Deliverable D9.21: ROUTES – Report on Evaluation of existing predisposal routes for SIMS with regard to disposal options

Work Package ROUTES

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Executive Summary

The generation of radioactive waste in various member states 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.

In the context of ROUTES Task 8, which aims to conduct a qualitative analysis of potential waste management solutions for Small Inventory Member States (SIMS), Subtask 8.1 compares different predisposal processing options within large inventory member states (LIMS) for selected waste types and identifies opportunities for collaboration in scenarios where national solutions are not feasible for managing small amounts of waste or cannot be implemented due to other reasons.

This report includes the results of Subtask 8.1, which aims at assessing the existing predisposal routes for SIMS based on the input of two workshops held in January 2022 (M30) and May 2022 (M34).

In this Subtask 8.1, four challenging waste types for SIMS were selected for detailed analysis and assessment in the frame of the workshops, with the aim of providing a base for future comparison with regards to the applicability of the predisposal options for managing small amounts of waste. These selected waste types are: Spent ion exchange resins (SIERs), disused sealed radioactive sources (DSRS), metals (from decommissioning) and concrete (from decommissioning). To facilitate the comparability between the predisposal option assessment and to allow a similar approach for the assessment of the disposal options in the subsequent Subtask 8.2, the NDA Value Framework, a value framework developed by the Nuclear Decommissioning Authority of the UK, was chosen as applied methodology. This methodology enables an analysis of all major factors affecting the choice of a radioactive waste management route. For each waste type, these factors where aggregated and discussed by the participants of ROUTES Subtask 8.1.1. Through this process, the positive and negative effects of each available predisposal route on the environment, risk / hazard reduction, health & safety, security, socio-economic impacts, lifetime cost, as well as the facilitation of the mission were documented. Additionally, the achievability of the predisposal route was discussed, along with potential factors impacting its feasibility, required facilities for the implementation, as well as other relevant information or comments. A special focus was given to the applicability of the predisposal routes for SIMS and the availability of shared solutions.

This deliverable D9.21 is the further development of ROUTES Milestone 281, titled “Internal memorandum with results of Part 8.1.1 for final report D9.21”, which was published in February 2023. Additionally, this deliverable encompasses the impacts of predisposal routes on disposal options. The comprehensive outcomes and evaluation of existing predisposal routes for SIMS are outlined below.

Spent Ion Exchange Resins:

- Cementation of resins is a low-cost and easy to implement conditioning method. This conditioning method could be acceptable for near surface disposal as well as for geological disposal.
- Polymer encapsulation is a technological complex process of higher cost but leads to lower increase of the waste volume than cementation. This option can be suitable for near surface disposal as well as for geological disposal.
- The predisposal options incineration of resins followed by cementation or super-compaction of the ashes, (hydro-)pyrolysis and super-compaction as well as thermal compaction are complex processes with high costs. Due to activity concentration, these methods have limited suitability for near surface disposal.

Disused Sealed Radioactive Sources:

- Encapsulation of sources after dismantling of DSRS is a recommended practice for storage. It is a low-cost and easy to implement option for sources of category 3 to 5. ^{226}Ra sources should be welded into capsules to avoid ^{222}Rn gas emanation. For the dismantling and encapsulation of High Activity Sealed Sources (HASS), IAEA offers a mobile hot cell facility. In cases where there are very limited resources for the management of DSRS of category 3 to 5, and immediate dismantling and encapsulation of the sources are not feasible, the DSRS can be packed in dedicated packaging for storage. Some short-lived DSRS such as ^{57}Co or ^{68}Ge, with a half-life of about 270 days, can be stored for decay and subsequent clearance.
- The export of DSRS, i.e., return to the producer for recycling or disposal in the country of origin, is a commonly practiced strategy. This solution should be considered by SIMS as its implementation leads to minimization of waste and reduces the needs for disposal.

Metallic waste from decommissioning:

- Cementation of metallic waste is a low-cost and easy to implement option. This conditioning method could be acceptable for near surface disposal as well as for geological disposal if waste acceptance criteria (WAC) are fulfilled.
- Specific matrices for conditioning, such as some geopolymers or alkali activated cements based on magnesium brucite, aim to better stabilize reactive metals, e.g., aluminium or magnesium.
- Super-compaction could be considered by SIMS in case of significant amounts of metallic waste, but the costs for necessary equipment are high. Super-compaction is suitable for near surface disposal as well as for geological disposal provided that the WAC are fulfilled.
- Thermal treatment in dedicated facilities is an available option for metallic waste. The final waste form could be suitable for any type of disposal facility if WAC are fulfilled. Thermal treatment can be also used before clearance of metals for recycling and reuse.
- For hazardous metallic waste, such as beryllium, the waste is welded into special steel capsules filled, e.g., with argon as inert gas. Also, polymers can be used for conditioning of beryllium. Beryllium after conditioning is suitable for near surface disposal as well as for geological disposal provided that the WAC are fulfilled.
- Conversion of sodium radioactive waste into glass is an available technology. This treatment option is suitable for near surface disposal if WAC are fulfilled, as well as for geological disposal.
- For the predisposal management of uranium, the direct conversion of metallic to oxide form allows management via more conventional disposal strategies and concepts developed for uranium oxides (e.g., direct disposal to a geological repository). Depleted uranium can be disposed of as low-level radioactive waste if it is converted to chemically stable uranium oxide compounds.

Concrete from decommissioning:

- Big Bags can be used to package very low-level waste (VLLW) concrete without further conditioning for disposal. This packaging is suitable for near surface disposal but might not be suitable for geological disposal due to the volume of waste generated.

- For low activity concrete from decommissioning, recycling or reuse might be an option if national regulations for clearance are available.
- Low and Intermediate Level Waste (LILW) concrete can be encapsulated in special containers for disposal and cementation. This is a low-cost and easy to implement option that can be adopted by SIMS.

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Acronyms and 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 activity sealed radioactive sources

HEU – high-enriched uranium

HIP – hot isostatic pressing

HLW – high level waste

IEX – ion-exchange chromatography

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

NDA – Nuclear Decommissionig Authority (in UK)

NORM – naturally occurring radioactive material

NPP – nuclear power plant

NSDF – near surface disposal facility

PP – polypropylene

RAW – radioactive waste

RR – research reactor

SF – spent fuel

SIER – spent ion-exchange resin

SIMS – small inventory member states

VLLW – very low level waste

VSLdW – very short-lived decay waste

WAC – waste acceptance criteria

1 Introduction

The generation of radioactive waste in various member states 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 or with only a small number of nuclear power plants. These countries have small amounts of waste from research reactors and from medicine, industry, and research but low volumes from nuclear power plants.

In the context of ROUTES Task 8, which aims to conduct a qualitative analysis of potential waste management solutions for Member States with less advanced programs, especially those lacking waste acceptance criteria (WAC) and dealing with small inventories (SIMS), Subtask 8.1 compares different predisposal processing options within large inventory member states (LIMS) for selected waste types, taking into account the results from [1], and identifies opportunities for collaboration in scenarios where national solutions are not feasible for managing small amounts of waste or cannot be implemented due to other reasons.

This deliverable includes the results of Subtask 8.1.1, which aims at assessing the existing predisposal routes for SIMS based on the input of two workshops held in January 2022 (M30) and May 2022 (M34).

During these workshops, four challenging waste types for SIMS, initially selected in ROUTES Task 4 and Task 5.2 were analysed (see [3] and [4]): spent ion exchange resins (SIERs), disused sealed radioactive sources (DSRS), metals (from decommissioning) and concrete (from decommissioning). The methodology for assessment is based on the NDA Value Framework and is presented in Section 2 of this report.

Chapter 3 is dedicated to the assessment of predisposal waste management options for the waste types SIERs, DSRS, metals and concrete from decommissioning. For each waste type, the implications of a predisposal waste management option on the following factors are discussed:

- Environment
- Health & Safety
- Risk / Hazard Reduction
- Security
- Socio-economic impacts
- Lifetime costs
- Enabling the mission
- Opportunity for shared solutions
- Applicability for SIMS
- Implications of the predisposal option on disposal options.

In Chapter 4, this report is concluded by a summary of the predisposal routes analysis.

All information gathered in the workshops, which is the main input data of this report, can be found in the appendices.

2 Methodology

Task 8 extends the evaluation of the possible waste management solutions for Member State without WAC and / or with small inventories (SIMS). Three objectives of Task 8 are:

- Qualitative analysis and assessment of the predisposal routes of challenging waste for SIMS;
- Qualitative analysis and assessment of existing disposal options for SIMS;
- Analysis of the applicability of the disposal options for SIMS (e.g., inventory, costs, retrievability).

To address these topics, the following assessment framework was chosen, and the predisposal and disposal options were analysed accordingly. The evaluation of predisposal options in Task 8 is based on the input of participants in the framework of a workshop in M34. The participants represented a total of 16 countries and 19 organisations, from research entities, waste management organizations and technical support organisations as well as civil society experts.

The assessment of the predisposal options utilises the NDA Value Framework [2] (see *Figure 1*). The framework analyses options based on seven factors: health & safety, security, environment, risk / hazard reduction, socio-economic impacts, lifetime cost and enabling the mission. These factors again form the three pillars of the NDA Value Framework regarding sustainability and social value: environmental, economic, and social. During the kick-off-meeting of Task 8 it was decided to apply the same methodology for both predisposal and disposal options, discussed in the second subtask of Task 8, as this approach will enable an equivalent evaluation. Four waste types, which are considered challenging by SIMS, were selected for detailed analysis: spent ion exchange resins (SIERs), disused sealed radioactive sources (DSRS), metals (from decommissioning) and concrete (from decommissioning). The chosen predisposal steps were defined in D9.5 [3]. While further research on predisposal options is currently ongoing in the PREDIS Project, they are not included in this report. The selection of waste types is based on Milestone 151 "Workshop predisposal routes for the disposal options for SIMS (T5.2)" [5].

For each waste type, a predesigned table was completed collecting the positive and negative effects of each available predisposal option on:

- the environment (i.e., the potential to generate radiological and non-radiological discharges),
- risk / hazard reduction (the potential harm to workers and the public from exposure to radiological and non-radiological substances, conventional hazards, and nuisance (e.g., noise, dust, vibrations) at the site or sites in question and any transport between them),
- health & safety (the risk or hazard reduction after the implementation of an option and on completion of the intervention),
- security & isolation (threats such as theft, sabotage and in case of disposal options also isolation),
- socio-economic impacts (social, economic, and environmental well-being of society as a result of procurement, employment and investment),
- lifetime cost (the cost of implementation, doing the work, maintaining the asset, maintaining controls, decommissioning in the future) as well as
- the enabling of the mission (sustainable radioactive waste management).

Furthermore, there was a discussion regarding the feasibility of the predisposal option, potential factors that might impact its achievability, required support facilities and expertise, as well as any other relevant information or comments.

After the workshop, the tables were distributed to participants for completion as well as for information and verification.

Based on the completed and verified tables, an evaluation of predisposal options was conducted for each selected waste type.

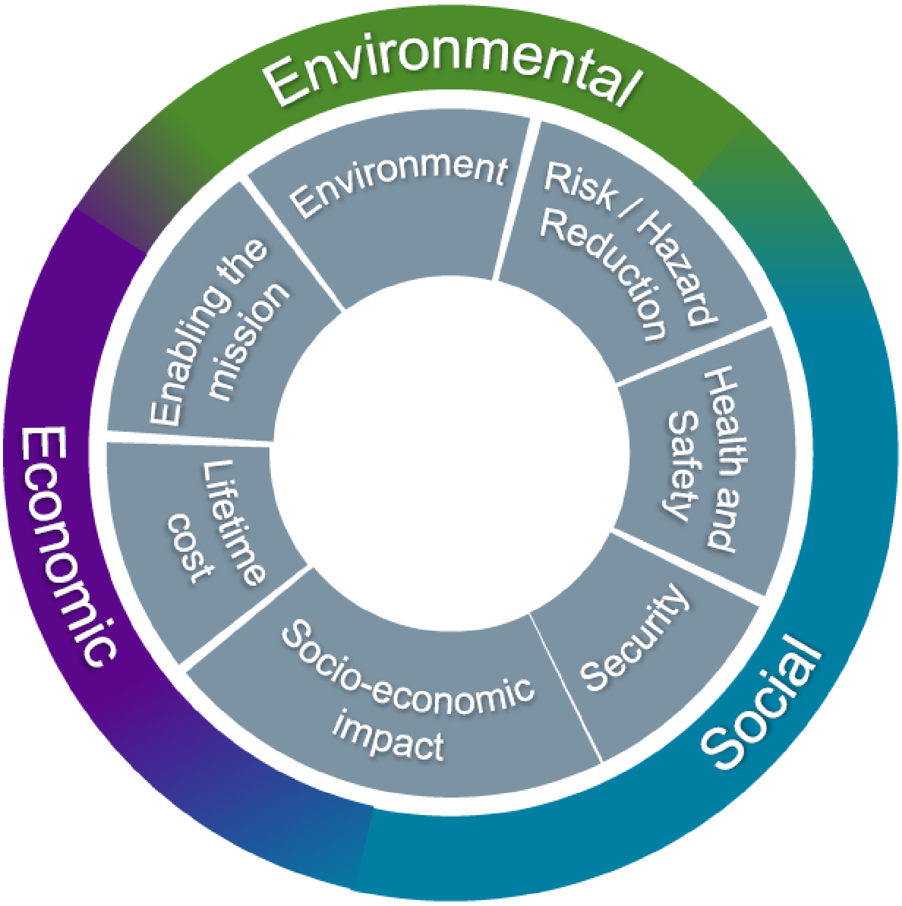

Figure 1 – NDA Value Framework and the 3 pillars of sustainability and social value [2]

The sections on implications of predisposal routes on possible disposal option have been drafted and discussed after the workshop by a subgroup of task participants from Austria, Czech Republic, Germany, and Greece.

