Deliverable 9.11: ROUTES – Report presenting the results of the workshop dealing with possible conditioning routes for SIMS

Work Package ROUTES

This project has received funding from the European Union's Horizon 2020 research and innovation programme 2014-2018 under grant agreement N°847593.

http://www.ejp-eurad.eu/

Document information

Project Acronym	**EURAD**
Project Title	**European Joint Programme on Radioactive Waste Management**
Project Type	**European Joint Programme (EJP)**
EC grant agreement No.	**847593**
Project starting / end date	**1st June 2019 – 30 May 2024**
Work Package No.	**9**
Work Package Title	**Waste management routes in Europe from cradle to grave**
Work Package Acronym	**ROUTES**
Deliverable No.	**9.11**
Deliverable Title	**ROUTES – Report presenting the results of the workshop dealing with possible conditioning routes for SIMS**
Lead Beneficiary	**NES**
Contractual Delivery Date	**May 2022**
Actual Delivery Date	**May 2023**
Type	**Report**
Dissemination level	**PU**
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To be cited as:

Bornhöft M.C., Langegger E. (2023): ROUTES – Report presenting the results of the workshop dealing with possible conditioning routes for SIMS. Final version as of 29.05.2023 of deliverable D9.11 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

Disclaimer

Acknowledgement

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

Status of deliverable		
	By	Date
Delivered (Lead Beneficiary)	NES	19.01.2023
Verified (WP Leader)	F. Marsal (IRSN)	08.03.2023
Reviewed (Reviewers)	Gunnar Buckau (KIT-PTKA)	02.05.2023
Approved (PMO)	E. Salat (IRSN)	23.05.2023
Submitted to EC (Coordinator)	ANDRA	31.05.2023

Executive Summary

The objective of Task 5 ("RWM solutions for small amounts of waste") is, among others, to evaluate both predisposal and disposal strategies for small inventory member states (SIMS). SIMS have small amounts of wastes from different origins, and their RWM strategies are not advanced.

This second deliverable of Task 5 focuses on the necessary predisposal routes including pre-treatment, treatment and conditioning of RAW for the disposal options for SIMS. The aim of this report is to compile the existing knowledge, shared during the workshop in January 2022 (month 32 of EURAD) of this subtask. For the disposal options discussed in Task 5.1 and published in Deliverable D9.10 of the EURAD project [1], the applicability of the predisposal routes discussed in this report were evaluated. This deliverable D9.11 was complemented with information provided by the participants after the workshop. The detailed methodology applied for this report is presented in Chapter 2.

In Chapter 3, the different distinct pre-disposal steps are described independent of waste types. This detailed introduction of the pre-disposal steps includes five different pre-treatment methods, four different treatment methods and four different conditioning methods. Each section presenting one of these methods includes a definition, the aim of the methods, advantages and disadvantages as well as examples of current applications in different member states (MS). Discussions on the techniques showed that often, for small amounts of waste, facilities are not feasible because of their cost. This shows the importance of shared and/or mobile facilities for SIMS. Examples for this are incineration (where shared solutions are available) and compaction (shared or mobile facilities) but also in-drum drying. Discussions on the pre-disposal steps showed that, when resources (regarding available facilities, financial and staff-wise) for pre-disposal and disposal are as limited as they are for SIMS, re-use, recycling and reduction of the generated waste is even higher. This is even more so for the challenging waste types discussed in the following chapter.

Within Chapter 4, waste type specific predisposal routes for available disposal options are presented. These are discussed for six selected waste types, namely: concrete wastes, disused sealed radioactive sources (DSRS), spent ion exchange resins (SIERs), spent fuel from research reactors, U/Ra/Th (URT) bearing wastes and hazardous wastes. The facility type options for on surface (only long-term interim storage falls under this category), near surface disposal and geological disposal are evaluated. Long-term interim storage though can only be seen as a disposal option if the waste is clearable afterward the foreseen storage period.

In the last chapter, Chapter 5, all information on RWM on the six selected waste types presented in the previous chapters are amalgamated, including waste type definition and inventories, possible predisposal routes and disposal options, as well as implications of the disposal option selection on qualifications of the predisposal routes. If applicable, additional information of specifications on RWM for the discussed waste type are added. During the workshop in January 2022, these management path for the six selected waste types were discussed with attending SIMS and large inventory member states (LIMS). This last chapter summarises the results of these discussions during the workshop and was completed by information provided by participants after the workshop. The main conclusions of each discussed waste type were:

Concrete is a large-volume waste with a low specific activity coming mostly from decommissioning projects. The general first pre-disposal step is clearance if possible. For treatment it is mostly crushed then packaged. This is sometimes even done reversible without a stabilizing matrix (DK) or using grout encapsulation (DE, UK). After crushing super-compaction is also used. It is also used to fill voids in drums (NL). Regarding disposal options: In general, the discussions identified that all borehole options were not suitable due to the volumes involved, but that all other near-surface options and geological disposal options are suitable (the latter mostly for waste with higher specific activities). It was pointed out that concrete waste can also be used as backfill material in containers or void spaces inside a disposal facility.

For DSRS reuse and recycling is the favourable option (especially for category 1 and 2 sources). Regarding pre-disposal the main steps identified were dismantling and then segregation by half-life of the nuclide and activity (category) and packaging. Further steps often involve either cementation or polymer fixation for near surface disposal, or encapsulation for disposal. Regarding disposal options boreholes were seen as a very suitable option for SIMS. LLW DSRS are currently mostly cemented and disposed in near-surface repositories and sources with long-lived nuclides are mostly in long-term storage waiting for deep geological disposal. Challenges arise from the long period of interim storage of DSRS until disposal facilities are available.

For SIERs currently cementation or incineration are the main methods used. Both have advantages and disadvantages (e.g., volume increase during cementation; incineration not recommended for high ^{14}C resins). There is also ongoing research into fixation processes into different matrix types (like geopolymer matrices). Also, there is the option for dried SIERs in specially licensed containers. Regarding disposal, boreholes were not recommended (regardless of their depth). Currently disposal is mostly near-surface.

Predisposal waste treatment for spent fuel from research reactors includes wet and dry storage, reprocessing or encapsulation. Disposal will be deep geological (which could be also in the form of deep boreholes for small amounts of SF). Many countries have agreements on repatriation to the producer country of the fuel for research reactors. For SIMS a shared solution can represent a disposal option if there is no other HLW in the country (which is often the case for SIMS).

For U/Ra/Th bearing waste the definition of the waste is strongly dependent on the country. In general, the amount of URT-waste is high. Different pre-disposal methods are being used for different kinds of URT-waste. For bulk materials it is mostly drying, compaction and cementation, for metals decontamination, melting and compaction and for liquid waste precipitation and drying of the resulting sludges. Most of the waste can be disposed of on public landfills as exempted waste (NORM), small amounts are for near surface disposal facilities (with some hundred Bq/g specific activity) and a very small amount needs a geological disposal solution (such as URT-waste with a high activity as in the case of URT-waste from Zirconium production). For SIMS a combination of disposal options was mentioned that could be a solution combining near-surface disposal with a borehole.

The last waste category discussed was hazardous waste. In accordance with national laws, non-radioactive hazardous waste can be disposed of at special landfills or other appropriate facilities. It consists of a huge group of substances where each subset has distinct characteristics. They have in common that it is radioactive waste that also contains non-radioactive toxic or hazardous substances. That means challenges can also come due to different legislations surrounding the waste type (on one hand due to the hazardous and toxic nature and on the other hand due to the radioactivity involved). Discussed were mostly lead and asbestos but also beryllium and mercury. Very low-level waste might be permitted to be disposed of at the same landfill as hazardous waste. Many countries are waiting for disposal options. Near surface disposal sites are where LLW with low or intermediate toxicity might be disposed and DGFs are applicable for HLW and wastes with higher toxicity.

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Glossary

Short-lived half life ($T_{1/2}$) < 30 years

Long-lived $T_{1/2}$ > 30 years

Very long-lived $T_{1/2}$ > thousand years

Abbreviations

DGF – deep geological facility

DNLEU - depleted natural and low enriched uranium

DSRS - disused sealed radioactive source

EW – exempt waste

FIBC - flexible intermediate bulk container

HASS - high-active sealed sources

HEU - high-enriched uranium

HLW - high level waste

ILW - intermediate level waste

LEU - low-enriched uranium

LILW - low and intermediate level waste

LIMS - large inventory member states

LLW - low level waste

MS - member states

NORM - naturally occurring radioactive material

NPP - nuclear power plant

NSDF - near surface disposal facility

RAW - radioactive waste

RR - research reactor

SF - spent fuel

SIER - spent ion-exchange resin

SIMS - small inventory member states

URT – Uranium/ Radium/Thorium

VLLW - very low level waste

VSLdW – very short-lived decay waste

WAC - waste acceptance criteria

1. Introduction

The generation of radioactive waste might be significantly different depending on the development of the nuclear programmes. Even though the technical issues for Large Inventory Member States (LIMS) and Small Inventory Member States (SIMS) are often similar, boundary conditions to consider for radioactive waste management may be completely different.

SIMS can be defined as countries without nuclear power programme (thereafter SIMS with Less Advanced Program (LAP)) or with a small number of nuclear power plants (thereafter SIMS with Most Advanced Program (MAP)). These countries have small amounts of waste from research reactors and from medicine, industry and research but low volume from nuclear power plants.

The objective of ROUTES Task 5 (“RWM solutions for small amounts of waste”) is, among others, to evaluate both predisposal and disposal strategies for small inventory member states (SIMS). Commensurate solutions are mostly not available for these countries, regarding safety, time and costs. Often, these countries have only limited expertise for planning, licensing, siting, design, construction, operation and closure of a disposal facility. And lastly, downscaling of existing disposal concepts for disposal of only a small amount of RAW is failing and special concepts for SIMS are needed.

Therefore, this second deliverable of Task 5 focuses on the necessary predisposal routes for different disposal options. The addressed disposal options are described within the first deliverable D9.10 (“ROUTES - Report about the knowledge for existing and potential disposal options for SIMS”) of Task 5 [1]. For the record, under the ROUTES framework [1], the EU Member States having a volume of conditioned or unconditioned radioactive waste between 20,000 and 25,000 m^3 are considered SIMS. Hence, SIMS are Austria, Croatia, Cyprus, Denmark, Estonia, Greece, Ireland, Latvia, Luxembourg, Malta, the Netherlands, Poland, Portugal, and Slovenia. The aim of this deliverable D9.11 is to compile the existing knowledge, shared during the workshop of this subtask.

Preparatory work to identify the most challenging predisposal routes was already done in a half-day workshop in December. In further preparation to the online workshop, a questionnaire was sent out to all SIMS. Additionally, selected large inventory member states (LIMS) also answered this questionnaire. The questionnaires were the basis for the discussion and structure of the workshop and the deliverable. Participants chose two different waste categories, where they had the most experience in, or were most interested in. With this information the organisers (NES and DMT) were able to set up a three-day online workshop.

The basis of this deliverable D9.11 comprises the results of the workshop organised within Subtask 5.2 in January 2022 (month 32 of EURAD). Participating countries of this workshop were Austria, Cyprus, Czech Republic, Denmark, France, Germany, Greece, Lithuania, the Netherlands, Poland, Portugal, Romania, Serbia, Slovakia and Slovenia. Information was also provided by the UK after the workshop. Therefore, nine SIMS and seven LIMS contributed to this deliverable. Serbia was invited to the workshop as being part of ERDO association and is per above definition a SIMS. Their experiences and best practices facilitated discussing the different aspects of the predisposal route. The methodology used to complete this deliverable is detailed in Chapter 2.

The deliverable is structured into three working chapters:

In Chapter 3, the choices for each respective predisposal step “pre-treatment”, “treatment” and “conditioning” are defined and described. Additionally, advantages and disadvantages, as well as examples of implementation for each choice are included.

The interdependencies between predisposal steps and disposal options are analysed in Chapter 4.

The implementation of predisposal steps for selected waste types is done in Chapter 5. It includes a section for each of the following waste types: concrete, disused sealed radioactive sources (DSRS), Spent Ion Exchange Resins (SIERs), spent fuel (SF) from research reactors (RRs), U/Ra/Th bearing waste and hazardous waste.

This deliverable is concluded by a summary in Chapter 6.

2. Methodology

This deliverable is based on the results of the Task 5.2 workshop in January 2022 (M32 of EURAD), evaluating predisposal routes applicable for the disposal options discussed in Task 5.1 and published in Deliverable D9.10 of the EURAD project [1]. This report was complemented using data provided by the participants after the workshop.

25 participants from 15 European countries attended the workshop, providing valuable information about the pre-disposal routes for selected waste types in their countries, sharing knowledge and discussing treatment approaches and objectives. Of these 25 participants, 13 participants represented a total of 9 SIMS countries. In two days and a half, the drafts for most parts of deliverable D9.11 were prepared and inputs were delivered, paving the way towards a comprehensive overview of waste treatment and disposal in SIMS. The content of this report was provided by both LIMS and SIMS participants, sharing valuable information both from the long-lasting experience in the field of waste management technologies and the challenges of economically, but safely managing small amounts of waste.

In detail, discussions during the workshop in January 2022 were held on the topics of:

- Predisposal steps definition and description (plenum discussion),
- Predisposal routes per waste type (working group discussion) and
- Predisposal steps for different disposal options (plenum discussion).

For each point the authors tried to find examples from SIMS, which was not always possible. In order to show some applicable solutions, also examples from LIMS were taken.

As the predisposal routes are highly dependent on the type of radioactive waste (RAW), six waste types have been selected for evaluation in a preparatory meeting in December 2021 (M31 of EURAD). These waste types were:

- Concrete,
- DSRS,
- Resin,
- SF from RRs
- U/Ra/Th bearing waste and
- Hazardous waste.

Each waste type was discussed in a half-day session with the aim to generate input for the following points:

- Definition of waste
- Predisposal waste treatment including Characterisation step and Treatment and conditioning
- Disposal Options
- Implication of disposal options on predisposal routes

Four of the six half day sessions were led by SIMS representatives, for Resin and DSRS a LIMS representative lead the session in order to transfer knowledge gathered in LIMS to SIMS.

Additionally, predisposal steps for a total of 11 disposal options have been analysed. The disposal options were selected in D9.10 [1].

3. Predisposal steps: Definition and Description

3.1 Introduction

Within this chapter, we will discuss the different distinct pre-disposal steps. General steps such as the collection, characterization and documentation of waste and principles such as minimization of waste, e.g. by reuse and recycling will not be discussed separately, they will be included in the distinct pre-disposal steps below. These general steps will not be discussed within this deliverable in detail and will only be addressed, if issues arise from these within the scope of this work. The example for each treatment step were mainly taken from SIMS if available. In order to provide an example for all applications also LIMS contributions were added.

