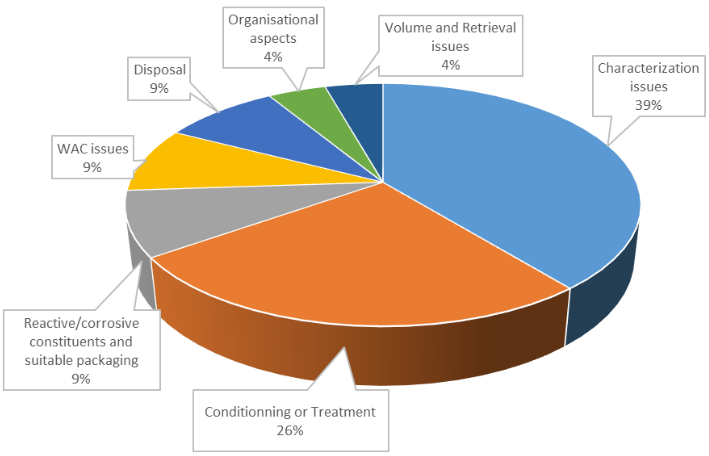

Figure 6: Main difficulties associated with the management of sludge

[1] The reader can refer to Country inventories (when available) i.e. https://ukinventory.nda.gov.uk/the-2019-inventory/2019-inventory-reports/

2.1.2 Focus on the characterization step

Regarding the characterization of the sludge, it turns out that MS are dealing with unknown radiological and chemicals inventories as well as various volumes of sludge (see *Table 2*). Large Inventory MS highlight the need to conduct impressive characterization campaigns in view of retrieval and conditioning of huge volumes of legacy sludges.

The spent fuel reprocessing process used in Sellafield to recycle Uranium and Plutonium from Magnox fuel gave rise to large amount of sludge streams (around 90 sludge waste streams). In this framework, UK notably highlights the fact that the implementation of sampling allowing a better knowledge of radiological and chemical inventories is very complicated, as sludge stored in tanks and ponds tends to settle. This results in different stratifications that make it challenging to obtain representative samples. Concerning the sludge already conditioned, some drums have corroded which implies reconditioning and transfer to new containers may be required. Therefore, further sampling and establishing a new analysis regime is possible at this stage of the waste lifecycle.

In France, the same difficulties as those mentioned by the UK are at stake, insofar as sludge presents high variability, whether by the different production processes implemented over time, or by the heterogeneity of precipitated sludge in tanks. An impressive work was needed to better determine the radiological and chemical composition of the sludges temporally stored in silos in La Hague (see *Focus 1 on the French case study provided at the end of this section*). The characterization work has been conducted on the basis of both historical records and characterization campaigns carried out in 1992, 2002, 2004, 2007, 2013 and 2014 with sampling at different depths (similar sludges were conditioned in the past in a bituminized matrix – see *section 2.4*).

Besides the issues related to the characterization of huge amounts of sludges of LIMS, Greece also raised the fact that major difficulties related to the characterization of sludge are related to homogeneity aspects[2].

For Belgium, chemical analysis techniques are not reliable for sludge, inducing little information about the chemical composition of those waste. However, the reliability of used chemical analysis techniques is important for the quality assurance of the conditioning process of sludges. In Belgium, it turns out that sludges are conditioned through homogeneous cementation, for which a specific mortar recipe is developed. As part of the development process of this mortar, a waste domain (min, max, average) is determined for each of the different chemical species present in the expected sludge types. Prior to each conditioning campaign, the correspondence of the sludges concerned with this waste domain must be demonstrated by chemical analysis. In most cases, the waste conditioner itself, using its own lab equipment and protocols, performs these chemical analyses. Until recently, ONDRAF/NIRAS did not focus very much on these protocols, which called into question the quality assurance of the conditioning process. It was not until 2021 that ONDRAF/NIRAS started qualifying the different labs, by checking the reproducibility and accuracy of the applied techniques (sampling, dilution and chemical analysis).

[2] Indeed, the information from the history of the sludge in Greece is that it may contain Tc-99 which is a pure beta emitter. The drums with this waste were opened and gross beta-gamma and gross gamma measurements were taken by scanning the surface of the waste form by a contamination monitor at integration mode for 1 min. The results of these measurements on some drums showed a ratio between gross beta-gamma and gross gamma of up to 80, confirming the presence of a pure beta emitter. Also, Cs-137 was detected in some drums with this waste. For each of the drums with cesium, measurements were performed by non-destructive gamma spectrometry at several points of the drum and different specific activities for Cs-137 were determined, indicating that Cs-137 is not homogeneously distributed in the waste form. Therefore, it is also possible the pure beta emitter contained is not homogeneously distributed in the waste form. In case of Difficult To Measure (DTM) radionuclides, inhomogeneity makes the characterization challenging and costly. Usually the matrix has to be crushed to obtain samples for radiochemical analyses.

2.1.3 Focus on the treatment and conditioning step

Uncertainties in the radiological and chemical inventory lead to difficulties in defining the treatment and conditioning processes which represent the main issue in sludge management. For the non-conditioned sludge, MS are testing and implementing various conditioning techniques. While cementation remains the favourite conditioning process (with or without specific pre-treatment), other techniques aiming to reduce the volume and overcome the difficulties associated with cementation of specific types of sludge are also explored or already implemented (i.e. drying, thermal treatment, etc.).

The UK shared that only a small portion of its sludge is already treated (around 8 out of 90 sludge waste streams). Processes consist of immobilisation of sludge in waste packages, through dewatering and grout encapsulation. Those packages are pending disposal to a Geological Disposal Facility (GDF) for Intermediate Level Waste (ILW) and the Low Level Waste Repository (LLWR) for Low Level Waste (LLW). A few trials with epoxy resins have been conducted. It is also noted that a freeze dredging/dewatering technology was used at Magnox Ltd Bradwell NPP to treat radioactive sludge in fuel storage ponds. Sellafield Ltd is planning to seek to develop a thermal treatment technology for pumpable solid waste, as an alternative to grout encapsulation in the future in the UK. A geopolymer for immobilisation of oily sludge is also under development by Lucideon.

In Belgium, pre-treatment procedures may include the addition of NaOH to increase the pH of the sludge before the conditioning step (cementation). To avoid the formation of crystals due to high salt concentrations, heating (>65°C) and continuous stirring are also implemented. Belgium also raised the fact that studies are currently ongoing to develop concentrates with lower boric acid concentrations through reverse osmosis and electrodialysis membranes. Spain also applies volume reduction of sludge by dewatering. Regarding Denmark, no operating facility for the treatment of sludge exists. In the past, bituminisation has been used but nowadays, a new method has to be developed. In Bulgaria, they are experimenting new treatment processes dealing with volumetric minimisation and chemical stabilization. For its part, Austria is not facing any difficulties regarding treatment as sludge is dried and high-pressure compacted. Slovenia also treats a part of its sludge through the application of drying processes.

Greece indicates that it is expected to solidify the sludge in cement before their disposal. The mass percentage of sludge in the mixture will be around 30 %. It is interesting to note that Greece has also to deal with some legacy sludges that have been cemented in the past and for which limited information on the cement composition is available. In Bulgaria, some studies have been initiated to test cementation processes on sludges. In Ukraine, the Project U4.01/14A is currently ongoing to select waste treatment and pre-conditioning or conditioning techniques using cement matrices.

In France, conditioning of STE2 sludge is not defined yet. However, since the early 2000s, different treatments and conditioning have been explored, for instance: heat treatment followed by vitrification, encapsulation in a cement-based matrix, or a drying process. It turns out that various difficulties arose, mainly coming from the chemical composition:

- large quantity of sulphates and nitrates contained in the sludge and their chemical variability are chemically incompatible with the usual encapsulation matrices,
- exothermic “runaway” reactions between the oxidizing (nitrates) and reducing salts (cobalt sulphide (CoS) and preformed precipitate nickel ferrocyanides (ppFeNi)) can occur in dry sludge with production of corrosive and toxic species (e.g. NOx, HCN),
- ppFeNi compounds containing Cs can degrade in a high pH environment (pH > 13).

Nevertheless, some MS identified problems related to the use of cement-based matrix for the already conditioned sludges. For its part, Belgium has shown that cementation of sludge amended with salts was affected by an alkali silica reaction leading to the production of gel-like substances that might degrade mechanically some barriers *(see Focus 2 on the Belgian case study provided in section 2.2)*. Therefore, cementation process is suspended. To be allowed to resume, the process needs to be adapted in such a way that future gel-formation is excluded. In Slovenia, major concerns regarding dried sludge waste packages relates to their chemical behaviour over time, with possible corrosion and presence of chelating and complexing agents. In Austria, sludges historically cemented have been reconditioned and repackaged into new 200 L drums.

2.1.4 Focus on the storage and disposal steps

When it comes to storage and disposal steps, MS agreed to say that the major difficulty is, apart from the existence or not of a final repository, the compatibility of sludge packages with the WAC of the disposal facility. Indeed, the presence of chemicals like sulphate or nitrate can induce possible interactions with the cemented structures and the host rock, leading to possible mobility of radionuclides in the environment. For now, no clear answers have been found and possible options to address these concerns lie mainly in the treatment and conditioning steps.

In France, a different type of sludge is stored in Malvési storage lagoons. This sludge comes from the treatment of nitrate-rich liquid effluents produced by the conversion of uranium concentrates into uranium tetrafluoride in the Orano plant on the Malvési. The effluents are first settled in storage ponds (B1 and B2) and the supernatants evaporation leads to nitrate-rich sludge bearing natural uranium. Nowadays, studies are ongoing to define the final disposal of this type of sludge.

FOCUS 1 – Management of the sludge from the effluent treatment facility STE2 in France

About 9,000 m^3 of LL-ILW sludge have been generated in La Hague by spent fuel reprocessing and liquid effluent treatment. They have been placed into 7 adjoining tanks, called “silos”, and are considered as legacy waste resulting from the 20 years of operation of the reprocessing plant. The sludge have to be retrieved and conditioned for final disposal in the deep geological disposal under development (Cigéo).

Since the early 2000s, different retrieval and conditioning scenarios have been evaluated. At first, bituminization of STE2 sludge was considered as the baseline scenario, since STE-type sludge had already been conditioned into a bitumen-matrix. Nevertheless, in the early 2000s, the French Nuclear Safety Authority stated that bituminization of STE2 sludge would not comply with safety requirements and a safer conditioning process had to be found. Different pre-disposal routes were explored and chemical and radiological characterization of the sludge was improved (historical records and sampling campaigns). The chemical composition of the sludge slightly changed over the years, but they mainly consist of barium sulfate, ferrocyanides, calcium carbonate, cobalt sulfide and others hydroxide.

Several options had been studied and successively abandoned: thermal treatments (large initial investment and high operation cost), encapsulation in a cemented-based matrix (low incorporation rate and uncertainty in the compatibility of the matrix with the whole variability of sludge composition), drying and compaction (difficulties for setting up and maintain such a complex process).

The current baseline scenario consists in retrieving and temporarily storing STE2 sludge, while studying final conditioning options. STE2 sludge will be retrieved by means of a remotely operated vehicle and centrifuged to limit the number of waste packages and introduced as such in canisters. Meanwhile, conditioning scenarios for final disposal are being evaluated: in-drum drying process, a specific dry grouting process and thermal treatment. Such a scenario presents the advantage of leaving options open, of reducing the initial investments and of enabling to improve waste characterization, but it requires future retrieval and repacking.

The example of STE2 sludge underlines that both technical and non-technical key factors lead to the choice of the conditioning option. Non-technical factors include economic and regulatory considerations, the availability of a final disposal site and associated WAC, and public acceptance. Technical aspects mainly include the composition of the waste, its volume, its radiological and physico-chemical properties, the waste/matrix interactions and the availability of treatment technology. In the case of STE2 sludge, technical issues are mainly related to chemical composition of the sludge: in case of temperature rise, exothermic runaway reactions can occur between oxidizing and reductant salts. Besides, due to large amount of sulfates and nitrates in the sludge, as well as their variability, such waste are incompatible with usual matrixes. Difficulties also arose due to limitations in the operation conditions: high radiation levels require all operations to be done remotely. Moreover, large quantity of sludge have to be retrieved and conditioned in a reasonable time frame, which require retrieval to be done efficiently with a high removal rate. Finally, the conditioning processes need to enable volume reduction or high incorporation rate, due to high disposal fees at Cigéo and a limited disposal capacity.

		AUSTRIA	BELGIUM	BULGARIA	DENMARK	FRANCE	GREECE	HUNGARY	UKRAINE	UK
NON CONDITIONED SLUDGE	Volumes	Arising sludges are getting conditioned so there is no volume of non-conditioned sludges to report.	Capacity of main sludge storage tanks at Belgoprocess : 90 m^3 + 60 m^3	About 60-70 m^3		STE2 sludges in LHA 9,000m^3	Total amount of sludge is about 0.6 m^3, as it is mentioned in the 3rd National Report of Greece on compliance with the directive 2011/70/Euratom	Few 100 m^3 for whole life time of NPP	104.4 m^3 total at Ukrainian's NPPs 2296.9 m^3 in the storage facilities of the Chernobyl NPP	Sludges are produced over 90 waste streams: 31,000 te of ILW 1,200 te of LLW 2.4 te of VLLW
	Main radiological inventory	The main radionuclides are: Co-60, Cs-137, Th-232, Am-241. Ra-226, Eu-154, Ag-108m	As well short-lived as long-lived radionuclides, and as well alpha as beta-gamma. Main nuclides are Cs-137, Co-60, Ni-63, Pu-241, Nb-94,	Co-60, Cs-137, Cs-134, Mn-54		LL-ILW	Typically VLLW and LLW H-3, Cs-137, Co-60, Fe-55, Ni-63, Mn-54, Zn-65, Ag-108m		Cs-134; Cs-137; Cs-136; Co-60; Co-58; Mn-54; Ag-100 0.705 TBq total at Ukrainian's NPPs 3.87 TBq in the storage facilities of the Chernobyl NPP	
	Main chemical inventory	Main Compounds: Organic Carbon (10%), Oxides of C, Al, Si, Ca and Fe; Traces of Cu, Zn, Ba, Pb	Boron (58000ppm), sulphates (800ppm), chlorides (600ppm), carbohydrates, salts	Inventory not available					Na: 0.014-0,72; K: 0.001-0.1. Fe: 0.0008-0.0029; NH_3: 0.00005-0.11; Cl: 0.00004-0.0285; NO_3: 0.012-0.84	
CONDITIONED SLUDGE	Volumes	Majority of sludges have been conditioned by cementation in about 3500 drums (200 L). In addition, about 700 drums (200 L) with at least one supercompacted pellet containing dried sludges.	Majority of sludge has been conditioned in cemented or bitumen matrices +/- 1500 drums of 400 L and 1,500 L of sludge conditioned in cemented matrix	Sludge are not conditioned and are stored in tanks.	Around 800 drums of sludge conditioned in bitumen matrix. These drums have cracked and swelled up so need to be reconditioned.				Sludge are not conditioned.	Majority of sludge is not conditioned. Total volume of conditioned sludge: 1,207.5 m^3 Total volume of conditioned waste: 2,687.6 m^3 365 waste packages
	Inventory information	Radiological inventory is the same (just concentrated) as the one of the unconditioned sludges.	Inventory is part of the national inventory of radioactive waste		Not a very good knowledge of the composition of our sludge. Gamma scans of cobalt and caesium are implemented but with bad calibration.					
	Other details	The cemented sludges are undergoing a reconditioning project (repackaging, milling, sampling). Waste minimization is also taken into account (checking for clearance).	Some productions have conditioned sludge with filters or other solid waste							Conditioned sludge may contain other materials incorporated during the conditioning process (e.g., resins, sands, oils, metals)

Table 2: Volumes and inventories of sludge held by some Member States

2.2 The management of Spent Ion Exchange Resins (SIERs)

2.2.1 General context and first insights

According to the responses from the ROUTES questionnaire, Members States consider that Spent Ion Exchange Resins (SIERs), resulted from water treatment and filtration processes, represent a widespread class of challenging waste. In total, 13 MS are facing difficulties with managing SIERs (*see Figure 7*). Issues are related to the treatment, conditioning and characterization of SIERs (*see Figure 8*).

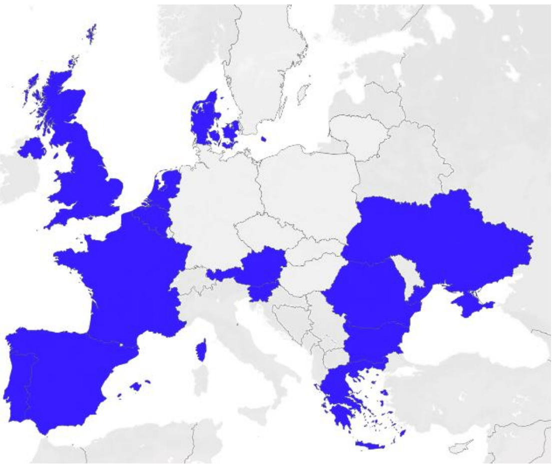

Figure 7: Member States facing difficulties with the management of SIERs

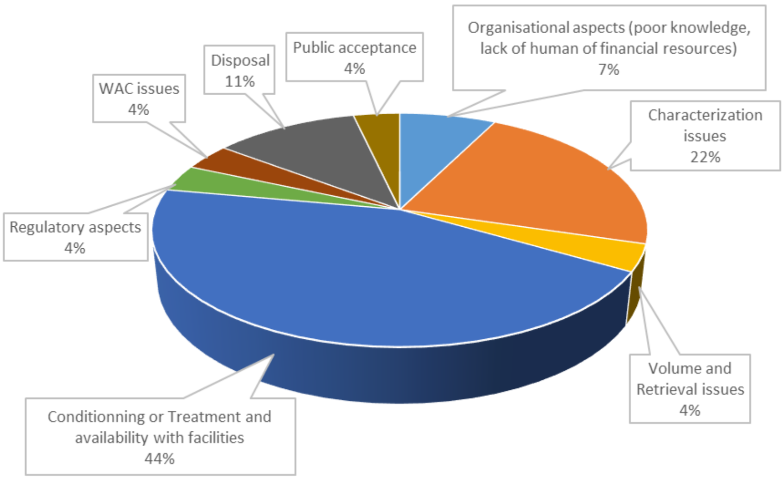

Figure 8: Main difficulties raised by the Member States concerned with the management of SIERs

2.2.2 Focus on the characterization step

For the characterization of SIERs, MS agreed that issues are similar to those faced with the characterization of sludge (see *Table 3*). Generally, Member States have succeeded in obtaining their SIERs radiological inventory thanks to widespread techniques like gamma spectrometry or scaling factors. For instance, Greece indicates that radiological inventory is based on gamma spectrometry from which activities of all the radionuclides are assessed using correlation factors. In Belgium, the radiological characterization is also not based on sampling analysis but is derived from dose rates (and in some cases gamma spectrometry measurements) and application of waste specific radionuclide vectors.

Concerning the chemical composition of SIERs, MS revealed the presence of chemical additives and corrosive products, but no further details on these elements were given. France has to manage large amounts of SIERs. Some of them raise issues related to their characterization since they were conditioned several decades ago and are stored in facilities which will be decommissioned in the next few decades. SIERs packages are retrieved and re-conditioned in most cases. Despite the large investigation and sampling work conducted in the past, the inventory is still uncertain.

The issue related to the representativeness of sampling has also been identified as challenging, such as it is for sludges.

2.2.3 Focus on the treatment and conditioning steps

Regarding treatment of SIERs, various processes are being studied by the MS and are often similar to those used for sludge. The most widespread is cementation, some MS are facing issues related to the stability of the matrix.

The following paragraphs present the management route of IERs or plans implemented in the different MS.

In Belgium, very low activity SIERs are sent for incineration to the Centralised Treatment/Conditioning Facility (CILVA) operated by Belgoprocess. The low and medium activity SIERs largely still reside with the waste producers but incineration in the CILVA installation might be considered for some of them. For those resins, a pre-treatment phase might include dehydration and addition of NaOH. Belgium also raised the fact that ashes produced by SIERs' incineration contain relatively high concentrations of sulphur and nitrogen. Therefore, pyrolysis is an alternative to incineration. Thermal compaction of SIERs was envisaged about a decade ago, but the project was suspended, based on the potential issue of swelling and mechanical damaging of barriers in case the thermo-compacted resins saturate again after their disposal.

Regarding the ashes from SIERs that are incinerated, Belgium opts for heterogeneous cementation. Here, the ashes are collected in 200 L drums that are compacted and then put in cemented 400 L drums. As it is the case for sludge (*section 2.1*), the homogeneous process (immobilization of resins by encapsulation in a cement matrix) has been suspended after the discovery of gel formation in a large number of conditioned waste (*see Focus 2 on the Belgian case study at the end of this section*).

France has to manage huge amounts of IERs coming from facilities in operation (i.e. NPP) or interim storages (conditioned or unconditioned) pending retrieval, treatment and conditioning (*see also section 2.2.2*). SIERs coming from NPP are conditioned in an epoxy matrix and this can be implemented thanks to mobile systems. It is worth mentioning that a number of IERs have required the development of specific processes and cementitious formulations adapted to the chemical composition of SIERs, and that others are also under development.

For MS that have not yet defined a management route of IERs, the solutions under development include the development of innovative conditioning processes and/or thermal treatments leading to a beneficial reduction of the associated volume.