3 Management of challenging types of radioactive waste

This chapter presents the management options for four types of radioactive waste, which are considered challenging by SIMS [5]: spent ion exchange resins (SIERs), disused sealed radioactive sources (DSRS), metals (from decommissioning) and concrete (from decommissioning). The treatment and conditioning options for these waste types were discussed in ROUTES task 2 [3]. In subtask 8.1 workshop, these processing options were further discussed, leading to the identification of other management options (e.g., export of DSRS, storage of short lived DSRS for decay, recycling of metals by clearance for melting) and evaluated using the NDA Value Framework.

To facilitate the discussion and the evaluation of the processing options, 4 tables were prepared and completed (see Appendixes B to E) by workshop participants of subtask 8.1 (see Appendix A). The outcomes of these workshop discussions, as well as the subsequent evaluation, are given in the following paragraphs. Moreover, the opportunity for shared solutions and the applicability of these options for SIMS based on subtask 8.1 discussions, are highlighted in the subsequent subsections.

3.1 Processing of spent ion exchange resins (SIERs)

3.1.1 Cementation

Cementation of resin without previous treatment is a well-used method, covered by regulations in respective countries. For low-level activity resins, cemented waste packages can be accepted in surface disposal facilities.

For implementation of this conditioning option, laboratories for determination of the physical properties (porosity, diffusion, coefficient, strength, elasticity) and chemical properties are necessary. Furthermore, cementation equipment as well as facilities for in-drum mixing and drying, are needed.

Environment: Except for possible ^{14}C release during the cementation process, no radiological emissions are expected for this treatment. New pre-cursor materials from the cement industry including graphene might result in higher ^{14}C generation if used for cementation of radioactive waste. Non-radiological discharges (e.g., CO_2 emission) during cement production might have an environmental impact. Furthermore, non-radiological discharges might occur after storage for decay and clearance of cement.

Health & safety: A radiological or non-radiological exposition of staff due to inhalation of active dust during cementation in case of a malfunction of the ventilation system. External dose can vary depending on the activity of the SIERs. Internal dose in case of long-term leakage of storage.

Risk / hazard reduction: Cementation results in the reduction of dose rate, as well as reduction of the risk of dispersion as well as of long-term corrosion and subsequent leakage.

Security: The increased weight through cementation complicates the diversion of the material.

Socio-economic impacts: Increase of storage space due to increase of waste volume (about five times), as well as large facilities necessary for cementation might have a psychological effect on the local public. The surface footprint required for additional cementation and the needed larger storage facility might have additional implications if the respective area has nature values.

Lifetime costs: Low costs for technology and support facilities, but increased costs for storage and disposal due to the increase of waste volume. Additional costs arise at decommissioning.

Enabling the mission: Possible non-compliance with future WAC of disposal due to non-compaction of waste. This point might not be relevant for SIMS as they have a low volume inventory. Alkali-silica reactions could occur and complicate disposal.

Opportunity for shared solutions: Already available (see [6]). Mobile solutions might result in benefits for the social-economic impact. Shared (non-mobile) solutions reduce lifetime costs of the facility but increase costs for transport and environmental risk.

Applicability for SIMS: If cementation of resins is in alignment with the WAC and disposal strategy of the respective SIMS, it is a low-cost and easy to implement conditioning method.

Implications of the predisposal option on disposal options: see Table 1.

Table 1 – Implications of cementation predisposal option on disposal options for SIERs

Disposal option	
Near surface	Suitable for low activity concentration if WAC are fulfilled. Waste volume increase due to cement and water incorporation in waste form but usually there is no volume limitations of the disposal site.
Geological	Suitable also for higher activity resins if no volume restriction. Possible WAC restrictions for organic resins due to radiolysis.
Borehole	Not suitable due to volume.

3.1.2 Polymer encapsulation

Polymer encapsulation is already used in some radioactive waste management programmes. E.g., UK and Czech Republic use polymerisation. Geopolymerisation is currently in the research phase and could be used in future [7]. Resins are commonly conditioned in epoxy matrices, e.g., in France and Belgium [3].

In some countries, polymer encapsulation is currently in the research phase. Further R&D is necessary for long-term properties of polymers (e.g., radiolysis is polymer type dependent) [3] [8] [9].

For implementation of the technique, besides the equipment for polymer encapsulation, a laboratory for the determination of the physical and chemical properties is a common request.

Environment: Polymer encapsulation might lead to non-radiological discharges after long-term storage for decay and clearance of the matrix. Regarding the containment of radionuclides, polymer encapsulation has good properties with respect to environmental impact, which might decline due to radiolysis over time.

Health & safety: During handling and processing of precursor material and the chemical treatment process, potential impact from chemicals on workers cannot be excluded.

Risk / hazard reduction: Polymer encapsulation might reduce the risk of dispersion and long-term leakage. Radiolysis impact on polymer is precursor dependent. Criticality needs to be addressed due to potential moderation of neutrons in polymers. Reduced heat resistance in comparison to cemented resins.

Security: Diversion of material is less complicated than the diversion of cemented material as the weight is lower.

Socio-economic impacts: Impact during construction phase of the necessary facilities (i.e., transport and building), as well as size of the facilities necessary for polymer encapsulation might have a psychological effect on the local public. The surface footprint required for additional polymerization facility might have additional implications if the respective area has nature values.

Lifetime costs: High costs due to technological complexity of process. Reduced costs for interim storage and disposal in comparison to cemented resins, due to higher matrix-waste-ratio. Additional costs arise at decommissioning.

Enabling the mission: Relatively new technology with proposed high agreement also for future WAC.

Opportunity for shared solutions: Mobile facility available in France [6]. Shared solutions would provide benefits for the socio-economic impact as well as lifetime costs.

Applicability for SIMS: Polymer encapsulation of resins is in general applicable for SIMS but leads to high costs due to the technological complexity of the process.

Implications of the predisposal option on disposal options: see Table 2.

Table 2 – Implications of polymer encapsulation predisposal option on disposal options for SIERs

Disposal option	
Near surface	Suitable for low activity concentration if WAC are fulfilled. Waste volume increase due to treatment but usually there are no volume limitations of the disposal site. Possible WAC restrictions for organic compound due to combustibility.
Geological	Suitable also for higher activity resins if no volume restriction. Possible WAC restrictions for organic resins due to combustibility and matrix due to radiolysis.
Borehole	Not suitable due to volume of waste.

3.1.3 Incineration and cementation

Incineration of resin followed by cementation is an available process that needs to be aligned with regulations concerning discharges. In general, monitoring of discharges is requested by the regulatory bodies.

The necessary facilities for this management option are:

- in-drum drying facility (dehydration of waste before incineration)
- incineration facility
- equipment for sampling, analysis, and continuous monitoring of radiological and non-radiological discharges
- chemical characterisation infrastructure for SIERs before incineration to ensure WAC for incineration (e.g., heavy metals, reactive substances, sulphur, nitrogen) as well as for disposal (e.g., heavy metals) are met.
- radiological characterisation infrastructure before incineration to ensure WAC (e.g., long-lived, and short-lived radionuclides) for incineration as well as for disposal are met.

Environment: Radiological discharges as well as non-radiological discharges might occur during the process of incineration. Due to high energy demand, higher amounts of CO_2 are produced.

Health & safety: Radiological (incl. internal and external dose) and non-radiological exposition of staff might occur during incineration, as well as during handling of high activity ashes. Radiological and non-radiological exposition of public might occur during malfunctioning at the incineration facility or human error as well as during transport of the incinerated wastes.

Risk / hazard reduction: Reduction of risk of dispersion due to cementation, and reduction of long-term corrosion in drums and subsequent leakage.

Security: After cementation, the security is improved due to weight increase. Potential risk during transport to and from incineration facility if it is not located at the same site as the cementation facility.

Socio-economic impacts: The smaller interim storage facility compared to only cementation will have a lower psychological effect for neighbours. The psychological effect can increase because of releases from the incineration facility. During the construction phase there is an impact on the neighbours due to transport and building. If the incineration takes place elsewhere and a mobile facility for conditioning and testing is used, this is beneficial for the socio-economic impact.

Lifetime costs: High costs of asset and support facilities, as well as high running costs due to a high energy demand of the plant and maintenance costs. Additional costs arise at decommissioning.

Enabling the mission: Compliance with future WAC unclear as no compaction is performed. Possibly more stringent WAC for incinerated wastes than for other waste forms.

Opportunity for shared solutions: Shared solution needs legislation that allows transport of radioactive waste (also across borders) and treatment of foreign waste (abroad incineration is possible e.g., at Cyclife in Sweden and Javys WMO in Slovakia). Shared solutions would additionally lead to a smaller plant site, improving the socio-economic impacts and reducing the lifetime costs. Costs for transport need to be considered.

Applicability for SIMS: With the availability of shared solutions for the incineration, the incineration of resins followed by cementation of the ashes is an applicable solution for SIMS. Before adoption of this process by SIMS, existing disposal strategy / facilities must be factored in with related WAC.

Implications of the predisposal option on disposal options: see Table 3.

Table 3 – Implications of incineration and cementation predisposal option on disposal options for SIERs

Disposal option	
Near surface	Limited suitability due to the activity of the waste processing (WAC dependent suitability).
Geological	Suitable due to volume reduction of the waste processing and the absence of organic compounds in the waste.
Borehole	Might be suitable due to volume reduction of the waste processing if drums / capsules fit in borehole and meet the requirements of the safety analysis.

3.1.4 Incineration and super-compaction

The technology for incineration of SIERs followed by super-compaction of the ashes is available. Incineration of SIERs needs to be aligned with regulations concerning discharges. Generally, monitoring of discharges is requested by the regulatory bodies. Activity concentration might lead to higher class of waste for future disposal.

For implementation of shared solution, legislation that allows transport of Radioactive Waste (RAW) (also across borders) and treatment of foreign waste or legislation for transport of incinerator and super-compactor across borders is needed.

The necessary facilities for this management option are:

- in-drum drying facility (dehydration of waste before incineration)
- incineration facility

- equipment for sampling, analysis, and continuous monitoring of radiological and non-radiological discharges
- chemical characterisation infrastructure for SIERs before incineration to ensure WAC for incineration (e.g., heavy metals, reactive substances, sulphur, nitrogen) as well as for disposal (e.g., heavy metals) are met.
- radiological characterisation infrastructure before incineration to ensure WAC (e.g., long-lived, and short-lived radionuclides) for incineration as well as for disposal are met.
- super compactor

Environment: Radiological discharges as well as non-radiological discharges (e.g., heavy metals) might occur during the process of incineration and super-compaction. Due to high energy demand higher amounts of CO_2 are produced.

Health & safety: Radiological (incl. internal and external dose) and non-radiological exposition of staff might occur during incineration, as well as during handling of high activity ashes before and during super-compaction (e.g., occurrence of dust). Radiological and non-radiological exposition of public might occur during malfunctioning at the facility as well as during transport.

Risk / hazard reduction: Maximised volume reduction, concentration of activity and dose rate lead to higher isolation needed (waste class might be higher than in case of incineration and cementation). Reduced risk of corrosion due to very low to no humidity in conditioned waste.

Security: Potential risk during transport to and from incineration facility if it is not located at the same site as the compaction facility. Increased risk of diversion due to highly concentrated activity.

Socio-economic impacts: Radiological and non-radiological discharges might have a psychological effect on the local public. The smaller interim storage facility might result in a positive effect. During the construction time there is an impact on the neighbours due to traffic and the facility building.