In the following pictures you can find the different treatment steps for solid (see) and liquid waste (see *Figure 2*). The general steps of predisposal RWM include pretreatment (e.g., aiming to collect, segregate, chemical adjust or decontaminate the waste), treatment (e.g., aiming to reduce the volume, remove activity or change the waste composition) and conditioning (e.g., aiming to immobilise radionuclides, pack or overpack the waste). SIMS countries stated that before treatment and conditioning countries should apply the waste management hierarchy as proposed by the IAEA in [3] including waste prevention, waste minimisation, re-use of materials, recycling and disposal.

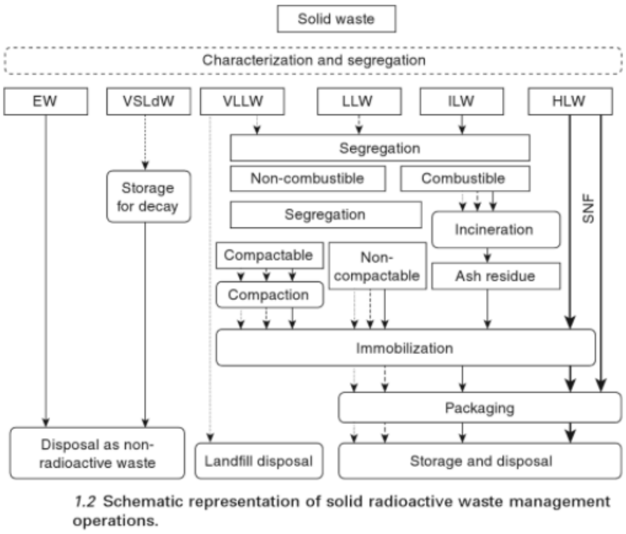

Figure 2 - Waste pre-treatment and treatment steps depending on the waste level for solid waste ([4], p. 7)

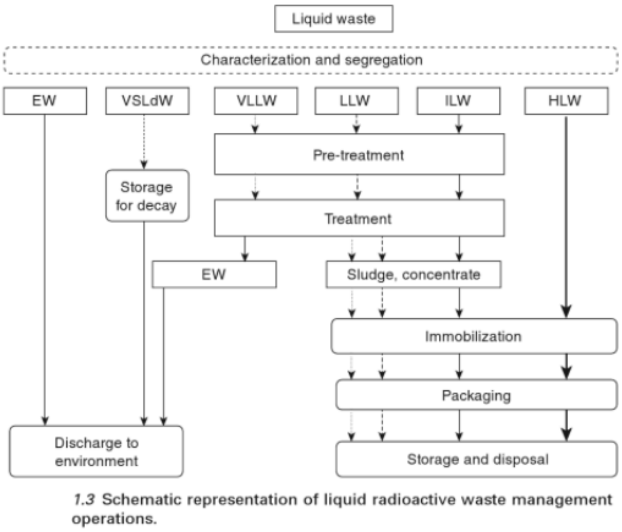

Figure 1 - Waste pre-treatment and treatment steps depending on the waste level for liquid waste ([4], p. 8)

3.2 Pre-Treatment

Within this section, selected pre-treatment options are discussed, which precede the further treatment and conditioning of the RAW. These pre-treatment options are sorting, fragmentation, decontamination, heat treatment and chemical precipitation.

3.2.1 Sorting

Waste is sorted into categories proposed by the respective country (solid/liquid, combustible/non-combustible etc.). It is a non-destructive method (for destructive see fragmentation).

The goal of sorting is waste minimization, preparation for treatment (either facility specific or waste specific, e.g. combustible waste/non-combustible waste) and to prepare for processing steps for individual waste.

The waste is sorted by :

- Chemical properties
- Physical properties
- Radiological characteristics/properties
- Release possibilities

Sorting is a prerequisite for most treatment steps with the advantage of allowing for waste minimization. It provides the opportunity for documentation of the raw waste as well as characterization before any treatment steps (this shall be done by the waste producer if applicable). In addition, there are small scale solutions and shared solutions available.

The disadvantage of hazardous material being present, is that sorting becomes more complex.

In France facilities are divided into different zones for contaminated waste/non-contaminated waste. This way not the entire facility has to be treated as a “RAW production zone” limiting the quantity of RAW waste produced.

In Austria waste producers have to sort the waste by waste categories due to waste acceptance criteria (WAC) for raw waste, or pay extra if it is not sorted ([5], [6]).

Sorting is done using facilities like sorting tables, glove boxes or sorting/manipulation boxes (caissons).

3.2.2 Fragmentation

Fragmentation is by definition a destructive process to reduce the size of parts for subsequent sorting or decontamination.

The goal of fragmentation is to minimize the waste, to get the waste into a form suitable for treatment from point of size and or contaminated part/non-contaminated part and to optimize waste treatment and conditioning.

The advantage of fragmentation is that it enables better sorting due to lower deviation in contamination, activation, material mix etc.

The disadvantage is that the material has to be handled more often.

Examples:

- Austria has caissons (equipped with a negative pressure ventilating system) where dismantling of larger equipment or fragmentation activities can be done by personnel in force-ventilated suits or using semi-automatic cutting techniques. ([5], [6])
- Germany has various cutting facilities [7] e.g. a cutting hall including a plasma cutting facility, a contact arc metal cutting facility as well as an oxy-fuel cutting facility ([8], p.13).

3.2.3 Decontamination

By the definition of the IAEA decontamination is: “*The complete or partial removal of contamination by a deliberate physical, chemical or biological process.*” ([9] p. 13).

By the definition of the IAEA chemical decontamination is: “*The removal or reduction of radioactive contamination from surfaces by chemical processes*” ([9], p. 13).

The goal of decontamination is the removal of surface adhesive radioactivity and waste minimization.

Advantages are the reduction of storage space needed and the reuse of decontaminated material (e.g. metals, depending on legal framework).

A disadvantage of decontamination for SIMS is that conditioning of the secondary waste product (e.g. high level waste (HLW)) might be challenging.

This means that the production of secondary waste during decontamination brings both an advantage as well as a disadvantage, which have to be weighed against each other in each specific case. On one hand, it has the advantage that the waste volume can be reduced. On the other hand, it has the disadvantage that the specific activity of the secondary waste can be higher, which makes handling the waste more difficult.

Examples:

- Decontamination chambers, where RAW can be cleaned by sandblasting, water blasting or chemical cleaning (Austria – water cleaning ([5], [6]), Germany – sand, water and chemical cleaning [11])

3.2.4 Heat Treatment

The IAEA provides the following definition for calcination: "*A process of drying and heating substances in air, to sufficiently high temperatures, so as to produce oxides of the constituents. A technique usually employed for processing of residues from evaporations of liquid wastes*." ([9], p. 7)

The IAEA's definition of evaporation reads: "Concentration of a liquid by conversion of some fraction of the volatile material content to the vapour state by latent heat. Evaporation, a treatment method, is used to concentrate some types of radioactive solutions." ([9], p. 18)

Drying means by definition: changing a material from liquid to solid by any treatment.

ONLY drying, evaporation and calcination are considered heat treatment. For incineration as pre-treatment for later on compaction and/or cementation see "incineration" (3.3.1). For in-drum drying see "drying" (3.3.3).

The goal of heat treatment is the minimization of waste, treatment of liquids, removal of liquids in RAW and immobilization of waste.

Advantages (for SIMS) are that heat treatment is the best way to stabilize liquid waste, it is a possibility to change liquid waste to a solid form and so to a physically stable form. This facilitates a storage of these waste forms before further treatment.

The disadvantage (for SIMS) is that having a complete treatment plant built is expensive.

Shared solutions for SIMS, which means sharing a facility with another country, are possible if the legislation allows it and public opinion approves – for examples see ROUTES Task 6 [12]. Mobile solutions for SIMS are favourable.

Examples:

- Konus drying facility in Austria (evaporation of liquids in a rotating drying drum) ([5], [6])
- Concentrate drying facility in Germany [14]

3.2.5 Chemical Precipitation

The IAEA definition of chemical precipitation reads: "*A standard chemical method that can be used in the treatment of liquid wastes where radionuclides are removed from the liquid by either forming or being carried by the insoluble product of a chemical reaction made to occur within the liquid*." ([9], p. 32)

The goal is the reduction of the amount of liquid waste (waste containing large amounts of water).

The advantage here is that mobile facilities do exist, which is the only solution for SIMS, since the specific facility needed is not feasible for them due to costs. It is also a good option for countries producing radio – isotopes.

A disadvantage is that chemical precipitation can only be used for known chemical compositions.

Examples:

- Poland and Greece: Ba Carbonate was used (for Cs) with a three stage osmoses in former times, now a single layer evaporator is used

3.3 Treatment

By the IAEA treatment is defined as "*Operations intended to benefit safety and/or economy by changing the characteristics of the waste. Three basic treatment objectives are: volume reduction, removal of radionuclides from the waste and change of composition. Treatment may result in an appropriate waste form*." ([9], p. 44)

3.3.1 Incineration

The IAEA definition of incineration is: "*A waste treatment process of burning combustible waste to reduce its volume and yield an ash residue*." ([9], p. 23)

The goals of incineration are waste minimization and treatment of liquids (in an incinerator).

Incineration brings several advantages (for SIMS) since it is the best way to minimize flammable liquid waste and it prevents rotting and fermentation (gas production) of the biological RAW.

Disadvantages (for SIMS) are the high expenses. Therefore, it is usually only implemented if a nuclear power plant (NPP) program is/was planned.

Shared solutions for SIMS are available – for examples see Routes Task 6 [12].

Examples:

- Austria has an incineration facility in place where low and intermediate level waste (LILW) is burned if burnable. Liquids are being treated there as well. In case of non-combustible liquids there are being dispersed into the flame of the gas-burner. ([5], [6]).
- Germany: For the combustion of low radioactive combustible waste the Juelich Incineration Process has been developed. It is a two-step-process consisting of a medium temperature pyrolysis step and an oxidation step. The pyrolysis gases are sucked through the waste column and pass the glowing bed of pyrolysis coke. Here high molecular compounds are cracked. In the oxidation step the pyrolysis gas and the non-gasified rest of pyrolysis coke is completely oxidized. The ash and the off-gas are of high quality. Radioactive dust and aerosols are retained by a simple dry filtration technique consisting of several steps (historic information).
- Furthermore, private companies do offer the incineration service in Germany (see [13])

3.3.2 Compaction

By the IAEA definition compaction is: "*A treatment method where the bulk volume of a compressible material is reduced by application of external pressure — hence an increase in its density (mass per unit volume)*". ([9], p. 9)

The goal is to reduce the volume of the waste.

Advantages (for SIMS) are said volume reduction, the simplicity of the system's application (from a technical point of view), the removal of free liquids, the destruction of bottles with (possibly) liquid content (e.g. in mixed wastes) and the fast technology.

Disadvantages (SIMS) are the costs of installation (funds must be available).

Advantages and disadvantages need to be weighed for each specific waste type. For example, the question arises whether compaction is really necessary for small amounts of waste. Sorting might be easier for small amounts as alternative to compaction, but it can not replace conditioning and a compaction conditioning method. Also, it is a non-reversable method. Shared and mobile solutions are available.

Examples:

- Austria: in drum compaction system (100 t press) ([5], [6])
- Germany, Forschungszentrum Karlsruhe 15 MN, Jülich

3.3.3 Drying

For the definition of drying see the section on "heat treatment" (3.2.4). Drying under vacuum with reduced temperature is possible.

The goals are to avoid gas production, corrosion etc., to minimize waste, to remove free liquid and to hinder fermentation by the removal of liquid in organics.

An advantage of this technique compared to other methods is that here the specific equipment needed is generally affordable.

A disadvantage, however, is that drying of low amounts of waste is expensive but shared facilities (for in-drum drying) are possible and (e.g. in Germany) available.

Examples:

- Germany: In drum drying systems for resins/sludges/liquid waste, PETRA drying facility [15], in-drum drying e.g. in MOSAIK® casks [16] by KETRA drying facility [17]
- Austria: 32 drum drying facility, 1-drum drying ([5]], [[6])

3.3.4 Solidification

The IAEA definition for solidification is: "*Immobilization of gaseous, liquid or liquid-like materials by conversion into a solid waste form, usually with the intent of producing a physically stable material that is easier to handle and less dispersible. Calcination, drying, cementation, bituminization and vitrification are some of the typical ways of solidifying liquid waste*." ([9], p. 40)

However, bituminization is outdated, and vitrification is associated with high costs.

The goal is, as mentioned by the IAEA in the definition of solidification is a physically stable form, since it is easier to handle.

The advantage is that the material is stabilized and therefore easier to handle.

The disadvantage of vitrification as technique for solidification is that it is in most cases not economic for LILW.

Shared facilities could be used if they are available.

Examples:

- Switzerland: Plasma Facility[18]
- France: vitrification facility for HLW [20]

3.4 Conditioning

The IAEA's definition of conditioning is: "*Those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, enclosure of the waste in containers, and, if necessary, providing an overpack*." ([9], p. 10)

3.4.1 Super Compaction

IAEA does not specify super compaction, but only has defined compaction in general: "*A treatment method where the bulk volume of a compressible material is reduced by application of external pressure — hence an increase in its density (mass per unit volume)*." ([9], p. 9)

In [4], super compaction is defined as volume reduction process where waste is placed inside a container, which is then crushed in an hydraulic press operating at 1000 t or higher. This force is sufficient to crush the container and its contents. The resulting pellet is then placed in a container or overpack for storage or disposal. Volume reduction factors of 2 to greater than 10 are typical, depending on the material being compacted.

The goals of super compaction are volume reduction and matrix stability.

Advantages are that a stable matrix is achieved, the waste volume is reduced, free liquid water is removed and also shared solutions exist.

Disadvantages are that the technique is costly and complex (see section "compaction" (3.3.2)). Also, a facility is necessary that is able to work with open radioactivity, that means e.g. decontamination must be possible.

Examples:

- Germany: Hydraulic supercompactor Fakir [22] for supercompaction of drums (mobile facility)
- Austria: 1500 t hydraulic supercompactor by Westinghouse ([5], [6])
- Further supercompactors can be found in [26], p.31

3.4.2 Cementation

By the IAEA definition cementation is "*Immobilization of gaseous, liquid or liquid-like materials by conversion into a solid waste form, usually with the intent of producing a physically stable material that is easier to handle and less dispersible. Calcination, drying, cementation, bituminization and vitrification are some of the typical ways of solidifying liquid waste*." ([9], p. 40) This specifies to either building a matrix around the drums (e.g. in a container) or the production of stable drums.

Its goals are the stabilization of drums or waste and the solidification of sludges or free liquids.

Advantages are: the increase of safety, e.g., due to high radiation stability, encapsulation of radionuclides, impact and fire resistance of waste forms. A radon barrier is built to retain at least for 10 times the Ra-half-life. A high flexibility with regard to the waste treated is given. This method is widely used for a variety of low-level waste (LLW) and intermediate level waste (ILW). The costs are low and the process is simple. There is no heat emission involved and thus it precludes volatile emissions. Cementation is seen as a confinement for radionuclide due to the waste matrix interaction.