Belgium, Bulgaria, Greece and Spain have made the choice to use cemented matrices. In Bulgaria for instance, treatment with volumetric minimisation and chemical stabilization are being tested (use of innovative matrices as ceramics for instance). In the Netherlands, incineration is envisaged in the near future with particular development of R&D programmes dedicated to organic liquid waste and resins. Volume reduction by thermal treatment is also under development in Spain and the UK.

Spain is nowadays also experimenting new techniques to increase the incorporation ratio of resins within cement. For the SIERs that will come from the dismantling activities (chemical decontamination of the primary circuit), the conditioning technique is not yet chosen and might potentially be challenging. Spain, for instance, is conducting research programmes using thermal treatment and innovative matrices (e.g. a geopolymeric matrix) which could include by-products (e.g. fly ashes and slag).

Direct cementation is not the recommended conditioning technology for SIERs generated by Romanian NPP operation (Cernavoda NPP, CANDU reactors). Indeed, some of the SIERs, especially those generated from the non-fuel contact systems of CANDU reactors, have a large C-14 inventory and during cementation, the C-14 can be released due to the temperature increase during the cement hydration processes. In 2022, an R&D project to select the optimum conditioning technology for the SIERs generated at Cernavoda NPP was initiated in the frame of RATEN R&D programme.

It is worth noting that the volume reduction resulting from the thermal treatments of IERs will increase the specific radioactivity, which might represent a challenge for some MS, especially SIMS. As an example, Greece specifies that SIERs incineration induces both volume reduction and concentration of the radiological activity, requiring disposal at other repository sites.

2.2.4 Focus on the storage and disposal steps

MS agreed to say that the major difficulty related to the storage and disposal of SIERs is the mechanical and chemical behaviour of the waste packages in terms of potential swelling, corrosion and presence of complexing substances that can increase the mobility of radionuclides in disposal facilities. To cope with these issues, Slovenia is developing an approach aiming to combine reconditioning of SIERs in a stable matrix, and enabling the presence of voids within disposal facility, to compensate potential swelling of the packages. For other MS, it turns out that cementation is used for low level activity resins, and cemented waste packages can be accepted in surface disposal facilities.

FOCUS 2 - Gel-producing waste packages of conditioned Sludges/SIERs in Belgium

In 2013, during a routine inspection, a yellow gel-like material was found on the outside of the cover of a 400-liter drum containing evaporator concentrate immobilized in a cementitious matrix. The waste package was produced by a Belgian NPP in 1995. Consequently, other drums containing conditioned concentrates were inspected. These inspections were extended to include drums of conditioned ion exchange resins after small spots of gel were also observed on the surface of the waste form. Other types of conditioned waste, e.g. cemented filters, were found to be not affected by the phenomenon.

Following the inspections, a research programme was launched. It was found that the gel most likely results from alkali silica reactions between the highly alkaline pore solution and the reactive siliceous aggregates of the matrix.

It was feared that the gel production and subsequent swelling of the cementitious matrix might mechanically degrade certain barriers of the future surface disposal facility where the waste was supposed to be disposed of. A specific research programme, aimed at determining viable disposal scenarios for the affected waste packages, was started in 2016 and is still ongoing. The cementation of concentrates and ion exchange resins by the NPPs has been suspended.

The cementation process for the concentrates and the ion exchange resins is being adapted such that gel-formation in future waste packages will be excluded. The adapted cementation processes are planned to be operational by 2025.

At present, the low and medium active SIERs are largely kept in storage by the waste producers. Only a fraction of the older and low active SIERs is sent to an incinerator. Pyrolysis might be an alternative because there is the concern that ashes from the SIERs contain relatively high concentrations of sulphur and nitrogen. The pre-treatment of SIERs might include dehydration and the addition of NaOH. Note that this technique involves pyrolysis only, and the objective of this alternative method is to avoid combustion processes.

For the medium active SIERs that will originate from dismantling of the NPPs, no process for treatment and conditioning has been decided yet. Incineration as well as cementation is being considered.

		AUSTRIA	BELGIUM	BULGARIA	DENMARK	NETHERLANDS	POLAND	PORTUGAL	ROMANIA	SLOVENIA	UKRAINE	UK
NON CONDITIONED SIERs	Volumes	No SIERs are arising in Austria.	Around 140 m^3 of low and medium active SIERs operational waste Less than 10 m^3 of medium active SIERs dismantling waste (challenging one)	2,200 m^3	Around 1 m^3	4 m^3	200-400 L/year	No data was provided yet	~ 300 m^3 – SIERs generated by 2 CANDU units in operation on Cernavoda site	142.312 m^3	1,168.45 m^3 total at Ukrainian's NPPs	Organic IERs : 430 te ILW and 200te LLW Inorganic IERs : 3,200 te ILW and 74 te LLW
	Main radiological inventory	See sludge's part	Mixture of long and short lived radionuclides, as well beta-gamma as alpha. Mainly 137Cs and 63Ni and in medium active SIERs also 60Co	Total activity is about 10 TBq. Cs-137, Cs-134, Co-60, Mn-54	Both short and long lived RNs. Total activity has to be determined C-14, Cs-137, Co-60, K-40, Ba-133, Eu-152 + other unknown RNs	ILW & LLW Cs-137, Sb-125, Cd-109, Co-60, Sr-90, Ni-63, Fe-55.	5,684 MBq in 2018 Zn-65, Mn-54, Sb-124, Co-60, Cs-134, Cs-137.	Unknown or uncertain characterization	No radiological measurement have been carried out.	Total beta/gamma activity : 2.1 TBq	Total activity is about 10 TBq. Cs-134; Cs-137; Co-60; Mn-54; Ag-110. Mn-40	
	Main chemical inventory	See sludge's part	Mainly Li and B (90%). Remainder contains Ni, Fe and Ca.	No chemical inventory available	Bakelite epoxy, lead, iron				No chemical inventory available		Na: 0.014-0.72; K: 0.001-0,1; Fe: 0.0008-0.0029; NH_3: 0.00005-0.11; Cl: 0.00004-0.0285; NO_3: 0.012-0.84	
CONDITIONED SIERs	Volumes	Some resins (8m^3) from the operation of the research reactor at Seibersdorf (until 1999) have been cemented together with the sludge.		SIERs are not conditioned and are stored under water in tanks					Not conditioned. Currently, SIERs generated by Cernavoda NPP operation are stored on site, under light water, in concrete vaults lined with epoxy, with capacity of 200m^3 each.		SIERs are not conditioned and are stored under water in barrels	
	Inventory information		Inventory is part of the national inventory of radioactive waste		Few information available related to legacy waste	Radiological inventory existing	Reliable inventories are existing	Not available inventory for waste collected prior to 2000				
	Other details		SIERs are normally not mixed with other waste		May be mixed with other materials like metals.							

Table 3: Volumes and inventories of SIERs held by some Member States

2.3 The management of Organic Waste

2.3.1 General context and first insights

Based on the ROUTES questionnaire responses, it transpires that organic waste include a wide variety of waste that can be either in solid or liquid form. 12 MS are experiencing difficulties in the management of organic waste (see *Figure 9*) and those difficulties are mainly related to conditioning or treatment issues (33%), characterization issues (22%), lack of disposal (17%) and volume and retrieval issues (11%) (see *Figure 10*).

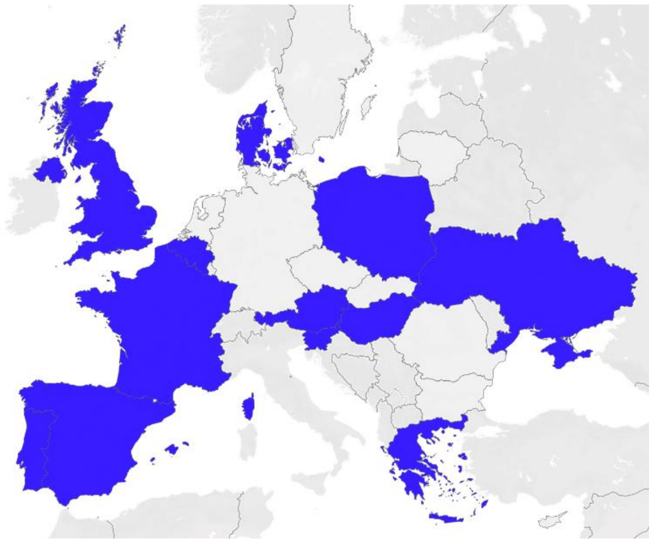

Figure 9: Member States experiencing difficulties in the management of organic waste

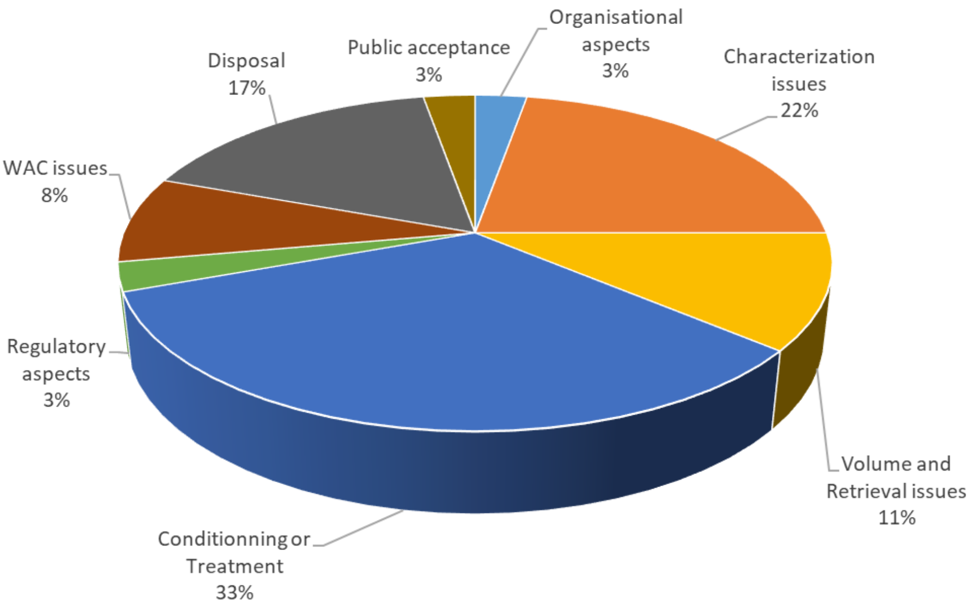

Figure 10: Main difficulties associated with the management of organic waste

2.3.2 Focus on the characterization step

Regarding the characterization of the organic waste, MS are dealing with various kinds of liquid and solid waste, with unknown radiological and chemicals inventories (see *Table 4*). More precisely, solid waste often consist of mixtures of different waste types (e.g. plastic, rubber, paper, cardboard, wood, etc.) that are not sorted and it can lead to some homogeneity issues during the characterization phase. In particular, Poland and Portugal mentioned that they have some problems to get representative samples of the organic waste to characterize. In Poland for instance, the major issue is the inhomogeneous structure of the waste, making it impossible to collect any representative sample. In Portugal, difficulties are related to the heterogeneity of the container and the fact that characterization involves transport from the storage facility to the appropriate laboratory with special authorization.

The UK also revealed that organic liquid waste are difficult to characterize insofar as they have a large number of organic reagent bottles present in contaminated areas on various sites. As it is not conceivable to characterize each bottle, trials are being conducted by Sellafield Ltd to use chemical kits and hand-held Laser Raman Spectroscopy to look at the inventory of organic bottled liquids across the Sellafield site, with a sampling plan that avoids opening every single bottle.

For their part, France and Spain also emphasized the difficulty of characterizing chemicals by-products and in particular the cocktails of complexing agents resulting from the degradation of plastics.

Finally, regarding already conditioned organic waste, it turns out that in Denmark, there is a lack of information related to legacy waste inventories. On the other hand, in the Czech Republic, some historic organic waste have to be reconditioned after the change of some WAC of existing disposal facilities, and so, new characterization programmes are ongoing.

2.3.3 Focus on the treatment and conditioning steps

For solid organic waste, mainly two potential conditioning processes are implemented in MS, namely: (i) grouting (with or without prior compaction) and (ii) incineration. The main challenge associated with grouting is the management of complexing substances that can increase the mobility of radionuclides in disposal facilities. As UK and Austria opts for these options for plastics and PVCs, they notably mention their degradation leading to the production of chloride. Poland is also using a compaction process to treat its solid organic waste that are conditioned in cemented matrices afterwards. A part of the French organic waste inventory is also treated and conditioned by compacting followed by cementation processes (see detailed description about the management of solid and liquid organic waste in *Table 4)*. In Belgium, it is also interesting to note that for ILW organic waste and/or alpha-bearing burnable waste, direct conditioning in a cemented matrix is performed, with a limit on the cellulose contents.

Regarding incineration routes, it is mainly implemented for LLW in Austria, Belgium, Czech Republic and the UK. In France, an incineration route is under development by Orano and CEA (PIVIC process) for Pu-bearing LL-ILW Solid organic waste. Note that in Denmark, for specific waste items with low activity, there is the possibility to have these items incinerated in a facility for conventional waste. This process allows the destruction of organic substances but it raises issues regarding the concentration of alpha emitters in the ash by-product. Therefore, appropriate matrices must be developed for encapsulating the ash. These issues have begun to be addressed by the former research project THERAMIN and now, the WP 6 of the current PREDIS research project is also working on it.

Some MS also tackled the particular case of biological waste. In Romania for instance, for radioactive sludges that present microbial activity, treatment in microwave field was proposed to dry and sterilize the sludge before its conditioning in cement. This microwave treatment is not applied yet and the sludges generated at Cernavoda NPP are dried and stored on site until the final decision for its conditioning for final disposal will be adopted.

In the case of liquid organic waste, discussions revealed that various difficulties are associated with their treatment and conditioning and this is why they constitute real challenging waste.

In France, an incineration route is not compatible for all the liquid organic waste because of its chemical composition and activity. To cope with this difficulty, other processes are under review (*see Focus 3 on the French case study at the end of this section*). Furthermore, in terms of transport, the presence of some chemicals prevents authorizations to allow the waste to be transferred to appropriate facilities for further treatment.

In Romania, liquid organic waste, including mainly pump oils and scintillation cocktails, are incinerated at European processors (i.e., Belgoprocess, Studsvik) on the basis of contractual agreements. Beforehand, to allow the waste to be transported to the incineration facility, organic liquid waste is incorporated in Nochar polymer. For the liquid organic waste that may not be in compliance with WAC for incineration, at RATEN ICN experimental work is being carried out on the formulation of geopolymer (based on Romanian furnace slag) in order to develop a suitable matrix for liquid organic waste direct conditioning.

In the UK, the preferred route for oils, greases and scintillation liquids is incineration, provided a regulatory authorization is in place. When incineration is not possible, liquid organic waste are encapsulated in a cement matrix and must comply with strict legislation ensuring the absence of free liquid. However, this cementation process leads to increase the volume of waste. This is a reason why UK is now looking for new thermal treatments to reduce volumes on the one hand, and to destroy organic compounds on the other hand. Studies on the conditioning of different liquid organic waste types in a Nochar polymer prior to grouting have also been demonstrated[3]. The WP 5 of the PREDIS project is dedicated to innovation for the direct encapsulation of organic liquid waste in geopolymers and related alkali-activated binders with the target of reaching high waste incorporation rates (>30 % vol.).

The issue associated with specific regulation for incineration of organic waste has also been raised by Denmark, which informs that above a certain activity limit, the operations of incineration are prohibited. This is the same situation in the UK as noted above.

In Spain, several management routes are considered:

- Scintillation Cocktails (from non-nuclear producers) are incinerated at El Cabril repository;
- Oils and greases arising from the operational or dismantling equipment and tools, are stored in the interim storage of NPPs;
- Decontamination liquids: experiments are ongoing to treat those waste abroad by incineration (slags and fly ashes will be sent back to Spain).

Finally, it is worth mentioning that in Greece, Portugal and Hungary, incineration is not implemented, either because it is not allowed in the regulations (cf. Portugal and Hungary), or because it is not economically viable regarding the small amount at stake (cf. Greece).

2.3.4 Focus on the storage and disposal steps

When it comes to storage and disposal of organic waste, MS agree that the major difficulty is associated with the degradation of plastics, which can produce complexing substances that will affect the mobility of some radionuclides. And currently, the CORI Work Package of EURAD is working on this issue.

In the UK, a number of research projects are either complete (some dating back to the 1980s) or ongoing to study the mechanisms that can take place with the presence of complexing and chelating substances in the context of deep geological disposal in the UK. For surface disposal at the LLWR, complexing substances are accepted provided they meet strict limits set in the WAC for certain complexing substances such as EDPA, DTPA, NTA, etc.

In France, within the framework of the Cigéo project, various research programmes are also being conducted to study the influence of complexing substances on the mobility of radionuclides in the host rock (Callovo-Oxfordian (COX) Clay). One outcome of these studies is that it is now envisaged to increase the distance between two galleries of the future Cigéo disposal facility to limit interaction between gallery hosting waste with complexing substances and gallery hosting waste without these particular species. For surface disposals, heterogeneous cellulosic waste (wood, cotton, paper) must

[3] Radioactive Waste Management, NDA, LLW Repository Ltd, Problematic Waste Integrated Project Team. Briefing Note on Nochar absorbed oils and oily wastes R&D, February 2019.

be identified and quantified. Similarly, for waste packages containing complexing substances, their contents must be identified and quantified and their acceptability is determined on a case-by-case basis.

Note that in Belgium, maximum cellulose contents in cemented conditioned waste is fixed depending on the type of disposal. For surface disposal, the maximum allowed cellulose content, being 100 g per 400 L drum, is 100 times lower than for geological disposal.

FOCUS 3 – Example of innovative options implemented for liquid organic wastes in France

Liquid organic waste (LLW) can be treated by incineration in the CENTRACO incineration unit (Cyclife Group EDF) and conditioned for final disposal. Nevertheless, some organic oils and liquids coming from all types of sites (operation, maintenance, dismantling) are not compatible with acceptance specification in the incineration facility due to their chemical composition (i.e. corrosive species, etc.) or activity. This waste can include mineral or organic oils from draining of circuits and hydraulic equipment or organic solvents (dodecane, ethanol, etc.) used as degreaser or like scintillation fluid by site laboratories. To cope with this difficulty, different management (conditioning routes) are being studied:

- Treatment by mixing with polymers (NOCHAR) (including incineration prior to disposal, or direct disposal) specific chemical destruction process or specific thermal destruction process;
- Incorporation in geopolymers and related alkali-activated materials. The acceptance in repository of such wasteform widely varies across EU. This topic is specifically address in the PREDIS Project WP 5 and will not be further addressed in this document.
- Thermal plasma processes are being developed in CEA (IDOHL and ELIPSE processes).

In conclusion, even though, in France, significant amounts of organic waste (liquid and solid) are currently treated and conditioned in a way suitable for final (surface) disposal, important R&D efforts are being made at national and international (EU) level to define a management solution for waste streams which cannot be treated by existing technologies.

		AUSTRIA	CZECH REPUBLIC	DENMARK	POLAND	PORTUGAL	SPAIN	UKRAINE	UK
NON CONDITIONED ORGANIC WASTE	Volumes	Arising waste volumes are conditioned, therefore the non-conditioned volumes cannot be reported.			Not specified – about 40-50 % of total received solid waste.	Not known		Organic liquid waste at Hmelnitskaya NPP is 0.43 m^3 LRW (Shelter Object waters) 2,324 m^3 (end of 2018)	Total (excluding SIERs): 7,316 te ILW, 212.100 te LLW, 62.140 te VLLW Including cellulosic, hydrocarbons, plastics, rubbers and other organic wastes
	Main radiological inventory	The main radionuclides are: H-3, Cs-137, C-14, Co-60, Pu.			Mainly Cs-137 and Co-60	Mainly C-14 and H-3	LLW Beta-gamma and beta-emitters and negligible amount of alpha emitters	Cs-137; Co-60; Sr-90	
	Main chemical inventory	The main compounds of the resulting ash (after incineration) are: Oxides of Mg, Al, Si, Ca and Fe; Traces of Cr, Cu, Zn, Mo, Ba, W, Pb			Cellulose, rags, plastic, lab gloves, IEX resins, etc.	Scintillation cocktails	Organic components	Organic components	
CONDITIONED ORGANIC WASTE	Volumes	About 200 drums (200 L) with cemented ashes and about 100 drums (100 L) drums of ashes in stainless steel cartridges	Solidified organic waste packages are disposed in Richard repository. One third has been reconditioned and is now disposed in hydraulic cage system.	Volume of organic waste in drums is unknown.					The 2019 UKRWI lists only one specific entry for conditioned organic waste: contaminated oils and solvents with a packaged volume of 397 m^3 in 696 packages.
	Inventory information	LLW mostly LL (as the activities are concentrated in the ashes)	Radiological and chemical inventories are assessed using old data coming from former producer. Some inventories are checked using analytical methods.	Not described.	Reliable inventory is existing.				
	Other details	Organic (solid and liquid) waste is incinerated.	Organic waste are not mixed with other waste.	Most of organic waste is legacy and is packed in drums where it is probably mixed with secondary waste.					Mixed waste from operations (bags, suits, tenting materials, paper, bottles, etc.)