Lifetime costs: High costs of asset (both incineration facility and super compaction are of high cost) and support facilities, as well as high running costs due to a high energy demand of the plant and maintenance costs. Additional costs arise at decommissioning. The costs for interim storage will be lower, as there is less space needed.

Enabling the mission: Compliance with future WAC is unknown, due to lack of matrix. Possibly more stringent WAC for incinerated wastes than for other waste forms, however it might be easier to meet the WAC than in case of conditioning with cementation. Lower total volume for disposal might enable larger selection of disposal options but higher activity concentration might exclude some options of lower cost.

Opportunity for shared solutions: Shared solution needs legislation that allows transport of radioactive waste (also across borders) and / or treatment of foreign waste (abroad incineration is possible e.g., at Cyclife in Sweden and Javys WMO in Slovakia). Shared facilities for in-drum compaction are available but no shared facilities for super-compaction is available yet. Abroad incineration e.g., at Cyclife is possible including super-compaction. Shared solutions lead to a smaller plant site, improving the socio-economic impacts and reducing the lifetime costs. Costs for transport need to be considered.

Applicability for SIMS: With the availability of shared solutions for incineration and super-compaction [6], this option is an applicable solution for SIMS. Before adoption of this process by SIMS, existing disposal strategy / facilities must be factored in with related WAC.

Implications of the predisposal option on disposal options: see Table 4.

Table 4 – Implications of incineration and super-compaction predisposal option on disposal options for SIERs

Disposal option	
Near surface	Limited suitability due to high activity concentration of the waste processing (WAC dependent suitability).
Geological	Suitable due to high volume reduction of the waste processing and the absence of organic compounds in the waste.
Borehole	Might be suitable due to high volume reduction of the waste processing, if drums / capsules fit in borehole and meet the requirements of the safety analysis.

3.1.5 (Hydro-)Pyrolysis and super-compaction

(Hydro-)pyrolysis is the chemical decomposition of organic materials by heating in the absence of oxygen and other reagents. Following the pyrolysis, the product can be super-compacted.

This technology is available and in alignment with regulations concerning discharges. Generally, monitoring of discharges is requested by the regulatory bodies.

The necessary support facilities for this management option are:

- in-drum drying facility (dehydration of waste before pyrolysis)
- (Hydro-)pyrolysis infrastructure
- equipment for sampling, analysis, and continuous monitoring of radiological and non-radiological discharges
- chemical characterisation infrastructure for SIERS before incineration to ensure WAC for incineration (e.g., heavy metals, reactive substances, sulphur, nitrogen) as well as for disposal (e.g., heavy metals) are met.
- radiological characterisation infrastructure before incineration to ensure WAC (e.g., long-lived, and short-lived radionuclides) for incineration as well as for disposal are met.

Environment: Radiological discharges as well as non-radiological discharges might occur during the process of (hydro-)pyrolysis. Due to high energy demand, higher amounts of CO_2 are produced.

Health & safety: Radiological (incl. internal and external dose) and non-radiological exposition of staff might occur during (hydro-)pyrolysis, as well as during handling of high activity product before and during super-compaction (e.g., occurrence of dust). Radiological and non-radiological exposition of public might occur during mal-functioning of the (hydro-)pyrolysis infrastructure as well as during transport.

Risk / hazard reduction: Maximised volume reduction and maximised concentration of activity and dose rate leads to higher isolation needed (waste class might be higher than for cemented waste).

Security: Potential risk during transport to and from pyrolysis facility if it is not located at the same site as the compaction facility. Increased risk of diversion due to highly concentrated radioactive waste.

Socio-economic impacts: Radiological and non-radiological discharges might have a psychological effect on the local public. The smaller interim storage might result in a positive effect.

Lifetime costs: Lower volume of waste after treatment and conditioning will results in smaller storage facility needed. High costs for facility ((hydro-) pyrolysis and super-compaction, as well as high running costs due to high energy demand and high-cost maintenance). Additional costs arise at decommissioning.

Enabling the mission: Compliance with future WAC is unknown, due to lack of matrix. Possibly more stringent WAC for pyrolyzed wastes than for other waste forms. Lower total volume for disposal might enable larger selection of disposal options but higher activity concentration might exclude some options of lower cost.

Opportunity for shared solutions: Shared solutions would provide benefits regarding the lifetime costs and the socio-economic impact but needs legislation regarding transport of radioactive waste (also across borders) and treatment of foreign waste. Costs for transport need to be considered.

Applicability for SIMS: (Hydro-)pyrolysis and subsequent super-compaction is a high technology, high-cost option for processing of resins and therefore a high-cost solution for SIMS.

Implications of the predisposal option on disposal options: see Table 5.

Table 5 – Implications of (hydro-)pyrolysis and super-compaction predisposal option on disposal options for SIERs

Disposal option	
Near surface	Limited suitability due to high activity concentration of the waste processing (WAC dependent suitability).
Geological	Suitable due to high volume reduction of the waste processing and the absence of organic compounds in the waste.
Borehole	Might be suitable due to high volume reduction of the waste processing if drums / capsules fit in borehole and meet the requirements of the safety analysis.

3.1.6 Thermal compaction

Thermal compaction (e.g., Hot Isostatic Pressing, HIP) is an available method used to densify and consolidate materials by applying isostatic pressure at an elevated temperature in a pressure vessel. In general, because of releases, monitoring of discharges is requested by the regulatory bodies. The resin hot compaction process is used to make dense homogenous organic blocks from a wide range of particulate waste.

Previously, it was evaluated to be unsuitable for the treatment of organic ion exchange resins and it was used only for inorganic ion-exchange chromatography (IEX) material [10]. A wet oxidation route for destruction of organic IEX resin is under investigation by University of Sheffield in PREDIS Task 6.3. Germany has however implemented this technology successfully by either destroying the bead resin structure before compaction or mixing bead with powder resins [11]. For implementation of this treatment technique, the waste requires pre-treatment to remove water (e.g., in drum drying system), organics and other volatiles via, e.g., calcination (to avoid gas generation during thermal compaction in a sealed vessel – the HIP canister). Glass / ceramic precursors need mixing with waste and loading into HIP canister, which is then evacuated of air, sealed, and immediately transferred to a high force compactor [12].

Environment: No discharges from the HIP step itself, but gaseous radiological and non-radiological discharges likely during high temperature pre-treatment.

Health & safety: Radiological (incl. internal and external dose) and non-radiological exposition of staff might occur during heat treatment. Safety requirements for workers needed due to high temperature (pre-) treatment.

Risk / hazard reduction: Reduction of chemical reactivity of waste and reduced potential for gas generation in waste. Additional, risk of dispersion and leakage is reduced. Potential issue of swelling and mechanical damaging of barriers if thermo-compacted resins saturate again after their disposal.

Security: Security during transport needs to be ensured if waste needs to be transported between facilities. Increased risk of diversion due to highly concentrated radioactive waste.

Socio-economic impacts: Lower socio-economic impact due to smaller storage facility necessary. Large facility for processing might have a psychological impact on local public, if no shared solution is available.

Lifetime costs: Lower volume of conditioned waste leads to lower costs for interim storage. High-cost facility needed for thermal compaction and pre-treatment. Additional costs arise at decommissioning.

Enabling the mission: Thermal compaction is a batch process, therefore suitable for low amounts of waste. Compliance with future WAC is unknown.

Opportunity for shared solutions: Due to batch process, this technique is suitable for mobile and shared solutions.

Applicability for SIMS: If mobile or shared solutions are available, the thermal compaction for resins is applicable to SIMS. It will possibly be a high-cost option for processing of resins and therefore a non-cost-effective solution.

Implications of the predisposal option on disposal options: see Table 6.

Table 6 – Implications of thermal compaction predisposal option on disposal options for SIERs.

Disposal option	
Near surface	Limited suitability due to activity concentration of the waste processing (WAC dependent suitability).
Geological	Suitable due to volume reduction of the waste processing. Possible WAC restrictions for organic compound due to combustibility.
Borehole	Might be suitable due to volume reduction of the waste processing if drums / capsules fit in borehole and meet the requirements of the safety analysis.

3.2 Management of disused sealed radioactive sources (DSRS)

3.2.1 Encapsulation

The DSRS are dismantled, i.e., the shielding is removed. Then, the source is conditioned in special cement and / or lead shielded containers usually without cementation or other matrices. It is a well-used method and regulations in many countries allow it. For implementation of this management option, dismantling infrastructure for DSRS [14] is necessary (i.e., in general a working bench for sources of category 3 to 5, a glovebox for damaged low activity sources and hot cell for High Activity Shield Radioactive Sources (HASS) (i.e., mainly sources of category 1 and 2).

Environment: Radiological discharges might occur during dismantling in case of leakage from a damaged source or due to an accident when cutting wheels are used in the disassembly process. The non-radiological discharges concern metals (mainly lead) originating from the dismantling process. Recycling of these metals is the best option.

Health & safety: The potential for significant external dose to personnel should be considered during dismantling on a bench or inside a glove box (for sources of categories 3 to 5). Moreover, internal dose to personnel in case of accident by a cutting wheel or during dismantling of a DSRS with leakage on a bench and not inside a glove box cannot be excluded. In general, the use of cutting wheels must be avoided [14]. Corrosion of DSRS after a few decades of storage hinder the disassembling process. Also, leakage of radioactive substances is possible after long-term storage. Therefore, deferred dismantling of DSRS should be avoided.

Risk / hazard reduction: Evaluation of doses inside the storage facility is easier after disassembly of the DSRS and encapsulation in special containers. This leads to better implementation of the radiation protection program. Also, reduction of the leakage risk after the implementation of this conditioning option is achieved.

Security: On the one hand, security is improved due to the high weight of the containers (i.e., the sources after dismantling and conditioning are more difficult to be stolen than the DSRS). On the other hand, the risk of diversion increases due to high concentration of activity.

Socio-economic impacts: Reduced socio-economic impact due to smaller storage facility needed after conditioning. The inspection, monitoring and tracking of sources is easier, leading to lower management cost as well as minimization of the possibility for contamination in the future, which could produce additional expenses. Moreover, the immediate dismantling of the DSRS avoids magnified dismantling difficulties in the future, which again would increase the total cost of management. Facilities for processing, particularly hot cells for HASS, which are of high cost might burden the society.

Lifetime costs: After the implementation of this management option, the costs for long-term storage are reduced due to the volume reduction of the waste. Nevertheless, the future conditioning for final disposal might be necessary and should be considered. For short-lived radionuclides, clearance after storage is possible due to retrievability of the sources. In general, the cost of implementation, execution, maintaining the asset, maintaining controls, and decommissioning in the future of the facilities for sources of cat. 3 to 5 is low.

Enabling the mission: Future WAC are easier to fulfil because of retrievability of the sources.

Opportunity for shared solutions: A mobile hot cell facility for dismantling of HASS is maintained by the IAEA [14].

Applicability for SIMS: Encapsulation is a low-cost and easy to implement option for sources of category 3 to 5. Regarding HASS, the IAEA mobile hot cell facility is available.

Implications of the predisposal option on disposal options: see Table 7.

Table 7 – Implications of encapsulation predisposal option on disposal options for DSRS

Disposal option	
Near surface	Limited suitability due to lack of matrix and high activity concentration (WAC dependent suitability).
Geological	Limited suitability due to lack of matrix (WAC dependent suitability).
Borehole	Suitable due to small volume of the waste. Specialised waste package necessary.

3.2.2 Welding into capsules (^{226}Ra sources)

The radium sources are welded into capsules, packed into lead shielding and put into a concrete shielded container. Because of ^{222}Rn gas production, a special container is needed. For borehole disposal the capsules can be packed in cement or lead-shielded containers. The conditioning process of welding and cementing is described in [15]. The process is used in many countries (e.g., Czech Republic, Germany, Portugal).

To implement this conditioning option, the following facilities are needed:

- dismantling infrastructure, i.e., a glovebox for category 3 to 5 and hot cell for HASS (i.e., category 1 and 2 sources).
- welding equipment
- cementation equipment
- laboratory for determination of physical properties (e.g., strength, elasticity)

Environment: Attention should be paid to ^{222}Rn release in the work environment. Also, ^{226}Ra discharges might occur during dismantling in case of leakage from a damaged source or due to an accident when cutting wheels are used in the disassembly process (the use of cutting wheels must be avoided [14]). The non-radiological discharges concern metals (mainly lead) that come from the disassembly of the DSRS. Recycling of these metals is the best option.