Disadvantages are the increased volume as the waste volume is smaller compared to the matrix volume. There remains crystal water in cement which might result in corrosion. Some fission and activation products show low retention in cement. It is not well suited for organic materials and materials with high salt content. The possibility of free liquids remains.

Example:

- Austria:

  - Homogeneous cementation: in-drum cementation facility (e.g. for sludges and salts)
  - Inhomogeneous cementation: cementation of 100 l drum in 200 l drum (e.g. for HLW, α-contaminated waste, other special waste, legacy waste) ([5], [6]). Inhomogeneous cementation of waste was done historically in Austria and produced legacy waste drums which are now being reconditioned.
- Netherlands: COVRA operates a cementation station for LILW ([23], [24])
- Czech Republic: LILW is cemented before transfer to disposal [25]

3.4.3 Encapsulation

The IAEA defines encapsulation as *"(1) Immobilization of dispersed solids (e.g. ash or powder) by mixing them with a matrix material in order to produce a waste form. […]. (2) Emplacement of a solid waste form (e.g. spent fuel assemblies) in a container."* ([9], p. 17)

The aim is to achieve a stable matrix in a final disposal cask, the safe encapsulation of high-risk waste (e.g. α-radiation, sources) and to create a safety barrier.

It has the advantage of providing a solution for ashes and high risk (radiation) waste as well as an easy way to have a save container with waste if the WAC are unknown.

Its disadvantage is that WAC are needed for the final conditioning if encapsulation is the final step before disposal.

Examples:

- Austria: ash and sources are encapsulated ([5], [6])
- Switzerland: Plasma oven produces encapsulated LILW ([18],[19])

3.4.4 Vitrification

The IAEA defines vitrification as "*The process of incorporating materials into a glass or glass-like form. Vitrification is commonly applied to the solidification of liquid high level waste from the reprocessing of spent fuel*." ([9], p. 46)

The goal of vitrification is the immobilization of radionuclides in waste. It has the advantage of providing a stable waste matrix for all wastes (LLW, ILW, HLW).

The disadvantage of this technique is the high costs. It is not feasible for SIMS except as a shared solution.

Examples:

- Usually connected to a reprocessing facility (except Plasma Oven in Switzerland).
- France: vitrification facility for HLW [20]

4. Implications of Disposal Option on Predisposal Routes

Within this section, waste type specific predisposal routes for available disposal options will be discussed. The predisposal routes discussed are valid for radioactive waste. Waste generated during accidents are not covered here, as for these wastes special solutions might be needed. In general, disposal options can be classified in three groups: [1]

- On Surface
- Near Surface (a few tens of meters)
- Geological (a few hundred meters to a few thousand meters)

For these classes, different options will be addressed here.

Concrete waste

As concrete waste in general is a large-volume and low-activity waste, a general first step is the clearance of it, if possible. For conditioning, the concrete blocks or fragments can be put inside containers or packed in Big Bags without further stabilising matrix. The pH-value of the waste has to be considered in order to avoid corrosion processes of the packaging material or other degradation of safety barriers. Also, other toxic characteristics of concrete should be considered.

In *Table 1* the implications of different disposal options for concrete waste on the predisposal route are shown.

Disused Sealed Radioactive Source (DSRS)

Five categories of disused sealed radioactive sources exist, which are classified e.g., in IAEA GSG-1 [27]. Distinctions in the disposal options are, i.a., that category 1 and 2 sources cannot be disposed of in a near surface disposal facility (NSDF) due to their high activity. For DSRS in general, but especially for category 1 and 2 sources and long-lived sources, reuse or recycling is a favourable option. Overall, several hazards should be considered, such as generation of gases like hydrogen, tritium, radon and krypton. Conditioning options for sources can be cementation or polymer fixation for near surface disposal. DSRS can be dismantled and placed in drums for long term interim storage or dismantled and encapsulated for disposal.[33]

The implications of different disposal options for DSRS on the predisposal route are listed in *Table 2*.

Spent Ion Exchange Resin (SIER)

There exist different options regarding treatment of SIERs. First option is cementation, although this treatment increases the waste volume by a factor of approximately ten. Another predisposal treatment is the polymerization of the SIERs by inserting the SIERs in a polymer matrix. Like cementation, this treatment increases the volume of the waste. A reduction in waste volume can be achieved by incineration or super-compaction. SIERs can also be put into specially licensed containers, for which the SIERs only has to be dried but not solidified. The advantage of this treatment is that there is no change in volume, however the radionuclides are not secured in a matrix.

In *Table 3* the implications of different disposal options for SIERs on the predisposal route are represented.

Spent fuel (from research reactors)

Reprocessing of SF from research reactors should be carefully considered and needs to be covered by the national law. This includes the availability of technology, the possibility of reuse in reactors, costs, including expenses for transport and secondary waste. Public acceptance needs to be taken into account separately.

The implications of different disposal options for SF on the predisposal route are presented in *Table 4*.

U/Ra/Th bearing waste (URT-waste)

The definition of this waste type is strongly depending on the country it is handled. In *Table 13* this classification per country is listed. In general, the amount of URT-waste is high. Most of the waste can be disposed of on public landfills as exempted waste, small amounts on a NSDF and a very small amount needs a geological disposal solution, such as URT-waste with high activity as in the case of URT-waste from Zirconium production. Recycling of URT- waste is also possible, as some naturally occurring radioactive material (NORM) can be used in the production of other materials. E.g., depleted uranium can be used for shielding.

In case of components with high URT-waste activity decontamination and removal of scales or melting of the metals in a special foundry is done. Alternatively, super-compaction of metals is possible. RAW is packaged and dried or cemented, if necessary. In general, cementation is avoided until a final decision about the disposal strategy is made.

The implications of different disposal options for URT-waste on the predisposal route are summarized in *Table 5*. The radionuclides U_{nat}, Th_{nat} and ^{226}Ra are not covered in this section.

Hazardous waste

In accordance with national laws, non-radioactive hazardous wastes can be disposed of at special landfills or other appropriate facilities. Very low-level waste (VLLW) might be permitted to be disposed of at the same landfill as hazardous waste.

The major categories of radioactive hazardous wastes are asbestos and lead. If asbestos waste is only contaminated, decontamination, clearance, and subsequent disposal together with non-radioactive hazardous waste might be possible based on national regulations. For activated lead, recycling after melting, e.g., for production of shielding, might be available. Also, storage for decay should be considered, if only short-lived RN are present.

The safety assessment of a NSDF should also include the possibility of additional toxic substances and hazardous materials. Restrictions can occur on total amount of specific hazardous materials for a disposal facility, as hazardous wastes are often covered by another responsible authority than radioactive waste. Therefore, contradictory restrictions might occur which must be considered during characterization of waste. In some cases, disposal facilities may restrict the disposal of radioactive waste with hazardous properties [10].

Below in *Table 6* the implications of different disposal options for hazardous waste on the predisposal route are shown.

Concrete waste		
On Surface	Long-term interim storage	Recommended if no long-lived nuclides exist
Near Surface disposal options	Cavern and bunker	Suitable Steps: 1. Characterisation and segregation 2. Depending on the specific activity cutting or decontamination and clearance of clearable parts 3. Crushing of concrete waste Can be directly filled in waste container or also be used as backfill material in containers or void spaces inside the disposal facility.
	Tunnel and galleries	Suitable Steps: 1. Characterisation and segregation 2. Depending on the specific activity cutting or decontamination and clearance of clearable parts 3. Crushing of concrete waste Can be directly filled in waste container or also be used as backfill material in containers or void spaces inside the disposal facility
	Borehole	Not suitable due to waste volume
	Silos	Recommended for LILW Steps: 1. Characterisation and segregation 2. Depending on the specific activity cutting or decontamination and clearance of clearable parts 3. Crushing of concrete waste Can be directly filled in waste container or also be used as backfill material in containers or void spaces inside the disposal facility.
Geological[1] disposal options	Used mine	More suitable for higher specific activities Steps: 1. Characterisation and segregation 2. Depending on the specific activity cutting or decontamination and clearance of clearable parts 3. Crushing of concrete waste Can be directly filled in waste container or also be used as backfill material in containers or void spaces inside the disposal facility.

Geological[1] disposal options	Deep cavern	More suitable for higher specific activities Steps: 1. Characterisation and segregation 2. Depending on the specific activity cutting or decontamination and clearance of clearable parts 3. Crushing of concrete waste Can be directly filled in waste container or also be used as backfill material in containers or void spaces inside the disposal facility.
	Use of new mines	More suitable for higher specific activities Steps: 1. Characterisation and segregation 2. Depending on the specific activity cutting or decontamination and clearance of clearable parts 3. Crushing of concrete waste Can be directly filled in waste container or also be used as backfill material in containers or void spaces inside the disposal facility.
	Tunnel	More suitable for higher specific activities Steps: 1. Characterisation and segregation 2. Depending on the specific activity cutting or decontamination and clearance of clearable parts 3. Crushing of concrete waste Can be directly filled in waste container or also be used as backfill material in containers or void spaces inside the disposal facility.
	Deep Borehole	Not suitable due to waste volume
	Very deep borehole	Not suitable due to waste volume

Table 1 - Implications of Disposal Option on Predisposal Routes: Concrete

DSRS		
On Surface	Long-term interim storage	Sorting according to activity (category) and half-life, storage until clearance in case of short half-life nuclides or low activity sources
Near Surface disposal options	Cavern and bunker	Dismantling and collection of sources in a special shielded container, if necessary, cementation, polymer fixation; not recommended for high-active sealed sources (HASS)
	Tunnel and galleries	Dismantling and collection of sources in a special shielded container, if necessary, cementation, polymer fixation; not recommended for HASS
	Borehole	Recommended, if only sources exist as waste, dismantling and collection of sources in standardized capsule and container necessary to be performed
	Silos	Dismantling and collection of sources in a special shielded container, if necessary, cementation, polymer fixation; not recommended for HASS
Geological[1] disposal options	Used mine	Recommended for HASS Dismantling and collection of sources in a special shielded container, if necessary, cementation, polymer fixation
	Deep cavern	Recommended for HASS Dismantling and collection of sources in a special shielded container, if necessary, cementation, polymer fixation
	Use of new mines	Recommended for HASS Dismantling and collection of sources in a special shielded container, if necessary, cementation, polymer fixation
	Tunnel	Recommended for HASS Dismantling and collection of sources in a special shielded container, if necessary, cementation, polymer fixation
	Deep Borehole	Recommended, if the radioactive waste inventory contains only sealed radioactive sources incl. HASS, dismantling and collection of sources in standardized capsule and container necessary to be performed
	Very deep borehole	Not recommended, if radioactive inventory contains only sealed radioactive sources exist

Table 2 - Implications of Disposal Option on Predisposal Routes: DSRS

SIERs		
On Surface	Long-term interim storage	Only applicable if the major radionuclides are short-lived
Near Surface disposal options	Cavern and bunker	Cementation or polyester fixation
	Tunnel and galleries	Cementation or polyester fixation
	Borehole	Not recommended
	Silos	Cementation, polyester fixation, drying, incineration
Geological[1] disposal options	Used mine	Cementation, drying, incineration plus super compaction
	Deep cavern	Cementation, drying, incineration plus super compaction
	Use of new mines	Cementation, drying, incineration plus super compaction
	Tunnel	Cementation, drying, incineration plus super compaction
	Deep Borehole	Not recommended
	Very deep borehole	Not recommended

Table 3 - Implications of Disposal Option on Predisposal Routes: SIERs

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[1] Recommended in case of significant content of very long lived nuclides ($T_{1/2}$ > 1.000 years)

Spent fuel		
On Surface	Long-term interim storage	Necessary for reducing heat production and for decay before disposal
Near Surface disposal options	Cavern and bunker	Not recommended
	Tunnel and galleries	Not recommended
	Borehole	Not recommended
	Silos	Not recommended
Geological[1] disposal options	Used mine	Package suitable for fuel element and drying, if loading under water. Addition of adsorbents in case leakage of fuel element can't be excluded
	Deep cavern	Package suitable for fuel element and drying, if loading under water. Addition of adsorbents in case leakage of fuel element can't be excluded
	Use of new mines	Package suitable for fuel element and drying, if loading under water. Addition of adsorbents in case leakage of fuel element can't be excluded
	Tunnel	Package suitable for fuel element and drying, if loading under water. Addition of adsorbents in case leakage of fuel element can't be excluded
	Deep Borehole	Recommended, depending on waste package dimension and safety assessment
	Very deep borehole	Depending on type of SF, waste package dimension and safety assessment

Table 4 - Implications of Disposal Option on Predisposal Routes: Spent fuel

U/Ra/Th bearing waste		
On Surface	Long-term interim storage	Not recommended, only for interim storage until disposal
Near Surface disposal options	Cavern and bunker	Depending on the specific activity (some hundred Bq/g s. WAC Centre Morvilliers) Packaging in Big Bags or containers
	Tunnel and galleries	Depending on the specific activity (some hundred Bq/g) Packaging in Big Bags or containers
	Borehole	Not generally recommended due to dimensions, option applicable for sealed sources
	Silos	Depending on the specific activity (some hundred Bq/g) Packaging in Big Bags or containers
Geological[1] disposal options	Used mine	Possible, necessary only for components with high specific activity from NORM industries
	Deep cavern	Possible, necessary only for components with high specific activity from NORM industries
	Use of new mines	Possible, necessary only for components with high specific activity from NORM industries
	Tunnel	Possible, necessary only for components with high specific activity from NORM industries
	Deep Borehole	Not recommended
	Very deep borehole	Not recommended

Table 5 - Implications of Disposal Option on Predisposal Routes: U/Ra/Th bearing waste

Hazardous waste		
On Surface	Long-term interim storage	Storage until clearance, otherwise not recommended
Near Surface disposal options	Cavern and bunker	Radiological and chemical characterization needed. Treatment and packaging should fulfil both regulations for radioactive and non-radioactive substances.
	Tunnel and galleries	Radiological and chemical characterization needed. Treatment and packaging should fulfil both regulations for radioactive and non-radioactive substances.
	Borehole	Not recommended for large amounts. Radiological and chemical characterization needed. Treatment and packaging should fulfil both regulations for radioactive and non-radioactive substances.
	Silos	Radiological and chemical characterization needed. Treatment and packaging should fulfil both regulations for radioactive and non-radioactive substances.
Geological[1] disposal options	Used mine	Radiological and chemical characterization needed. Treatment and packaging should fulfil both regulations for radioactive and non-radioactive substances.
	Deep cavern	Radiological and chemical characterization needed. Treatment and packaging should fulfil both regulations for radioactive and non-radioactive substances.
	Use of new mines	Radiological and chemical characterization needed. Treatment and packaging should fulfil both regulations for radioactive and non-radioactive substances.
	Tunnel	Radiological and chemical characterization needed. Treatment and packaging should fulfil both regulations for radioactive and non-radioactive substances.
	Deep Borehole	Not recommended for large amounts. Radiological and chemical characterization needed. Treatment and packaging should fulfil both regulations for radioactive and non-radioactive substances
	Very deep borehole	Not recommended

Table 6 - Implications of Disposal Option on Predisposal Routes: Hazardous Waste

5. Waste type discussion

During the workshop in January 2022, different waste treatments for selected waste types in the attending SIMS and LIMS were discussed. The discussed waste types have been selected during a preparatory meeting in December 2021. Available for selection were all waste types previously proposed by SIMS representatives and indicated as challenging for their country. Therefore, only wastes classified as challenging by SIMS are discussed within this deliverable. This chapter summarises the results of the discussions during the workshop in January 2022 and the information provided after the workshop. It needs to be emphasised, that the time dedicated to the elaboration of common conclusions was limited and therefore the evaluations in the following need further common work to be consolidated.