Table 4: Volumes and inventories of organic waste held by some Member States

2.4 The management of Bituminized Waste

2.4.1 General context and first insights

Bituminized waste arise from the conditioning of sludge resulting from the liquid waste treatment processes often associated with fuel reprocessing plants and eventually spent resins. Bitumen was the matrix mainly used from the 1960s to condition those types of reactive waste. 5 MS are experiencing difficulties in the management of bituminized waste (see *Figure 11*) and those difficulties are mainly related to disposal (41%), reactive/corrosive constituents and suitable packaging (23%), characterization issues (18%), conditioning or treatment (12%) and WAC issues (6%) (see *Figure 12*).

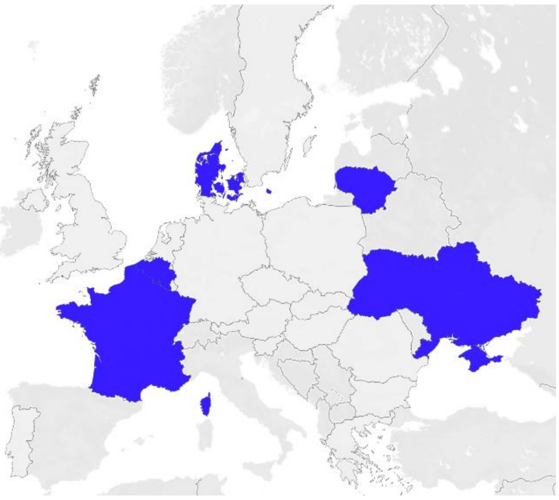

Figure 11: Member States experiencing difficulties in the management of bituminized waste

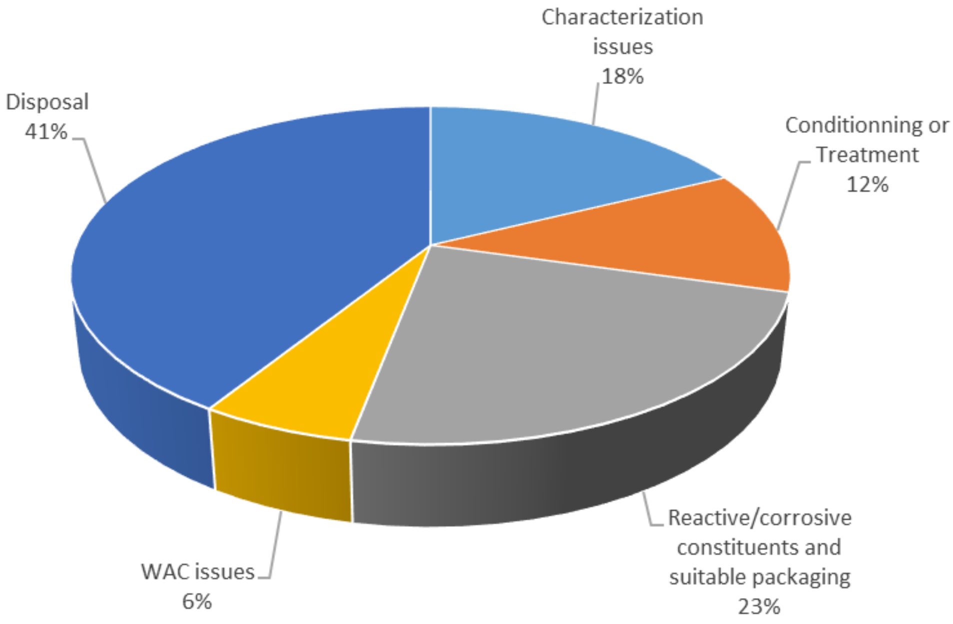

Figure 12: Main difficulties associated with the management of bituminized waste

2.4.2 Focus on the characterization step

Regarding the characterization of the bituminized waste, most of the MS are confronted with uncertainties on the radiological and chemicals inventories (see *Table 5*).

Belgium, France and Denmark raised the fact that they have to deal with large volumes of historical waste for which a lot of uncertainties are at stake about their radiological and chemical inventories. In

France, bituminized waste have been mainly produced both by CEA (in Marcoule) and Orano (in La Hague) and consisted mainly in LL-ILL bituminized waste drums. At Marcoule, five production periods have taken place with limited information about the potential radiological and chemical components of the produced waste for the eldest waste, so CEA carried out in the past decades and is still developing programmes to better characterize its bituminized waste.

For Belgium, the homogeneous bituminized waste is of medium activity (dose rate value of around 1 Sv/h) and the heterogeneous ones are of low activity (dose rate values range from 0.1 to 1 mSv/h). These waste came from various installations operated at different periods, but the largest and most active part of the waste comes from the former EUROCHEMIC reprocessing plant at Belgoprocess. It turns out that a characterization programme is under process for those waste but, as the allocated budget is rather limited, this programme might take a long time.

Note that in Denmark, the same issues are at stake but presently there are not enough resources to progress the characterization of their bituminized waste.

For Bulgaria, Czech Republic, Lithuania, and Ukraine, the radiological and chemical inventories are almost complete for their bituminized waste. Notably, the Czech Republic mentions that they are not facing any particular difficulties in characterizing bituminized waste. Analysis such as pH tests, total β/γ activity, content of asphalt, thermal stability, leachate tests, etc., are routinely carried out. Due to the large volumes of bituminized waste in Lithuania, there is a problem with determining how homogeneous these waste are.

2.4.3 Focus on the treatment and conditioning steps

For some MS such as Belgium, Bulgaria, Czech Republic, Denmark, France, and Ukraine, bituminized waste have already been packed in drums. However, for most cases, old drums have often swollen and corroded, making it necessary to recondition them to ensure new and safer containment of the waste itself. Thus, some MS are now working on the reconditioning in new packages using different processes.

In France, bituminized waste produced by CEA has been historically conditioned in 200 L drums. Because of corrosion and swelling of some drums, all these historic drums are being reconditioned in 380 L stainless steel metallic drums. A new storage facility is also being implemented on the CEA premises. Note that for the bituminized waste produced at La Hague, reconditioning is not being considered at the moment, as their drummed waste is still in good shape. It was also mentioned that the French National Plan for the management of radioactive waste provides recommendations aiming to study treatment of chemicals in bituminized waste, so that exothermic reactions could be avoided.

In Denmark, a number of older bituminized waste drums has been reconditioned in new steel packages underway (not final conditioning). The reconditioning process will continue as all waste drums are moved to a new, upgraded storage facility, which is presently under planning. The reconditioning is done taking into consideration the preliminary state of the drums, i.e. “Are they badly corroded or not? Have they swollen or not? etc.”.

In Belgium, they are also facing some difficulties related to the swelling of “old” drums. Some studies are considering cementation processes for reconditioning these drums. In Ukraine, it is planned to place bituminized waste in reinforced concrete containers, 5 drums each, just before disposal[4].

The particular case of Lithuania should also be mentioned. As discussed in the Focus 4 case below, it turns out that bituminized waste has been stored in large canyons (each with a capacity of 2,000 m^3) without any further treatment or conditioning. Nowadays, the main difficulty faced by Lithuanian authorities is the retrieval of this large quantity of waste. Reconditioning is not under consideration. A

[4] Dedicated presentation on this topic is available here: [ROUTES workshop Subtask 4.2 - Sharing Experience on Waste Management with / without WAC | Eurad (ejp-eurad.eu)]

project is currently looking at transforming the legacy bituminized waste storage facility into a final repository.

2.4.4 Focus on the storage and disposal steps

When it comes to storage and disposal of bituminized waste, MS agree that the major difficulty is associated with the degradation of steel drums, which have been stored for several decades, and can lead to radiological and chemical releases.

In Belgium, the bituminized waste are stored at the producer specific installations which have been designed and licensed to keep these waste for many decades. For some of the bituminized waste, the main difficulties with storage and disposal are the associated fire hazards.

R&D programmes are also ongoing to study the maximum swelling that could be managed within a final disposal facility, without compromising the safety of the whole facility.

In Denmark, for now, no plan has been decided regarding the final disposal of bituminized waste. When all the Danish waste has been moved to a new, upgraded storage facility, R&D programmes will be set up looking at how to predict the evolution (e.g., corrosion, swelling) of the drums.

In France, as already mentioned, a new storage facility for CEA historical waste is being built to store the reconditioned drums. Regarding final disposal issues, a number of specific issues have been identified, such as gas production that could further affect the integrity of the disposal. In fact, the major difficulties are related to (i) fire hazards and (ii) long-term safety with regarding to possible leakage of sulphides and nitrates that would influence the mobility of radionuclides. To address this, French R&D programmes are investigating the issues of water intake in disposal situations leading to the leakage of radionuclides and nitrates (and eventually sulfates) and swelling of the matrix. Fire hazards associated with bituminized waste and the possible development of special disposal containers improving fire resistance are also under research.

Regarding the interesting case of Lithuania, the option to reconstruct and transform the current storage facility into a bituminized waste final repository is being considered (*see Focus 4 on the Lithuanian case study*). The decision on further waste management should be made before the end of the decommissioning period of the Ignalina NPP.

In Ukraine, bituminized waste will be disposed of in the near surface repository, which is located in the Vector site in the exclusion zone. Note that currently, studies aim to determine whether disposal WAC relating to the explosiveness of the bituminized waste packages can be met.

Note that the Czech Republic already has a disposal facility in Dukovany where bituminized waste may be disposed respecting WAC.

FOCUS 4 – Particular case of the bituminized waste storage facility in Lithuania

The Bituminized Waste Storage Facility (BWSF) is located in the protected Ignalina NPP (Lithuania) industrial site. It comprises an above-ground, rectangular reinforced concrete structure (75.3 m x 74.1 m x 12.5 m (L x W x H)). BWSF is connected to Liquid Radioactive Waste (LRW) processing, bituminisation and cementation buildings by pedestrian and process galleries. Construction of the BWSF begun in 1981, and it was operational in 1987. Loading of bituminized RW into canyons was finished in 2015. There are 12 canyons in total, each may contain 2000 m^3 of RW and the canyons No. 12 is 800 m^3 of volume, see Figure 13.

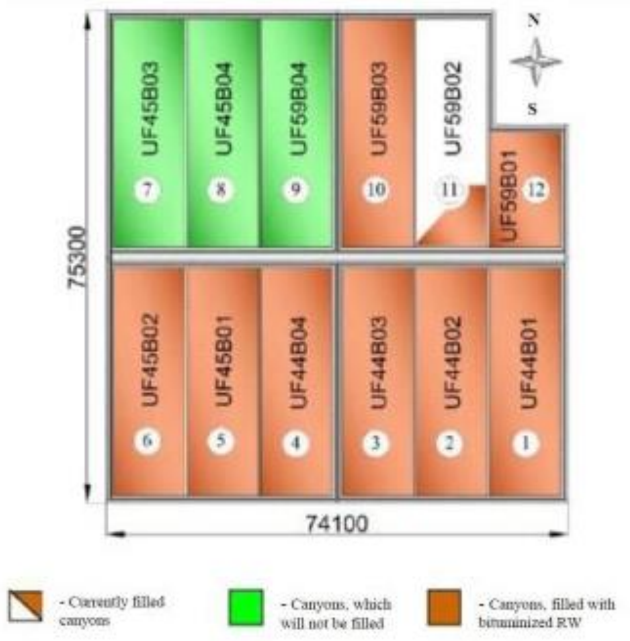

Figure 13: Layout of the BWSF

The BWSF is designed for acceptance and storage of bituminized RW, i.e., short-lived low and intermediate level waste. Currently, canyons No. 1 - 6, 10 and 12 are completely loaded with bituminized RW. In the period of 1987 – 2015 approximately 14,422 m^3 bituminized RW were loaded in the BWSF.

The total activity of bituminized RW is approx. 30 TBq, and mainly consists of Cs-137 but some long-lived radionuclides (Pu-241, Am-241, Pu-240, Pu-238, etc.) are also included.

In 1998 – 2000, SKB (from Sweden) performed an assessment of the long-term safety of the BWSF. In 2007 – 2009, a Feasibility Study of converting the Interim Bituminized Radioactive Waste Storage Facility into the Repository was performed (justification of long-term storage). In 2018, a project was started to confirm the feasibility of the conversion of the existing BWSF into a long-term repository. A technical design and relevant supporting safety documents are under preparation. Based on this, the Ukrainian regulator will take a decision on whether or not it is allowable to transform the BWSF into a long-term repository for bituminized waste.

		BELGIUM	CZECH REPUBLIC	LITHUANIA	FRANCE	SWEDEN	UKRAINE
NON CONDITIONED BITUMINIZED RW	Volumes	approximately 13,000 drums of 200 L, (by EUROCHEMIC) approximately 1,700 drums of 200L and ±700 drums of 400 L (by SCK CEN until 1989) approximately 750 drums of 200 L and ±1,700 drums of 400 L (by Belgoprocess until 2004)	Approx. 250 m^3 per year of waste processed to bitumen matrix	Approx. 14,400 m^3 (in total) RW is in big vaults (each with a capacity of 2,000 m^3) without packaging.	Around 70,000 drums of bituminous mixture (FEB) have been produced: • CEA/Marcoule: 32,900 LLW & 28,500 ILW • Orano/La Hague: 11,850 ILW	6,000 m^3	739 drums, 148 m^3
	Main radiological inventory	EUROBITUM: Co-60, Ni-63, Sr-90, Cs-137, Pu-241, Am-241, Pu-239, Pu-240 SCK.CEN: Co-60, Cs-137, Pu-238, Pu-241, Am-241 MUMMIE: Co-60, Ni-63, Sr-90, Cs-137, Pu-241	Predominantly C-14, Ni-63, Sr-90, Cs-137, LLW type, certain amount of long-lived RN (e.g., ^{239}Pu, ^{241}Am).	Main nuclides Cs-137, Ni-63, C-14, Sr-90, Tc-99. RW is radiologically characterized	Drums from Orano/La Hague – total activity from 1.04 to 1.54 TBq/drum – Pu-238, Am-241, Pu-240, Pu-241, Ru-106, Rh-106, Cs-137, Sr-90. Drums from CEA/Marcoule – total activity from 0.9 to 2.7 TBq/drum – Pu-239, Pu-238, Am-241, Pu-240, Cm-242, Pu-241, Cs-137, Sr-90, Ce-144, Ru-106, Ce-144.	Short lived, 50 TBq.	Main nuclides Cs-137, Cs-134, Co-60, Sr-90, Tc-99, Ni-63 (C-14<1 Bq/g, Tc-99 <1Bq/g,)
	Main chemical inventory	EUROBITUM: mainly conditioned sludges and salts, also some metallic parts (aluminum, stainless steel) SCK.CEN: conditioned solid waste, ashes, sludges and salts MUMMIE: conditioned sludges	Mainly Ion-exchange resins and sludge's from water cooling system in NPP	Evaporator concentrate of drainage water from the primary coolant, decontamination liquids, laboratory waste, floor decontamination drains, water from showers and laundries, and liquids used for the regeneration of ion exchange resins. Homogeneity of bituminized waste is under question.		Spent ion exchange resin, filter additives and concentrate	Main chemical inventory: BO_3^-, Na^+, NO_3^-, SO_4^{2-}
CONDITIONED BITUMINIZED RW	Volumes		952 m^3 bituminized RW in 200L galvanized drums.			Reconditioning of bituminized waste is not planned.	Reconditioning not planned. Drums with bituminized waste placed in concrete containers in concrete matrix and disposed.
	Inventory information	Mixture of long and short-lived nuclides	Both short and long-lived nuclides				
	Other details	Reconditioning is not planned		Retrieval is a problem, no technology is available Disposal in-situ is under consideration.			

Table 5: Volumes and inventories of bituminized waste held by some Member States

2.5 The management of Graphite Waste

2.5.1 General context and first insights

Based on the ROUTES questionnaire responses, it transpires that graphite waste result from both former nuclear research and Nuclear Power Plant (NPP). Depending on their position within the reactor, they were more or less in contact with the fuel and therefore, have been activated. These waste are considered highly flammable.

As shown in *Figure 14*, 15 MS are facing difficulties in the management of graphite waste. More precisely, these difficulties are mainly related to the availability of final disposal options (30%), organisational aspects/lack of knowledge (24%) and conditioning and treatment issues (19%) (see *Figure 15*).

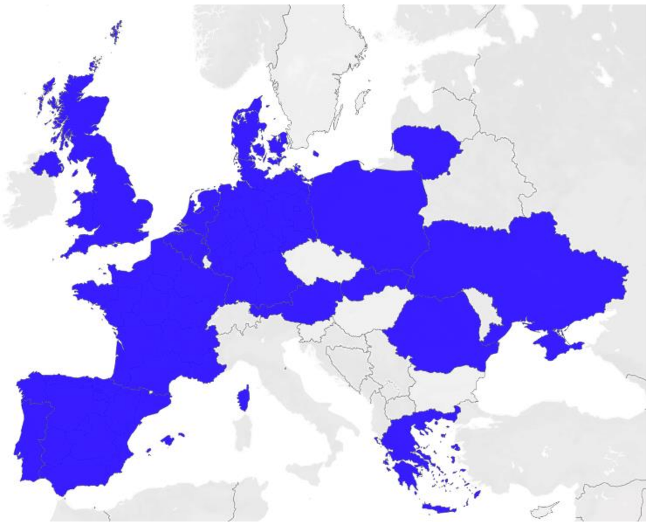

Figure 14: Member States experiencing difficulties in the management of graphite waste

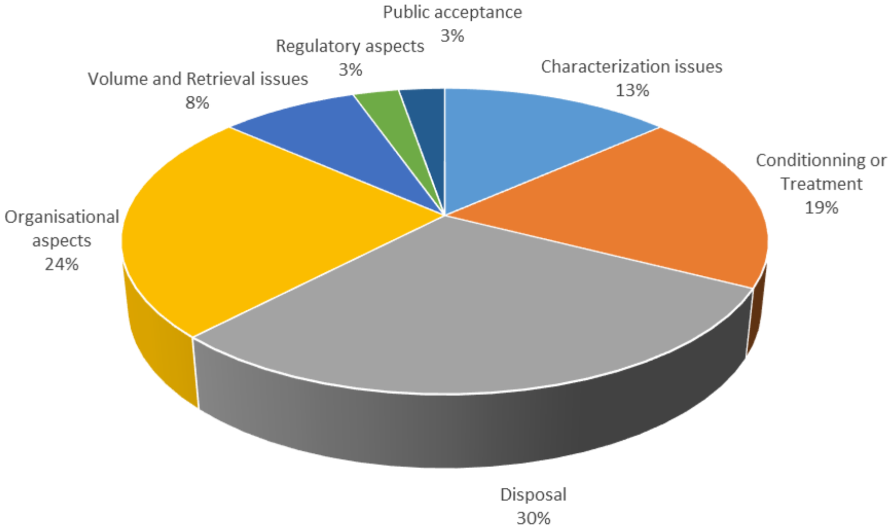

Figure 15: Main difficulties associated with the management of graphite waste

2.5.2 Focus on the characterization step

Regarding the characterization of the graphite waste, it turns out that MS are dealing with unknown radiological and chemicals inventories as well as various volumes of graphite waste (see *Table 6*).

In Ukraine, they will have to deal with more than 5,000 te of graphite coming from the future decommissioning of the Chernobyl NPP. Notably, these waste include rings, sleeves and blocks of graphite. Regarding the characterization of these waste, it turns out that the main issue lies in the identification of the existing nuclide correlation vector that depends on the assumption of homogenous impurity distribution in the virgin graphite. Taking into consideration the inhomogeneity usually observed in graphite due to different operation parameters within the graphite stack, this medium vector should be adjusted or modified. The appropriate characterization methodology has to be developed and described before the beginning of the Chernobyl decommissioning works. In the same way, Lithuania also raised the fact that they have major difficulties related to the characterization of graphite waste due to the heterogeneous distribution of impurities in graphite and therefore, the distribution of radionuclides associated with activation of impurities is uneven. This prevents the realistic radiological characterization of irradiated graphite.

In Denmark, they are dealing with small volumes of graphite (90 te). These are well characterized and their radionuclide content is mainly C-14 and Ni-63. As some of the data is based on old estimates, new calculations are now necessary and will be based on Monte Carlo simulations.

The UK noted that the largest population of current stocks of graphite is Advanced Gas-cooled Reactor (AGR) fuel assembly component/graphite sleeves from reprocessing fuel assemblies: 4730 m^3 with 2806m^3 as future stocks. The UK also mentioned that there are no reported issues for graphite characterization other than the use of fingerprints to define activities inside reactor cores. Some historic models based on neutron flux inside the reactors are known to overestimate dose rates but no additional sampling is planned to refine the models. In France, the majority of their graphite waste is still in-situ within old reactors shut down since the 1980s. Only graphite sleeves have been gathered in dedicated silos. At the beginning, the characterization process consisted of neutron flux calculations, as in the UK. However, the presence of Cl-36 raises safety concerns for disposal. Initial sampling regimes have shown a very heterogeneous distribution of Cl-36, with concentrations varying by a factor of 1000. In order to understand this variability, statistical methods are being implemented which, in addition to characterizing the impurities, seek to estimate the presence of Cl-36 as accurately as possible. The objective is now to extend this methodology to all French reactors[5]. The CEA is also working on developing this statistical approach. In Spain, it turns out that innovative actions are also implemented to better characterize graphite waste, trying to establish nuclide vectors, mapping nuclides distribution within the graphite pile, as well as identify volatile materials[6].