Health & safety: Significant dose from inhalation of ^{222}Rn cannot be excluded. High-activity ^{226}Ra DSRS should be dismantled inside a glove box or a hot cell. Consideration should be given to the possibility of external dose to personnel during dismantling of sources inside a glove box.

Risk / hazard reduction: The encapsulation of Ra sources will limit the possibility of ^{222}Rn emanation and thus reduce storage difficulties regarding inhalation / contamination. But regarding disposal, limits of alpha-emitting radionuclides per container are possible. These restrictions are based on long-term safety considerations. Encapsulation and cementation have positive effects on the exhalation of ^{222}Rn as well as the mobility of ^{226}Ra (reduction of the leakage risk). But as ^{226}Ra is a long-lived radionuclide, this kind of conditioning might not help for the whole assessment period. Evaluation of doses inside the storage facility is easier after the implementation of this conditioning option. This leads to better implementation of the radiation protection program.

Security: The higher weight of the containers after conditioning has a positive effect on the security, however, the risk of diversion might increase due to high concentration of activity.

Socio-economic impacts: Positive socio-economic impact due to smaller storage facility needed. The inspection, monitoring and tracking of sources is easier, leading to lower management cost as well as a minimization of the possibility for leakage in the future, which could produce additional costs.

Lifetime costs: After the implementation of this management option, the costs for long-term storage are reduced due to the volume reduction of the waste. Nevertheless, the possible additional conditioning in the future for final disposal should be considered in the cost. In general, the cost of implementation, execution, maintaining the asset, maintaining controls and decommissioning in the future of the facilities for sources of cat. 3 to 5 is low.

Enabling the mission: The method enhances the potential to meet future WAC, but future reconditioning of the waste cannot be excluded.

Opportunity for shared solutions: A mobile hot cell facility for dismantling of HASS is maintained by the IAEA [14].

Applicability for SIMS: For category 3 to 5 ^{226}Ra sources, welding followed by cementation is a low-cost and easy to implement predisposal option. Regarding HASS (category 1 and 2 sources), the IAEA mobile hot cell facility is available.

Implications of the predisposal option on disposal options: see Table 8.

Table 8 – Implications of welding and cementation predisposal option on disposal options for DSRS

Disposal option	
Near surface	Limited suitability due to longevity of ^{226}Ra and its alpha-decaying properties.
Geological	Suitable (WAC dependent suitability).
Borehole	Suitable due to small volume of the waste. Specialised waste package necessary.

3.2.3 Encapsulation and cementation in ordinary Portland cement grout

In general, encapsulation of DSRS and cementation in ordinary Portland cement grout is not implemented. Usually, cementation should only be carried out when the sources are disposed shortly after conditioning.

Processes for encapsulation of DSRS are in place with CEM II type cement in Romania. The drums used contain a special metallic basket, where the sources are embedded in the ordinary Portland cement grout. Around these baskets, the same grout is poured. This conditioning option is currently intended for the UK Geological Disposal Facility (GDF).

For implementation of this conditioning option, the following facilities are needed:

- dismantling infrastructure [14] (i.e., a working bench for most of the sources of category 3 to 5, a glovebox for damaged low activity sources and a hot cell for HASS (i.e., mainly category 1 and 2 sources).
- cementation equipment
- laboratory for determination of physical (permeability, porosity, diffusion coefficient, strength, elasticity) and chemical properties of cement.

Environment: Radiological discharges might occur during dismantling in case of leakage from a damaged source or due to an accident when cutting wheels are used in the disassembly process (the use of cutting wheels must be avoided [14]). The non-radiological discharges concern metals, mainly lead, that originate from the disassembly of the devices. Recycling of these metals is the best option.

Health & safety: The potential for significant external dose to personnel should be considered during disassembly on a bench or inside a glove box (for sources of categories 3 to 5). Moreover, internal dose to personnel in case of accident by a cutting wheel or during dismantling of a DSRS with leakage on a bench and not inside a glove box is possible. It should be mentioned that corrosion of DSRS after a few decades of storage hinder the disassembling process. Also, leakage of radioactive substances is possible after long-term storage. Therefore, deferred dismantling of DSRS should be avoided.

Risk / hazard reduction: Evaluation of doses inside the storage facility is easier after disassembly of the DSRS and encapsulation in special containers. This leads to better implementation of the radiation protection program. Also, reduction of the leakage risk after the implementation of this conditioning option is also achieved.

Security: Security is improved due to the high weight of the special containers containing cemented sources.

Socio-economic impacts: Reduced socio-economic impact due to smaller storage facility required. The inspection, monitoring and tracking is easier, leading to lower management cost as well as to minimization of the possibility for contamination in the future, which could produce additional expenses. Facilities for processing, particularly for HASS, might have a psychological impact on local public and the cost for purchase of a hot cell might burden the society. The surface footprint required for additional cementation facility might have additional implications if the respective area has nature values.

Lifetime costs: After the implementation of this management option, the costs for long-term storage are reduced due to a possible volume reduction of the waste. In general, the cost of implementation, execution, maintaining the asset, maintaining controls and decommissioning in the future of the facilities for sources of cat. 3 to 5 is low.

Enabling the mission: Sources encapsulation in mortar based on Portland cement should be used only for sources complying with the WAC of an existing near surface disposal facility.

Opportunity for shared solutions: A mobile hot cell facility for dismantling of HASS is maintained by the IAEA [14].

Applicability for SIMS: This option should be avoided by SIMS without near surface disposal facility because sources will not be retrievable for future conditioning under the future WAC.

Implications of the predisposal option on disposal options: see Table 9.

Table 9 – Implications of cementation and cementation in ordinary Portland cement grout predisposal option on disposal options for DSRS

Disposal option	
Near surface	Limited suitability depending on source activity and longevity (WAC dependent suitability).
Geological	Suitable (WAC dependent suitability).
Borehole	Suitable due to small volume of the waste; specialised waste package necessary.

3.2.4 Packaging with their shielding

DSRS of category 3 to 5 can be packed without previous disassembly of source and shielding in dedicated packaging for storage. Following options are:

- export of the DSRS,
- disassembling and then export of the sources in appropriate containers (e.g., of Type B),
- disassembling and conditioning for storage or disposal,
- decay with subsequent clearance.

Environment: The DSRS are interim stored for future management and therefore no radiological or non-radiological discharges occur during this procedure if regular inspections for package integrity are implemented.

Health & safety: There is no major health and safety issue as the DSRS of category 3 to 5, as the sources are simply transferred in special packages.

Risk / hazard reduction: The risk of radioactivity dispersion due to leakage after long-term interim storage is reduced.

Security: No changes in security.

Socio-economic impacts: Larger storage space is needed than in case of storage after dismantling. The inspection, monitoring and tracking become easier in case of storage on shelfs compared to dismantled and packed sources.

Lifetime costs: Due to the large number of packages required, the costs for interim storage are relatively high. On the other hand, the cost of implementation is low. Nevertheless, the future costs, e.g., for dismantling and conditioning or export should be considered.

Enabling the mission: The future WAC can be fulfilled. Nevertheless, the management of the DSRS is essentially postponed to the future and therefore corrosion, which will hinder the dismantling process as well as enhance the probability of leakage from the sources, cannot be excluded.

Opportunity for shared solutions: Not relevant.

Applicability for SIMS: In case of very limited resources, not allowing the immediate management of the DSRS, this solution for storage can be implemented. Nevertheless, the deferred management is not recommended.

Implications of the predisposal option on disposal options: Not applicable. This option is solely a predisposal practice.

3.2.5 Specific container for multiple HASS

For management of High-Activity Sealed Radioactive Sources (HASS), specific containers able to hold multiple high-level activity sources are under consideration in France. For implementation of this option, a hot cell for dismantling of HASS and placement into the specific container is necessary.

Environment: Radiological discharges might occur during dismantling in case of leakage from a damaged source or due to an accident when cutting wheels are used in the disassembly process (the use of cutting wheels must be avoided [14]). The non-radiological discharges concern metals, mainly lead, or depleted uranium that come from the disassembly of the devices. Recycling of lead and steel is the best option.

Health & safety: External dose for staff during manipulation of HASS as well as during manipulation of specific containers with multiple sources and internal dose in case of leakage cannot be excluded.

Risk / hazard reduction: Reduction of the leakage risk after the implementation of this conditioning option is achieved.

Security: Increased risk of diversion due to highly concentrated activity.

Socio-economic impacts: Reduced socio-economic impact due to a smaller storage facility required as well as to a smaller volume for disposal. Inspection and monitoring are easier, leading to lower management cost as well as to minimization of the possibility for leakage in the future, which could produce additional expenses. By the immediate dismantling of DSRS, difficulties in the future that would lead to additional costs are avoided.

Lifetime costs: Reduction of costs for long-term storage because of volume reduction. Nevertheless, the costs of a hot cell for dismantling of HASS as well as its decommissioning in the future is high. The use of the IAEA mobile hot cell facility for dismantling of HASS might be a cost-effective option in case of limited number of HASS [13].

Enabling the mission: This technology is available, but regulations are required for adoption by a state. It might represent a solution that will respect WAC for deep geological disposal in the future.

Opportunity for shared solutions: For dismantling of HASS, IAEA offers a mobile hot cell facility [14].

Applicability for SIMS: To apply this option in SIMS, the specific container must be applicable also for small-scale solutions, e.g., disposal in boreholes.

Implications of the predisposal option on disposal options: see Table 10.

Table 10 – Implications of use of specific container for multiple HASS predisposal option on disposal options for DSRS

Disposal option	
Near surface	Not suitable due to source activity and longevity of HASS.
Geological	Suitable (WAC dependent suitability).
Borehole	Not suitable due to the design of the borehole disposal and suitable containers.

3.2.6 Decay storage and clearance for short-lived DSRS

Some short-lived DSRS such as ^{57}Co or ^{68}Ge, with a half-life of about 270 days, can be stored for decay and subsequent clearance. For this option, approval by the regulatory authority is necessary. It should be noted that in some cases it is binding to send back the radioactive sources to the manufacturer.

For this management option, radiological characterization equipment (i.e., non-destructive gamma spectrometer systems) and skills for verification of clearance after storage for decay is necessary. Also, interim storage space for decay of short-lived DSRS should be foreseen.

Environment: There are no radiological discharges if regular inspections and monitoring are performed during storage and clearance regulations are met before release. The non-radiological discharges concern metals, mainly lead or plastics. Recycling of lead and steel should be performed.

Health & safety: External dose as well as internal dose for personnel in case of leakage during manipulation cannot be excluded.

Risk / hazard reduction: During storage there is a risk of external dose as well as internal dose for personnel in case of leakage. Regular inspections and monitoring should be carried out. After interim storage and clearance there is no further radiological risk, provided that the clearance regulations are met.

Security: Security measures for the interim storage site is necessary.

Socio-economic impacts: Additional space inside the interim storage is needed and therefore larger building which might have a negative psychological effect on the local public. The cost for storage should be considered.

Lifetime costs: Costing should be performed including costs for decay storage, security means, inspections, clearance measurements and disposal of conventional waste. Possibly the costs are lower than for export of the short-lived sources.

Enabling the mission: This option enables minimization of waste by clearance.

Opportunity for shared solutions: Not relevant.

Applicability for SIMS: Decay storage is a management option that can be considered by SIMS, especially in case of limited resources for export of sources.

Implications of the predisposal option on disposal options: Not applicable. This option is solely a predisposal practice.

3.2.7 Export for recycling or disposal

Export of DSRS, i.e., return to producer for recycling or disposal in the country of origin, is a commonly practiced strategy. A return of the source to the producer might be necessary by law in some countries. Most countries seek to export their DSRS, mainly of category 1 to 3.

For implementation of the strategy, regulations for international transport should be in place. Also, infrastructure for packaging of sources after dismantling or for packaging directly the DSRS in special containers for transport is necessary. In case of dismantling, dismantling infrastructure is necessary (e.g., a work bench for sources of category 3 to 5, glovebox for damaged low activity sources and hot cell for category 1 and 2 sources [14]). Furthermore, logistics relevant for transport and export of radioactive sources or DSRS is needed.

Environment: Radiological discharges might occur during dismantling in case of leakage from a damaged source or due to an accident, e.g., when cutting wheels are used in the disassembly process (the used of cutting wheels should be avoided [14]). The non-radiological discharges concern metals, mainly lead, that originate from the disassembly of the DSRS. Recycling of these metals should be favoured.

Health & safety: The potential for significant external dose to personnel should be considered during disassembly on a bench or inside a glove box (for sources of categories 3-5). Moreover, internal dose to personnel in case of accident by a cutting wheel or during dismantling of a DSRS with leakage on a bench and not inside a glove box is possible. Corrosion of DSRS after a few decades of storage hinder the disassembling process. Also, leakage of radioactive substances is possible after long-term storage. Therefore, deferred dismantling of DSRS should be avoided.