Further analysis of the predisposal steps for selected wastes types can be found in ROUTES Deliverable D9.21 [28].

5.1 Selection of waste types

This section focuses on six selected waste types:

- Concrete,
- DSRS,
- SIERs,
- SF from RR,
- URT bearing waste and
- Hazardous waste.

These waste types have been selected by voting in the course of the preparatory workshop of Task 5.2 in December 2021. The voting and the evaluation of the voting has been done using the tool “Mentimeter” by Mentimeter AB (publ). Available for voting were the waste types defined in ROUTES Task 2, which aimed to aggregate a list of challenging wastes. In addition, the waste type “hazardous waste” was selected. This was based on the proposal of one attendee of the preparatory workshop representing a SIMS and was accepted by the group.

If tables presented in the following sections are missing information on specific countries, the authors did not receive any information concerning the specific topic.

For each waste type the aftermath mentioned bullet points were discussed. The following sections summarizes the results achieved during the workshop. Especially the points “Disposal Options” and “Implications of disposal options on predisposal routes” reflect the view of the participants. The point “Waste Inventory for the waste type” was fed with information from the first ROUTES Questionnaire distributed to participants in 2019, information from D 9.5 [29] or with information handed in by the workshop participants after the workshop in a separate questionnaire.

- Definition of waste
- Waste Inventory for the waste type
- Predisposal waste treatment – Characterisation and Pre-Treatment
- Predisposal waste treatment - Treatment and conditioning
- Disposal Options
- Implication of disposal options on predisposal routes

5.2 Concrete waste

5.2.1 Definition of waste type

Concrete waste falls under the challenging waste category of “decommissioning wastes” within ROUTES D9.5 [29]:

> « *According to the responses from the ROUTES questionnaire, Members States consider that Decommissioning wastes represent a widespread class of challenging wastes that can correspond to construction materials (e.g., rubble, contaminated concrete), soils, scrap metal, wood, tools and safety equipment or even contaminated liquids*. » ([29], p. 44)

With the aim of unambiguity, it should be mentioned here that, although the terms cement, cementitious material and concrete often are used interchangeably, cement is an ingredient of concrete and used as raw material and cementitious material is concrete without aggregate material which gives it structural properties. This document uses the term concrete when referring to the waste type, while cemented waste refers to conditioned waste utilizing cementation as immobilization process. Within this section only contaminated and/or activated concrete such as building concrete, reinforced concrete and heavy concrete will be discussed. Additionally, it is assumed that there will be metallic parts in the concrete from construction but possibly also other inserts (e.g., pipes, cables).

The two major origins of concrete wastes are decommissioning projects and legacy waste. Therefore, this waste stream can be divided into two sub-categories:

- Raw waste from decommissioning projects – this category includes
    - Activated concrete (heavy concrete from biological shielding) and
    - Contaminated concrete.
- Legacy waste and other conditioned wastes – this category includes
    - Cemented waste as originating from prior immobilization treatments (especially legacy waste in reconditioning projects which might include residual free liquid water or crystal water) as well as
    - Containers (packaging), which are not waste per se but could become waste in reconditioning projects.

5.2.2 Waste inventory of participating member states

The following table (*Table 7*) summarises the waste inventory of concrete waste as well as predisposal treatment and disposal options of different countries. Only countries providing information are included.

Country	Waste Inventory	Predisposal Treatment	Disposal Option
Austria	Cement is present as waste from decommissioning projects (around 200 t), as homogenous cemented waste (about 3000 drums, e.g. cemented sludges, ashes) and in the form of shielding (for mostly 100 litre drums cemented into 200 litre drums).	Raw concrete waste is treated by drying and super-compaction. The other waste of this type is from cemented waste that is undergoing a reconditioning project. The concrete that makes up the shielding will be mostly cleared.	No final disposal or disposal concept yet (for any kind of RAW). An advisory board has been formed in 2021 to start making suggestions for possible concepts.
Czech Republic	Not estimated (total decommissioning waste volume is 11000 m^3)	Currently not performed (until end of operation of the NPP)	Surface repository Dukovany (36 vaults available for all decommissioning waste)
Denmark	Concrete waste inventory makes up 840Mg and is a large part of the entire inventory	Reversible packing On stock in a steel container	No disposal facility yet
Germany	No information available	Crushing and packaging	Deep geological disposal (DGF), if no clearance is possible
Lithuania	From 50.000 up to 150.000 m^3 of waste, mainly VLLW that occurred during dismantling activities of building structures	Cementation for LILW and disposal in near surface repository (NSDF) Crushing and packaging to flexible intermediate bulk container (FIBC) for VLLW	Disposal at landfill facility or conditional free release for VLLW LILW will be disposed in NSDF
Netherlands	Concrete (mainly LILW) estimated to be a small portion of LILW, around 10% of the total volume according to OPERA Waste families report [31] The total volume of LILW is estimated to be 12,000m^3.	The perforated 90 l drums are compacted with a pressure of 15,000 kN. The resulting pucks are loaded in 200 l waste drums. On average between 4-7 pucks are loaded per drum (about 250 kg of waste). The residual space around the compact waste is filled with concrete; a maximum in size of coarse aggregate of 8 mm is used to fill small voids, about 250 kg of concrete is casted	Geological disposal facility (DGF)

		in these waste drums. The maximum total weight of 200 l drums is 750 kg	
Republic of Serbia	No significant amounts at this moment (significant amounts will be generated in the future due to decommissioning of the RA RR and old waste storages.)	Currently not performed	No disposal facility yet
Romania	Will be generated in the future due to decommissioning activities	N/A	N/A
Slovakia	VLLW (with the activity being slightly over the free release level) and LLW, from NPP A1 as well as from V-1, both in Jaslovske Bohunice	Incombustible waste can be compacted by a high-pressure press. The final product of the predisposal treatment is a fiber-reinforced concrete container filled with a cement mixture, or solid waste covered with a cement mixture. [32]	LLW repository in locality Mochovce
UK	Of the non-conditioned decommissioning waste concrete and rubble will add up to 2,490,000 m^3 of VLLW 457,000 m^3 of LLW and no ILW	Grout encapsulation is standard	LLW Repository for LLW (no specific requirements for concrete) DGF for ILW

Table 7 - Waste Inventory of SIMS and LIMS: Concrete[2]

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[2] The states not listed either do not have waste of this type or did not send the adequate information.

5.2.3 Predisposal waste treatment: Characterisation and Pre-treatment

The two major challenges in the characterization of concrete waste from decommissioning projects are the anticipation of final waste volume and the determination of compliance with clearance values. Below some country examples are given:

- For Denmark, predicting the quantities of concrete which includes the quantity of LLW and quantity of uncontaminated material, to be managed as a result of decommissioning activities, is a current issue and to be further determined.
- For the UK 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.
- Germany stated that clearance is important for waste minimization e.g. for concrete structures. In the case of not clearable concrete, it is possible to use contaminated concrete as filling or shielding material for waste packages.
- In the Czech Republic the regulator allows the clearance of the waste according to the general clearance levels.

In general, characterization is done using in-situ gamma scanning, sampling (e.g., for ^{3}H activity and determination of nuclide vectors/scaling factors), as well as the utilization of specialized clearance measurement devices e.g.[21]. The importance of adequate sampling methods should be emphasized here, as the material might not be homogeneous, and hotspots could remain unnoticed.

Pre-treatment steps are

- Measurements, preferably be made on the standing structure
- Segmentation depending on the results of the above described measurement.
- Surface-Decontamination and "activity specific cutting" off of blocks for clearance as well as
- Segregation of reinforcement materials and inclusions (like pipes), after which iron can be sent to a melting facility
- Crushing of segmented waste (e.g. to get materials for filling-up spaces)
- Sorting and characterization in conveyor belt type facilities (e.g. soil measurement facility in Austria, NUKEM facility for α-bearing soil in Germany)

5.2.4 Predisposal waste treatment: Treatment & Conditioning

The treatment and the conditioning steps of concrete waste are shortly summarized below:

- Drying (especially if wet techniques were used for cutting/milling)
- Supercompaction of rubble: in general, optimal if reduction to 30% or less of the original volume can be achieved but with the disadvantage of additional packages and costs
- In Germany, Konrad containers are used for concrete structures, which can be fixed by cementation (especially when there is no intention of crushing the concrete before filling it in the container).

In general, major difficulties concern the treatment of decommissioning wastes as they consist of very large volume waste streams and secondly to the fact that concrete and rubble are generally chemically inert and stable to heat. They are therefore not good candidates for thermal treatment or volume reduction treatments but do have some re-use potential (e.g. as void fillers following decommissioning activities). Therefore, waste minimization is of great importance (see for example “FOCUS 6 – Strategy of waste minimization of decommissioning waste in Czech Republic" ([29], p. 47)). This continues with the waste package. Safety criteria for the waste package must be fulfilled as well (old drums could be put inside an overpack).

The Czech Republic serves as an example. Here, national standards for the concrete matrix (solidification) and acceptance criteria/limits for concrete mixes used for waste solidification are specified in the relevant instruction for the safe repository operation. They place requirements on properties such as leachability, compressive strength and the future quantity and activity of activated concrete.

In France there is no clearance threshold in force. 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 wastes for a NSDF.

5.2.5 Disposal options

Disposal options depend on WAC and the waste activity. Bulk material is likely VLLW and/or LLW and therefore NSDF might be sufficient. Disposal with ILW can be viable under certain conditions, e.g. as filling material.

Another idea is to use it to produce containers (similar to the use of metals) or as shielding materials (inlay) inside the containers (i.e. to be used as aggregate in production of concrete fillings of containers). In the Czech Republic, low contaminated concrete is considered for stabilizing/closing off the mine or disposal facilities (since concrete is needed for these tasks anyway) and as material used in construction of technical barriers of the facilities. Contaminated concrete is further considered as material for the construction of new facilities (inside controlled areas). However, this could be an issue for decommissioning. [29]

In France, for VLLW the reference solution is a centralized surface disposal, but complementary routes and alternative disposal options are considered e.g. simplified disposal capacities on or near dismantling sites, with the advantage that transportation of high volumes of non-harmful waste across the country could be avoided. Also, co-disposal with conventional industrial wastes would be considered.

5.2.6 Implications of disposal options on predisposal routes

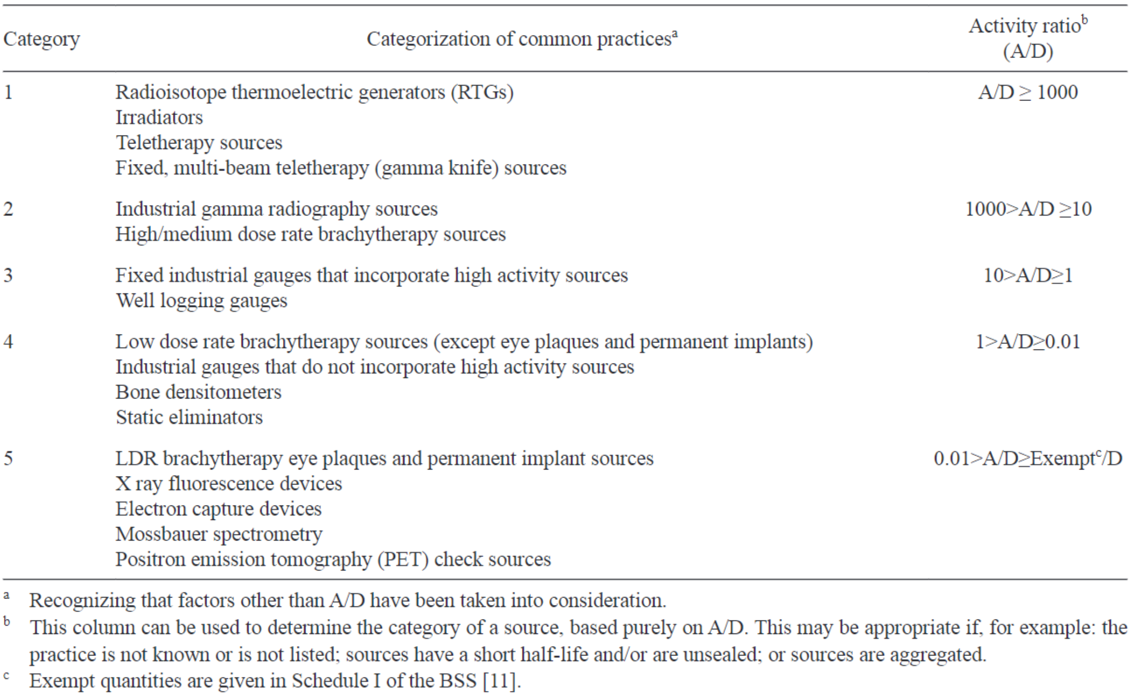
The implications of disposal options on predisposal routes include that large volumes need large space. This, again, places the focus on volume minimization. Also, the container size (especially important for cutting off blocks) needs optimization between decommissioning use and disposal (WAC) and the space in containers needs to be filled up.

Furthermore, sufficient characterization is necessary or even obligatory.

5.3 DSRS

5.3.1 Definition of waste type

The definition of a disused sealed radioactive source (DSRS) from the IAEA Safety Glossary reads: "*A radioactive source that is no longer used, and is not intended to be used, for the practice for which an authorization has been granted.*" ([3], p. 220). Further, the IAEA defines 5 categories of radioactive sources which are shown in *Figure 3*:



Category	Categorization of common practices[a]	Activity ratio[b] (A/D)
1	Radioisotope thermoelectric generators (RTGs) Irradiators Teletherapy sources Fixed, multi-beam teletherapy (gamma knife) sources	$A/D \geq 1000$
2	Industrial gamma radiography sources High/medium dose rate brachytherapy sources	$1000 > A/D \geq 10$
3	Fixed industrial gauges that incorporate high activity sources Well logging gauges	$10 > A/D \geq 1$
4	Low dose rate brachytherapy sources (except eye plaques and permanent implants) Industrial gauges that do not incorporate high activity sources Bone densitometers Static eliminators	$1 > A/D \geq 0.01$
5	LDR brachytherapy eye plaques and permanent implant sources X ray fluorescence devices Electron capture devices Mossbauer spectrometry Positron emission tomography (PET) check sources	$0.01 > A/D \geq \text{Exempt}^{c}/D$

[a] Recognizing that factors other than A/D have been taken into consideration.