2.5.3 Focus on the treatment and conditioning steps

The MS agreed that graphite waste management is difficult. Indeed, they present different challenges in terms of safety, for instance, the mobility of C-14 emphasized by Greece or the Wigner effect mentioned by Austria, Belgium, Denmark and Greece. However, no solution has been found to overcome these safety issues except for Austria where all graphite waste exposed to a fast neutron flux of >10^{19}n/cm^2 at low temperature (<50°C) was heat-treated at 370°C to release 95% of the Wigner Energy *(see Focus 5 on the Austrian case study)*. In addition, the MS also underlined difficulties related to the absence of appropriate treatment and conditioning.

Concerning treatment and conditioning of graphite waste, Ukraine announced that the strategy of deferred dismantling (SAFSTOR) is accepted for the Chernobyl NPP. This strategy will consist of

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[5] Nicaise G. and Poncet B., A reverse method for the determination of the radiological inventory of irradiated graphite at reactor scale, Eurosafe 2015.

[6] For further details, please refer to the presentation given by G. Pina during the ROUTES Workshop of subtask 4.2: [ROUTES workshop Subtask 4.2 - Sharing Experience on Waste Management with / without WAC | Eurad (ejp-eurad.eu)]

preservation and long-term (up to 50 years) safe enclosure under supervision of the most contaminated equipment. The reactor space and cavities of reactor metal structures will be completely sealed after dismantling of the channels for safe storage of graphite. An active phase of the graphite stack management will start after 2045 at the stage of dismantling. By this time, a geological repository and appropriate containers for irradiated graphite will be built in Ukraine. For now, the dismantled channels are planned to be sent to the long-length waste cutting facility on site. It must be noted that processing of the special items is on the critical path and will define the duration of the Final Shutdown and Preservation Stage. The long-length waste cutting facility will enable operators to (i)in particular, remove graphite rings and sleeves from channels; (ii) cut the special items (technological channels, channels of the control and protection system); (iii) pack, characterize and track the received radioactive waste. Graphite rings will be packed into 200L stainless steel drums. Around 2,900 packages are planned to be generated. The packages with graphite will be stored in temporary storage (up to 30 years) into the existing solid RAW storage facility at Chernobyl NPP site.

In France, it turns out that a few years ago, the National Waste management plan requested a study of thermal and chemical treatment of graphite waste. However, these studies have shown that thermal treatment is effective in reducing graphite volumes but it induces the production of secondary waste difficult to manage as, for instance, ashes contain high concentrations of C-14. For that reason, studies are now focusing on characterization in order to define appropriate disposal route, as explained in the following paragraphs.

Regarding the situation in the UK, graphite is cracked from AGR fuel assemblies, assembly and crushed, before falling under gravity into a drum liner. Once the liner is full, it is placed into a 500 L drum. From 1987 to 1993 mild steel drums were used. Stainless steel drums have been used post this date. The current stock is 3,300 mild steel drums and 10,500 stainless steel drums (2018 data). A further 10,000 stainless steel drums are anticipated to be generated until the end of the dismantling operations in 2037. The UK also raised the fact that major difficulties related to the treatment of graphite waste are due to the fact that they are chemically inert and stable to heat, which makes them poor candidates for thermal treatment.

Lithuania specified that their management strategy starts with removal of graphite rings/sleeves from the channels. These will be placed into 200 L drums; eight drums will be placed into one reinforced concrete storage container and this container will be transferred to the storage facility. Various measurements (dose rate, mass, etc.) on the container will be performed in line in order to meet therequirements. This process, with any necessary adaptation, could be extended to other countries dealing with similar problems. They also raised the fact that major difficulties related to the treatment and conditioning of graphite waste are related to the fact that, due to the neutron activation, the entire volume of the graphite is contaminated. This led to the release of volatile radionuclides during crushing operations.

During the discussions, the existence of the GRAPA research project was raised. Led by IAEA, this project aimed to study treatment and disposal concepts for graphite waste. However, since the end of GRAPA project, it appears that treatment alternatives are no longer being studied and that the focus is on disposal issues.

2.5.4 Focus on the storage and disposal steps

When it comes to storage and disposal steps, MS agreed to say that the major difficulties are related to the inventory of C-14 and Cl-36, as well as the impact of possible Wigner energy. Concerning the storage issue of graphite waste, Ukraine announced that the Chernobyl NPP should develop actions for efficient ventilation of stored containers, including management of in-take air in relation to its temperature and humidity, and diurnal and seasonal variations. On the question of disposal, according to the national regulatory and legal framework, the whole amount of the Chernobyl NPP irradiated graphite will represent long-lived waste and will be subject to disposal in stable geological formations. In the UK, most of the graphite is still located in the reactors. These waste will represent a large volume for which the boundaries between LLW and ILW are not very clear. For the part of graphite considered as ILW, they will be accepted in the future GDF but a near-surface disposal (60-200 m) concept is also being investigated for those waste. Note that either in the case of LLW or ILW, the presence of C-14 and Cl-36 raised an important challenge in terms of dose contribution inside the repository.

For Belgium, the management of graphite waste is not a priority as the associated volumes are small. Part of the volume, considered as LLW, could be targeted for surface disposal in the future, but additional safety assessment would be necessary. Although limits of C-14 and Cl-36 already exists for surface disposal, adaptation would be needed to consider the specific case of graphite waste. Similarly, in France, some graphite waste are disposed of in a LLW repository. This leads to a significant contribution of Cl-36 to the total radiological capacities of the repository. In parallel, a near-surface disposal facility is under study and will aim to handle other graphite waste. In relation with this project, various studies are ongoing and are related to the Wigner effect and the mobility and possible release of C-14 and Cl-36.

Finally, Lithuania also mentioned that according to their legislation, graphite waste could be disposed of in a GDF. Such facility is not available yet. Preliminary investigations in relation to geological disposal are currently performed. It is foreseen that the start of operation of such a facility could be expected in 2068.

FOCUS 5 – Treatment of Graphite with fast neutron flux in Austria

Graphite waste in Austria stems from the research reactor (a 10 MW pool type reactor) at the Seibersdorf site. The reactor was in operation from 1960-1999 and decommissioned from 2000-2006. The total decommissioning waste amounted to about 1600 t total of which 95% could be cleared, with only 5% radioactive waste remaining. Part of that total waste was 9t of graphite mainly from the thermal column and from reflector and irradiation elements. 2 t of graphite could be cleared for re-use.

The graphite was irradiated at a temperature of less than 50°C with a maximum neutron fluence of 10^{21} n/cm^2. This led to a build-up of Wigner Energy in the graphite. To avoid a possible release of this energy during storage, all graphite waste exposed to fast neutron fluence of >10^{19} n/cm^2 was heat-treated between 300 and 400°C maximum in an oven in a hot cell. 1,6t of graphite waste was annealed this way and 95% of the Wigner Energy released.

The maximum contact dose rate of a graphite brick of the inner thermal column was 3 mSv/h. Activities are around 1000 Bq/g C-14 with some Co-60 and Eu-142. As no Chlorine was used for cleaning, there is no Cl-36 in the graphite.

The graphite bricks then were encapsulated in a Konrad type II steel container in 2005 and are in interim storage since then.

		AUSTRIA	FRANCE	GERMANY	GREECE	LITHUANIA	PORTUGAL	ROMANIA	SLOVAKIA	SPAIN	UKRAINE	UK
NON CONDITIONED GRAPHITE WASTE	Volumes	About 10 te of graphite from thermal column (also reflector and irradiation elements) of the decommissioned research reactor in Seibersdorf.	Pure irradiated graphite (22, 000 te) + graphite mixing with Mg, U (around 10, 000 te)	1,000 te – dominant waste stream is graphite reflector and in lesser extent carbon bricks	5.6 m3	In general, graphite coming from decommissioning of Ignalina NPP RBMK reactors: •Graphite blocks (~3,500 te for 2 reactors) •Graphite rings/sleeves (~250 te for 2 reactors) Total activity for both Ignalina NPP RBMK reactors graphite is estimated as ~5,800 TBq for 2028. + 55te of operational graphite waste, which are currently stored in existing RAW storages.	Graphite related to former research reactor swimming pool 1 MGW	5.3 te	86 te	4,000 te	5,687 te (or 4,082.5 m^3) of irradiated graphite will be produced in total during decommissioning of Chernobyl NPP Units 1, 2 and 3	82,000 te ILW and 15,500 te LLW Most of this is graphite cores from AGR (~1,800-2,500 m^3 ILW and 450-650 m^3 LLW, except Dungeness B which is an outlier at 1,694 m^3 LLW) and Magnox Reactors (~3,000-3,500 m^3 ILW and 33-1,800 m^3 LLW per Magnox Reactor except for Wylfa (5,915 m^3 ILW and 2,737 m^3 LLW) and is future arisings (still in-situ).
	Main radiological inventory	About 1,000 Bq/g C-14, some Co-60 and Eu-152		Fuel elements – H-3, C-14, Sr-90, Cs-137, Co-60 + presence of fission products in fuel elements	Radiological characterization has been calculated but not validated by measurements.	The most important radionuclides are C-14, Co-60 and H-3		H-3, C-14, Co-60, Fe-55, Ni-53, Ni-59, Cs-137, Eu-152, Eu-154, Eu-155	Carbon + trace elements (Co, Cr, Eu, Fe, Ni)	Co-60, H-3, Cl-36, Ni-63 + other beta/gamma and alpha RNs	C-14, H-3, Cl-36 Fe-55, Ni-59, Co-60, Ni-63, Nb-93m, Ag-108m, Ba-133, Sr-90, Cs-134, Cs-137, Eu-154, Eu-155.	
CONDITIONED GRAPHITE WASTE	Main chemical inventory					Graphite used for graphite rings/sleeves and graphite blocks of RBMK reactor is of different grades, however in both cases it is a polycrystalline graphite manufactured from petroleum coke mixed with coal-based binder pitch. This graphite is chemically pure material containing a low level of impurities (orders of ppm typically).						

Table 6: Volumes and inventories of graphite waste held by some Member States

2.6 The management of Decommissioning Waste

2.6.1 General context and first insights

According to the responses from the ROUTES questionnaire, Members States consider that decommissioning waste represent a widespread class of challenging waste that can correspond to construction materials (e.g., rubble, contaminated concrete), soils, scrap metal, wood, tools and safety equipment or even contaminated liquids. In total, 14 MS are facing difficulties in the management of decommissioning waste (see*. Figure 16*). Among the difficulties raised by the countries, it was found that major issues are related to the characterization, volume and retrieval issues, final disposal options (and regulatory aspects) (see *Figure 17*).

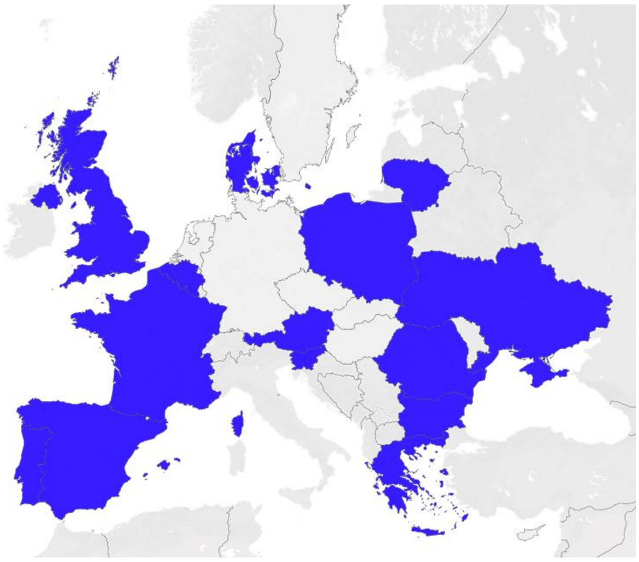

Figure 16: Member States facing difficulties with the management of Decommissioning waste

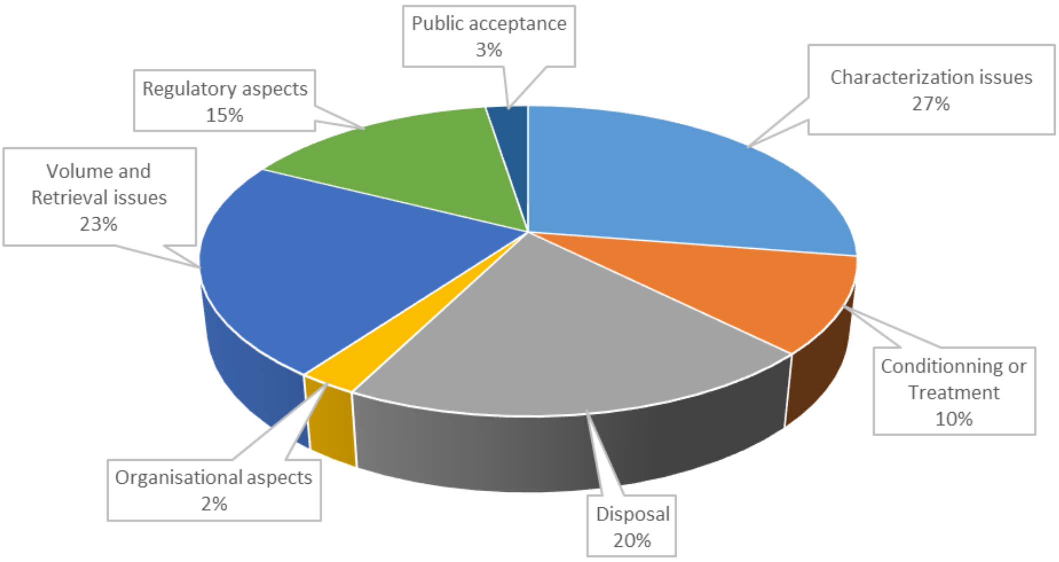

Figure 17: Main difficulties raised by the Member States concerned with the management of Decommissioning waste

2.6.2 Focus on the characterization step

For the characterization of decommissioning waste, MS agreed to say that major challenges lie in anticipating the volumes of dismantling waste to be produced and their related activities (see *Table 7*).

In the UK, decommissioning waste are defined as concrete and rubble; miscellaneous contaminated materials; activated metals; contaminated metals; soil (contaminated land), etc. Among these waste, a large part will be produced in the future decommissioning activities and will include significant volumes. The case of concrete considered as VLLW can be cited as an example of challenging waste with large volumes that will have to be managed in the coming years. In Denmark, predicting the quantities of concrete to be managed as a result of decommissioning activities is also a current issue. In particular, they stressed that it is necessary to determine in advance the quantity considered as LLW and the quantity of uncontaminated material that can be managed conventionally. In the same line, Bulgaria, Czech Republic and Slovenia raised the fact that, although dismantling operations will not start for several years, the associated waste will represent large volumes and this information is needed as soon as possible to identify appropriate disposal routes. France also requires similar information, especially as there is no French clearance threshold in force. France and Belgium also tackled the challenge related to determining reliable chemical inventories in order to prevent the production of by-products in the long-term (e.g., cellulose and production of Isosaccharinic Acid (ISA)). Lithuania also mentioned the particular case of hazardous waste that can be produced by dismantling activities (*e.g.*, waste containing asbestos) for which there is currently no appropriate disposal route.

Regarding the management of dismantling waste following a nuclear accident, Ukraine highlights that operation (maintenance) of the Shelter Object in safe condition, as well as Chernobyl NPP decommissioning activities, where more than 20,000m^3 of liquid radioactive waste (LRW) with a total activity of over 388 TBq have been accumulated. LRW in storage tanks are classified as low- and intermediate-level LRW.

2.6.3 Focus on the treatment and conditioning steps

Regarding treatment and conditioning of decommissioning waste, MS mention the implementation of various initiatives from the building of new treatment facilities to the testing of innovative alternatives. In that sense, Ukraine highlights that a Complex facility, dedicated to the treatment of solid radioactive waste (SRW) coming from the Chernobyl NPP, is planned and is at the stage of “active testing”. It combines two relatively independent installations: (i) a facility for the removal of SRW from existing storage; (ii) a plant for sorting SRW of all categories and processing of low- and intermediate-level short-lived SRW. In Lithuania, decommissioning waste are also processed in a new dedicated facility called the Solid Waste Management and Storage Facilities (SWMSF). They note that a treatment technology is also under consideration for the case of their hazardous wastes.

The UK raised the fact that major difficulties related to the treatment of decommissioning waste are related to: (i) the very large volume of waste streams and (ii) the fact that concrete and rubble are generally chemically inert and stable to heat, therefore they are poor candidates for thermal treatment or volume reduction treatments but do have some re-use potential (e.g. as void fillers following decommissioning activities). In the UK, some metals are recyclable and can generate income.

Regarding the French situation, it was mentioned that there was a request from the French National Plan for the management of radioactive waste for conducting further research studies into the incineration of some of the French dismantling waste, and the stabilization of chemical components. It is also specified that for the case of VLLW produced by dismantling activities, conditioning consists of transfer into simple big bags with no further conditioning. Note that ILW concrete, rubble and soil are also candidate waste for a Near-Surface Disposal Facility.

In addition to all these initiatives, MS also acknowledge the fact that the SHARE Research project is dedicated to the management of decommissioning waste and will provide new interesting alternatives for the future.

2.6.4 Focus on the storage and disposal steps

MS agreed to say that the major difficulty related to the storage and disposal of decommissioning waste is often related to the large volumes involved. To cope with this issue, various options are implemented. For instance, Lithuania and Czech Republic highlight the fact that minimizing the volume of waste is one cornerstone of their strategies (*see Focus 6 on the Czech case study*). In the UK, various actions are also implemented in order to divert dismantling waste from repositories. Therefore, processes of recycling/reuse (e.g., metals) and minimisation are used. It should be noted that disposal to LLW repositories or a GDF are also considered as viable options to ultimately manage these waste. In France, having to deal with large volumes of dismantling waste without the possibility to implement clearance actions, leads authorities to think about various strategic options. More precisely, the French National Plan for the management of radioactive waste opens a range of complementary routes to be investigated in the next years. These routes are particularly dedicated to VLLW with lower radioactivity or even only suspected of being potentially radioactive. Along with potential recycling[7], alternative disposal options are also considered: simplified disposal capacities at or near dismantling sites, avoiding the transportation of high volumes of non-harmful waste across the country; potential co-disposal with conventional industrial waste. The development of decentralized facilities close to nuclear sites would allow a reduction in energy consumption and greenhouse gas emissions linked to lower transport, which would be a positive point. The health and environmental impacts of such installations, even if potentially low, taking into account the level of radioactivity of the waste considered, can be compared to the impacts assessed for the disposal of CIRES (industrial Centre for collection, storage and disposal) or a new centralized disposal site. This comparison could be related to transportation gains.

Belgium specifies that there are currently no particular guidelines or requests coming from the government in relation to the possible minimisation of dismantling waste. Currently, all actions depend on waste producers' strategies.

On the other side, other MS are anticipating increasing storage capacities. For instance, Ukraine specifies that prior to the commissioning of the Complex facility (see above), LLW from the Chernobyl NPP and Shelter Object are to be sent to the Buryakivka disposal site, and are to be temporarily stored in a dedicated storage facility within the Chernobyl industrial site. Poland noted the fact that major difficulties related to the disposal of decommissioning waste are related to the absence of deep repository for long-lived radioactive waste. For now, waste that did not meet the WAC of the Rozan repository (LLW) are stored in dedicated facilities in Swierk to allow for radioactive decay to take place.

[7] Study are ongoing about the possible creation of a facility aiming to decontaminate metals and reuse them

FOCUS 6 – Strategy of waste minimisation of decommission waste in Czech Republic

The management of decommissioning wastes in the Czech Republic is ensured in accordance with (i) the Atomic Act and its associated regulations as well as with (ii) the state Concept of radioactive waste and spent fuel management, underpinned on international legal requests. These regulations are applicable for all nuclear installations, including research reactors. ČEZ Company, as the main waste generators and NPP operator, regularly evaluates the amount and composition of waste that will be produced from the decommissioning activities and the associated timeframes. Decommissioning plans detailing the different management routes are updated every 5 years.

The main principles of waste management from NPPs decommissioning are the following: (i) Seek to minimize the amount of waste produced. (ii) The holder of the NPP operating permit is responsible for the choice of waste processing and treatment procedures. (iii) Effective waste reduction procedures meeting legislative requirements will be used in waste management. (iv) Decommissioning waste will be processed into a form acceptable for the Dukovany disposal facility. If not, it is assumed that they will be disposed of in a deep geological repository. (v) Measures to prevent and minimize the generation of solid waste will be established. Procedures leading to the reduction of the solid waste will be used: e.g., sorting of waste for their release into the environment as inactive waste, storage before release from the workplace, sorting according to the method of subsequent processing. (vi) RAW to be disposed have to be in a solid state. (vii) In the area of handling large-volume components (e.g., reactor pressure vessel, steam generator), dismantling on site will be applied. In the same way, the use of mobile equipment for treatment of liquid waste will be implemented in order to encourage their storage in pre-approved packaging. (viii) Commonly available and proven technologies will be used for the processing and treatment of decommissioning waste (centrifugation, evaporation, solidification by means of stiffeners, decontamination, fragmentation, crushing, low pressure pressing, combustion, high pressure pressing, metal remelting).