Risk / hazard reduction: External dose for personnel might be reduced due to the reduction of the number of sources inside the storage facility. The risks for dispersion of radioactivity and internal dose for personnel in case of leakage might also be reduced due to the lower number of DSRS in the storage.

Security: The level of security of the storage facility can be lower due to the much lower number of DSRS. On the other hand, increased number of transports for DSRS leads to lower security.

Socio-economic impacts: Positive psychological effect for the community due to lower number of sources in storage but negative psychological effect due to increased number of transports of radioactive materials.

Lifetime costs: The costs for security are lower due to low amount of DSRS in storage. Also, the costs for storage and future disposal are much lower. Nevertheless, the costs for export-return to producer need to be considered.

Enabling the mission: This option enables minimization of waste and reduces the space needed for disposal.

Opportunity for shared solutions: For dismantling of HASS, IAEA offers mobile hot cell facility [14].

Applicability for SIMS: This solution should be considered by SIMS because its implementation leads to minimization of waste and reduces the needs for disposal. A feasibility study is recommended for the decision to select sources for export.

Implications of the predisposal option on disposal options: Not applicable.

3.3 Management of decommissioning waste containing metals

3.3.1 Cementation

Cementation of metals is a low-technology process, which is often used for non-reactive metals. Reactive metals such as aluminium or magnesium are not covered by this section. For implementation of this conditioning option, a laboratory for determination of the physical (e.g., permeability, porosity, diffusion, coefficient, strength, elasticity) and chemical properties of cement is necessary. Furthermore, cementation equipment as well as in-drum mixing, and drying facilities are needed.

Environment: There are no radiological or non-radiological discharges during cementation of metallic waste. However, the cemented waste after decay storage and clearance is considered as non-radiological discharge to the environment.

Health & safety: Non-radiological exposition of personnel due to inhalation of dust during cementation cannot be excluded. External dose to the personnel in case of manipulation of high activity metals during cementation as well as internal dose in case of manipulation of metallic waste with significant activity of loose surface contamination cannot also be excluded.

Risk / hazard reduction: Cementation results are the reduction of dose rate, as well as the reduction of risk of dispersion, long-term corrosion in drums and leakage.

Security: Security is improved due to weight increase.

Socio-economic impacts: The cementation process increases the total volume of waste. Additionally, the surface footprint required for additional cementation facility might have additional implications if the respective area has nature values.

Lifetime costs: The cost of the asset and support facilities is not high but without any reduction of the waste volume, the cost for storage and future disposal might be high, especially if priced by volume. Additional costs arise at decommissioning.

Enabling the mission: The waste form might not comply with the future WAC. Innovative research on chemical composition of cement matrix is on-going to improve its properties for compliance with future WAC. This research aims to develop and qualify new conditioning matrices (e.g., geopolymers, magnesium phosphate cements), which might be used as alternatives to cement-based matrices not only for reactive metals, but also for all the metals.

Opportunity for shared solutions: Currently no shared solutions are in place. A mobile facility for cementation would be advantageous from both a socio-economic and cost perspective.

Applicability for SIMS: Cementation is a low-cost and easy to implement option. It could be appropriate for small amounts of metallic waste if WAC for disposal are in place.

Implications of the predisposal option on disposal options: see Table 11.

Table 11 – Implications of cementation predisposal option on disposal options for metallic wastes

Disposal option	
Near surface	Suitable for low activity concentration if WAC are fulfilled
Geological	Suitable also for higher activity metals if there is no volume restriction
Borehole	Not suitable due to volume

3.3.2 Thermal treatment

Thermal treatment is an available management option for metallic waste and can be used also for recycling and reuse of metals (see subchapter 3.4). The metallic wastes are melted inside a controlled area. This management option is usually outsourced to specialised contractors. Facilities, which accept metals for melting from nuclear decommissioning are, e.g., Cyclife in Sweden. For melting of metals, WAC should be fulfilled (e.g., for Studsvik facility [16] or UK’s LLW Repository Ltd, WAC Metallic Waste Treatment [18]).

Reliable radiological characterisation of metals (i.e., scaling factors, non-destructive measurement with low uncertainty) is necessary for cross-border transport.

Environment: In general, there are no discharges at the local facility because this management option is outsourced. The releases of radionuclides including ^3H, and heavy metals at the melting facility cannot be excluded. Additionally, due to high energy demand higher amounts of CO_2 are produced.

Health & safety: Radiological (i.e., internal dose) and non-radiological exposition of the personnel during sampling cannot be excluded. Moreover, thermal cutting of metallic components for packaging causes release of radioactive aerosols. Measures for radiation protection of workers are necessary (e.g., special ventilation system). External dose to the personnel in case of manipulation of high activity metals during characterization and cutting, as well as internal dose in case of manipulation of metallic waste with significant activity of loose surface contamination cannot be excluded.

Risk / hazard reduction: Loose contamination of thermally treated metals can be excluded after completion of the intervention. The secondary wastes (e.g., sludge, filters) should be treated and disposed of according to waste type. In general, the owner of the metallic waste is responsible for management of the secondary waste from melting inside a control area.

Security: For both the untreated and treated metallic wastes, as well as the secondary wastes, there is a risk associated with the transport of radioactive material.

Socio-economic impacts: In case of outsourcing, no melting facility (including control zone) needs to be built, operated, and decommissioned in the future as nuclear facility. Moreover, smaller interim storage is needed due to the reduction of the waste volume. In case of melting inside a control area, the secondary waste (e.g., sludge, filters) with concentrated activity will be returned to the waste owner and should be managed appropriately.

Lifetime costs: There is no cost for construction, maintenance and decommissioning of treatment facility in case of outsourcing. The cost for purchase and maintenance of characterization equipment as well as the employment of specialised personnel for characterization should be considered. Moreover, the cost for transport, transport containers and outsourcing of the treatment should be factored in.

Enabling the mission: After melting, homogeneous activity distribution is achieved, and the accuracy of the metallic waste characterization is higher. Therefore, WAC are easier to prove. The waste form after melting is a robust metallic matrix, acceptable for direct disposal.

Opportunity for shared solutions: For shared solution, legislation that allows transport of radioactive waste (also across borders) and treatment of foreign waste at a melting facility is needed.

Applicability for SIMS: Due to higher waste minimization, this management option is preferred to super compaction of metals. In general, a release of metals for recycling or recycling inside the nuclear domain, e.g., casks or shielding production is achievable after melting. Nevertheless, the applicability depends on the amount of metallic waste in the specific country. All the parameters and costs should be factored in for decision.

Implications of the predisposal option on disposal options: see Table 12.

Table 12 – Implications of thermal treatment predisposal option on disposal options for secondary waste after thermal treatment of metallic wastes

Disposal option	
Near surface	Suitable for low activity concentration if WAC are fulfilled
Geological	Suitable also for high activity concentration if WAC are fulfilled
Borehole	Might be suitable, if drums / capsules fit in borehole and meet the requirements of the safety analysis.

3.3.3 Super-compaction

In some countries, like Austria and Germany, super compaction of metals is in alignment with regulations. For higher minimization of metallic waste, melting and then compacting the resulting slag and filters is preferable. In case of direct super-compaction, large metallic pieces might pose a problem, as there is a risk of blocking the compaction ram (see Table IV and Appendix A.25 in [1]).

For implementation of this conditioning method, a super-compactor as well as radiological characterization equipment and specialised personnel are needed.

Environment: Liquid discharges are possible, and the production of dust cannot be excluded.

Health & safety: The noise during compaction could harm the workers and protective measures should be taken. Radiological (i.e., internal dose) and non-radiological exposition of the personnel during pre-treatment and preparation of super-compaction of metallic components might cause release of radioactive aerosols or dispersion of loose surface contamination. Measures for radiation protection of workers are necessary (e.g., special ventilation system).

Risk / hazard reduction: There is significant reduction of potential dispersion, long-term corrosion in drums and leakage.

Security: Security is improved due to weight increase.

Socio-economic impacts: Smaller interim storage is needed due to volume reduction.

Lifetime costs: The purchase and maintenance of super-compaction equipment is expensive. Decommissioning might not be expensive due to the low contamination of the asset. The cost for characterization equipment and specialised personnel for characterization should be considered.

Enabling the mission: Compacted metals generally meet WAC requirements (e.g., solid, no explosives / burnable substances, no critical masses etc.). Also, the additional requirement of a minimal compaction force of 30 MPa is, by definition, met by super compaction.

Opportunity for shared solutions: There are already shared facilities for super-compaction available [17].

Applicability for SIMS: This conditioning option could be considered by SIMS only in case of significant amounts of metallic waste, due to the high costs of necessary equipment.

Implications of the predisposal option on disposal options: see Table 13.

Table 13 – Implications of super-compaction predisposal option on disposal options for metallic wastes

Disposal option	
Near surface	Suitable for low activity concentration if WAC are fulfilled
Geological	Suitable also for high activity concentration if WAC are fulfilled
Borehole	Not suitable due to volume

3.3.4 Recycling / reuse

For recycling and reuse of metals, legislation is necessary including the option of specific clearance. BSS Directive sets the exemption and clearance criteria for recycling / reuse as referred to in Articles 24, 26 and 30 and in Annex VII [19][20][29]. Also, the guidance on the practical application should be considered.

For implementation of this policy, reliable characterisation of metals (i.e., scaling factors determination, non-destructive measurement with low uncertainty and high sensitivity) is necessary. Research is in progress, e.g., in the frame of PREDIS project WP4, T4.5 “Optimisation of metallic waste characterisation and procedures for waste minimization and recycling”.

Decontamination techniques and clearance procedures after dismantling (i.e., mechanical, or chemical decontamination, melting after clearance at a conventional foundry; melting inside a control area and then general clearance or clearance for melting at a conventional foundry) are very important in case of selection of this management option.

Environment: The radiological discharges during decontamination can be liquids (e.g., in case of chemical decontamination) or gas through filters in case of melting. Also, non-radiological discharges during decontamination are possible (e.g., decontamination chemicals)

Health & safety: Radiological and non-radiological exposition of personnel to aerosols during sampling for characterization as well as during decontamination cannot be excluded. Internal dose to the personnel in case of manipulation of metallic waste with significant activity of loose surface contamination is possible. Also, the noise during mechanical decontamination could harm the workers and protective measures should be taken.

Risk / hazard reduction: On completion of recycling or reuse of metals after the appropriate decontamination, no loose contamination remains on the metals.

Security: For both the untreated, as well as the secondary wastes of the treated metallic wastes, there is a risk associated with the transport of radioactive material.

Socio-economic impacts: Since the amount of waste is minimised, there are positive socio-economic impacts due to smaller storage pace needed. Nevertheless, a large facility for characterization, decontamination and clearance may have negative psychological effect for neighbours. Furthermore, the recycling and use of materials for other purposes support the concept of circular economy.

Lifetime costs: The cost for storage and disposal is reduced. Nevertheless, the cost for purchase and maintenance of characterization equipment as well as for specialised personnel should be considered. Also, the cost for purchase, operation, maintenance and decommissioning of equipment for decontamination should be factored in.

Enabling the mission: This management option enables minimization of waste by clearance and reuse.

Opportunity for shared solutions: For shared solution, legislation that allows transport of radioactive waste as well as specific cleared materials (also across borders) and treatment of foreign radioactive waste at a melting facility is needed.

Applicability for SIMS: This management option can be considered by SIMS in case of significant amounts of metallic waste.

Implications of the predisposal option on disposal options: Not applicable

3.4 Management of Reactive Metals

The following chapters describe specific treatment of selected reactive metals, which were mentioned as examples in D9.5 [3].

3.4.1 Welded into steel capsules filled with argon

For hazardous metallic waste, such as beryllium, the waste is welded into special steel capsules filled with argon as inert gas [3]. Another option is to replace the argon by silica sand [22].

Environment: There are no radiological and non-radiological discharges utilizing this method.

Health & safety: Beryllium is a high toxicity material, which might harm seriously workers' health. Protection measures should be taken.

Risk / hazard reduction: On completion of this conditioning method, the risk from beryllium storage is lower.

Security: There is no change in security threats after conditioning.

Socio-economic impacts: Not relevant.

Lifetime costs: The cost for purchase and maintenance of structure is reasonable.

Enabling the mission: After conditioning, beryllium is safe for storage, remaining retrievable for future processing. In general, the amount of hazardous waste materials like beryllium that are allowed to go into disposal is limited.

Opportunity for shared solutions: Not relevant.