[b] This column can be used to determine the category of a source, based purely on A/D. This may be appropriate if, for example: the practice is not known or is not listed; sources have a short half-life and/or are unsealed; or sources are aggregated.

[c] Exempt quantities are given in Schedule I of the BSS [11].

Figure 3: Recommended Categories for Radioactive Sources used in common Practices ([33], p 14)

Given categorization is based on ratio of source activity A and D-value which is defined for each radionuclide in Annex II of IAEA Safety Guide RS-G-1.9 [34].

DSRS have in contrast to other radioactive wastes several additional options regarding their treatment: They can be returned to the supplier, reused or recycled. This chapter only discusses their treatment for final disposal.

DSRS are small devices with high activity concentrations and sometimes high activities that can still represent a radiological threat. Sealed radioactive sources have a wide area of application and commonly found also in non-nuclear facilities, see Appendix I of [34].

5.3.2 Waste inventory of participating member states

The following table (*Table 8*) shows the waste inventory, predisposal treatment and disposal options for DSRS of MS that have DSRS. Only countries providing information are included.

Country	Waste Inventory	Predisposal Treatment	Disposal Option
Austria	Lightning rods, smoke detectors, medical and industry sources About 200 drums of 200 l and 8 drums of 400 l Mainly: 2,600 ^{60}Co sources with 60TBq (mostly in decay storage), 1,600 ^{137}Cs sources with 5TBq, about 670,000 ^{241}Am sources with 4TBq (mostly smoke detector sources), 2,000 ^{3}H sources with 3.2TBq, 2,600 ^{90}Sr sources with 1TBq, 1,900 ^{226}Ra sources with 0.5TBq	Minimization with reuse and recycling options For treatment: encapsulation and cementation of the canisters; radium sources are welded into stainless steel capsules before further encapsulation (and later cementation)	No final disposal or disposal concept yet (for any kind of RAW). An advisory board has been formed in 2021 to start making suggestions for possible concepts.
Cyprus	No estimation available	Kept in special storage rooms	Export
Czech Republic	Stored in repository Richard: 34,463 pcs, total activity: 4.67E+05 GBq Disposed in repository Richard: 19,971 pcs, total activity: 3.17E+05 GBq Disposed in repository Bratrství: 6,672 pcs, total activity:1.01E+03 GBq	Cementation for conditioning or no conditioning if robust long-lived shielding/long-term storage is used for DSRS Dismantling of DSRS (by producers) Storage in NSDF Richard in the case that DSRS does not meet WAC in operated disposal facilities	2 NSDFs used for DSRS (short lived LLW and ILW) and a deep geological repository (DGF) in project. Waiting for WAC of DGF or are disposed of in NSDF
Denmark	The inventory contains 1,742 sources	In most cases shielding is removed to reduce volume Packed reversibly in drums with concrete, and in containers again with concrete	No disposal facility yet
France	Approx. 3.5 million DSRS, 74% belong to electronic fire safety industries (smoke detectors), 23% to armed forces and 3% are industrial and medical sources	Special container, which could hold sources is considered	Part of the DSRS can be disposed of in LLW repositories, but DSRS can not be mixed with other waste due to WAC. Some specific DSRS with long lived nuclides are planned to be disposed in DGF.
Germany	In Germany about 100.000 sealed radioactive sources are used in industry, medicine,	Dismantling and packaging	DGF, if no recycling is possible

	research and in agriculture, this excludes ionization smoke detectors[30]		
Lithuania	About 90,000 DSRS in total, About 30,000 DSRS (mainly category 5) are mixed with operational waste	Segregation as much as possible, put to separate containers and stored in long-lived waste intermediate storage and then will be put in DGF Special case with historical DSRS mixed with other waste (it is attempted to establish WAC for NSDF and landfill facility to have the possibility to be disposed); DSRS are kept with their shielding waiting for WAC of DGF except for smoke detectors (mostly).	3 Disposal options are available, depend on types of DSRS: 1) Mixed wastes with DSRS are disposed of in landfill or NSDF 2) If this is not possible, it will be disposed of in DGF 3) The rest of DSRS (separately stored or separated from mixed wastes) will be disposed of in DGF
Poland	Smoke detectors, sources for medical and scientific applications, calibration sources	Short-lived: disposed in special underground concrete chambers (several meters), sealed with cement. Smoke detectors are dismantled, radioactive sources are preserved in polyester SIER. LL currently long-term storage	Short-lived isotopes: repository in Rozan Long-lived isotopes: final disposal in DGF Between these two possibilities: new facility for ILW and some transfers will be built, but characterization of historical wastes and possibly repacking is needed
Republic of Serbia	About 2000 DSRS currently stored in storage facilities (from different industrial, medical and research applications) Over 100,000 sources from smoke detectors Over 10,000 low activity radium sources from different signaling or measuring devices (night vision devices, compasses, etc).	DSRS are stored in their original containers or storage containers. Operations are planned for dismantling.	No disposal option yet
Romania		Low activity sources: embedded in cement (in 220 l standard drums) and sent for final disposal	National Repository Baita Bihor
	– 60 pieces of high activity ^{60}Co sources from dismantling the ^{60}Co teletherapy facilities	Stored in the storage pits located in a hot cell of the post irradiation examination laboratory of the Institute	DGF

	– 10 neutron sources (Am-Be and Pu-Be) used for the first criticality of TRIGA reactor (in 1980)	for Nuclear Research Pitesti (RATEN ICN)	
	~100,000 pcs of ^{241}Am sources	Stored on IFIN-HH Bucharest site	Not decided yet
Slovenia	11 m^3 stored in Central Interim Storage Facility (CISF) with total activity of 3E+12 Bq	All in containers, planned to remove part of them from the country (repatriation of DSRS category 1&2)	LILW repository (DSRS category 3-5) or together with HLW (DSRS category 1&2)
UK	19 waste streams containing DSRS are declared in the 2019 United Kingdom Radioactive Waste Inventory (UKRWI) Detailed Data Report (NDA/BEIS); 13 are LLW and 6 are ILW. Of the 13 LLW streams, 11 arose from Magnox Ltd sites; 9 from the stations (9B960, 9C950, 9D923, 9E63, 9F950, 9H28, 9J952, 9R113, 9R121 and are all <0.1m^3) and 2 arose at the Harwell (5C56) and Winfrith (5G24) Research Laboratories and are 2.0m^3 each. Sellafield Ltd are reporting 2 LLW streams on their site (2C931, <0.1m^3 and 2X65, 0.4m^3). Of the 6 ILW streams, the largest is Ministry of Defense AWE stream 7A32 which has 92m^3 arising in the future (called "closed sources"). Magnox Ltd reported 4 streams: Hinkley A has two sets of reactor neutron sources (9D322 and 9D323) each containing 0.5m^3, Berkley (9R112) and Winfrith (5G04) have 0.1m^3 each of redundant radioactive sources. GE Healthcare is reporting <0.1m^3 in waste stream 1A11 arising in the future	Recycling if possible (by Active Collection Bureau (ACB) or Eckert & Ziegler) Otherwise grout encapsulation Storage of ILW sources in the MBGW store in Sellafield	LLW Repository for LLW DGF for ILW Discrete item WAC for LLW Repository could constrain acceptance

Table 8 - Waste Inventory of SIMS and LIMS: DSRS

5.3.3 Predisposal waste treatment

DSRS have to undergo several predisposal steps:

- Collection of the source
- Source identification.
- If necessary dismantling
- Sorting and segregation by nuclide, half-life and activity
- Conditioning includes depending on nuclide welding into containers that are specially designed [33]

For SIMS with low amounts of DSRS a complete pre-treatment facility might not be feasible, so mobile or shared solutions are an alternative. The IAEA has already developed such a facility for DSRS. Solutions might be mobile facilities for dismantling and encapsulation of DSRS (e.g. mobile tool kit facility (MTKF) of IAEA [35]) or mobile hot cells for handling [35].

After dismantling, Austria uses encapsulation and cementation for DSRS treatment and conditioning. Welding into stainless steel capsules (for Radium sources) is mostly done because of possible emanations and not so much because of the long-live of the nuclide. Therefore, welding into stainless steel capsules is also done for H-3 sources but not necessarily for Am-241 sources. Additionally, recycling activities should reduce the number of sources ([5], [6], [36]).

In the Czech Republic, cementation is used for conditioning of DSRS. For robust, durable shielding of DSRS during long-term interim storage no conditioning is currently foreseen, until WAC of DGF or NSDF are defined. The dismantling of DSRS is a responsibility of the producers.

In Poland, short-lived DSRS are cemented and disposed. Smoke detectors are dismantled. For long-lived DSRS, a long-term storage is currently foreseen.

Lithuania uses segregation as much as possible – DSRS are put into separate containers depending on nuclide and activity. They are stored together with other LL ILW before disposal in DGF. For historical DSRS mixed with other waste, work is ongoing to create WAC for NSDF and landfill facilities to establish a disposal possibility. A disposal facility for sorted wastes is available. DSRS are kept with their shielding waiting for WAC of DGF except for smoke detectors (mostly).

In Serbia only a storage facility is available for DSRS. DSRS are stored in their original containers or storage containers and operations are planned for dismantling.

5.3.4 Disposal options

Many SIMS have currently no disposal options, especially for sources with higher activities. DSRS with low activity and short-lived sources are in part disposed of in landfills or NSDF.

The Czech Republic operates two NSDFs for DSRS (short-lived LLW and ILW). A DGF is currently in development.

In Poland a repository for short-lived isotopes exists in Rozan. For long-lived isotopes the final disposal will be a DGF.

Lithuania has disposal options in place, depending on the types of DSRS. Three disposal options are available: mixed wastes with DSRS are disposed of in landfill or NSDF. If the WAC are not met, the DSRS will be disposed of in a DGF. All other types of DSRS will also be disposed of in a DGF.

5.3.5 Implications of disposal options on predisposal routes

If disposal concepts in the respective country are not yet developed and the corresponding WAC are missing, treatment and conditioning processes might not be in place. For example, the design of disposal container will influence predisposal routes.

Challenges arise from the long period for interim storage of DSRS, until disposal facilities are available. Solutions must be found, e.g. for the package assemblies of DSRS in interim storage for multiple decades. Because of this long period of interim storage, the retrievability, re-treatment and re-conditioning needs to be discussed. Additionally, legacy and mixed waste might not be sufficiently characterized to define a disposal route, as well as the corresponding treatment and conditioning process.

In general, the container design must fit to the chosen disposal option, e.g. a borehole disposal.

5.4 SIERs

5.4.1 Definition of waste type

As the IAEA does not define SIERs, the authors use a description by Wang and Wan [37] *“Ion exchange resins are employed extensively in the nuclear industry to remove the radioactive contaminants such as neutron activation products and fission products which may have leaked from fuel elements. The spent radioactive ion exchange resins have been produced during the operation of the nuclear facilities in the nuclear industry. The resins loaded with radioactive nuclides could not be regenerated and reused. These waste resins should be properly treated and disposed in order to minimize their potential hazard to the environments.”*

A more detailed analysis of the challenges arising in the radioactive waste management of SIERs can be found in D9.5 [29]

5.4.2 Waste inventory of participating member states

In the following table (*Table 9*) shows the waste inventory, predisposal treatment and disposal option for resin in various countries. Only countries providing information are included

Country	Waste Inventory	Predisposal Treatment	Disposal Option
Austria	No new spent ion-exchange resins (SIERs) arise in Austria. Some SIERs from the operation of the RR at Seibersdorf (until 1999) have been cemented (< 8 m^3) together with sludges. (See D9.5 chapter 2.2 with the entry for Austria in the table[29])	Formerly: either incinerated (therefore no longer considered SIERs) or homogeneously cemented	No final disposal or disposal concept yet (for any kind of RAW). An advisory board has been formed in 2021 to start making suggestions for possible concepts.
Cyprus	Approximately a few kg of very low activity (α-nuclides)	Air drying	No disposal option yet (most likely export)
Czech Republic	The SIERs waste flow to the repository is in the lower hundreds of m^3 per year (100 -200 m^3, i.e. 500 – 1000 disposal units) Mass of ion exchangers and sludges estimated to be up to 1000 t from NPP Dukovany until the end of the NPP operation	Till 2010, ion exchangers and sludges were stored in tanks and waste producer was responsible for their management including measurement and testing solidification method.	Disposal started in 2010, after the licensing process that led to permission of disposal of waste solidified in geopolymer matrix.
Denmark	The SIER waste inventory weighs 185 kg.	Volume reduction via distillation, solidification of some Typically stored in drums If the matter is dry it is stored in drums and additional containers	No disposal facility yet
France	Uncertain [29]	Conditioning using epoxy matrix	
Germany	No information available	Dewatering and drying	DGF
Greece	Ion exchange resin (IER) waste (styrene divinylbenzene copolymer of density 0.84g/cm^3) from the water	They are in raw form, the radiological characterization was carried out. The treatment technique is to be selected.	NSDF

	demineralization system of the GRR-1 open pool-type RR. 5.6m^3 of raw SIER (dominant radionuclides ^{108}Ag < 4.70 Bq/g, ^{137}Cs < 160 Bq/g, ^{60}Co, ^{252}Eu, possibly radionuclides from the irradiated fuel and fission products (sampling and radiochemical analyses is needed))		
Lithuania	In total it is expected to generate about 6000 containers with cemented SIERs in 200 l drums. At the moment over 30% of final packages (more than 2000 pcs.) are prepared	At Ignalina NPP SIERs are cemented in 200 l drums, about 125 l of SIERs are cemented in 1 drum, drums are placed into the FRAMATOME containers (8 drums in 1 container).	Disposal is foreseen in NSDF near Ignalina NPP. Ignalina NPP is responsible for implementation of the NSDF project (construction and operation). Until start of operation of the NSDF, drums with cemented SIERs will be stored in containers in cemented LLW storage facility at Ignalina NPP.
Netherlands	18Mg LILW originating from water purification	COVRA is developing a (new, thermal) processing route for organic liquid wastes and SIERs.	DGF
Poland	200-400 l/year of different resins from radiochemical laboratories (science, RR operation, medicine) are collected in Radioactive Waste Management Plant (ZUOP) Main radiological inventory involves mainly short-lived radionuclides like ^{64}Zn, ^{54}Mn, ^{124}Sb, ^{60}Co, ^{134}Cs, ^{137}Cs, total activity 5,684 MBq (2018).	Predisposal procedure steps: interim storage for cooling, then conditioning aimed at preparing for storage or transportation. Previously, resins were conditioned by dewatering and mixing with polyester resin and packed into the standard metal drums. At present, since they are high-active, they are stored for cooling in ZUOP facilities.	Disposal in Rozan NSDF
Republic of Serbia	Exact amount will be determined in process of preparation of decommissioning	Currently not performed	No disposal option yet
Romania	~ 12 m^3 (raw waste) resins generated by TRIGA reactor operation	Bituminized in 60 l drums which are then cemented in 220 l standard drums for final disposal	National Repository Baita Bihor

	~ 300 m^3 of resins generated by operation of 2 CANDU units on Cernavoda site	Stored under light water in concrete vaults lined with epoxy on Cernavoda site	Near surface disposal for fuel contact resins DGF for non-fuel contact resins
Slovenia	689 drums of cemented resin, 106 overpacks with three drums of cemented resin, 4 drums with dried resin, 103 overpacks with three drums of dried resin	Drying or solidification with vermiculite	LILW disposal
UK	As of 2019 non-conditioned SIERs added up to: Organic Ion Exchange Materials: 430 Mg ILW and 200 Mg LLW Inorganic Ion Exchange Materials: 3,200 Mg ILW and 74 Mg LLW	Mostly grouted into waste packages, other technologies are available	LLW Repository for LLW DGF for ILW

Table 9 – Waste Inventory of SIMS and LIMS: Resin

5.4.3 Predisposal waste treatment

Regarding the characterization of SIERs, samples of SIERs are analysed e.g. through gamma spectrometry and application of the scaling factor methodology. A special focus must be laid on potential damages of fuel rods, as this impacts the scaling factors.