Note that the current legislation in the field of radioactive waste management has introduced the category of VLLW. In accordance with international practices, the amount and composition of VLLW from NPP decommissioning are currently evaluated so that they do not have to be disposed of at the Dukovany waste disposal site. By allocating these waste elsewhere and ensuring appropriate disposal capacities, it allows creating conditions for more efficient use of the capacities of existing repositories for LLW and ILW.

Inventories of decommissioning waste to be produced (both from nuclear production and research sectors) are based on qualified estimates, technical documentation and calculations. Balance sheets of future decommissioning waste are prepared / derived for different decommissioning variants - immediate and also phasing-out decommissioning. A variant consists of, after 40 years of NPP operation, the fuel will be removed from the reactor and the NPP technology will be preserved and all activities will be postponed for 40-50 years. The benefit of this variant is to reduce the radiation exposure of workers performing dismantling and decommissioning work. Due to the time delay, there will be several half-lives of short-lived radionuclides that will allow a *reduction in* the amount of operational waste produced during decommissioning activities, including reducing the complexity of dismantling.

		AUSTRIA	CZECH REPUBLIC	LITHUANIA	NETHERLANDS	POLAND	PORTUGAL	UKRAINE	UK
NON CONDITIONED DECOMMISSIONING WASTE	Volumes	Arising waste volumes are conditioned, therefore the non-conditioned volumes cannot be reported. For conditioned waste: 5 Mosaik-type containers (5 m³) and 5 Konrad type II containers (23 m³) with waste from the decommissioning of the research reactor at Seibersdorf. About 500 m³ in 200 L drums	Predicted inventory of RAW from decommissioning: total volume aprox. 22,000 m³ total activity more than 1,017 Bq/kg	Total amount of radioactive waste at Ignalina NPP (decommissioning and operational waste): VLLW-SL: 127,550 m³ LILW-SL: 26,887 m³ LILW-LL: 6,435 m³ Additional RW from INPP decommissioning: 1. WASTE CONTAINING RADIOACTIVE ASBESTOS (serpentinite mixture from reactor unit zone) ~4,800 te 2. ION-EXCHANGE RESINS (ICLUDING NORM) ~433 te 3. OTHER HAZARDOUS AND SPECIFIC WASTE a. Lead waste – 624 te b.Disused activated carbon – 205 te c.Oil and oily rags waste – 15.6 te d. Mercury-containing fluorescent lamps and galvanic cells – 11 te	-	Approx. 250 m³ solid and liquid LLW and ILW	Inventories not yet available. Decommissioning of research reactor 1MGW closed in 2019, (SF was sent to the USA in March 2019) has not yet started. This will include various types of waste that need to be characterized. Decommissioning of former Pilot Installation (chemistry labs building) used to produce yellow cake in the 60s-70s at large scale reproducing the real chemical facility in the mines, will be carried out in the future but no concrete plans exist yet.	1,168.45 m³ total at Ukrainian's NPPs At present, about 2,500 m³ of SRW of various categories with a total activity of about 132 TBq have been accumulated in the storage facility. At each stage of decommissioning, the formation of solid to liquid RW will be provided. This means the formation of 8,500 m³ of LRW and 274,809 m³ of SRW total calculated activity in the equipment, premises and structures of the reactor of each of the three power units of the order of 10^5TBq.	VLLW 2,836000 m³ LLW 1,477700 m³ ILW 76,200 m³
	Main radiological inventory	Conditioned only: Mainly from the inventory of the 5 Mosaic containers: H-3, Ni-63, Ag-108m, Ni-59, Co-60	Mainly Ni-63, Ni-59, Nb-94 (pressure vessel welds), C-14 (internal reactor parts) and Ca-41 (for serpentinite concretes and backfills). C, Mn, Si, P, S, Cr, Ni, Ti, Co, N, Cu		Co-60, Ni-63, Fe-55	Zn-65, Co-60, Cs-137		Cs-137, Sr-90, Pu, U	
	Main chemical inventory	Conditioned only: Varies: Mostly concrete and building rubble as well as soil		1.Serpentinite – natural mineral containing asbestos 2.Other hazardous and specific waste: a. Lead waste – solid lead, blankets/mats from lead wool b. Disused activated carbon – chemically activated carbon c. Oil and oily rags waste – solid materials contaminated by various oils (organic materials) d. Mercury-containing fluorescent lamps and galvanic cells – glass, mercury and lead from cells		Among others, water from primary circuit and reactor vessel, decontamination liquids			

Table 7: Volumes and inventories of decommissioning waste held by some Member States

2.7 The Management of Disused Sealed Radioactive Sources (DSRS)

2.7.1 General context and first insights

Based on the ROUTES questionnaire responses, it transpires that disused sealed radioactive sources (DSRS) arise from various economic sectors (e.g., industrial, medicine, research, education) and include a wide variety of different types. 14 MS are experiencing difficulties in the management of DSRS (see *Figure 18)* and those difficulties are mainly related to disposal issues (33%) and characterization issues (21%) (see *Figure 19*).

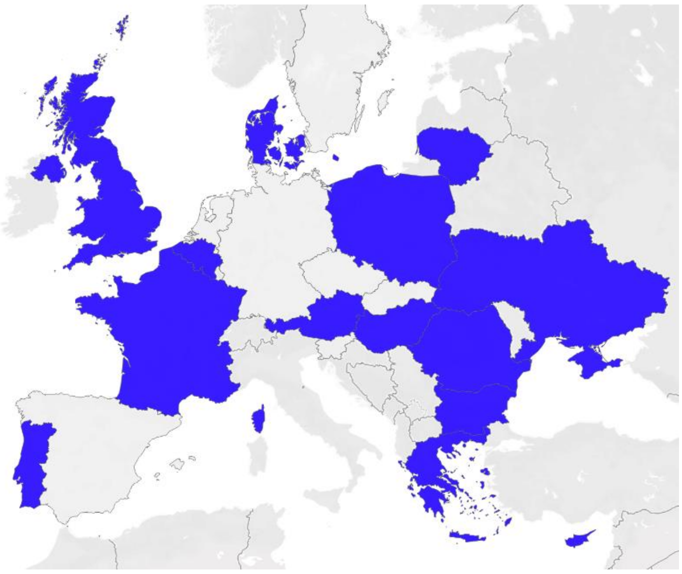

Figure 18: Member States experiencing difficulties in the management of DSRS

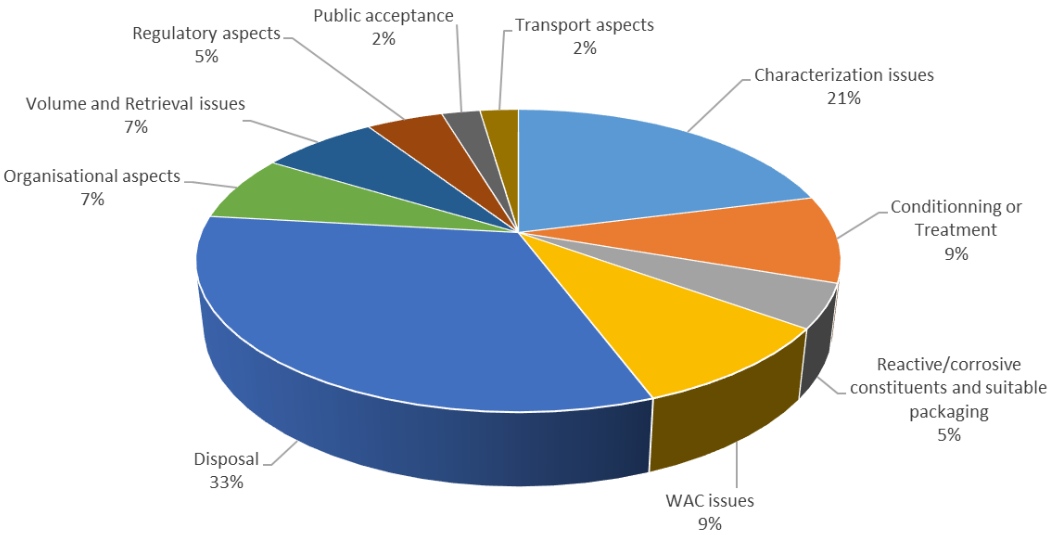

Figure 19: Main difficulties associated with the management of DSRS

2.7.2 Focus on the characterization step

When speaking about DSRS, it turns out that a wide variety of different waste types are involved: disused measurement devices, smoke detectors, calibration sources, medical and research sources, lightning rods, etc. Where they are known, radiological and chemical inventories are diverse (see *Table 8*) but it is also the case that characterization remains a difficult pre-disposal step for many countries.

First, MS acknowledge the work conducted by IAEA[8], providing international requirements to control disused sources and helping to implement technologies to recover, condition and store them. However, some MS (e.g., Belgium, Greece, Portugal) have raised the fact that, for part of their sources inventory, in addition to orphan ones, they are facing difficulties in finding reliable documentation and certificates to accurately determine the activity and the related radiological inventory. Belgium points out that transport certificates are not currently available and that this prevents the transfer of sources to storage facilities. In Greece, some characterization campaigns (e.g., gamma spectrometry) have been implemented in order to identify radionuclides present. In addition, dose rate measurements are also carried out at different time periods (over 2 years) in order to identify particular radionuclides from their radioactive decay profiles (e.g., Sr-90). In Portugal, a gamma spectrometer specific for drums was acquired for similar purposes as well as for measures supporting the clearance process of historical drums (heterogeneous waste with short-lived radionuclides from medical and research areas). Documents related to legacy and orphan DSRS at the centralized storage facility are scarce; only after the 1990s, new legislation made it possible to exercise better and more efficient control over the waste entering the facility. Dose rates at drum surfaces and at 1 meter including the recent DSRS storage in stacks are sporadically taken as protection for the workers and to avoid unnecessary hot spots. Anyway, the situation is very much similar to other European Countries. In France, thermal power can sometimes be measured in order to calculate the Sr-90 activity. Regarding Denmark, radioactive sources, received from e.g. institutional users, are registered and described only by material type, physical condition, weight, size, origin, degree of contamination, date of registration, etc. If full characterization is not possible when the waste item is received, samples are taken for the purpose of later characterization.

Other MS have mentioned that DSRS have been stored for decades in RADON[9]-type facilities, without any proper characterization or separation from other waste. This is how Lithuania reveals that historical sources have been put in their bulk form in its RADON-type facility. In Ukraine, they have to deal with a former RADON-type facility where sources are mixed with other waste. Also, in Hungary, DSRS that have been disposed of in such facilities for decades have been observed with their shielding corroded, implying radiological contamination has occurred inside the storage facility *(see Focus 7 on the Hungarian case study)*. The UK also shared that DSRS are coming from various waste streams with diverse radiochemical characteristics. Since these sources are currently located throughout the country, the wide geographical distribution presents an additional difficulty in terms of characterization.

In Cyprus, nowadays, a limited number of DSRS are properly stored and an extensive collection and inventory campaign is planned for the coming months, organised by the Radiation Protection Authority in that country. A similar campaign is desired in Portugal also with the Regulator support but lack of human resources is delaying the process.

In brief, the main difficulties associated with the characterization of DSRS are:

- Radiological and chemical inventories are not reliable or unknown;
- Identification of particular radionuclides (e.g., Sr-90) is difficult;
- Historical sources have been stored without proper identification and are mixed with other waste;
- Wide geographical distribution of sources within each country.

[8] https://www.iaea.org/topics/disused-sources

[9] Designed and operated in the 1990s as disposal facilities for LLW and ILW without intention of retrieval. Typical repositories consisted in vaults below the ground level. Basement were made of concrete plates, walls were made of concrete blocks, and the repositories were divided into cells thanks to concrete or wooden walls. The top was covered with reinforced concrete plates, sand and waterproof asphalt layer. For further information, see the CRAFT Project working group presentation: https://gnssn.iaea.org/RTWS/craft/Shared%20Documents/2013%20Technical%20Meeting/IP05.%202013%20Guskov%20Radon.pdf

2.7.3 Focus on the treatment and the conditioning steps

The treatment and conditioning of DSRS remains a pending issue for the MS as many of them do not have a solution or are testing different options.

Lithuania and Cyprus have notably mentioned that no treatment or conditioning options are implemented at the moment. Disused sources are stored as such, waiting for long-term solutions.

Other MS have decided to condition disused sources in a cement matrix. This is the case for Austria, where radium from medical applications is welded into capsules and cemented. The same was carried out in Portugal for old radium needles, lightning rods, DSRS sources (Cs-137-, Am-241-, Ra-226-, others). Czech Republic also implements this conditioning process, as well as Poland for a part of its DSRS inventory (beta/gamma emitters). However, it is specified that for Czech sources encapsulated in long-lived shielding (e.g., lead or tungsten), no particular conditioning is needed. In addition, in Poland, it is worth mentioning that sources from smoke detectors are conditioned in a particular matrix which consists of polyester resin. For the sources intended for the UK GDF, encapsulation in an ordinary Portland Cement grout is currently planned. Regarding Portugal, they have cemented their disused sources in 200 drums for many years, but as this solution offers no volume reduction, this activity is stopped now. Registration of the dose rate and identification of the radionuclide exist but activity inside the drums does not exist for all of them. The DSRS are being stored in racks as they are received and no treatment is applied. Portugal has no facilities for dismantling sources.

In Denmark, DSRS have been packed in drums after removal of the shielding for several years - except for the high-level sources which have always been kept in their original shielding, before storage in a dedicated building. In the last few years, they have changed their strategy and now almost all low-level DSRS are packed with their shielding in dedicated packaging, so safe reversible packing of the sources is possible before they are packed for disposal/landfill. The aim is to be able to safely reduce the volume of DSRS waste before they are packed for disposal, and to reuse the shielding metals. As part of the design phase of the new upgraded storage facility for radioactive waste in Denmark (named NOL[10]), Danish Decommissioning[11] is in the process of developing a new concept for packing DSRS in special boxes. This process can easily be transferred to containers approved for the NOL storage. The system will ensure easy access to the DSRS sources, when the waste has to be packed for disposal.

Finally, some MS are developing particular containers dedicated to DSRS. This is the case in Ukraine, where sources are sent to a centralized facility to be identified, characterized, sorted and conditioned in special containers. In France, a specific container that will hold multiple high-level activity sources is under consideration. This could be a solution that meets the WAC for deep geological disposal and allows multiple sources to be managed at the same time.

2.7.4 Focus on the storage and disposal steps

Regarding storage and disposal issues related to the management of DSRS, various options are implemented by the MS. However, there is a clear need to deploy further storage and disposal capacities notably for higher activity sources.

In some countries, disposal facilities are already available where disused sources can be disposed of. This is the case in Czech Republic where two near-surface repositories (Richard and Bratrstvi) are accepting DSRS if they meet the WAC. Some sources do not meet the disposal WAC because of their high activity level or their particular shapes; where this is the case, temporary storage is also operating within the Richard facility, pending disposal in a deep geological facility. In Poland, the Rozan repository for LLW is also accepting a part of the inventory of gamma and beta sources. In parallel, other higher activity sources are stored either in Swierk plant, or in Rozan repository, waiting to be disposed of to a

[10] When in operation the NOL facility will accommodate all the Danish radioactive waste (except NORM waste)/

[11] Danish Decommissioning is a state owned company with the purpose of decommissiong the nuclear facilities (recearch reactors, hot cell facility etc.) at the Risoe area in Denmark, receive, treat and store all Danish radioactive waste and contribute to the process towards the final disposal of the radioactive waste.Danish Decommissioning is the only waste operator in Denmark.

deep geological repository, which is under development. As in Czech Republic and Poland, in the UK low-level activity sources that meet the appropriate WAC can also be disposed of at the LLWR. For higher activity sources, the disposal route is supposed to be the geological disposal facility. A dedicated flow chart (see Appendix A) has been designed to identify how source properties can challenge the waste package performance requirements. Finally, in France, it is possible to dispose part of DSRS in the VLLW and LLW repositories. However, WAC should be respected, notably that of not mixing sealed sources with other waste.

In other MS, including Austria, Lithuania, Portugal, and Romania, no final repositories are available and DSRS are then placed in temporary storage facilities. Some temporary storage facilities are reaching their capacity limits, as noted for Portugal. In Greece, it is interesting to note that short-lived DSRS are managed by radioactive decay and clearance options. This is a process that will also be applied in Portugal soon, in cooperation with its regulator, in order to identify sources that are under clearance levels, and can be managed in a different way, which will open up space in the interim storage facility. In other countries such as Bulgaria, dedicated storage and disposal facilities for DSRS are undergoing commissioning. For Ukraine, a centralized facility for the long-term storage of conditioned sources is being commissioned, but no specific decision on the disposal of the sources has been made.

Finally, it is worth mentioning that for some MS, no solution exists. In Cyprus for instance, the management of DSRS will necessarily involve export to another willing country, in accordance with Directive 2011/70/Euratom dispositions.

FOCUS 7 – Case of a RADON-type facility in Hungary

The radioactive waste treatment and disposal facilities that operated in the 1960s-1980s were the only possible solution for the radioactive waste producers to handle their unused equipment and contaminated waste. These facilities were built and operated by the safety considerations of their period. The safety culture did not include to apply any criteria against the waste shipments only those basic considerations that directly affected the operation of the facilities; such as dose rate of the waste and state or consistency of the shipments.

The lack of WAC resulted that the waste producers and organizations responsible for the treatment, dealt sealed sources as part of the “ordinary” radioactive waste. However there were dedicated disposal units for DSRS (spiral tubed cells, well type disposal tubes, etc.), large number of DSRS were mixed with other type of waste. These mixed packages were often put into the final disposal cells without proper conditioning.

Also, retrievability was not among the considerations of the radioactive waste management. In some cases the radioactive waste with DSRS among them was immobilized by pouring concrete into the packages and/or onto the disposed containers, drums, etc. The disposal had no quality assurance resulted an inconsistent waste disposal.

The post closure safety consequences were assessed at these sites in later periods (late 1990s, 2000s) when these disposal facilities were already full or were close to be filled up. Many of the operators decided to upgrade the safety of their site. These efforts are challenging, since the lack of quality assurance, the improper conditioning, the difficulties of characterization and even the to gain access to the legacy waste.

The safety upgrading operations have to be carefully planned. Sensitive optimization process has to be carried out to balance the long-term post closure - possible – dose consequences and the short term dose consequences and usage of resources of the present.

	AUSTRIA	BELGIUM	CYPRUS	CZECH REPUBLIC	DENMARK	FRANCE	GREECE	LITHUANIA	POLAND	PORTUGAL	ROMANIA	UKRAINE	UK
Kind of DSRS	Lightning rods, smoke detectors, medical and industry sources (e.g. point sources, rod sources, H-3 sources, Kr-85 sources, Gas-chromatograph (ECD sources), neutron sources (Troxler gauges)	Source material, capsule material	Lightning rods, smoke detectors, calibration sources		Diverse DSRS coming from mainly external users		Lightning rods, radium smoke detectors, consumer products, instruments, objects with Ra-226, Am-241,Th-232, Sr-90	Various sources used for industrial, medical and research purposes	Smoke detectors, sources from medical and scientific applications, calibration sources	(iodine seeds, smoke detectors, lightning rods, etc.)	Co-60 sealed spent sources from medical application	RITEG (Radioisotope thermoelectric generator) type DSRS; DSRS in biological protection; Neutron DSRS; "Historical" DSRS, which are stored in a mixture with other radwaste or located in well-type storages (some storages of both types are cemented)	19 waste streams covering "sealed sources", "closed sources", "redundant radioactive sources", "reactor neutron sources" have been listed in the United Kingdom Radioactive Waste Inventory. 13 are listed as LLW and 6 as ILW.
Volumes	About 200 drums (200 L) and 8 drums (400 L)	Very limited quantity	Limited number of DSRS already collected. The Radiation Protection Authority plans collection and inventory campaigns.	34 ,63 DSRS are stored in Richard repository 19,971 are disposed in Richard repository 6,672 are disposed in Bratrstvi repository			Americium and radium lightning rods: 9 m^3 Americium and radium smoke detectors : 0.2 m^3 Products containing Ra-226, Am-241, Th-232, Sr-90 : 4 m^3	79,350 DSRS items are stored in Ignalina NPP 9,872 DSRS are stored in Maisiagala Storage Facility (RADON-type facility)		No information		Total number is more than 625,000 [pcs] RS of all types of disused RS. Most of them are currently stored at Radon SISEs, NPPs, and were used in medicine, research and industry. DSRS include a wide range of RNs and different type of ionizing radiations (alpha, beta, gamma, neutron)	The largest is AWE stream 7A32 (ILW closed sources) which has 92 m^3. Others range from <0.1 m^3 to 2 m^3.
Main radiological inventory	Mainly: 2,600 Co-60 sources with 60TBq (mostly in decay storage), 1,600 Cs-137 sources with 5 TBq, about 670,000 Am-241 sources with 4TBq (mostly smoke detector sources), 2,000 H-3 sources with 3.2 TBq, 2,600' Sr-90 sources with 1TBq, 1,900 Ra-226 sources with 0.5 TBq	From low to high activity	No data available	Both short and long lived RNs. In Richard disposal facility, total activity of $3.17.10^5$ GBq In Bratrstvi disposal facility, $1.01.10^3$ GBq.	Both short and long lived RNs.	Variable Cf-252, Am-241, Ra-226, I-192, Co-60, Cs-137, Sr-90, etc.		Main RNs are Co-60, Pu-239, Sr-90, Cs-137, etc.	Main RNs are Co-60, Cs-137, Am-241 Total activity stored in Rozan repository : 5,627 GBq	Mainly long-lived RNs	622TBq	The total activity is about $2,5.10^4$ TBq	Exact inventory is unknown. LLW Ra-226 containing sources are known to be an issue, particular for sources owned by Magnox Ltd.
Main chemical inventory			No data available	Not evaluated				Not evaluated		No information			Mixed and can include solid, liquid and gaseous components

Table 8: Volumes and inventories of DSRS held by some Member States

2.8 The Management of Particular Spent Fuel

2.8.1 General context and first insights

Based on the ROUTES questionnaire responses, it appears that particular spent fuels (PSFs) include all non-UOX (uranium oxide) spent fuel and can also include Magnox spent fuel, aluminium cladding, spent fuel used in former Natural Uranium Graphite Gaz (UNGG) reactors, or even PSF developed for R&D activities.