Applicability for SIMS: The method is applicable for SIMS. SIMS with research reactors usually have activated beryllium waste, which was used as neutron reflector.

Implications of the predisposal option on disposal options: see Table 14.

Table 14 – Implications of welded into argon-filled steel capsules (or using silica sand instead) and cementation / using polymer for conditioning predisposal option on disposal options for hazardous metallic wastes

Disposal option	
Near surface	Suitable for low activity concentration and short-lived radionuclides if WAC are fulfilled (conditioning for reactive metals)
Geological	Suitable also for high activity concentration and long-lived radionuclides, if WAC are fulfilled (conditioning for reactive metals)
Borehole	Not suitable due to volume

3.4.2 Conditioning in specific matrices

Specific matrices for conditioning, such as some geopolymers or alkali activated cements based on magnesium brucite, aim to better stabilise reactive metals, e.g., aluminium and magnesium. Research is on-going to develop and qualify new conditioning matrices that may be used as alternatives to cement-based matrices not only for reactive metals, but also for other metals.

In France, these matrices have been under development for over 15 years, seeking not to completely avoid corrosion itself but rather to reduce the impact of corrosion reactions.

Magnesium brucite based cement is one of several innovative high-pH cement formulations that could keep reactive metals in alkali conditions and so limit production of hydrogen over time. Geopolymers is another category of high-pH cement [23]. Currently, the European Research Project PREDIS (WP 4) is working on these aspects.

This high-pH cement formulation is to address the potential for detrimental interactions such as expansive corrosion between reactive metals (e.g., aluminium) and more conventional, low-pH cement formulations under storage and disposal conditions.

For implementation of conditioning in cement or other specific matrices options, equipment for cement preparation or the corresponding equipment for geopolymers as well as in-drum mixing and drying facilities are needed. Furthermore, infrastructure for determination of the physical properties (porosity, diffusion, coefficient, strength, elasticity) and chemical properties of the matrices is necessary.

Environment: There are no radiological or non-radiological discharges during conditioning of metallic waste. However, the cemented waste after decay storage and clearance is considered as non-radiological discharge to the environment.

Health & safety: Non-radiological exposition of personnel due to inhalation of dust during cementation in case of malfunction of the ventilation system is possible. External dose to the personnel in case of manipulation of high activity metals during conditioning or internal dose in case of manipulation of metallic waste with significant activity of loose surface contamination cannot be excluded.

Risk / hazard reduction: Conditioning in specific matrices results in the reduction of dose rate as well as the reduction of dispersion of radionuclides and chemical contaminants, potentially over longer time periods than for conventional cement formulations. Long-term corrosion in drums and leakage is reduced than in the case of more conventional cement formulations. Wastes containing Al, particular research is notably seeking to develop magnesium brucite based cement that could keep Al waste in alkali conditions and so limit production of hydrogen over time [3].

Security: Security is improved due to weight increase.

Socio-economic impacts: The surface footprint required for additional cementation facility might have additional implications if the respective area has nature values.

Lifetime costs: The cost of the asset and support facilities is not high but without any reduction of the waste volume, the cost for storage and future disposal might be high especially if priced by volume. Additional costs arise at decommissioning.

Enabling the mission: The waste form might not comply with the future WAC. Innovative research on chemical composition of matrices is on-going to improve the properties. These innovative matrices aim to ensure a waste form that could be compatible with disposal conditions. The characteristics of these types of conditioning are largely identical to those for conventional cements, except that their long-term performance is supposed to be better but is subject to more uncertainty because a far less extensive body of research underpins it.

Opportunity for shared solutions: There are currently no shared solutions. A mobile facility for conditioning and testing would be advantageous from both a socio-economic and lifetime costs perspective.

Applicability for SIMS: It is a low-cost and easy to implement option. It could be appropriate for SIMS because they have small amounts of metallic waste and usually the reduction of volume of waste after processing is not a must. In case SIMS operate a near surface disposal facility and the WAC for disposal are known, this conditioning option can be implemented.

Implications of the predisposal option on disposal options: see Table 15.

Table 15 – Implications of conditioning in specific matrices predisposal option on disposal options for metallic wastes

Disposal option	
Near surface	Suitable for low activity concentration if WAC are fulfilled (i.e., depends on longevity of radionuclides and treatment of reactivity of metals with the matrix)
Geological	Suitable also for high activity concentration if WAC are fulfilled (i.e., depends on reactivity of metals with the matrix)
Borehole	Not suitable due to volume

3.4.3 Conversion of sodium waste into a thermally treated and stable product (glass)

Sodium and sodium-potassium eutectics have been used as coolants in several research reactors as well as in a small group of prototype and commercial nuclear reactors with fast neutrons. Some of the reactors are still in operation; however, most of them have been already shut down either for their age or for economic reasons. Sophisticated sodium cooled reactors with fast neutrons are considered as a prime candidate for the next generation of future reactors with advanced fuel cycles maximizing resource utilization and minimizing waste production [21].

Conversion of sodium radioactive waste into glass is an available technology [24] in alignment with regulations in many countries.

For implementation of this process, glass formers need to be mixed with the waste. Chemistry needs controlling to ensure sodium metal is oxidised and immobilised in the product glass. Furthermore, off-gas treatment systems (potentially including scrubbers and filters) are required to comply with site discharge authorisations.

Environment: Gaseous discharges of radionuclides and heavy metals are likely during high temperature treatment. These discharges could require mitigation, potentially resulting in secondary waste streams (e.g., filters, scrubbers).

Health & safety: Careful control of operating conditions is essential due to high-temperature treatment of chemically hazardous material.

Risk / hazard reduction: The waste form after processing ensures the reduction of dose rate through radiological shielding provided by the glass matrix, a significant reduction in chemical reactivity of the waste (essential to generate a disposable waste form) and a significant reduction in potential for corrosion in drums and leakage of waste during storage and disposal.

Security: Security is improved due to weight increase.

Socio-economic impacts: The surface footprint required for additional thermal treatment facility might have additional implications if the respective area has nature values. Visual and noise impact may occur for the facility neighbours, particularly during construction. On the other hand, an additional plant could provide employment to the local area.

Lifetime costs: High costs associated with constructing, operating (energy-demanding high-temperature process) and decommissioning the processing facility would likely only be cost-effective if the facility were also used to treat other waste streams (this has been demonstrated).

Enabling the mission: The treatment results in a durable waste form, ideal for disposal. The batch process is more suited to relatively small volumes of waste, rather than large volume LILW streams. In-container vitrification is relatively versatile and can also be applied to other waste streams.

Opportunity for shared solutions: There are currently no shared solutions. A shared solution, which could be also applied to other waste streams, would be advantageous from both a socio-economic and lifetime costs perspective.

Applicability for SIMS: This treatment could be an appropriate solution for SIMS in case they have small amounts of Na waste, if shared solutions are available or the process could be also applied to other waste streams.

Implications of the predisposal option on disposal options: see Table 16.

Table 16 – Implications of conversion into glass predisposal option on disposal options for metallic wastes

Disposal option	
Near surface	Suitable for low activity concentration if WAC are fulfilled.
Geological	Suitable
Borehole	Might be suitable, if drums / capsules fit in borehole and meet the requirements of the safety analysis.

3.4.4 Conversion of uranium from metallic to oxide form

The technology for direct conversion of uranium to oxide form is available, although possibly not at industrial scale yet. Oxide production for enrichment and fuel fabrication generally proceeds via UF_6 [26]. The direct conversion process allows management via more conventional disposal strategies and concepts developed for uranium oxides (e.g., direct disposal to a geological repository). Depleted uranium can be disposed of as low-level radioactive waste if it is converted to chemically stable uranium oxide compounds, such as triuranium octoxide (U_3O_8) or uranium dioxide (UO_2), which are similar to the chemical form of natural uranium [25].

Besides the appropriate infrastructure for conversion of uranium to oxide form, metallic uranium is likely to require some degree of cutting / size reduction prior to conversion at high temperature.

Environment: Gaseous discharges, potentially including hydrogen, might be expected. These discharges could require mitigation, potentially resulting in secondary waste streams (e.g., filters, scrubbers).

Health & safety: High temperature, multi-step treatment of reactive metal requires careful control of both radiological and non-radiological risks to workers.

Risk / hazard reduction: Conversion of uranium to a more chemically stable form, with significant associated reduction in corrosion (leaching) rates, oxidation via exothermic process, pyrophoricity, as well as hydrogen and uranium hydride production.

Security: By processing the waste, uranium is converted to a more passively safe form. Further requirements for security and safeguarding (and therefore desire for conversion and further conditioning) are strongly linked to the uranium enrichment level.

Socio-economic impacts: Surface footprint is required for additional processing facility. The additional plant could provide employment to the local area.

Lifetime costs: The costs for construction and operation of the processing facility, as well as for the decommissioning in the future are high.

Enabling the mission: The waste form for disposal is significantly improved, which is compatible with existing disposal concepts for spent uranium oxide fuel.

Opportunity for shared solutions: Shared solutions are currently not available.

Applicability for SIMS: It could be appropriate for SIMS in case they have small amounts of uranium waste and provided that shared solutions are available.

Implications of the predisposal option on disposal options: see Table 17.

Table 17 – Implications of conversion of uranium to oxide form predisposal option on disposal options for metallic wastes.

Disposal option	
Near surface	Suitable Depleted uranium can be disposed of as low-level radioactive waste if it is converted to chemically stable uranium oxide compounds, such as triuranium octoxide (U_3O_8) or uranium dioxide (UO_2), which are similar to the chemical form of natural uranium.
Geological	Suitable
Borehole	Might be suitable if drums / capsules fit in borehole and meet the requirements of the safety analysis.

3.5 Management of decommissioning waste containing concrete

3.5.1 Transfer into simple Big Bags without conditioning

A “Big Bag” is a bulk container. It can be used for the transport of goods that come in a grainy or powdery form. Big Bags are made from polypropylene (PP) and can hold goods weighing from 200 kg to 2000 kg. In general, the regulations in many countries allow the use of Big Bags for VLLW.

The major difficulties for the implementation of this management option for concrete from decommissioning of nuclear facilities are related to the large volumes as well as the low and heterogeneous activities of the waste. This impedes the characterisation, storage, and disposal of concrete from decommissioning.

Infrastructure and equipment, as well as specialized staff is required for precise, accurate and sensitive enough radiological characterisation. Also, in case of activated concrete, determination of tritium is necessary. Neutron activation calculations support the classification of concrete from decommissioning.

<u>Environment</u>: In general, the radiological and non-radiological discharges during interim storage of VLLW (i.e., impact of corrosion and leaching) as well as after clearance of material is low.

<u>Health & safety</u>: Radiological and non-radiological exposition of personnel due to inhalation of dust during crushing of concrete cannot be excluded. Concrete might include also heavy metals. In addition, exposition to vibration, noise and dust during crushing should be considered. The use of diamond cutting should be preferred to mitigate these expositions.

<u>Risk / hazard reduction</u>: Reduction of the possible dispersion compared to not using any packaging.

<u>Security</u>: Not relevant.

<u>Socio-economic impacts</u>: Large buildings are needed for storage, which has implications, especially if area has nature values. Psychological effects of big interim storage facilities for neighbours cannot be excluded. Within the construction phase, the impact to neighbours due to transport and handling of materials as well as the construction itself is possible. Nevertheless, the very low level of activity and the related short time until clearance is possible.

<u>Lifetime costs</u>: The costs for interim storage are increased due to the high amount of waste. The cost for purchase and maintenance of radiological equipment is reasonable but specialized staff is required.

<u>Enabling the mission</u>: Due to the large volume, the disposal strategy should foresee the case of large amounts of VLLW.

<u>Opportunity for shared solutions</u>: Characterization of cement from decommissioning by specialised organizations is possible.

<u>Applicability for SIMS</u>: It is a management option that can be adopted by SIMS. Nevertheless, in case a disposal facility is available in the country, the direct disposal of this waste is preferable.

<u>Implications of the predisposal option on disposal options</u>: see Table 18.

Table 18 – Implications of use of Big Bags without conditioning predisposal option on disposal options for concrete wastes.

Disposal option	
Near surface	Suitable for VLLW
Geological	Might not be suitable due to volume
Borehole	Not suitable due to volume

3.5.2 Encapsulation special containers and cementation

In general, regulations in many countries allow the encapsulation and cementation of LILW concrete (similarly ILW rubble and soil) in special containers. The cementation of this waste directly into disposal container is a good practise also for safety reasons during transport. Cemented concrete from decommissioning (similarly ILW rubble and soil) might be accepted by a Near-Surface Disposal Facility.

The main difficulties are related to the large volume as well as the heterogeneous activities of the waste, which impede characterization, storage, and disposal.