Regarding the further treatment, there is no general solution in place. Currently the drivers for treatment are volume reduction, waste stability and affordability. This comes either from the fact that the country specified WAC which demand this, or that storage capacity is limited. The Netherlands emphasized that, in addition to the points mentioned, the economic feasibility of treatment and conditioning must be kept in mind.

For volume reduction the Netherlands use incineration. This reduces the volume of waste and removes burnable material of the waste, while increasing the activity per waste volume. Incinerated SIERs are subsequently stored in MOSAIK® casks.

For countries, where an incineration facility might be economically unfeasible, incineration abroad, e.g. at Studsvik in Sweden, or mobile incineration facilities might be of interest. For further volume reduction, incinerated waste might be supercompacted.

Table 10 contains the answers of several countries which conditioning issues arise with SIERs.

Country	Issue description
Germany	Although all conditions for drying were met, it can happen, that after several years of interim storage there can be found again some liquid water at the bottom of the drum. For this reason, all drums with resins will be checked again for liquid water after a specified storage time
Greece	The increase of volume after cementation is an issue. A cement testing laboratory is also required. This laboratory will only be used for small amounts of waste e.g. for about 10 m^3 of resin.
Lithuania	The cementation formula has to be updated continuously **(**concentration evaporates, sediments, perlites, resins are cemented together by small portions and filled into 200 l drums)
Poland	The elaborated conditioning technique used for a long time was based on the use of polyester resin to stabilise the waste. It is not used any more. Most of ion exchange resins produced today are high-activity materials (ion exchangers from the Maria reactor); high dose rate does not allow for further handling, including processing and conditioning; they are stored in the ZOUP (organisation responsible for the radioactive waste processing and disposal) facilities for cooling.
Romania	Direct cementation is not the recommended conditioning technology for SIERs generated by a CANDU reactor as some of the SIERs, especially those generated from the non-fuel contact systems of CANDU reactors, have a large ^{14}C inventory and during cementation the ^{14}C can be released due to the temperature increase during the cement hydration processes
Slovakia	LLW fixation in matrix, ongoing research on geopolymer matrices

Table 10 – Conditioning issues with SIERs

Regarding conditioning issues with SIERs, most countries are currently either not conditioning SIERs at all or face no issues with the conditioning.

MS were further asked if there were any on-going R&D programs for predisposal waste treatment of SIERs. Those, who affirmed, are listed in the *Table 11* together with a description of the program.

Country	Description
Denmark	On solidification of SIERs
Lithuania	the cementation formula is updated continuously, but no scientific programs

Poland	Thermal method of SIERs treatment is considered (Concept study incinerator for ZUOP); Various cementitious binders and the Nochar material are tested in parallel.
Romania	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.
Slovakia	Done by state company JAVYS on the SIAL® matrix that resin is supposed to be fixed with ([39], p. 10)
Slovenia	Studies on the change of volume of ion exchangers due to swelling in contact with water are conducted to determine the mechanical response to swelling of ion exchangers in order to definitively determine the processing of ion exchangers. Then it will be possible to give final answers regarding the further treatment and conditioning of these types of LILW from NPP.
UK	The Sellafield Thermal Active Demonstrator Trials are looking at developing a thermal Treatment Technology for SIXEP Wastes (Clinoptilolite) in 5-7 years as an alternative to grout encapsulation. MOD are trialing a thermal treatment technology to treat SIERs (starts 2022).

Table 11 – On-going programs for predisposal waste treatment of SIERs

5.4.4 Disposal options

There are already several disposal solutions for SIERs in place. The above described issues in *Table 10* regarding treatment and conditioning however halter some countries in their path towards a disposal option for SIERs.

The Netherlands have a DGF for all RAW including LLW foreseen. Thus, volume reduction is a main driver for predisposal treatment. Prior to a disposal in a DGF, a 100 years interim storage is planned to ensure waste stability.

In Greece, the chosen option will be a NSDF. As there is currently no predisposal treatment this has to be further evaluated.

In Slovenia, WAC for SIERs are already in place. SIERs will be disposed off in the LILW NSDF, that is currently being developed.

In Poland, SIERs are currently disposed of in the NSDF in Rozan after interim storage and conditioning.

In the Czech Republic the disposal of SIERs started in 2010. The process has been approved for disposal of waste solidified in geopolymer matrix.

In Lithuania, disposal is foreseen in a NSDF near Ignalina NPP, which is currently developed. Until the start of operation of the NSDF, drums with cemented SIERS are stored in containers in the LLW storage facility at Ignalina NPP.

5.4.5 Implications of disposal options on predisposal routes

The biggest impact of the predisposal route on the choice of disposal option will be the generated volume through treatment and conditioning. It has been observed, that SIERs show a significant volume increase and crystalline water may remain in the matrix. Additionally, alkali- silica reactions might occur and need to be closely monitored. Some countries have chosen a polymer matrix for conditioning. Currently the long-term stability of this matrix is under investigation. As described in chapter 5.4.3, R&D is still ongoing for both conditioning options.

Most countries have identified NSDF as best choice for SIERs. Borehole options are currently not recommended due to the waste volume or size of the containers. For disposal in DGF, the minimization of waste is of high importance. This can be achieved through additional conditioning steps, e.g. supercompaction.

5.5 Spent fuel

5.5.1 Definition of waste type

The IAEA defines spent fuel as nuclear fuel removed from a reactor following irradiation that is no longer usable in its present form because of depletion of fissile material, poison build-up or radiation damage.

Council Directive 2011/70/EURATOM of 19 July 2011 defines that spent fuel means nuclear fuel that has been irradiated in and permanently removed from a reactor core; spent fuel may either be considered as a usable resource that can be reprocessed or be destined for disposal if regarded as radioactive waste.

The work within this section is limited to spent fuel (SF) from research reactors (RRs).

5.5.2 Waste inventory of participating member states

The following table (*Table 12*) lists countries with SF of RR in their waste inventory. It shows the waste inventory, predisposal treatment and disposal options for SF in several MS. Only countries providing information are included.

Country	Waste Inventory	Predisposal Treatment	Disposal Option
Austria	SF has been or will be repatriated to the US DOE so there is no need for either treatment or disposal of SF in Austria.		
Czech Republic	LVR-15 reactor fuel assemblies: 286 pcs (IRT-2M, enrichment less 20% wt. of ^{235}U); Fuel from the LVR-15 reactor with enrichment of ^{235}U higher than 20% was sent to Russia for reprocessing. LR-0 reactor fuel assemblies: 64 pcs (shortened VVER-1000) VR-1 school reactor fuel assemblies: 21 pcs (IRT-4M)	sent to reprocessing to the Russian Federation, afterwards dry storage, cementation or reuse of VR-1 in LVR-15	Geological repository (2065)
France	SF will be reprocessed and is not classified as waste.		
Germany	There are approx. 1Million pebbles stored in CASTOR® THTR/AVR, and around 4000 Fuel elements from various RR. Many FE went back to the US after permanent shut down of the reactors ([40][38])	Dewatering and packaging in a dry cask, partly reprocessed (e.g. RR Otto Hahn)	DGF, if no repatriation is possible
Netherlands	There are three RRs that produce or have produced SF for storage at COVRA ([43], p. 76): • The High-Flux Reactor (HFR) 45 MWth in Petten. • The Low-Flux Reactor (LFR) 30kWth in Petten was shut down in 2010. • The Hoger Onderwijs Reactor (HOR) 2 MWth in Delft.	Previously sent back to the USA ([43], p. 6) as part of the larger US nuclear non-proliferation policy, now storing SF in the Netherlands is the preferred option Ultimately, reprocessing of spent RR fuel may be necessary to minimize the probability for criticality and potential gas generation in the post-closure phase.	If a national repository is built, geological disposal of this waste in a facility constructed either in clay or salt host rock is foreseen. The Netherlands also studies actively international repository option (dual-track policy), this option has not decided concept or disposal method.

	The conversion from high-enriched Uranium (HEU) (with an enrichment of 93% ^{235}U) to low-enriched uranium (LEU) (fuel with an enrichment of 19.75% ^{235}U) was completed in 2005 for HOR and in 2006 for the HFR; the LFR was closed Inventory: 30 ECN containers of HEU and 120 of LEU		
Poland	Returned to the producer in Russian Federation		
Republic of Serbia	Natural metal uranium rods in dry storage in reactor hall and LEU fuel elements TVR-S type in the reactor core, burn-up level of fuel is very low due to low power.	No predisposal treatment of SF is planned	No disposal option yet
Romania	~ 1,325 TRIGA LEU elements (~0.33t U) to be generated until TRIGA shut down for decommissioning (2035)	Interim storage in the TRIGA reactor storage pool (in operation on RATEN ICN site) Building of a dry storage facility on RATEN ICN site is taken into consideration (after 2035)	DGF
Slovenia	Fuel pins from the Triga Reactor (250 kW) are transported back to USA (this will continue in 2030)	Transport of left-over fuel pins back to US and other management routes are under discussion (e.g. deep borehole repository)	No disposal route defined
UK	SF from NPP (Magnox, AGR, PWR) and from several test and prototype reactors ([44], p. 15).	SF from test and prototype reactors was mostly reprocessed and will be stored	Will be sent to the future DGF and assumed to be disposed of in the High Heat Generating Waste area. Although the exact geology of the DGF is unknown, so the disposal concept is unknown, these are NOT considered to be challenging. Post-closure assessment modelling treats this as having an Instant Release Fraction of 1, the moment the canister is breached and groundwater contacts the fuel, the whole inventory will be released.

Table 12 - Waste Inventory of SIMS and LIMS: Spent Fuel (Research Reactors)

5.5.3 Predisposal waste treatment

Predisposal waste treatment of SF includes wet and dry storage, reprocessing or encapsulation. If the SF is still emitting thermal energy, a cooling down phase might be necessary before any treatment takes place.

In the Netherlands RR fuel elements are packed in borated steel baskets in ECN canisters (see *Figure 4*). The canisters are stored in a HLW storage building (HABOG) and around 2100 a decision will be made about the disposal.

The typical weight of a loaded canister is 1,000 kg. An empty waste container weighs 340 kg. The wall thickness is 5 mm. The lid on the container is welded, and the canister is filled with helium to check the weld and to verify the canister's integrity during storage. An additional ring is put on the weld in order to accommodate the tension forces during lifting the container at the mushroom.

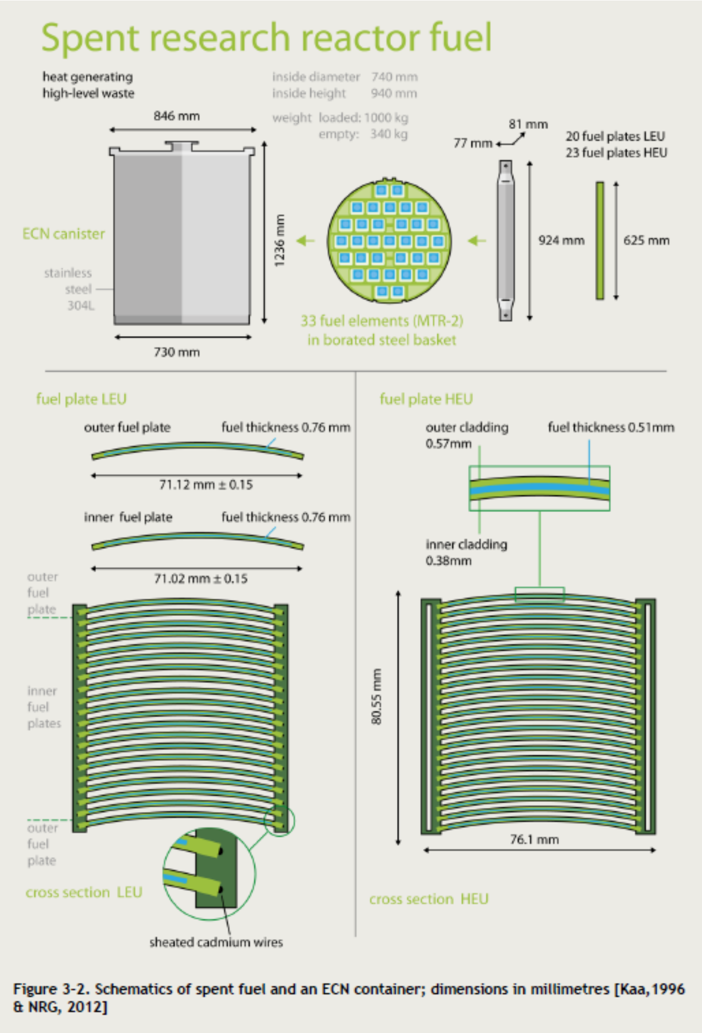


Figure 3-2. Schematics of spent fuel and an ECN container; dimensions in millimetres [Kaa,1996 & NRG, 2012]

Figure 4 - Spent research reactor fuel in long-term storage packaging. ([31], p. 15)

In addition, the Netherlands have ongoing R&D projects for pre-disposal treatment of SF from RRs, to ensure criticality safety and hinder gas generation.

In Romania, SF from RRs is stored in wet and dry storage.

In the Czech Republic, SF from NPPs is stored in wet and dry storage facilities. SF from RRs were sent to reprocessing abroad, followed by dry storage and cementation as HLW, as well as reuse of reprocessed fuel in RRs.

The UK used to reprocess its SF from RR, as they do no longer have RR there is only a small amount of SF that is currently stored and waits for disposal [44]. France is reprocessing its SF and does not consider it as waste [41].

5.5.4 Disposal options

Principal disposal options for SF from RRs are deep geological solutions, such as deep boreholes, used or new mines and deep caverns or tunnels, due to the high safety and security requirements. Many countries have agreements on repatriation to the producer country of the fuel of RR. For SIMS a shared solution can represent a disposal option if there is no other HLW in the country.