As shown in *Figure 20*, five MS are facing difficulties with the management of PSFs. More precisely, these difficulties are mainly related to the lack of available facilities for some of the considered treatment/conditioning options (40%), for pre-disposal handling (20%) or for final disposal (40%) (see *Figure 21*).

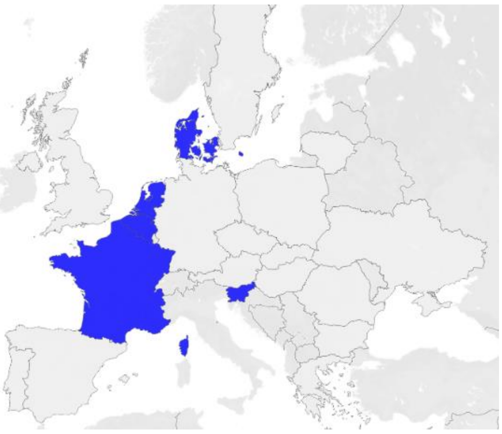

Figure 20: Member States experiencing difficulties in the management of PSF.

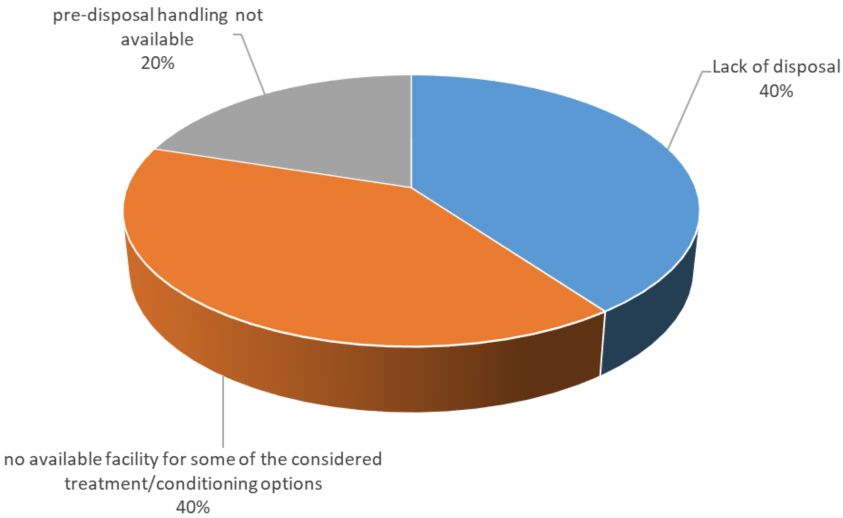

Figure 21: Main difficulties associated with the management of PSF.

2.8.2 Focus on the characterization step

Discussions revealed that the MS are dealing with different kinds of PSF as well as various associated volumes (see Table 9***Erreur ! Source du renvoi introuvable.***). For instance, in Ukraine, PSFs consist of damaged spent fuel from the Chernobyl NPP. It is stored without reliable inventories, in special canisters of various configurations in storage ponds (SP) of Interim Spent Nuclear Facility-1 (ISF-1). The main defects of damaged spent fuel are mechanical in nature, including leakage (of radionuclides) of fuel rods. Structural defects include separation of the fuel assembly from the rod; displacement of fuel rods; deformation of fuel rods; or missing shanks of natural uranium graphite gaz reactor or nuts. Greece will have to manage spent fuel aluminium cladding with stainless steel screws and activated aluminium arising from the future decommissioning of its research reactor. Also, Portugal will have to decommission its former swimming pool reactor in the near future. In the Netherlands, PSFs are related to spent research reactor fuel assemblies containing plates of aluminium-uranium-alloy. The Czech Republic has to process PSFs from the LVR-15 research reactor with an enrichment of U-235 higher than 20%. Regarding the UK, the inventory of PSFs comprise mostly Magnox spent fuel that are still in the reactors or ponds and will not undergo reprocessing, in addition to submarine fuels, other uranium metal spent fuels or even exotic fuels resulting from research activities. In France, PSFs mainly arise from former research reactors that used enriched U-Pu fuels and Zr cladding, and from nuclear submarines.

Regarding characterization, MS did not raise any particular challenges. In fact, for most of the MS, PSFs are not considered as "waste" as such but rather as reusable resources. Therefore, accurate inventories of radionuclides and chemicals are not currently an issue.

2.8.3 Focus on the treatment and conditioning steps

In MS that consider PSFs as "waste", treatment and conditioning processes are generally not considered a priority, as disposal routes are not yet available and the requirements associated with packaging waste are not yet known.

The question of reprocessing PSFs is considered by some MS and is sometimes delegated to a foreign country. In Greece, for instance, Al cladding is supercompacted and then conditioned in drums. The spent fuel was exported to the USA in 2019; Portugal also chose this option. Similarly, Poland and the Czech Republic sent their PSFs arising from their research reactors to Russia for reprocessing. In Belgium, spent fuels from fast reactors are still with the waste producer (SCK CEN) and there is no available facility for some of the considered treatment/conditioning options. In the Netherlands, spent research reactor fuel is stored in canisters within a basket containing boron and steel plates to ensure stability. In France, the management of PSFs used in former research reactors or nuclear submarines is pending the development of a dedicated reprocessing chain in La Hague. The intention is to reuse the reprocessed fuel in 4^{th} generation nuclear reactors. Finally, it is worth mentioning that in the UK, Magnox fuels have been reprocessed at the Magnox Reprocessing Plant at Sellafield for many years. These reprocessing activities were due to be completed in 2020 but the plant underwent a "controlled shutdown" in March 2020 due to the impact of the Covid-19 pandemic. The plant fully resumed operations in August 2020 and Sellafield Ltd expects all Magnox reprocessing operations to be completed by the end of 2021 (*see Focus 8 on the UK case study*).

2.8.4 Focus on the storage and disposal steps

Generally, PSFs are temporarily stored for different reasons, either because they are still considered to be reusable resources, or because they are scheduled for reprocessing. In this way, in many MS, these fuels are not even considered in the inventory for future geological disposal. For instance, in the Netherlands, spent research reactor fuel is stored at COVRA's premises. Similarly, in France and Belgium, PSFs are stored at producers' premises. In Poland, fuels pending exportation to Russia are temporary stored in cooling pools. Ukraine raised the fact that for the badly damaged spent fuel, there is still no long-term solution and final disposal has to be developed. In the UK, it was specified that, historically, Magnox fuels pending reprocessing were stored in cooling pools dosed with sodium hydroxide to maintain the pH of the pond waters to 11.5. However, Mg present in Magnox alloy reacted to become MgO that started the cladding corrosion. For this particular issue, research has been conducted to study how to dry Magnox fuels formerly stored in pools and how to store them in dry conditions[12]. As the reprocessing of Magnox will end in 2021, the UK announced that any remaining fuel

[12] Reference of the work conducted by University of Leeds:

will be committed to dry storage in self-shielded cast iron boxes with vents/filters and then conditioned and disposed of to GDF, timing and location to be decided. It was noted that the impending change in Magnox Fuel Management strategy from reprocessing to dry storage pending geological disposal will trigger research projects on the long-term behaviour of Magnox fuel in a GDF and its possible dissolution in contact with groundwater. Regarding their smaller inventory of exotic fuels, these will not be reprocessed and will be sent to the future GDF and disposed of in the High Heat Generating Waste Vaults.

FOCUS 8 – Management of Magnox spent fuel in the United Kingdom

The largest constituent of the UK's 'particular spent fuel' (PSF) inventory arises from the UK's fleet of Magnox reactors, the last of which was shut down in 2015 and defueled in 2019. Much of the resulting spent fuel has been reprocessed but the Magnox Reprocessing Plant at Sellafield will cease operating at the end of 2021 and any remaining fuel will not undergo reprocessing. It is currently stored in cooling ponds on the Sellafield site, which are dosed with sodium hydroxide to maintain high pH conditions that minimise fuel degradation. Nevertheless, corrosion of the fuel and surrounding Magnox cladding has occurred.

The long-term strategy for managing this material involves geological disposal, once a suitable site and facility have been developed. Radioactive Waste Management Ltd (RWM) is responsible for implementing geological disposal in the UK. At the present stage of its programme, various illustrative geological disposal concepts are under consideration, based on disposal in three generic geological environments: a higher strength rock; a lower strength sedimentary rock; and an evaporite. All of these disposal concepts involve packaging the spent fuel in high integrity cylindrical containers fabricated out of either copper (with a cast iron insert for mechanical strength) or thick-walled carbon steel [1]. Depending on the geological environment, these would be placed underground in disposal tunnels or boreholes and surrounded by a bentonite buffer or crushed host rock backfill.

A process to identify a suitable site for the UK GDF is in progress, but at an early stage [2,3]. In the meantime, legacy storage facilities for non-reprocessed Magnox spent fuel are ageing and there is a pressing need to empty them so that they can be decommissioned. With this in mind, work is underway to transfer Magnox spent fuel into high integrity containers called Self-Shielded Boxes (SSBs). These thick-walled, vented, ductile cast-iron containers will be used for ongoing storage of the spent fuel at Sellafield in a new waste and spent fuel store, the Interim Storage Facility (ISF), so as to enable decommissioning of the ageing storage facilities to proceed [4]. Further information on SSBs is available elsewhere [5].

RWM is currently undertaking work to assess whether the filled SSBs would be suitable for direct disposal to the GDF (as an alternative to implementing the disposal concepts above); if this is not feasible then further conditioning or repackaging would be required [6]. In the meantime, research into the long-term behaviour of Magnox fuel under dry storage and in the GDF is ongoing.

[1] Radioactive Waste Management (2016), Geological Disposal: Technical Background to the generic Disposal System Safety Case, NDA Report no. DSSC/421/01, December 2016. Available here.

[2] Department for Business, Energy and Industrial Strategy (2018), Implementing Geological Disposal – Working with Communities: An updated framework for the long-term management of higher activity radioactive waste, December 2018. Available here.

[3] For the latest updates on the UK GDF siting process, see RWM's website at: https://www.gov.uk/government/organisations/radioactive-waste-management

[4] Nuclear Decommissioning Authority (2021), Strategy – Effective from March 2021, SG/2021/48, Page 53. Available here.

[5] Magnox, Gamechangers and Sellafield Ltd (2021), Challenge: Monitoring of Waste Packages, Call for Applications. Available here.

[6] L. Harvey, C. De Bock, M. Maitre, R. Strange, E. Leoni, C. Bucur, Sharing experience on waste management with/without WAC available, ROUTES Sub-task 4.2 Memorandum, Milestone 144, Draft 2, October 2021.

- Jackson, M, Hunter, T (2020) Drying Wet Stored and Corroded Magnox Fuel for Interim Dry Storage. In: WM2020 Conference Proceedings: Reducing Long-Term Environmental Liability Through Efficient, Effective Clean-Up. WM2020: Waste Management Symposia, 08-12 Mar 2020, Phoenix, AZ, USA. WM Symposia.

		CZECH REPUBLIC	PORTUGAL	UKRAINE
NON CONDITIONED PSFs	Volumes	Total weight of SF for existing and planned NPPs in Czechia 40 y: 3,490 te HM 60 y: 9,910 te HM	SF from the IST (Instituto Superior Tecnico) swimming pool Research Reactor has been sent to the USA in 2019. Irradiated graphite and some contaminated Mo exist. Also irradiated Al, SS, tiles, etc.	56 damaged spent fuel assemblies are stored in the compartments of the SP ISF-1 in special canisters.
	Main radiological inventory	All spectrum of radionuclides, including long-lived radionuclides whose contribution is greater than 0.001%		Cs-137, Sr-90, Pu, U
	Main chemical inventory	NPPs use fuel from TVEL company and Westinghouse Electric Company		
CONDITIONED PSFs	Volumes	No conditioning		
	Inventory information			
	Other details			

Table 9: *Volumes and inventories of particular spent fuel held by some Member States.*

2.9 The Management of Ra/Th/U bearing waste

2.9.1 General context and first insights

According to the responses from the ROUTES questionnaire, Members States consider that Ra/Th/U bearing waste originate from various economic sectors (e.g., industrial, medicine, research) and includes a wide variety of waste types. In total, 9 MS are facing difficulties in managing Ra/Th/U bearing waste (see *Figure 22*). Among the difficulties raised by the countries, it turns out that major issues are related to the lack of disposal options (31%), characterization aspects (20%) and treatment/conditioning issues (17%) (see *Figure 23*).

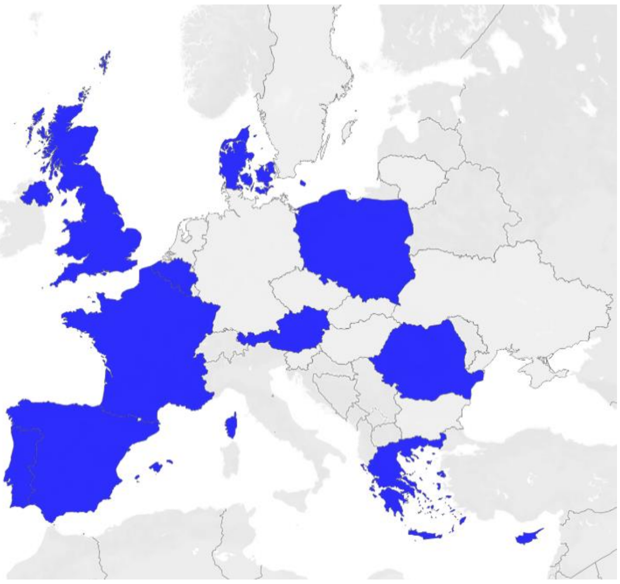

Figure 22: Member States facing difficulties with the management of Ra/Th/U bearing waste

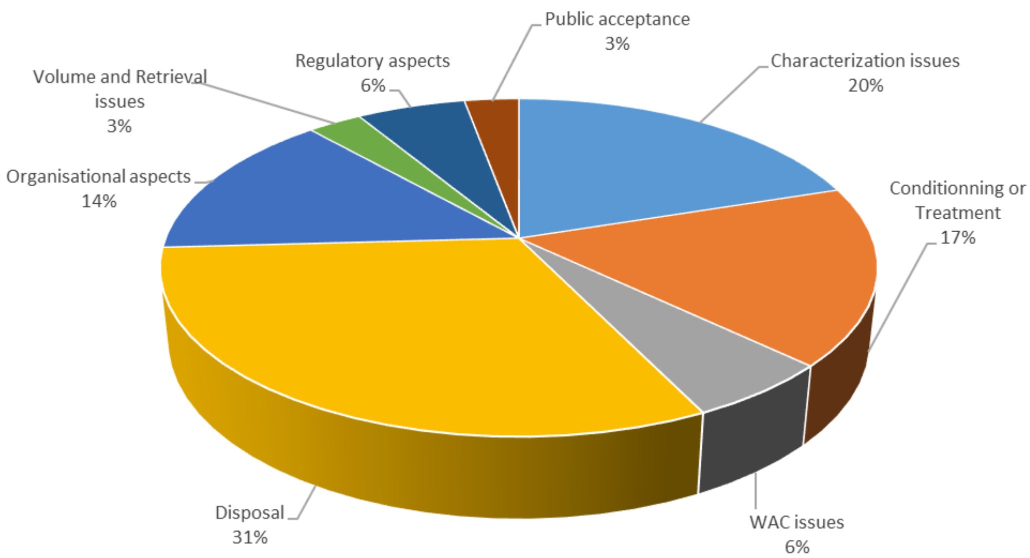

Figure 23: Main difficulties raised by the Member States concerned with the management of Ra/Th/U bearing waste

Discussions among the MS showed that various types of Ra/U/Th waste are at stake (see *Table 11)*. For instance, Austria has to deal with waste arising from the decommissioning and decontamination of historical facilities and laboratories as well as residues from fertilizer industries. In Cyprus, waste coming from the use of gypsum by the fertilizer industry have also to be managed. Greece has to deal with powders containing uranium from research activities and thorium used in its airplane industry. Portugal is managing Ra/Th/U waste mainly arising from mining and NORM-producing industries. In France, a major part of its Ra/U/Th waste inventory has arisen from mineral processing (zircon, monazite), mining, gypsum and fertilizer industries, as well as by-products from foundries for the airline industry.

2.9.2 Focus on the characterization step

In terms of characterization, no particular difficulties were mentioned for the majority of the MS. However, it was pointed out that in some countries, historic Ra/U/Th waste have been disposed of without detailed characterization data. This is also the case in Ukraine where, in the 1960s, Ra/Th/U bearing waste were sent to RADON-type facilities (see *section 2.7*) and mixed with other radioactive waste, without proper characterization first. Some MS have also raised the fact that there are difficulties in characterizing waste that are heterogeneously contaminated. Belgium, for instance, has to characterize large volumes of contaminated soil coming from the dismantling of a former radium factory. To better manage the large quantity of contaminated soil, methods like contamination mapping have to be deployed in order to identify the hot spots (*see Focus 9 on the Belgian case study*).

Finally, MS have also tackled the particular case of depleted uranium. Previously considered as a reusable resource, in some countries (e.g., France, the UK), it is in the process of being reclassified as waste. This will result in significant volumes of long-lived waste to manage. In this context, the concerned MS agreed that a specific strategy should be devised and shared.

2.9.3 Focus on the treatment and conditioning steps

Treatment and conditioning processes of Ra/Th/U bearing waste have either been implemented or not. So, for Denmark, Greece and Ukraine, current stocks of Ra/Th/U waste remain unconditioned. Cyprus also announced that treatment and conditioning facilities are not economically viable and so, all waste remain in their raw form. Belgium has historically conditioned Ra/Th/U bearing waste in 200 L-400 L drums. Nowadays, regarding the large volumes of contaminated soils coming from the former radium factory, innovative treatment will be implemented; this will depend on the levels of contamination that will be measured during the characterization step. It is worth mentioning that for some MS including the Czech Republic, no particular difficulties are at stake for the management of Ra/Th/U bearing waste as. Indeed, these waste were historically conditioned in containers (200 L drums) mostly solidified by cementation. In Portugal, legacy Ra/Th/U waste from mining industry are being treated *in-situ* according to the IAEA best practices and it is the responsibility of the private/state ownership.

Other MS have also noted that since Ra/Th/U bearing waste involves large volumes, appropriate treatment and conditioning is still under consideration. This is the case in the UK and France, where no treatment or conditioning routes is currently clearly defined, although France mentioned nitrate treatment could be used for some French waste.

The particular case of depleted uranium and its possible reuse in some conditioning processes was also highlighted by some countries. In particular, the UK mentioned that in the 1990s-2000s, research was dedicated to study cement formulations using depleted uranium (DUCRETE). At present, processes seeking to use depleted uranium for shielding and as containers for other waste are being studied. France pointed out that research on cement using depleted uranium had also taken place some years ago but the amount of uranium used was too small to make the concept viable. In Denmark, it turns out that depleted uranium happens to be used for shielding of former encapsulating sources. In Portugal, depleted uranium is classified as safeguard material and that implies many difficulties such as the need of safe storage, inspection and security measures.

2.9.4 Focus on the storage and disposal steps

The storage and final disposal of Ra/Th/U bearing waste has a number of problems as, on the one hand, their radiological content is not very high and does not justify a deep geological disposal solution, but on the other hand, as they contain long-lived radionuclides, surface disposal solutions are not recommended. Therefore, several alternatives or ongoing projects are implemented in the MS. In the Czech Republic for instance, waste are disposed of in the Bratrství repository, situated in a part of a former uranium mine (50 m depth). In Cyprus, phosphogypsum waste are permanently disposed of at a coastal area of Cyprus, inducing long-term risks related to spreading of radionuclides in the environment. Legacy sludges from the former phosphate industry in Portugal are kept on the premises waiting regulatory intervention. In other MS like Belgium or Denmark, Ra/Th/U bearing waste are temporarily stored, waiting for decision on the management route. In France, a shallow depth disposal option (30 m depth) is under study and can host of part of the Ra/Th/U waste. In the UK, depending on their activity, Ra/Th/U waste can be sent to existing LLW repositories or stored until a GDF is available***Erreur ! Source du renvoi introuvable.***. Associated WAC for the LLWR in the UK list Ra and Th isotopes as Category A and U isotopes as Category B1. Quantities are restricted per consignment under the Discrete Items limits listed in *Table 10.*

Table 10: LLW Repository Ltd, UK, *Extract from LLWR WAC 5.0 (WSC WAC LOW, Version 5.0, issue 1, July 2016) - Discrete Items Limits*

Radionuclide	Mass 1 kg or less	Mass between 1 and 100 kg	Mass 100 kg or greater
Group A	0.001 GBq	1 GBq/t	0.1 GBq
Group B1	0.01 GBq	10 GBq/t	1 GBq
Group B2	0.3 GBq	300 GBq/t	30 GBq
Group C	1 GBq	1000 GBq/t	100 GBq

In addition to those disposal routes, it should be noted that a project is underway looking at a UK Near-Surface Disposal Facility. This project is mainly focusing on bulk graphite waste, but it can also be an option for disposal of depleted uranium.