For implementation, equipment and specialized staff for radiological characterisation, cementation equipment as well as laboratories for the determination of physical (permeability, porosity, diffusion, coefficient, strength, elasticity) and chemical properties are necessary.

Environment: Radiological and non-radiological discharges during cutting or fragmentation of cement for conditioning cannot be excluded. The necessity to ensure a sufficient volume of primary material for waste matrix (request for a quarry / excavation which could indirectly affect environment) should be considered. Convenient properties such as high chemical stability, which significantly reduces leachability and high strength should be proved (e.g., proof of the insensitivity of the concrete and the matrix to expansion reactions like the alkali-silica reaction and the delayed ettringite formation).

Health & safety: Radiological and non-radiological exposition of personnel due to inhalation of dust during cutting or fragmentation of the concrete or due to waste form degradation during storage cannot be excluded. Monitoring throughout the storage period is necessary. Concrete might include also heavy metals. In addition, exposition to vibration, noise and dust during crushing should be considered. The use of diamond cutting should be preferred to mitigate these expositions.

Risk / hazard reduction: After conditioning, the potential dispersion or leakage of radioactivity during storage and disposal is reduced. A reduction of dose rate is also achieved.

Security: There are no identified security threats.

Socio-economic impacts: Large buildings are needed for conditioning and storage, which has implications, especially if area has nature values. Psychological effects of big interim storage facility for neighbours cannot be excluded. Within the construction phase, the impact on neighbours due to transport and handling of materials as well as the construction itself is possible.

Lifetime costs: The cost for purchase and maintenance of characterization equipment (radiological, physical, chemical) is reasonable but specialized staff for radiological characterization might be required.

Enabling the mission: Possible non-compliance with the future WAC due to non-compaction. After conditioning, a new special matrix for this type of waste could be developed with better physico-chemical characteristics.

Opportunity for shared solutions: Waste characterization can be performed by specialised organizations. A mobile facility for characterization, conditioning and testing would be advantageous from both a socio-economic and cost perspective.

Applicability for SIMS: It is a low-cost option that can be adopted by SIMS. Nevertheless, in case a disposal facility is available in the country, the direct disposal of this waste is preferable.

Implications of the predisposal option on disposal options: see Table 19.

Table 19 – Implications of encapsulation special containers and cementation predisposal option on disposal options for concrete wastes

Disposal option	
Near surface	Suitable for low activity concentration if WAC are fulfilled.

Geological	Might not be suitable due to volume
Borehole	Not suitable due to volume

3.5.3 Recycling / reuse

An option for concrete from decommissioning is the recycling or reuse of the material. A European guidance [27][28][29] is available, enabling national specific clearance regulations. Recycled concrete can be used in the nuclear sector, e.g., for shielding etc.

Because of the large volume of concrete from decommissioning as well as the low level of activity and the natural activity of concrete, sampling is challenging. It should be mentioned that in the case of activated concrete, the determination of tritium is necessary.

The implementation of this management option requires infrastructure equipment and personnel for radiological characterization of concrete. Also, skills for activation calculations are usually necessary for classification of the reactor concrete.

Environment: There are no radiological or non-radiological discharges in case of recycling or reuse provided that the clearance regulations are met. This management option has positive effect on environment due to lower use of "new" resources.

Health & safety: Radiological and non-radiological exposition of personnel due to inhalation of dust during cutting or fragmentation of the concrete before clearance cannot be excluded. It should be noted that this has already been considered for non-radiation workers during consideration of clearance levels. Concrete might include also heavy metals. In addition, exposition to vibration, noise, and dust during cutting or fragmentation should be considered. The use of diamond cutting should be preferred to mitigate these expositions.

Risk / hazard reduction: There is no identified risk / hazard reduction.

Security: There are no identified security threats.

Socio-economic impacts: There is benefit from minimization of waste (lower interim storage space and lower volume of concrete for disposal). It should be mentioned that the reuse of concrete is of high demand for recycling of conventional building rubble.

Lifetime costs: The cost for purchase and maintenance of radiological equipment is reasonable but specialized staff is also required for radiological characterization. A mobile facility for characterisation and cutting or fragmentation of concrete might be cost effective.

Enabling the mission: Minimization of waste is achieved. The amount of waste for management and disposal is lower, resulting in lower cost for waste management.

Opportunity for shared solutions: The characterization can be performed by specialised organizations. A mobile facility for characterization of cement and logistics for recycling and reuse would be advantageous from both a socio-economic and cost perspective.

Applicability for SIMS: This option is applicable for SIMS. A mobile facility for characterization of cement, safe cutting or fragmentation of concrete and logistics for recycling and reuse would be helpful.

Implications of the predisposal option on disposal options: Not applicable. This option is solely a predisposal practice.

4 Conclusions

During the workshops held in ROUTES Subtask 8.1.1, four challenging waste types for SIMS were selected for detailed analysis and assessment of the processing methods and their implications on the disposal options. The selected waste types are spent ion exchange resins (SIERs), disused sealed radioactive sources (DSRS), metals (from decommissioning) and concrete (from decommissioning). The methodology used for the assessment of different predisposal routes is the NDA Value Framework. The outcomes of the waste type specific analyses are briefly summarised as follows:

Spent Ion Exchange Resins:

Cementation of resins is a low-cost and easy to implement conditioning method. It could be a good choice for SIMS, even though it significantly increases the waste volume. It remains suitable for SIMS, as long as it is in alignment with the waste acceptance criteria (WAC) for disposal and there are no volume limitations of the disposal site. This conditioning method could be acceptable for near surface disposal as well as for geological disposal. Polymer encapsulation is a technological complex process of higher cost but leads to lower increase of the waste volume than cementation. This option can be suitable for near surface disposal as well as for geological disposal. The predisposal options, such as incineration of resins followed by cementation or super-compaction of the ashes, (hydro-)pyrolysis and super-compaction as well as thermal compaction are complex and costly processes. These methods result in a reduction of waste volume. The high concentration of radioactivity after these predisposal options should be factored in by SIMS before adoption. Due to activity concentration, these methods have limited suitability for near surface disposal. With regards to a borehole disposal, these options might be suitable if the waste packages are suitable for borehole disposal and meet the requirements of the safety analysis.

Disused Sealed Radioactive Sources:

Encapsulation of sources after dismantling of DSRS is a good practice for storage. It is a low-cost and easy to implement option for sources of category 3 to 5. The ^{226}Ra sources are welded into capsules to prevent ^{222}Rn gas emanation. Regarding High Activity Sealed Sources (HASS), a hot cell is required for dismantling, which is an equipment of high acquisition cost. IAEA offers a mobile hot cell facility for dismantling and encapsulation of HASS. In general, cementation of sources should be avoided if no WAC are in place. Encapsulation of sources in special containers without cementation is suitable for borehole disposal but for near surface or geological disposal, cementation might be necessary. In case of very limited resources for the management of DSRS of category 3 to 5, and if immediate dismantling and encapsulation of sources are not feasible, the DSRS can be packed in dedicated packaging for storage. Nevertheless, the deferred management is not recommended. For HASS the use of specific containers able to hold multiple sources are under consideration in France. These containers are suitable for geological disposal but not for borehole disposal due to the specific geometry of the suitable containers. Some short-lived DSRS such as ^{57}Co or ^{68}Ge, with a half-life of about 270 days, can be stored for decay and subsequent clearance. Finally, the export of DSRS, i.e., return to producer for recycling or disposal in the country of origin, is a commonly practiced strategy. This solution should be considered by SIMS because its implementation leads to minimization of waste and reduces the need for disposal.

Metallic waste:

Cementation of metallic waste is a low-cost and easy to implement option. It could be appropriate for small amounts of metallic waste, if WAC for disposal are in place and there are volume limitations of the disposal site do not oppose this conditioning method. This conditioning method could be acceptable for near surface disposal as well as for geological disposal if WAC are fulfilled. Specific matrices for conditioning, such as some geopolymers or alkali activated cements based on magnesium brucite, aim to better stabilize reactive metals, e.g., aluminium or magnesium. Research is on-going to develop and qualify new conditioning matrices that may be used as alternatives to cement-based matrices not only for reactive metals, but also for other metals. Super-compaction could be considered by SIMS in case of significant amounts of metallic waste, but the costs for necessary equipment are high. Super-compaction is suitable for near surface disposal as well as for geological disposal provided that the WAC are fulfilled. Thermal treatment in dedicated facilities is an available option for metallic waste. The final waste form could be suitable for any type of disposal facility if WAC are fulfilled. Thermal treatment can be also used before clearance of metals for recycling and reuse. This management option can be considered by SIMS in case of significant amounts of low activity metallic waste. For hazardous metallic waste, such as beryllium, the waste is welded into special steel capsules filled, e.g., with argon as inert gas. Also, polymers can be used for conditioning of beryllium. Beryllium after conditioning is suitable for near surface disposal as well as for geological disposal provided that the WAC are fulfilled. Sodium and sodium-potassium eutectic have been used as coolants in several research reactors. Conversion of sodium radioactive waste into glass is an available technology in alignment with the regulations in many countries. This treatment could be an appropriate solution for SIMS in case they have small amounts of Na waste, if shared solutions are available or the process could be also applied to other waste streams. This treatment option is suitable for near surface disposal if WAC are fulfilled, as well as for geological disposal. Regarding borehole disposal, this predisposal option might be suitable, if the waste package geometry is suitable and meets the requirements of the safety analysis. For the predisposal management of uranium, the direct conversion of metallic to oxide form allows management via more conventional disposal strategies and concepts developed for uranium oxides (e.g., direct disposal to a geological repository). Depleted uranium can be disposed of as low-level radioactive waste if it is converted to chemically stable uranium oxide compounds, such as triuranium octoxide (U_3O_8) or uranium dioxide (UO_2), which are similar to the chemical form of natural uranium. Regarding borehole disposal, the oxide form of uranium might be suitable if the waste package geometry meets the spatial requirements and the requirements of the safety analysis.

Concrete:

The use of Big Bags without conditioning to package VLLW concrete for disposal is in compliance with regulations in many countries. This packaging is suitable for near surface disposal but might not be suitable for geological disposal due to the waste volume. Regarding the LILW concrete, encapsulation in special containers for disposal and cementation is a good practice. This is a low cost and easy to implement option that can be adopted by SIMS. Another option for low activity concrete from decommissioning is the recycling or reuse, if national regulations for clearance are available.

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Appendix A. Assessment of spent ion exchange resins (SIERs)

Table 20 – Evaluation of management options for SIERS by utilizing the NDA Value Framework

SIERs	Environment	Health & safety	Risk / hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
Cementation	*No radiological discharges *Non-radiological discharges for cement production (green-house emissions) *Non-radiological discharges (minimization principle, interim storage and clearance of material) *During cementation process, C-14 may be released in gas phase due to the temperature increase as result of cement hydration	*Radiological and non-radiological exposition of personnel due to Inhalation of active dust during cementation (in case of malfunction of ventilation system) *External dose to the personnel in case of manipulation of high activity resin during cementation	*Reduction of dose rate *Reduction of potential dispersion *Reduction of long-term corrosion in drums and leakage	*Theft of material complicated (high weight)	*Implications if area has nature values (big interim storage that takes space from animals) *Psychological effect of big interim storage facility versus small interim storage facility for neighbours *Within construction phase: impact of neighbours due to transport and building *Mobile facility for conditioning and testing: advantage regarding socio-economic	*Low cost of asset and support facilities *High cost for long term interim storage *High cost for disposal (if price by volume) *Shared (non-mobile) facility: cementation, drying facilities (for liquids in general) could reduce the lifetimes costs but the cost for transport of raw waste should be considered	*Possible non-compliance with the future WAC due to non-compaction (maybe not relevant for SIMS due to low total amount of waste)
Polymer encapsulation	*Potential non-radiological discharges (polymer matrices after storage and clearance of polymer matrices) *Better properties with respect to the safety and impact on environment	*Potential harm to workers during chemical treatment process of raw resin	*Reduction of potential dispersion *Criticality needs to be addressed (due to moderation of neutrons in polymer in case there is issue) *Possible reduction of long-term leakage (radiolysis polymer dependent)	*Theft of conditioned waste less complicated than cementation (medium weight) *In case of sabotage the waste form has lower heat capacity and thermal conductivity than cement	*Implications, if area has nature values (takes space from animals) *Within construction phase: impact of neighbours due to transport and building *Mobile facility for conditioning and testing: advantage regarding socio-economic *Still high technological and financial complexity	*High cost of the technology *Lower cost for long term interim storage than for cementation *Lower cost for disposal than for cementation *Shared (mobile) facility: could reduce the lifetimes costs	*New perspective technology *It should be not a problem to comply with the future WAC, esp. in case of WAC for specific storage / disposal facility and it should comply with legal request of radioactive waste management programme in the country.