The Czech Republic is planning to dispose the SF in a DGF, which is planned to start its operation in 2065.

5.5.5 Implications of disposal options on predisposal routes

If a fuel element leakage can't be excluded, adsorbants can be added to the packaging.

Denmark has returned its solid fuel elements of its RR to the US, and the fuel from DR1 facility needs a predisposal and disposal solution([45], [46]). If no DGF for radioactive waste will be build, a borehole compartment/deep geological department for fuel could be an option.

In the Netherlands a supercontainer was adopted from the ONDRAF/NIRAS concept developed in the Belgian research programme on geological disposal of RAW for the national DGF facility in clay (the OPERA programme). In OPERA, the possibility of disposing of two canisters in a supercontainer was proposed but criticality and potential gas generation had not been investigated. The safety case highlighted the uncertainties concerning the criticality of this disposal package as well as the potential gas generation in the post-closure phase that could enhance the transport of radionuclides. For now, at least a single canister is assumed to minimize the probability for criticality, perhaps re-packaging may be necessary. For salt the concept is not yet decided, but the preferred container option suits both salt and clay host rock disposal facilities. The possible multinational disposal option has not decided on a concept or disposal method, either.

It is also possible to repackage the waste for smaller containers for disposal, if that is required.

5.6 URT bearing wastes

5.6.1 Definition of waste type

The definition of this waste type is strongly depending on the country it is handled. In *Table 13* this classification per country is listed. In general URT bearing waste contains uranium, radium and thorium nuclides and/or other naturally occurring radioactive nuclides.

Special consideration has to be given to materials arising from historic sites (e.g. radium facilities) or long-lived sources (Ra sources from medical applications). Some countries (e.g. UK) see depleted uranium as a resource and reuse it, others (e.g. Austria) declare it directly as waste if clearance is not possible.

5.6.2 Waste inventory of participating member states

In the following table (*Table 13*) countries state their URT-wastes, together with their respective classification and amount of waste, predisposal steps and disposal steps for URT- wastes. Only countries providing information are included.

Country	Inventory & Classification	Predisposal Steps	Disposal Steps
Austria	Classification: The Austrian legislation defines the conditions under which NORM falls under the provisions of the radiation protection legislation. If such material is declared as RAW, it is subject to the same requirements as other RAW and is RAW. This kind of RAW cannot be conventionally disposed. It has to be sent to NES for treatment, conditioning and interim storage. At present there are no large amounts of such waste arising in Austria. It is classified as LILW possibly long-lived (if above 400 Bq/g α-radioactivity). In regard to the minimization concept the Austrian legislation also includes the possibility for release for material which contains NORM. If this material originates from one of the regulated tasks, and emits a dose below 0,3 mSv/year, the material can be released (e.g. water processing facilities, Th-industry, cement production etc...). Inventory: For waste inventory see D9.5 chapter 2.9 Ra/Th/U bearing waste with the entry for Austria in the table ([29], p.61).	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 neutralization, precipitation and/or coprecipitation followed by drying and supercompaction. 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. Waste is being conditioned upon arrival at the waste management facility.	No final disposal or disposal concept yet (for any kind of RAW). An advisory board has been formed in 2021 to start making suggestions for possible concepts.
Cyprus	Classification: According to IAEA definitions Inventory: 1. Phosphogypsum disposal site 2. Very small amounts (< 500 g) of lab waste	1. No solution yet 2. Air dried	1. Permanently disposed at a coastal area in Cyprus and covered with soil/vegetation 2. No disposal option yet (most probably export)
Czech Republic	Inventory: α-bearing waste has to be declared as RAW by its producer. Total activity of Ra/Th/U radionuclides disposed in Bratrství repository (as of 2019 [49]): ^{226}Ra 1.36E+12 Bq U 6.38E+11 Bq	Available management options are clearance, exemption, treatment, storage, and disposal. No specific regulation is available for NORM waste.	Disposal site at Bratrství, storage at Richard

Country	Inventory & Classification	Predisposal Steps	Disposal Steps
	^{232}Th 3.20E+09 Bq The chemical inventory is mostly $RaSO_4$ in platinum cases (medical sources), Ra-Be neutron sources, laboratory waste containing natural radionuclides, DSRS, depleted uranium and natural thorium. Classification: Czech legislation (such as Atomic Act No. 263/2016 Coll. [50], Decree No. 377/2016 Coll. [51]) does not define a special waste category such as waste containing natural radionuclides. Institutional waste (from industry, research, agriculture or healthcare) are divided into two groups according to whether they contain natural radionuclides (e.g. uranium, radium, natural thorium isotopes) or artificially created radionuclides (e.g. americium, plutonium, cesium). They are then disposed in different repositories: wastes containing natural radionuclides to the Bratrství NSDF, other wastes of this type to the Richard NSDF. For α-bearing waste no special classification is available. Possible options are storage by producer or disposal in repository Bratrství (WAC have to be met). Uranium industry is the principal producer of this waste, and U and Th are the prevailing radionuclides.		
Denmark	Inventory: 13Mg Tailings (waste product from uranium extraction experiments) and uranium ore (a resource that is potentially waste) is handled by Danish Decommissioning, this includes waste products generated in Greenland in uranium mining. Classification: Classified as NORM and safeguard material.[46]	Currently stored for further treatment[47]	No disposal facility yet
France	Mainly from mineral processing, mining, gypsum and fertilizer industries and the airline industry	Under consideration Nitrate treatment could be applied	Shallow depth disposal option (30 m depth) is under consideration for part of the U/Th/Ra bearing waste

Country	Inventory & Classification	Predisposal Steps	Disposal Steps
Germany	Classification: Materials with more than 1 Bq/g of U/Th/Ra-nuclides are NORM. Material with up to 5 Bq/g can be released for disposal in an underground hazardous waste disposal facility. Normally, this criterion is not exceeded for residual materials. Inventory: Not estimated	Treatment depending on physical and chemical waste form	Public landfill
Greece	Classification: The first criterion for distinguishing RAW and NORM is the origin of them. Specifically radioactive materials produced by the industries mentioned in ANNEX VI of 2013/59/EURATOM ([52], p. 44) are NORM. The second criterion is the presence of the above (chains) of isotopes (U, Th, K) and at the same time the absence of other isotopes. It is worth mentioning that some materials (e.g. tubes, machinery) contaminated by NORM radioactive salts (e.g. ^{226}Ra) in high concentrations (e.g. >100Bq/g), should be managed with more strict rules as RAW. Natural radionuclide values in solid materials in radioactive equilibrium with their daughter isotopes for exclusion or release: 1. Natural radionuclides from the chain of ^{238}U: 1kBq/ kg 2. Natural radionuclides from the chain of ^{232}Th: 1 kBq/ kg 3. ^{40}K: 10 kBq/kg	Currently not performed	No disposal option for U/Th/Ra bearing waste in case it cannot be disposed in a near NSDF In some cases, the specific activity of ^{226}Ra in pipes from NORM industries is 5E3 Bq/g. Also, there are lightning rods with ^{226}Ra as well as depleted uranium from shields, Th from airplane engines which belong in the safeguards. For these wastes a NSDF possibly is not appropriate. Something else is needed e.g. a silo.
Lithuania	Classification: NORM from water treatment system is generated and classified as NORM (only at Ignalina NPP, in other water treatment facilities it is not indicated that NORM is generated). Decision on disposal solution will be made based on WAC of repositories as for other RAW. No other solution is available, because NORM are not specially described in Lithuanian legislation.	Treatment as other VLLW.	Disposal in FIBC in Landfill is currently expected
The Netherlands	In the Netherlands, RAW is divided into categories: HLW, LLW and ILW (including NORM waste), short-lived waste	Under certain conditions, and if there is no increased risk for man and the environment, NORM may be mixed with	Waste with an activity concentration that is more than 10 times higher than the

Country	Inventory & Classification	Predisposal Steps	Disposal Steps
	and exempt waste. These categories are based on activity and half-life. A special category of LILW consists of NORM waste (i.e. waste produced from the use of natural raw materials). NORM waste is produced when naturally radioactive substances that occur in industrial ores are concentrated in waste as the result of an industrial process. Estimated for disposal: 70,000 m^3	other materials for reuse (forbidden if its sole purpose is to reduce the activity concentration). Otherwise stored until disposed	exemption threshold must be entrusted to COVRA and will go to DGF. NORM waste with an activity concentration of up to 10 times higher than the exemption threshold can be safely dumped as VLLW at special licensed dumpsites.
Poland	Classification: There is no special classification of NORM waste. There are only criteria for LLW; NORM are considered according to generally accepted definitions (material enriched in natural radioactive isotopes). Such material is not managed as RAW. Inventory: Nuclear materials like ^{238}U (natural uranium), ^{232}Th or ^{226}Ra, disused ^{226}Ra sources from medical applications.	Usually, prevented from leaking into the environment. For nuclear materials like ^{238}U, ^{232}Th or ^{226}Ra only storage at ZUOP premises, some part of depleted uranium is temporarily stored in Rozan repository Special predisposal conditioning of Ra sources from medical applications is done.	Some part of depleted uranium is stored in Rozan repository
Republic of Serbia	Classification: The only criteria are clearance levels, if total activity and activity concentration of material is above limits prescribed in national legislation the material is considered radioactive and thus becomes RAW when declared as such.	Currently not performed Treatment facility will, once operational, provide for characterization, segregation and compaction of RAW.	No disposal option yet
Romania	Classification: The Romanian RAW classification scheme does not apply to the RAW generated from mining and milling activities and the national strategy for RAW and SF management does not address these waste categories. The radioactive tailings resulting from milling processes are currently stored in 2 special insulated tailings ponds (Cetatuia II and Mittelzop) of the Feldioara repository, under a variable water stratum. A solid radioactive material discharge area, composed by two old trench type storage facilities and a new storage facility, is located between the	1. In storage on RATEN ICN site 2. In storage in special insulated tailings ponds located on CNE-Feldioara site 3. In storage in trench type facilities located on CNE-Feldioara site 4. Storage on CNU-Suceava, CNU-Stei, CNU-Oravita sites	Not decided yet

Country	Inventory & Classification	Predisposal Steps	Disposal Steps
	two tailings ponds. A dedicated strategy for the management of mining and milling waste is intended to be elaborated. Inventory: 1. ~13 Mg of depleted uranium 2. ~2.7E+06 m^3 of mill tailings 3. ~23E+03 m^3 of low activity solid waste 4. ~7E+06 m^3 of sterile and radioactive rocks		
Slovakia	Classification: U/T/Ra are generally present only as a part of SF, therefore, rules as at SF. Inventory: N/A	N/A	N/A
Slovenia	Inventory: There is a small amount of depleted uranium amongst the waste stored in central radwaste storage facility Classification: These wastes are currently stored at the CISF for RAW from small producers.	Ra needles were characterized and repacked in containers in the frame of IAEA TC project, depleted uranium also well characterized Currently stored at CISF Material may under certain conditions be pyrophoric, however, no concern for the repository WAC	LILW disposal
UK	Inventory: N/A Classification: Depleted uranium is not currently classified as waste, but rather, as a nuclear material that may have to be managed as waste in the future. See [48][44] for more information.	Depleted natural and low enriched uranium (DNLEU) and HEU are not currently considered as wastes, but U, Th and Ra wastes are all compatible with grouting Strategy for long term storage, treatment or re-use is yet to be developed. UF6 requires conversion to oxides prior to disposal due to issues with potential HF gas release and incompatibility with standard grout encapsulation. Waste needs to be immobilized and packaged to suitable container for disposal in future DGF.	Currently uncertain, but DNLEU is unlikely to be consigned to the LLW Repository, owing to capacity limits.

Table 13: Waste Inventory of SIMS and LIMS: URT- waste

5.6.3 Predisposal waste treatment

Different methods can be applied for different kinds of URT- waste.

For the bulk material these are drying, compaction and cementation whereas for metals they are decontamination, melting and compaction. For liquid waste they consist of dissolution/precipitation and drying of sludge.

For sources the IAEA recommends sorting them according to the nuclides they contain ([33], p. 76/77). The sorting might be followed by emplacement into specific waste drums.

5.6.4 Disposal options

Each disposal option from D9.10 [1] is appropriate for particular types of URT- waste:

- Specific landfill disposal: appropriate for low activity NORM but only for limited amounts
- Near surface disposal: not appropriate for long-lived radionuclides and not for huge amounts
- Disposal for ILW – Intermediate depth: suitable for NORM with significant activities which can be disposed in shallow depth
- Geological disposal: appropriate for NORM with high activities, ^{226}Ra sources, depleted U
- Borehole disposal: suitable for ^{226}Ra sources
- Used mines: appropriate for NORM with high activities, ^{226}Ra sources, depleted U

A combination of disposal options can be the solution for SIMS, for example a near surface disposal with a borehole.

5.6.5 Implications of disposal options on predisposal routes

For borehole disposal no cementation of the source is performed.

Also, cementation is not an ideal option for α- emitting nuclides since the cement matrix is not stable. As an additional engineered barrier an inactive layer is inserted between cemented waste and outer drum. The filling of voids in the disposal facility with concrete represents another engineered barrier. The maximum activity per drum can be derived from the safety assessment considering all barriers.

5.7 Hazardous waste

5.7.1 Definition of waste type

Hazardous waste describes a huge group of substances, each subset of which has distinct characteristics and thus is easy to define. Hazardous waste in general and hazardous RAW in specific has multiple definitions, but a broad definition would be the following:

Hazardous RAW is RAW *with particles or substances which can pose a risk to health, safety, property or the environment*.

A more precise definition of mixed waste is given by the IAEA. By their definition, mixed waste is: "*Radioactive waste that also contains non-radioactive toxic or hazardous substances*" [53].

In this section the IAEA definition of "mixed waste" is applied. In general, it depends strongly on the country which waste is defined as hazardous. For SIMS, the most relevant mixed wastes are those, where large amounts of these wastes exist or the characterization (e.g. for clearance or recycling) is challenging. For Lithuania, these challenges exist for lead and asbestos. Greece's most relevant mixed wastes are lead and asbestos, due to large amounts of these wastes, as well as beryllium, which is highly activated. For lead, Greece has implemented recycling options and for asbestos, it has developed decontamination strategies for subsequent near surface disposal, supported by the safety studies.

5.7.2 Waste inventory of participating member states

In the following table (*Table 14*) countries state their hazardous wastes. The table shows waste inventory, predisposal treatment and disposal option for hazardous waste in several countries. Only countries providing information are included.