FOCUS 9 – The Belgian case of the former Radium factory in Olen

In Belgium, in the northeastern Campine area, an historic Radium factory site is situated near the town of Olen. Radium was produced out of Uranium ore from 1922 up to around 1970, and the factory produced a significant part of the world's Radium stock. At a later stage, Uranium was also extracted from the residues coming from the Radium production. As a result of the decommissioning of the facility and also of the remediation of contaminated soil and brook deposits, significant volumes of material are stored at the site in different storage facilities. They are awaiting a final solution for their management. In total it concerns a few hundreds of thousands cubic meters of material. That volume contains more than 40 TBq of Radium in total (although the total activity is not yet precisely known), from which most of it is located in one facility containing about 55,000 m^3 of material.

The Belgian regulator AFCN/FANC and the Belgian waste management organization ONDRAF/NIRAS developed a common vision on potential management routes for this material, that is currently still under the management of the Umicore company. Depending on the Radium activity concentrations in the material, different management routes could be envisaged. AFCN/FANC and ONDRAF/NIRAS developed the following guidance values: For material with radium concentrations below 0.1 Bq/g (or 0.5 Bq/g in case of a limited volume below 10^4 m^3), the material could be released. Between 0.5 and 15 Bq/g of Radium concentration, the material could be stored in a landfill (potentially at the site) and it could be labeled as a radon sensible area, although most of the risk would be chemotoxic. Between 15 Bq/g and 1000 Bq/g, disposal at shallow depth (repository roof at least 10m deep) would be acceptable, while waste containing more than 1000 Bq/g of Radium would have to be disposed of in a deep geological repository.

One of the challenging aspects for this waste is that large heterogeneities exist in activity concentrations within the stored materials. As the potential management route would depend on the activity levels, it will be challenging as well from a characterization point of view as from a segregation/treatment point of view to orient these large volumes of waste towards the appropriate management routes. The technical plans for the practical implementation of the routes and final solutions for this challenging waste are at this moment not yet developed.

		AUSTRIA	CZECH REPUBLIC	CYPRUS	POLAND	PORTUGAL	UKRAINE	UK
NON CONDITIONED Ra/Th/U BEARING WASTE	Volumes	Ra/Th/U bearing waste is conditioned as the waste category it is in. Waste is being conditioned upon arrival at the waste management facility so no non-conditioned waste volumes to report.	Activity of naturally occurring Ra/Th/U radionuclides on the date 31st December 2019 Ra-226- 1.36 TBq U – 0.638 TBq, Th-232- 3.20 GBq	Lab waste solutions: < 1L ; Phosphogypsum waste: ~30 ktons	Not specified, present in radioactive waste Long lived. U-238 (53.352MBq); Th-232 (20MBq), Ra-226 (10MBq)	Mining and milling in-situ wastes (U, Th, Ra and isotopes) (Large volume but not specified). Phosphogypsum wastes (Large volume but not specified) NORM wastes from the industry Small volume of wastes from R&D	Unspecified. Mixed with others RW	U: DNLEU-111,600teHM Capenhurst is holding a number of urani residues totalling ~30thM, DSRL- 63.4 m AWE- - 116.4 m^3 Th ~ 0.2 tHM Ra - 2.0 m^3
	Main radiological inventory	Ra-226 sources (about 1,900) with $4.9.10^{11}$ Bq.	**Ra-226, U, Th-232**	Lab waste solutions: < 50g U (DU); Phosphogypsum waste: ~150Bq/kg U; ~600Bq/kg Ra-226; ~30Bq/kg Th-232	U-238, Ra-226, Th-232	U-238, Ra-226, Th-232. Other disused sealed sources with (lightning rods, smoke detectors). Lab waste with U and Th salts.	SRW: Ra-226 65.TBq, Th-232 0.7 TBq , U-235+238 5TBq LRW: Ra-226 5.10^{-2}TBq, Th-23.2 GBq , U-238 5.10^{-2} GBq	U, Th and Ra isotopes
	Main chemical inventory	Ra sources (mostly medical needles) are encapsulated in stainless-steel capsules that are welded shut, the lead container containing the capsules is then cemented into 200 L drums. Thorium and Uranium salts Ashes from organic waste bearing these nuclides (see organic waste).	The chemical inventory is mostly RaSO4 in platinum cases (medical sources), Ra-Be neutron sources, laboratory waste containing natural radionuclides, disused sealed sources, depleted uranium and natural thorium (mostly as Th(NO3) 4.5 H2O and ThO2).	Lab waste solutions: aqueous solutions; Phosphogypsum waste: gypsum	No data available	Liquid/organic solutions. No other data available.		U, UO2, UO3 UF6, U3O8 (yellowcake) U residues, MOX, ThO_2, Th.
CONDITIONED Ra/Th/U BEARING WASTE	Volumes	60m^3, conditioned LILW-LL in total (not just Ra/Th/U bearing waste)			The waste is not conditioned	U, Th, Ra mining and milling wastes are being treated in-situ (IAEA technical recommendations). Phosphogypsum waste waits regulatory decision.	Not processed	DNLEU and HEU are not currently considered as wastes in the UK. Strategy for long term storage, treatment or re-use is yet to be developed
	Inventory information	LILW-LL primary radionuclides: Ra-226, Am-241, $4.6.10^{12}$ Bq						
	Other details	Ra/Th/U bearing waste is conditioned according to its waste category. e.g. sources via encapsulation, liquids and combustible waste via incineration. Water soluble salts are treated by neutralisation, precipitation and/or coprecipitation followed by drying and supercompaction				DU is not mentioned in the National Plan for the Management of Radioactive Waste. It is considered a safeguard material subject to inspections and security measures in place.		

Table 11: Volumes and inventories of Ra/Th/U bearing waste held by some Member States

2.10 The management of waste containing reactive metals

2.10.1 General context and first insights

Based on the ROUTES questionnaire responses, it appears that waste containing reactive metals often come from the nuclear power production or during decommissioning activities. These waste can include a wide range of metals, e.g., Al, Be, Mg, etc. As shown in *Figure 24*, 12 MS are facing difficulties in the management of waste containing reactive metals. More precisely, these difficulties were mainly related to disposal issues (33%), treatment and conditioning issues (25%) and characterization aspects (25%) (see *Figure 25*).

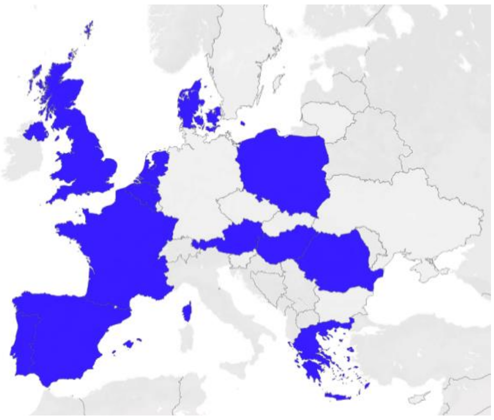

Figure 24: Member States experiencing difficulties in the management of waste containing reactive metals.

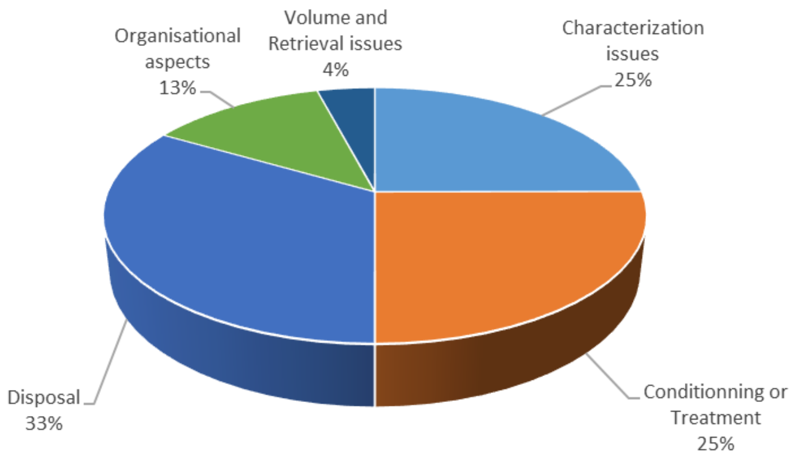

Figure 25: Main difficulties associated with the management of waste containing reactive metals.

2.10.2 Focus on the characterization step

Regarding the characterization of waste containing reactive metals, the major challenge faced by the MS was to obtain precise and reliable radiological inventory data and more specially, the exact list of activation products (see *Table 12*). In the UK, various waste streams containing different reactive metals, e.g., Al, mixed Al-Mg (Magnox fuel cladding alloy), Cd-Al (from the Imperial College Reactor Centre) and mixed Na-K (from the Dounreay Fast Reactor) must be dealt with. As these waste involve various volumes distributed throughout the UK, a coordinated characterization process is a challenge.

In Denmark, Al and Be are present in some waste. The total volumes are not well established as there are difficulties in precisely determining how much metal has been activated within the reactor and therefore, which radionuclides have been produced. Various calculations using Monte Carlo methods have been implemented but it remains difficult. On this topic, France also specified that they are facing difficulties optimizing the characterization of waste containing magnesium arising from former fuel cladding of former Natural Uranium Graphite Gaz (UNGG) reactors. Refining this characterization is a major challenge, as it could lead France to direct some of the waste towards a surface disposal route rather than a deeper geological one. Note that Belgium, Germany, Spain and Greece also have to manage waste containing Mg, Al or Be and the characterization step raises difficulties for them too.

In addition to the UK, the Netherlands and France also deal with waste in which sodium is present. In the Netherlands, Na waste arise from research reactors, whereas in France, Na waste arise from the former Superphénix and Phénix reactors, which used Na as a moderator or within bundles. If part of those waste now consist of cemented blocs of Na, the bundle will currently not have a management route. In any case, as the following paragraphs show, Na waste involve difficulties in terms of treatment, conditioning and storage.

2.10.3 Focus on the treatment and conditioning steps

Presence of reactive metals raises challenges for treatment and conditioning, as corrosion reactions can occur and lead to cracking and modifications of the waste forms, and changes in the mechanical properties of the waste containers. To cope with these difficulties, various options are implemented. For instance, in Germany, Romania and the Netherlands, no treatment and conditioning processes are currently available. In Denmark, Al and Be waste are packed in containers with no particular conditioning. In Austria, Be waste have been welded into steel capsules filled with argon in two MOSAIK® type containers (*see Focus 10 on the Austrian case study*). Finally, in Belgium, a PAMELA-canister (150 L) has been developed for Be waste but the associated treatment/conditioning method no longer exists.

In addition to these initiatives, other MS have launched various research programmes to develop treatment and conditioning processes that can be adapted to waste containing reactive metals. In France, specific matrices (*e.g.*, geopolymer and alkali activated cement) have been under development for over 15 years, seeking not to completely avoid corrosion itself but rather to reduce the impact of corrosion reactions. It is worth mentioning that currently, the European Research Project PREDIS (Task 4) is working on these aspects.

Concerning waste containing Al, specific research aims to develop magnesium brucite-based cement that could keep Al waste in alkali conditions and thus limit production of hydrogen over time[13]. All these innovative matrices aim to ensure a waste form that could be compatible with disposal conditions. France also underlines that fuel cladding treatment can lead to the production of small metal particles that could settle to the bottom of waste containers. For this particular case, oxidation techniques aiming to remove the radioactive content from these metal pieces have been developed. The UK noted that research is also being conducted on innovative matrices to slow down corrosion reactions[14]. For the case of waste containing sodium, the UK is aware that Veolia has an existing plant located in the USA that can convert Na waste into a thermally treated and stable product (glass).

Finally, Belgium indicated that most issues they face relate to the treatment and conditioning of waste containing uranium that can be highly reactive. For now, no treatment processes have been

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[13] List of recent publications on this particular topic:

- C. Cau Dit Coumes and al.; Selection of a mineral binder with potentialities for the stabilization/solidification of aluminum metal; Journal of Nuclear Materials, October 2014
- H. Lahalle and al.; Investigation of magnesium phosphate cement hydration in diluted suspension and its retardation by boric acid; Cement and Concrete Research, September 2016
- H. Lahalle and al.; Influence of the w/c ratio on the hydration process of a magnesium phosphate cement and on its retardation by boric acid; Cement and Concrete Research, 26 April 2018
- D. Chartier and al. ; Behaviour of magnesium phosphate cement-based materials under gamma and alpha irradiation; Journal of Nuclear Materials, 25 July 2020

[14] References on this subject:

- A.R. Hoch, et al., 2010, A Survey of Reactive Metal Corrosion Data for use in the SMOGG Gas Generation Model, report SA/ENV0895 issue 2 (available from RWM website).
- J. Cronin, N. Collier, 2012, Corrosion and Expansion of grouted Magnox, Mineralogical Magazine, 501.

implemented to cope with this. The UK noted that they are facing the same challenge with U waste resulting from Magnox fuels. A project aiming to convert U from metallic to oxide form is under consideration but given the large volumes requiring treatment, questions on cost effectiveness remain.

2.10.4 Focus on the storage and disposal steps

As explained in the above section, the storage and disposal steps will depend on the stability of the resulting waste containers after the treatment and conditioning processes are completed. This explains why no storage solution has yet been found in some MS such as Belgium, Hungary or the Netherlands. In France, it was specified that two main producers are dealing with the management of waste containing reactive metals and notably, magnesium: Orano and CEA. Even though no final conditioning solution has yet been implemented, sound work is ongoing to manage legacy waste. For CEA waste, as Mg has already been separated from other fuel cladding components, the plan is to compact Mg in order to reduce the surface of reactive metals. The compacted Mg will then be stored in dedicated packages pending acceptable conditioning solutions, potentially geopolymers. For Orano waste, as Mg is mixed with graphite, sorting operations will be needed first.

Regarding the situation in the UK, ILW containing reactive metals will be accepted in the future geological disposal facility, provided that stable conditioning can be achieved. For the case of LLW, reactive metals can be accepted provided that surface area does not exceed 10 m^2.

FOCUS 10 – Conditioning of waste containing Be into steel capsules filled with Argon in MOSAIK® type containers in Austria

Because of the high Tritium content and high toxicity of Beryllium, the Be elements from the research reactor (a 10 MW pool type reactor) at the Seibersdorf site in Austria (see Focus 4) were conditioned by encapsulation without further treatment. Each Beryllium element was singly encapsulated in its own stainless-steel cartridge (in some cases together with the activated ends of the control rods and ends of the graphite reflector elements).

After a leakage test and transport into a hot cell, each element was put into a 5mm think stainless steel cartridge, backfilled with silica sand and then dried. Then the lid was pressed on and welded shut using 3-layered orbital welding. The welding seam was quality checked using metallography of samples. One welding was found to be leaking, so the cartridge had to be cut open again and the Beryllium element was put into a new cartridge, which then was welded without any problems. In total there were 25 Be-elements. Each element was encapsulated this way. After welding the cartridges, they went back into the pool.

Then the cartridges were inserted into two loading baskets with welded tubes (one for each of the cartridges) which were inserted under water into two MOSAIK® type containers. The loading schema of the tubes in the baskets was devised to minimize the surface dose rate of the containers (the cartridges with the Be-elements went into the tubes in the middle). After loading, the MOSAIK® containers were dried and filled with Argon before closing. Since 2006 they are in interim storage.

		NETHERLANDS	PORTUGAL	UK
NON CONDITIONED WASTE CONTAINING REACTIVE METALS	Volumes	Small volume of LILW containing Sodium from research and experiments	Information not yet available	Magnox/Magnesium: • ILW: 6500 te • LLW: 130 te • VLLW: 0.11 te Aluminium: • ILW: 1900 te • LLW: 19 000 te • VLLW: 8.1 te
	Main radiological inventory		Information not yet available	No particular details
	Main chemical inventory		Information not yet available	Magnox is a mixed Mg-Al alloy used to clad uranium metal fuel. For example, Al80 has 0.8% Al and 0.004% Be in its composition.

Table 12: Volumes and inventories of waste containing reactive metals held by some Member States

2.11 The management of waste containing chemotoxic substances

2.11.1 General context and first insights

According to the responses from the ROUTES questionnaire, waste containing chemotoxic substances often result from production or decommissioning activities. They can contain a wide range of chemotoxic substances (e.g., Cd, Hg, Be, etc.). In total, 12 MS are facing difficulties managing waste containing chemotoxic substances (*see Figure 26*). Among the difficulties raised by the MS, there are major issues related to treatment and conditioning (28%), characterization (27%), and disposal (17%) (*see Figure 27*).

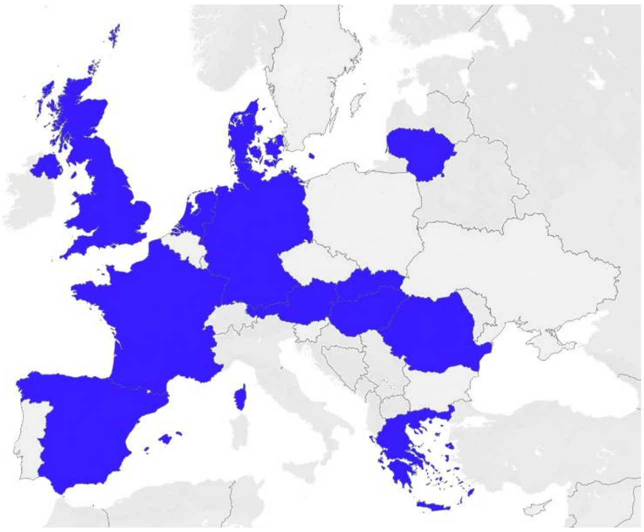


Figure 26: Member States facing difficulties with the management of waste containing chemotoxic substances.

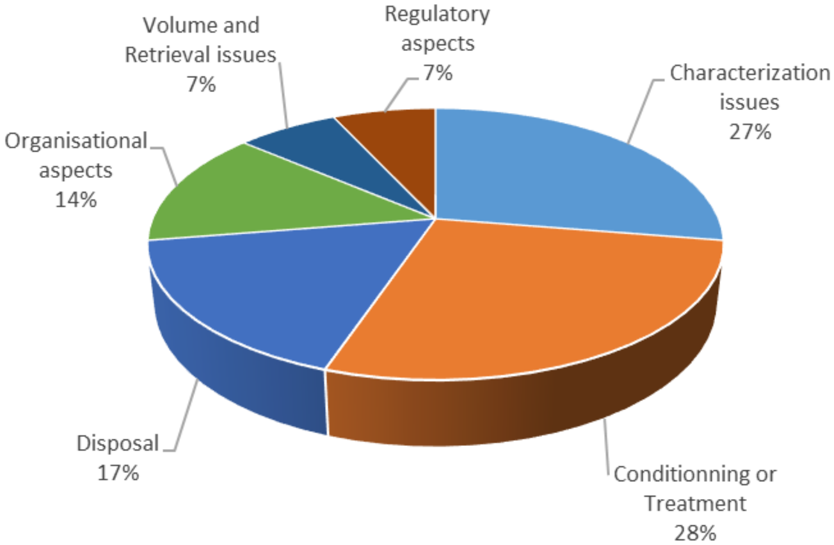


Figure 27: Main difficulties raised by the Member States concerning the management of waste containing chemotoxic substances.

2.11.2 Focus on the characterization step

Characterization of waste containing chemotoxic substances is challenging as a result of the simple presence of chemicals, which at low doses, are much more difficult to identify than radioactive content. Therefore, development of appropriate tools to carry out accurate chemical inventories is necessary. Indeed, many MS are dealing with waste containing chemotoxic substances, without reliable inventories (see Table 13). Germany, for instance, has no clear information about the quantity of uranium and cadmium present in some of its waste. Greece and Portugal also have to manage lead blocks that are not currently characterized. Spain also stresses that chemotoxic substances are often heterogeneously distributed within the waste, which adds difficulty to their characterization. Similarly, the UK mentions that radiologically contaminated bulk elemental mercury is one of the main challenging chemotoxic substances they are facing; the major issue is the ability to obtain representative samples.

The particular case of asbestos has been also highlighted by some MS. The UK notably mentions that an important area of research is dedicated to the better characterization of asbestos that has not been retrieved from the Sellafield nuclear site. Currently *in situ* samplings are implemented to determine not only the level of contamination of asbestos, but also the fibre typology. This information is needed to direct the asbestos to the appropriate disposal route. France also highlights that one of the main issues for producers, in addition to assessing the volume of asbestos that will be produced by dismantling activities, is to characterize the type of fibres. For now, these particular details are poorly known, resulting in uncertainties in the current inventory of asbestos. Note that the French National Plan for the management of radioactive waste raises this point and encourages studies to be carried out to resolve this issue.

2.11.3 Focus on the treatment and conditioning steps

The treatment and conditioning of waste containing chemotoxic substances raises difficulties in the different MS. In Germany for instance, no treatment and conditioning processes are available for waste containing Hg or Cd. Greece also announces that no particular processes have been developed to treat or condition waste containing Pb. Spain insists on the need to improve segregation of chemicals and develop stabilization and treatment processes of those substances. In France, a treatment to transform mercury into mercury sulphide (stable and non-toxic form) is now available and is being used to treat this type of waste. The UK also announced that in 2019, a review was completed that looked into the credible options for treating mercury waste[15]. The review identified sulphidation as the highest-ranking credible option for the treatment of mercury waste, due to the confidence in the waste product, its passivity and suitability for disposal, as well as the maturity of the technique and its apparent tolerance for a range of waste. However, the review also pointed out a disadvantage related to this higher process complexity than other approaches such as thermal treatment (incineration), pin-hole distillation, amalgamation and Sulphur Polymer Stabilization / Solidification (SPSS).

The case of treatment and conditioning of asbestos has also been tackled by the UK. Given the large volumes that will be produced in the coming years in the UK, a number of commercial services for treating asbestos, either via thermal treatment or chemical reconversion, have been developed (*see Focus 11 on the UK case study*).

Belgium also raised the case of batteries containing heavy metals. Treatment and conditioning of those waste is challenging in several MS (e.g., Belgium, France, the UK) and no clear solutions have been

[15] References associated with this review:

- Abraitis, P., Collier, N. and Godfrey, I. (2019). Technical Note: Techniques for the Management of Radiologically Contaminated Mercury, Nuclear Decommissioning Authority Direct Research Portfolio Report ENE-0210AD D3, Issue 1, September 2019. https://ecosystem.org.uk/docs/DOC-45840
- Godfrey, I. and Abraitis, P. (2019). Summary of Credible Options for the Management of Radioactively Contaminated Mercury. Nuclear Decommissioning Authority Direct Research Portfolio Report ENE-0210AD/D7.1, Issue 1, September 2019. https://ecosystem.org.uk/docs/DOC-45911

found. However, the UK mentions that the US DOE has identified some solutions that could be applicable for batteries.

The presence of Be in waste, considered both as reactive metal and an highly reactive substance, also seems to pose problems for some MS such as Belgium, France and the UK, which agree that further research focusing on this case is required.

2.11.4 Focus on the storage and disposal steps

As no clear treatment and conditioning processes are implemented for waste containing chemotoxic substances, storage and disposal steps are also pending issues for the management of those particular waste. To cope with this difficulty, various temporary options are implemented. For example, in Germany, waste containing Hg are stored in plastic containers in interim storage. In Lithuania, WAC for surface disposal will accept a small quantity of waste containing Pb; however, these WAC will be updated in the coming years in order to accept higher volumes of Pb and other waste containing chemotoxic substances. In the UK, asbestos and Hg contained in ILW could be accepted in the future GDF once waste are immobilised and packaged in a suitable container. Regarding the particular case of Hg, the UK also highlights that the EU Regulation (2017/852, Article 13) presents an ongoing barrier for disposal of low level radiologically-contaminated mercury waste. Indeed, the EU Regulation states that: *"mercury waste shall only be permanently disposed of in the following permanent storage facilities licensed for disposal of hazardous waste:*

a) salt mines that are adapted for the permanent storage of mercury waste that underwent conversion, or deep underground hard rock formations providing a level of safety and confinement equivalent to or higher than that of such salt mines; or

b) *above-ground facilities dedicated to and equipped for the permanent storage of mercury waste that underwent conversion and solidification and that provide a level of safety and confinement equivalent to or higher than that of the facilities referred to in point (a).*"

However, although there is a disposal facility in the UK which aligns with option (a), it currently cannot accept radioactive waste for disposal, which leads to ongoing uncertainty on whether there is a UK disposal facility that can accept low level radiologically-contaminated mercury waste.

For the management of asbestos, France and the UK specify that low level waste repositories (LLWR) are now accepting those particular waste. However, in the UK, the amount of moderately or highly friable asbestos that can be disposed of to the LLWR is limited. This is because of the potential effects of coastal erosion on the multi-barrier containment model maintained by LLW Repository Ltd. This means that the current LLWR disposal limits are 1te of moderately friable asbestos per consignment, and 10 kg of highly friable asbestos per consignment (maximum external volume of 40 m^3). In France, it should be mentioned that only non-friable asbestos is accepted in LLWR. The case of friable asbestos is considered on a case-by-case basis.

Given the large volumes of asbestos that will be produced in the coming years as the UK moves from operations into broad-front decommissioning, the Nuclear Decommissioning Authority (NDA) is initiating the asbestos Innovation Partnership, which aims to create an operational service within 8-10 years that converts bulk asbestos and asbestos-containing materials into a reusable product.

FOCUS 11 – Management of radiologically contaminated asbestos in the UK

In the nuclear industry, asbestos has been used as a lagging material around pipes, in boards, in reactor components and in other areas where contamination and activation may have occurred. In addition to items which may be considered as individual components (such as asbestos sheets) there are materials which may be contaminated with asbestos fibres.

There are currently significant stocks of asbestos and ACM (Asbestos-Containing Materials) owned by, and known about by, the Nuclear Decommissioning Authority (NDA). The 2019 UK Radioactive Waste Inventory (UKRWI) reports the following quantities and sources of radiologically contaminated asbestos [1,2]:

Classification	Mass (tonnes)	Notes
ILW	66	558 entries in the UKRWI but ~92% by mass belongs to two Sellafield waste streams: • 2S313 Windscale Piles Miscellaneous ILW 31.55te • 2D39 Miscellaneous Beta-gamma Waste Store 29.19te
LLW	22,000	556 entries in UKRWI, the largest being: • 2E191 Sellafield decommissioning wastes for Clifton Marsh ~17,743te • 9F324 Magnox reactor area LLW/VLLW ~1,138te • 5B358 Previously disposed LLW to be retrieved ~793te • 8A103 Capenhurst decommissioning wastes ~459te
VLLW	28,000	14 entries in the UKRWI; 7 with recorded masses. Dominated by: 2D148 Sellafield high volume VLLW (HVVLLW) from final decommissioning 27,017te

For all classes, the reported figures are predominantly estimates of future arisings, with only small quantities associated with current stocks. These volumes may increase due to more materials being discovered as the NDA starts broad front decommissioning and associated assaying of asbestos and ACM waste.

The UK asbestos industry generally disposes of asbestos to permitted hazardous waste landfill, which can accept VLLW asbestos. However, landfill capacity for asbestos is decreasing over time. Moreover, much of the asbestos yet to be stripped from reactors (both Magnox and Advanced Gas-cooled Reactors contained asbestos) may be either LLW or ILW rather than VLLW. Unless these materials can be treated or disposed of promptly, there may potentially be delays to decommissioning or increased disposal costs. The WAC for UK incinerators include restrictive limits on asbestos fibre contamination so are only likely to be suitable for treatment of some ACM. There are also restrictions on disposal of moderately or highly friable LLW asbestos at the LLWR due to potential coastal erosion resulting in exposure of the waste in future, which results in current LLWR disposal limits of 1 te of moderately friable asbestos per consignment, and 10 kg of highly friable asbestos per consignment (maximum external volume of 40 m^3 [3]. In future, asbestos would be acceptable at a UK GDF, once immobilised and packaged in a suitable container [4], but this is not expected to be available for a number of decades. Therefore, alternative treatment or disposal methods are being sought.

In the UK, a number of commercial services that treat asbestos, either by thermal treatment or chemical deconversion, have been developed:

- ARI Global Technologies Ltd (part of Windsor Integrated Services Group Ltd) has a patented a “unique thermochemical conversion technology that destroys asbestos fibres and produces a non-hazardous product that can be recycled in many construction applications”.
- Thermal Recycling Ltd has a small-scale demonstration plant (“first in the world”, Technology Readiness Level (TRL) 6-7) in Wolverhampton that denatures (chrysotile) asbestos roof sheets (an ACM) into a new material that can be converted into a sustainable aggregate.
- Veolia-Costain is looking to develop a thermal treatment capability at their Ellesmere Port Incinerator plant that could be used to treat radiologically-contaminated asbestos; the process is not currently designed to produce a reusable product.
- Tetronic Ltd (now Plasma Processing UK Ltd) has published a paper on the use of Plasma Arc Technology that treats ACM and converts it into “a harmless slag product, with the potential for reuse”. This technology is described as mature (it was assessed at TRL 8-9 in 2007-10 when the work took place).

The NDA is also aware of a number of overseas companies who offer commercial asbestos treatment services, and is currently investigating whether any UK or overseas companies could form an Innovation Partnership to offer a treatment service for bulk asbestos or ACM, converting these into a reusable product. Management routes that enable treatment of both contaminated and uncontaminated asbestos from the nuclear industry could also be beneficial to the wider asbestos industry.

[1] NDA/BEIS, 2019 UK Radioactive Waste Inventory Waste Report Final, December 2019 The 2019 Inventory | UK Radioactive Waste Inventory (UKRWI) (nda.gov.uk)

[2] NDA/BEIS, 2019 UK Radioactive Waste Inventory Detailed Data Report Final, December 2019 The 2019 Inventory | UK Radioactive Waste Inventory (UKRWI) (nda.gov.uk)

[3] LLW Repository Ltd, Waste Acceptance Criteria – Low Level Waste Disposal, WSC-WAC-LOW, Version 5, Issue 1, July 2016. https://ecosystem.org.uk/docs/DOC-38016

[4] Some ILW has already been packaged for storage, with the intent that it will be disposed of at a GDF, that contains asbestos (e.g., from the decommissioning of WAGR), following engagement with RWM's disposability assessment process.

		LITHUANIA	UK
NON CONDITIONED WASTE CONTANING CHEMOTOXIC SUBSTANCES	Volumes	Waste containing radioactive asbestos (serpentinite mixture from reactor unit zone)~4,800te (VLLW-SL (mainly), LLW-LL) Ion-exchange resins (including NORM)~433 te (VLLW-SL) Other hazardous and specific waste: a. Lead waste – 624 te (VLLW-SL) b. Disused activated carbon – 205 te (VLLW-SL) c. Oil and oily rags waste – 15.6 te (VLLW-SL) d. Mercury-containing fluorescent lamps and galvanic cells – 11 te	Data from the UK Radioactive Waste inventory : • ILW asbestos: 66 te • LLW asbestos: 22 000 te • HLW asbestos: 28 000 te Regarding waste containing mercury : • ILW: 52.06 te • LLW: 28.95 te
	Main radiological inventory		
	Main chemical inventory		

Table 13: Volumes and inventories of waste containing chemotoxic substances held by some Member States

3. First needs and future R&D actions for a better management of challenging waste

During the different work meetings, some needs or possible R&D actions have emerged. *Table 14* summarises the main needs identified for each challenging waste.

Sludge	• Address the issue of sampling representativeness at the level of ROUTES Task 3, and encourage the sharing of good practices on this topic; • Share among the MS treatment/conditioning technologies already used in some countries.
SIERs	• Address the issue of sampling representativeness at the level of ROUTES Task 3; • Share among the various countries the best practices and initiatives implemented in some MS notably for conditioning processes.
Organic Waste	• Study actions that arose from the THERAMIN project; • Develop strong links with the ongoing CORI and PREDIS projects and share with their representatives our current questions; • Address characterization issues related to the identification of complexing substances and case of oil/organic waste within ROUTES Task 3; • Some R&D needs might be raised although much work has already been done. These actions may aim to go beyond laboratory scale and try to develop industrial processes on real waste packages. This implies to work on the consideration of uncertainties to move from R&D aspects to real issues.
Bituminized Waste	• Investigate the particular needs to launch R&D programmes about treatment of bituminized waste in order to destroy the chemical reagents. This action should be in line with current work carried out by the PREDIS project; • Encourage sharing of best practices and feedback experiences on the initiatives implemented in the management of bituminized waste.
Graphite Waste	• Address the issue of sampling representativeness in the case of graphite waste at the level of ROUTES Task 3, and encourage the sharing of good practices on this topic; • Review the outcomes of research projects already dedicated in the management of graphite waste: GRAPA, CAST and CARBOWASTE.
Decommissioning Waste	• Share good practices about minimisation and valorisation processes of part of dismantling waste is consider a major issue • Take into account outcomes of the SHARE project.
DSRS	• Possible R&D actions dedicated to characterization issues could be useful, either in terms of methodologies for radiological characterization of DSRS and orphan sources or identification techniques for particular radionuclides (e.g., Sr-90).
Particular Spent Fuel and Depleted Uranium	• In the event that particular spent fuel and depleted uranium are reclassified as waste, there will be a real need to review disposal strategies and sharing of possible solutions between MS.
Ra/Th bearing waste	• Need to share future disposal strategies and discuss the associated difficulties.
Waste containing reactive metals	• Share good practices about management of waste containing reactive metals; • Make contacts with the PREDIS project so learning can be shared.
Waste containing chemotoxic substances	• Launch research programmes on a better characterization of chemotoxic substances in radioactive waste, considering heterogeneity and sampling representativeness issues; • Share findings on treatment initiatives implemented for asbestos and mercury; • Develop a particular research programme dedicated to the management of waste containing Be.

Table 14: Major needs and possible R&D actions identified for each challenging waste

In summary, it is interesting to note that all MS highly **encourage sharing experiences and good practices** among the interested countries, about different initiatives that can be implemented for the management of challenging waste. Among the topics mentioned to be interesting to share, the following ones can be highlighted:

- Case of innovative treatment and conditioning for sludges, SIERs and Organic waste,
- Minimisation and recycling processes of decommissioning waste,
- Disposal strategy for particular spent fuel and depleted uranium,
- Treatment initiatives of asbestos and mercury.

In addition to those sharing aspects, a **strong link with ROUTES Task 3** dedicated to characterization aspects has been stressed. According to the MS, ROUTES Task 3 could indeed take over and investigate some blocking points preventing a good characterization of some challenging waste types as for instance:

- Sampling representativeness;
- Identification of chemotoxic and complexing substances;
- Chemical and radiological characterization of oils;
- Radiological characterization of graphites.

Strong links with former research projects (e.g., THERAMIN, GRAPA, CAST, CARBOWASTE) have been also encouraged in order to benefit from their results and progresses and to see what can be either directly implemented or completed by new research programmes. **Interactions with current research programmes** exploring some issues of interest for the management of challenging waste, as for instance: the CORI work package of the EURAD EJP, or PREDIS and SHARE European Research Projects.

Finally, **possible topics of future R&D programmes have been identified** and could maybe help to improve the management of some challenging waste types. MS notably insisted on the need to **go beyond the laboratory scale and rather focus on industrial processes on real waste packages**. The list of possible topics is the following:

- Explore the long-term behaviour of innovative matrices notably developed to manage SIERs, sludges and organic waste;
- Develop treatment processes dedicated to bituminized waste coming from reprocessing;
- Investigate characterization methodologies and identification techniques for DSRS and orphan sources, with focus on particular radionuclides like Sr-90;
- Identify possible strategies for the management of waste containing beryllium.

4. Conclusion

Deliverable 9.5 provides an overview of the different types of challenging waste and the difficulties encountered within each country at different steps of the waste lifecycle.

Globally, MS face difficulties when attempting characterization, which are often an important reason why waste are regarded as challenging to manage. These difficulties are related to the representativeness of the samples, but also the techniques for detecting particular species such as activation products or complexing substances. It was pointed out that some types of waste, such as oils or orphan sources, require innovative measurement techniques. These issues, which are directly linked to ROUTES Task 3, will be further addressed in this framework. In addition to the vicious circle regarding characterization that is mentioned at the beginning of this report[16], another vicious circle was shared by all the MS, which is that *'to be characterized, waste needs to be retrieved, but in order to be retrieved, it requires a detailed inventory that needs to be characterized first".* Future progress in terms of non-destructive characterization may provide a route out of these vicious circles.

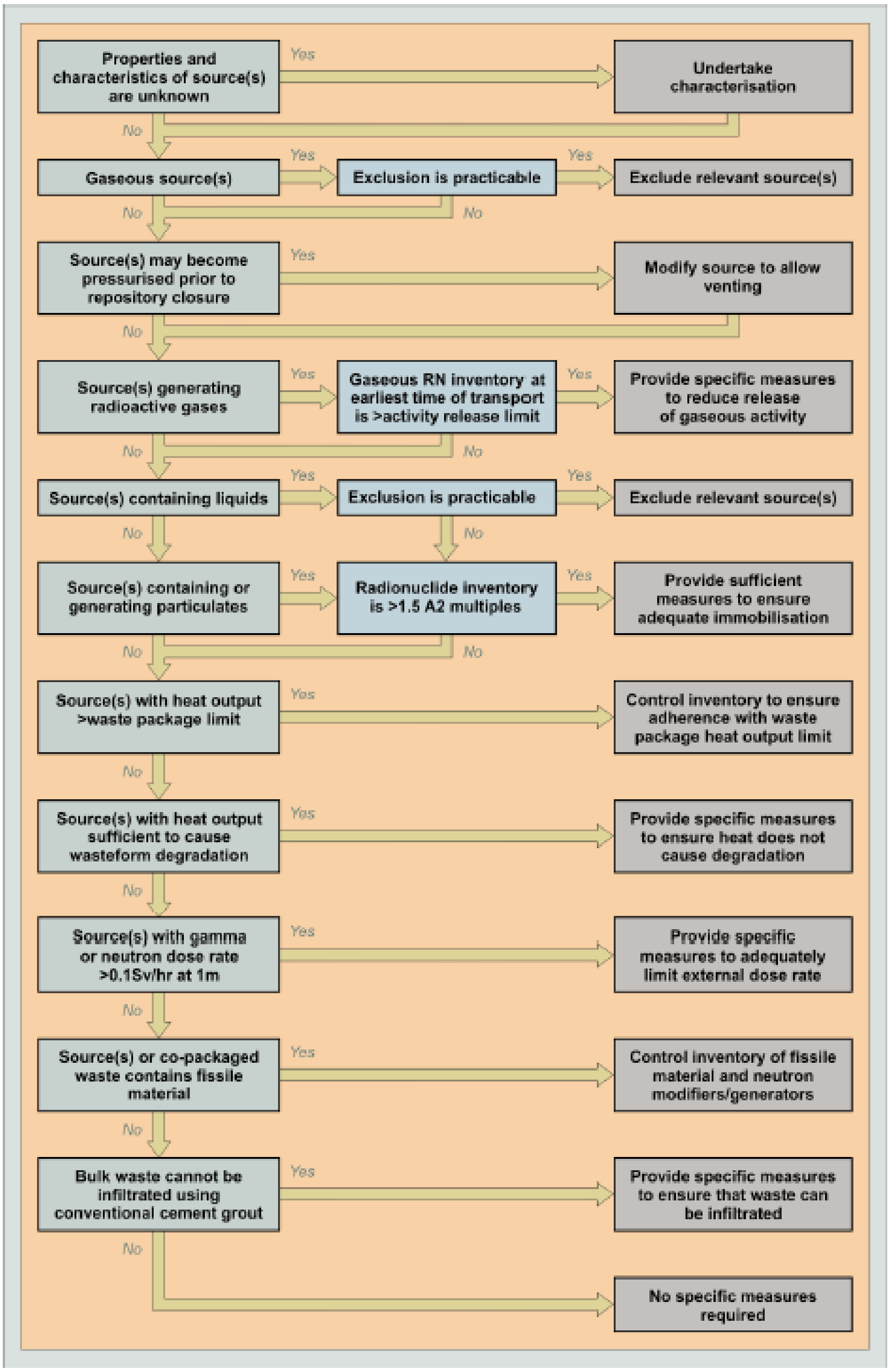
Regarding treatment and conditioning, MS are still awaiting the development of innovative techniques for a number of challenging waste: graphite, waste containing reactive metals, organic waste, etc. Initiatives have been implemented in some countries, and there is interest in sharing these good practices. However, these new techniques raise R&D issues about, for instance, the lifespan of the innovative matrices that could be used. Similarly, an interest in the sharing of mobile treatment facilities between countries has also been highlighted by some MS, particularly regarding treatment of sludges and resins.

In the case of disposal, as mentioned in the beginning of the report, MS are often faced with a lack of permanent solutions that prevents them from developing or using appropriate treatment and conditioning techniques, as the packages produced may not be in line with future WAC. The dilemma of early or delayed conditioning is addressed in ROUTES Task 4. Furthermore, regarding existing disposal solutions, an interesting question that could be further explored is whether certain waste types are considered to be challenging only because they are not covered by the existing disposal WAC? It is also worth noting that for some challenging waste, the question of disposal has not yet arisen, as they are not yet considered as waste, e.g., PSFs or depleted uranium. For these waste, the whole disposal strategy has still to be developed, and sharing among the countries concerned is highly encouraged in order to discuss possible solutions and common difficulties.

Based on all this work, ROUTES Task 2 has identified a set of needs and possible R&D topics in order to better manage challenging waste in the future. The following months will allow for the continuation of this work, followed by a consolidated reflection on the R&D topics that could be carried out within EURAD. To do so, the results of past projects such as CAST, CARBOWASTE or THERAMIN will be analysed. Subsequently, close links with ongoing projects such as SHARE, PREDIS or CORI will be established and will provide an opportunity to collaboratively identify potential R&D programmes of interest to the European community.

[16] '*Not having a management route prevents prioritizing the characterization of waste and the lack of characterization prevents the identification of management routes'*

Appendix A. Properties of closed sources which may challenge waste package performance requirements (flow chart from the UK)



References

References have been mentioned throughout the document.