Country	Waste Inventory	Predisposal Treatment	Disposal Option
Austria	Examples regarding raw waste: • Infectious materials first have to be sterilized to be accepted. • Chemicals whose acidity is too high are first being neutralized. • No mercury in raw waste. So far mercury in the waste has been below or nearly at detection limits. • Asbestos waste from decommissioning activities so far could mostly be cleared, small amounts were conditioned by supercompaction. Example regarding conditioned waste: 25 Be elements from former RR in Seibersdorf	The 25 Be elements from the RR have been welded into 5mm think stainless steel capsules using 3-layer welding. Before welding the capsules also have been backfilled with silica sand and then stored in 2 MOSAIK® containers that were flooded with Argon gas. Small amounts of asbestos from decommissioning activities were conditioned via supercompaction.	No final disposal or disposal concept yet (for any kind of RAW). An advisory board has been formed in 2021 to start making suggestions for possible concepts.
Czech Republic	Nuclear and environmental legislations are separated. In the period of siting, hazardous effects of RAW are evaluated in the environmental impact assessment process. It is forbidden to add substances presenting chemical/ toxic/ biological hazards to RAW. The waste acceptance protocol includes a declaration of the waste producer on non-presence of dangerous substances listed above.	Not applicable	
Denmark	The inventory of hazardous waste weighs 18Mg.	On stock in drums and in a steel container, reversible packing	No disposal facility yet
France	No detailed information available	Mercury can be transformed into mercury sulphide, other techniques have yet to be researched	LLW repository for non-friable asbestos

Germany	No detailed information available	Packaging according to both regulations for toxic and radioactive substances In WAC of Konrad site upper limits of hazardous materials (e.g. Hg) are defined	LILW repository site in development
Greece	Beryllium and control rods (highly activated) Lead (huge blocks, difficult to be characterized and cut) Liquid Scintillators	Beryllium and control rods: no solution for conditioning yet. Lead: melting (if possible) to produce shielding for disposal casks, recycling Liquid Scintillators: treatment of liquid in case they cannot be cleared after storage, no facilities for treatment in the country at the moment.	Beryllium and control rods: no near surface disposal solution Lead: the disposal solution, if necessary, has not been specified yet Liquid scintillators: the disposal solution, if necessary, can be a near surface solution.
Lithuania	The main problem is characterization (e.g. for clearance or recycling) No regulation exists for disposal of non-radioactive hazardous waste in the same manner as for disposal facilities of RAW. Establishing of WAC for landfill and NSDF is problematic, especially in long term period status of these facilities. Inventory mainly consists of lead and asbestos (huge amount), other hazardous waste exists as well (e.g. platinum catalyst) but in smaller amounts than lead and asbestos	Decontamination: release of non-radioactive toxics allowing “conventional” disposal. Packaging: WAC fulfillment to dispose hazardous RAW.	In case of disposal of hazardous RAW in NSDF: unclear status of landfill and NSDF disposal facilities after institutional control period.
The Netherlands	Small amount of irradiated Be from RR	Treatment is currently subject to research	DGF
Poland	There is no specific category of hazardous waste in the waste inventory. Biological waste, which is produced in small amounts in laboratories, can be considered as such.	Animal waste is placed in a special container stabilized with urea-formaldehyde resin. Non-animal waste is treated as regular solid waste.	Disposal in Rozan NSDF
Republic of Serbia	There is a lack of information for certain amounts of RAW stored before 1990s. There is a possibility that this RAW contains other hazards.	Currently not performed, will be analyzed and adopted once the total amount of hazardous waste is determined (if there is any) and its characterization is performed.	No disposal option yet
Romania	~ 2.5 m^3 aluminium waste ~ 0.5 m^3 beryllium waste	Currently not performed, will be generated after 2035	Depending on the radionuclide inventory: disposal in Baita

			Bihor National repository or in the future DGF
UK	In the UK the two main chemotoxic substances that are challenging are “asbestos/asbestos-containing materials (ACM) and manufactured man-made fibres” and “radiologically-contaminated mercury”. 1. Asbestos: 66Mg ILW (amount might be underestimated) 22,000Mg LLW 28,000Mg VLLW 2. Mercury: top 9 streams add up to about 81Mg	1. Asbestos: might be recycled, if not recyclable then options are thermal treatment and chemical deconversion See also FOCUS 11 of D9.5 ([29], pp. 69-71) 2. Mercury: sulphidation, thermal treatment (incineration), pin-hole distillation, amalgamation and Sulphur Polymer Stabilization / Solidification (SPSS). Grout encapsulation, immobilization, packaging	Landfill for VLLW (sites with permits for hazardous waste) LLW repository for LLW DGF for ILW

Table 14 - Waste Inventory of SIMS and LIMS: Hazardous waste

5.7.3 Challenges of hazardous waste pre-disposal routes and disposal

Hazardous and toxic waste yield some additional challenges in contrast to other challenging waste types. In the questionnaire countries were asked if there are any challenges in the respective countries special to hazardous waste (e.g. regarding treatment and disposal).

Greece so far has no predisposal waste treatment strategy for hazardous and toxic waste. The main hazardous waste types of concern in Greece are lead and asbestos, which occur in high quantities, beryllium due to high activation and mercury. VLLW might be released for disposal as standard hazardous waste in landfill disposal sites. For higher levels of radiation, no disposal site is available yet. Most challenging is the disposal of Beryllium from the Greek RR, which is too highly activated for NSDFs.

In the Czech Republic disposal of toxic waste and RAW has two different legislations. Their Atomic act [50] does not define this category of RAW, which means hazardous materials must not be added to RAW. The same regarding legislations applies to France.

In Lithuania, a major challenge that was raised is of legislative nature: The regulations for RAW in general do not cover hazardous waste, and regulations for hazardous waste do not apply to RAW. Thus, hazardous and toxic waste might be caught between two contradicting regulations. Besides, safety justification might differ for hazardous waste and RAW. Challenges also arise from the objective of reducing the generated waste. Due to the hazardous and toxic nature of this type of waste, it has been stated that separation is complicated and leads to increased volume of hazardous RAW for disposal. Requirements for disposal facilities of hazardous waste (non-radioactive waste) should be established within the country in the same manner as it is done for RAW disposal facilities. Following the establishment of WAC for non-radioactive hazardous waste, WAC for radioactive hazardous waste can be established.

In Germany, areas with toxic substances like asbestos can be found in nearly all decommissioning projects. Teams responsible for decommissioning are trained to look for and to manage those toxic substances. In WAC of Konrad site upper limits of hazardous materials (e.g. Hg) are defined.

The UK does face a challenge special to hazardous waste, but here it has to be taken into account that hazardous waste is a broad category. Regarding wastes generated in the nuclear industry that are primarily of concern due to their chemotoxicity, two main substances have been highlighted for the UK: “asbestos/asbestos-containing materials (ACM) and manufactured man-made fibres” and radiologically contaminated mercury.

In Romania waste predisposal options have to be decided for some RAW considered hazardous, such as aluminium and beryllium. Currently ongoing studies on aluminium and beryllium waste are focused on their characterization and on formulation and testing the magnesium phosphate cements for aluminium embedding. The lack of experience with hazardous waste management and the difficulty to measure the hazardous components in some RAW fluxes/categories can be considered the main challenges.

5.7.4 Predisposal waste treatment

The absence of legislation for hazardous RAW disposal is the main problem for establishing WAC for disposal of hazardous RAW.

In Lithuania, the predisposal treatment strategy requires an accurate inventory of the hazardous and toxic RAW. The sorting, as well as the accuracy of sorting and further processing depends on the radiation level. When applicable, the release of non-radioactive toxics allowing conventional disposal is foreseen after decontamination. The packaging of hazardous and toxic RAW should apply to WAC. Currently, the handling of hazardous RAW in Lithuania consists of sorting, preparation of packages for disposal and interim storage in drums. Compaction of hazardous RAW is only foreseen for wastes, were the necessity of repackaging or re-characterization can be excluded. Disposal is currently impossible due to missing legislation.

The main types of hazardous RAW in Greece are lead, asbestos, beryllium and mercury. The predisposal waste treatment for lead often consists of melting and subsequent production of shielding material for disposal casks. Asbestos is decontaminated and if applicable, subsequently released as non-radioactive material for conventional disposal. The predisposal waste treatment of beryllium and mercury are not defined yet. The current solution for activated beryllium from the RR is storage in the reactor building until a disposal facility is available.

Predisposal treatment of hazardous and toxic wastes in France consists of decontamination and deactivation for the disposal in a NSDF or DGF. Currently under development is a device for the determination of the potential harmfulness of hazardous and toxic RAW. WAC with maximum concentration limits are defined for hazardous/toxic RAW.

Predisposal waste treatment routes of hazardous and toxic RAW in Austria heavily depend on the nature of its toxicity. Infectious materials first have to be sterilized to be accepted by NES. Chemicals whose acidity is too high are first being neutralized. An acceptance restriction is mercury, which is not allowed in raw waste. So far mercury in the waste has been below or nearly at detection limits. Asbestos from decommissioning activities have not been relevant so far, as the materials with asbestos could be released from radiation control. 25 beryllium elements from the RR in Seibersdorf are thus far stored in MOSAIK® containers ([5], [6]).

5.7.5 Disposal options

Many countries are waiting for disposal options for hazardous RAW. In the following are illustrations of what is implemented now in different MS:

In Lithuania disposal options are available in NSDF for some amount and for some types of hazardous RAW, such as asbestos and lead. The WAC for hazardous and toxic RAW are described in the WAC of the NSDF.

In France there are WAC for hazardous and toxic RAW available, which define the maximum allowed concentration. A NSDF is available for hazardous/toxic RAW, a DGF is under development. Nevertheless, the disposal of toxic waste and the disposal of RAW have two different legislations.

In the Czech Republic disposal of hazardous and toxic RAW is not foreseen, as it is forbidden to add substances presenting chemical/toxic/biological hazards to RAW. The waste acceptance protocol includes a declaration of the waste producer about the absence of dangerous substances.

5.7.6 Implications of disposal options on predisposal routes

In landfill disposal sites, only very low level hazardous RAW can be disposed. Limitations regarding spread of toxicity exist (usage of assumption for safety justification). A sorting of hazardous/toxic RAW regarding the radiation level and possibly the toxicity is necessary.

In near surface disposal sites, LLW with low or intermediate toxicity might be disposed. Restrictions might apply depending on area or other factors.

DGFs are applicable for HLW, wastes with higher toxicity and wastes needing higher security measurements.

6. Summary

The aim of this deliverable is to compile the results of a three-day online workshop with participants from both SIMS and large inventory member states. Before the workshop, a questionnaire for preparation had been sent out to provide the foundation for the discussions. Open points, which could not be clarified during the workshop were addressed after the workshop and the information included in this report. The objective was the evaluation of predisposal strategies for small inventory member states for the disposal of small amounts of waste from different origins. Six waste types (concrete, DSRS, SIERs, spent fuel from research reactors, U/Ra/Th bearing waste and hazardous waste), which had been declared as challenging waste types previously, were selected for evaluation.

For each of the pre-disposal steps (pre-treatment, treatment, and conditioning) descriptions are being given of what techniques are associated with each step together with examples from participating countries. Discussions on the techniques showed that often, for small amounts of waste, facilities are not feasible because of their cost. This shows the importance of shared and/or mobile facilities for SIMS. Examples for this are incineration (where shared solutions are available) and compaction (shared or mobile facilities) but also in-drum drying. Discussions on the pre-disposal steps showed that, when resources (regarding available facilities, financial and staff-wise) for pre-disposal and disposal are as limited as they are for SIMS, the importance of waste minimization is even higher. This is even more so for the challenging waste types discussed.

To discuss the implications of disposal options on predisposal routes – and vice versa – the disposal options were divided into three groups: On surface (only long-term interim storage falls under this category), near surface and geological disposal. Long-term interim storage though can only be seen as a disposal option if the waste is clearable afterward the foreseen storage period.

For each of the selected, challenging waste type first disposal options were discussed, followed by information given on the inventory, the pre-disposal steps and disposal options by SIMS and LIMS participants. The waste types were:

Concrete is a large-volume waste with a low specific activity coming mostly from decommissioning projects. The general first pre-disposal step is clearance if possible. For treatment it is mostly crushed then packaged. This is sometimes even done reversible without a stabilizing matrix (DK) or using grout encapsulation (DE, UK). After crushing super-compaction is also used. It is also used to fill voids in drums (NL). Regarding disposal options: In general, the discussions identified that all borehole options were not suitable due to the volumes involved, but that all other near-surface options and geological disposal options are suitable (the latter mostly for waste with higher specific activities). It was pointed out that concrete waste can also be used as backfill material in containers ore void spaces inside a disposal facility.

For DSRS reuse and recycling is the favourable option (especially for category 1 and 2 sources). Regarding pre-disposal the main steps identified were dismantling and then segregation by half-life of the nuclide and activity (category) and packaging. Further steps often involve either cementation or polymer fixation for near surface disposal, or encapsulation for disposal. Regarding disposal options boreholes were seen as a very suitable option for SIMS. LLW DSRS are currently mostly cemented and disposed in near-surface repositories and sources with long-lived nuclides are mostly in long-term storage waiting for deep geological disposal. Challenges arise from the long period of interim storage of DSRS until disposal facilities are available.

For SIERs currently cementation or incineration are the main methods used. Both have advantages and disadvantages (e.g., volume increase during cementation; incineration not recommended for high ^{14}C resins). There is also ongoing research into fixation processes into different matrix types (like geopolymer matrices). Also, there is the option for dried SIERs in specially licensed containers. Regarding disposal, boreholes were not recommended (regardless of their depth). Currently disposal is mostly near-surface.

Predisposal waste treatment for spent fuel from research reactors includes wet and dry storage, reprocessing or encapsulation. Disposal will be deep geological (which could be also in the form of deep boreholes for small amounts of SF). Many countries have agreements on repatriation to the producer country of the fuel for research reactors. For SIMS a shared solution can represent a disposal option if there is no other HLW in the country (which is often the case for SIMS).

For U/Ra/Th bearing waste the definition of the waste is strongly dependent on the country. In general, the amount of URT-waste is high. Different pre-disposal methods are being used for different kinds of URT-waste. For bulk materials it is mostly drying, compaction and cementation, for metals decontamination, melting and compaction and for liquid waste precipitation and drying of the resulting sludges. Most of the waste can be disposed of on public landfills as exempted waste (NORM), small amounts are for near surface disposal facilities (with some hundred Bq/g specific activity) and a very small amount needs a geological disposal solution (such as URT-waste with a high activity as in the case of URT-waste from Zirconium production). For SIMS a combination of disposal options was mentioned that could be a solution combining near-surface disposal with a borehole.

The last waste category discussed was hazardous waste. In accordance with national laws, non-radioactive hazardous waste can be disposed of at special landfills or other appropriate facilities. It consists of a huge group of substances where each subset has distinct characteristics. They have in common that it is radioactive waste that also contains non-radioactive toxic or hazardous substances. That means challenges can also come due to different legislations surrounding the waste type (on one had due to the hazardous and toxic nature and on the other hand due to the radioactivity involved). Discussed were mostly lead and asbestos but also beryllium and mercury. Very low-level waste might be permitted to be disposed of at the same landfill as hazardous waste. Many countries are waiting for disposal options. Near surface disposal sites are where LLW with low or intermediate toxicity might be disposed and DGFs are applicable for HLW and wastes with higher toxicity.

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