SIERs	Environment	Health & safety	Risk / hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
					which needs to be solved / improved		
Incineration and cementation	*Radiological discharges during incineration *Non-radiological discharges (e.g., heavy metals and CO_2 production because of high energy demand) during incineration	*Radiological and non-radiological exposition of personnel during incineration (accident, incident / malfunction) *Fire danger for personnel during incineration *Internal dose and non-radiological exposition of personnel due to Inhalation of high activity ashes during manipulation & cementation (in case of malfunction of ventilation system) *External dose to the personnel due to manipulation of high activity ashes before and after cementation *Radiological and non-radiological exposition of public (accident, incident / malfunction during incineration) and during transport	*Reduction of dose rate after cementation *Reduction of potential dispersion *Reduction of long-term corrosion in drums and leakage	*Theft of material complicated (high weight) *Risk in transport to and from incineration facility (e.g., Studsvik) then to waste producer / cementation facility	*Less psychological effect for neighbours because smaller interim storage facility is needed after incineration but higher psychological effect because of releases *Within construction phase: impact of neighbours due to transport and building *Incineration is a high-cost investment *Incineration elsewhere and mobile facility for conditioning and testing: advantage regarding socio-economic	*High cost of asset and support facilities *High running costs due to its energy demand *Maintenance expensive *Decommissioning expensive due to activity concentration *Shared solution: incineration, cementation, drying facilities (for liquids in general) could reduce the lifetimes costs but the cost for transport of raw waste should be considered	*Possible non-compliance with the future WAC due to non-compaction (maybe not relevant for SIMS due to low total amount of waste) *More stringent WAC for incinerated wastes than for other waste forms possible *Ensure long-term capability of waste treatment in own country (COVRA) / independence of other countries / waste treatment facilities
Incineration and super-compaction	*Radiological discharges *Non-radiological discharges (e.g., heavy metals and CO_2 production because of high energy demand)	*Radiological and non-radiological exposition of personnel during incineration (accident, incident / malfunction) *Fire danger for personnel during incineration *Internal dose and non-radiological exposition of personnel due to Inhalation of high activity ashes during	*Max. volume reduction and max.-concentration of activity and dose rate *Higher isolation needed due to higher activity → waste classification might be higher than for cemented resins *No free liquids and very low to no humidity → reduced risk of radiolysis	*Security risk in transport to and from incineration facility (e.g., Studsvik) then to waste producer / super-compaction facility *Risk of theft: low volume, highly concentrated radioactive waste	*Less psychological effect for neighbours because smaller interim storage facility is needed after incineration but higher psychological effect because of releases *Within construction phase: impact of neighbours due to transport and	*Less psychological effect for neighbours because smaller interim storage facility is needed after incineration but higher psychological effect because of releases *Incineration elsewhere and conditioning elsewhere or by a mobile facility is advantage regarding	*More stringent WAC for incinerated wastes than for other waste forms, possible WAC easier to meet than in case of conditioning by cementation *No uncertainty regarding WAC due to no matrix, but might not fulfil future WAC → additional

SIERs	Environment	Health & safety	Risk / hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
		manipulation & compaction (in case of malfunction of ventilation system) *External dose to the personnel due to manipulation of high activity ashes before and after compaction *Radiological and non-radiological exposition of public (accident, incident / malfunction during incineration)			building *Incineration elsewhere and conditioning elsewhere or by a mobile facility is advantage regarding socio-economic	socio-economic *Higher investment into site needed than for cementation plant	treatment might be needed in the future *Ensure long-term capability of waste treatment in own country (COVRA) / independence of from other countries / waste treatment facilities *Lower total disposal volume enables more disposal options
(Hydro-) pyrolysis and super-compaction	*Radiological discharges *Non-radiological discharges (e.g., heavy metals and CO_2 production because of high energy demand)	*Radiological and non-radiological exposition of personnel during (Hydro-)Pyrolysis (accident, incident / malfunction) *Fire danger for personnel during (Hydro-) Pyrolysis *Internal dose and non-radiological exposition of personnel due to Inhalation of high activity ashes during manipulation & compaction (in case of malfunction of ventilation system) *External dose to the personnel due to manipulation of high activity ashes before and after compaction *Radiological and non-radiological exposition of public (accident, incident / malfunction during incineration)	*Max. volume reduction and max.-concentration of activity and dose rate *Higher isolation needed due to higher activity	*Risk in transport to and from (Hydro-) pyrolysis facility, then to waste producer / super-compaction facility	*Less psychological effect for neighbours because smaller interim storage facility is needed after treatment but higher psychological effect because of releases *Within construction phase: impact of neighbours due to transport and building *Incineration elsewhere and conditioning elsewhere: advantage regarding socio-economic *Mobile facility for conditioning: advantage regarding socio-economic	*Amount of waste will be minimised: low storage place needed *Super-compaction more expensive than cementation *Both expensive techniques *High running costs due to its energy demand *Maintenance expensive *Decommissioning expensive due to activity concentration *Shared solution: treatment, compaction, drying facilities (for liquids in general) could reduce the lifetimes costs but the cost for transport of raw waste should be considered	*More stringent WAC for (Hydro-) Pyrolysis wastes than for other waste forms, possible WAC easier to meet than in case of conditioning by cementation *No uncertainty regarding WAC due to no matrix, but might not fulfil future WAC → additional treatment might be needed in the future *Ensure long-term capability of waste treatment in own country (COVRA) / independence of from other countries / waste treatment facilities

SIERs	**Environment**	**Health & safety**	**Risk / hazard reduction**	**Security**	**Socio-economic impacts**	**Lifetimes costs**	**Enabling the mission**
Thermal compaction (e.g., Hot Isostatic Pressing, HIP)	*No discharges from the HIP step itself, but gaseous radiological and non-radiological (i.e., heavy metals, sulphur, and nitrogen oxides) discharges likely during high temperature pre-treatment. These could require mitigation, potentially resulting in secondary waste streams (e.g., filters, scrubbers)	*Danger because of high temperature pre-treatment step *Danger because of high temperature, high pressure HIP process, but waste is sealed within HIP can and placed within HIP vessel *Radiological and non-radiological exposition of personnel during process (accident, incident / malfunction) *External dose to personnel during transportation of high active drums to storage	*Good waste form volume reduction achievable through combination of pre-treatment and HIP *Reduction in reactivity of waste and potential for gas generation *Reduction of potential dispersion *Reduction of leakage potential	*Security during transport to and from treatment facility *After conditioning, theft of material complicated (high activity and weight)	*A reduced waste form volume could result in a smaller facility being required for interim storage (although this would only be a noticeable factor for large volume waste streams, for which this treatment route may not be best suited)	*Amount of waste will be minimised *Relatively costly approach	*Batch process, more suited to relatively small volumes of waste, rather than large volume L/ILW streams *Might have challenges with WAC

Appendix B. Assessment of DSRS

Table 21 – Evaluation of management options for DSRS by utilizing the NDA Value Framework

DSRS	Environment	Health & safety	Risk / hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
Encapsulation without cementation	*Radiological discharges in case of leakage from a damaged source (in case of malfunction of the ventilation system) *Non-radiological discharges: metals including lead from dismantling of radioactive devices (recycling of metals is the best option)	*External dose for personnel during dismantling on a bench or inside a glovebox (for sources of categories 3-5) *Internal dose for personnel in case of dismantling a radioactive device with leakage on a bench and not inside a glove box (by mistake)	*Evaluation of doses inside the storage facility is easier after encapsulation, better implementation of the radiation protection program *Reduction of the leakage risk after encapsulation	*Theft of material complicated (high weight) → higher security *Sealed encapsulation also helps	*Lower storage area is needed *Easier inspection and monitoring *Avoidance of devices dismantling difficulties in future	*Reduction of costs for long-term storage (volume reduction) *Conditioning in future necessary, it should be considered in the cost *For short lived radionuclides: clearance possible due to retrievability *Low cost of implementation, doing the work, maintaining the asset, maintaining controls and decommissioning in the future for sources of cat. 3-5 *Shared solutions for dismantling of high activity sources (hot cells) available (e.g., by IAEA)	*Future WAC are easier to fulfil
Welded into capsules and cemented	*^{222}Rn release in the work environment *Radiological discharges in case of leakage from a damaged source (in case of malfunction of ventilation system) *Non-radiological discharges metals including lead from dismantling of radioactive devices	*Inhalation dose due to ^{222}Rn *External dose for personnel during dismantling on a bench or inside a glovebox (for sources of categories 3-5) *Internal dose for personnel in case of dismantling a radioactive device with leakage on a bench and	*Evaluation of doses inside the storage facility is easier after encapsulation, better implementation of the radiation protection program *Reduction of the leakage risk after encapsulation *Reduction of hazard due to inhalation of radon	*Theft of material complicated (high weight) → higher security	*Lower storage area is needed *Easier inspection and monitoring and better monitoring of ^{222}Rn *Avoidance of devices dismantling difficulties in future	*Reduction of costs for long-term storage (volume reduction) *Low cost of implementation, doing the work, maintaining the asset, maintaining controls and decommissioning in the future for sources of cat. 3-5 *Shared solutions for dismantling of high activity sources (hot	The method enhances the potential to meet (future) WAC, but it is a priori not easy to fulfil future WAC for radium sources In the worst case the 200 litre drums into which the canister with the capsules are cemented are not feasible for disposal they could be retrieved and put

DSRS	Environment	Health & safety	Risk / hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
	(recycling of metals is the best option)	not inside a glove box (by mistake)				cells) available (e.g., by IAEA)	into a different canister (overpack). This might be the case for example for possible borehole-disposal due to the diameter of 200-Liter drums.
Encapsulation in an ordinary Portland cement grout	*Radiological discharges in case of leakage from a damaged source (in case of malfunction of ventilation system) *Non-radiological discharges metals including lead from dismantling of radioactive devices (recycling of metals is the best option)	*External dose for personnel during dismantling on a bench or inside a glovebox (for sources of categories 3-5) *Internal dose for personnel in case of dismantling a radioactive device with leakage on a bench and not inside a glove box (by mistake)	*Evaluation of doses inside the storage facility is easier after encapsulation, better implementation of the radiation protection program *Reduction of the leakage risk	*Theft of material complicated (high weight) → higher security	*Lower storage area is needed *Easier inspection and monitoring *Avoidance of devices dismantling difficulties in future	*Reduction of costs for long-term storage (volume reduction) *Low cost of implementation, doing the work, maintaining the asset, maintaining controls and decommissioning in the future for sources of cat. 3-5 *Shared solutions for dismantling of high activity sources (hot cells) available (e.g., by IAEA)	*Sources encapsulation in mortar based on Portland cement is used only for low activity sources, that do not require hot cells for dismantling and comply WAC for near surface disposal.
Packed with their shielding in dedicated packaging	*No radiological or non-radiological discharges	*No major health and safety issue (as there is just a need to transfer the sealed sources to dedicated package)	*Reduction of radioactivity dispersion risk (possibly leakage after long-term interim storage)	*Theft of material complicated (high weight) → higher security	*Large storage area is needed than in case of dismantling the sources *Easier inspection and monitoring	*High volume → large costs for storage *Low cost of implementation *The cost for dismantling and conditioning in the future should be considered	*Corrosion after a few decades hinder the dismantling process *Future WAC are easy to fulfil *The tracking of devices is easier
Specific container for multiple HASS	*Radiological discharges in case of leakage from a damaged source during dismantling *Non-radiological discharges metals including lead from	*External dose for personnel during manipulation of high-level activity sources *External dose for personnel during manipulation of specific	*Evaluation of doses inside the storage facility is easier after encapsulation, better implementation of the radiation protection program *Reduction of the	*Theft of material complicated (high weight) → higher security	*Lower storage area is needed *Easier inspection and monitoring *Avoidance of devices dismantling difficulties in future	*Reduction of costs for long-term storage (volume reduction) *Conditioning in future necessary, it should be considered in the cost *Shared solutions for	*Future WAC are easy to fulfil because of retrievability

DSRS	Environment	Health & safety	Risk / hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
	dismantling of radioactive devices (recycling of metals is the best option)	containers with multiple sources	leakage risk after encapsulation			dismantling of high activity sources (hot cells) available (e.g., by IAEA)	
Radioactive decay and clearance	*No radiological or non-radiological discharges	*External dose for personnel during storage *Internal dose for personnel in case of leakage during storage	*After interim storage: No risk due to decay of radioactive isotopes and clearance	*Security measurements for interim storage site necessary especially in case of HASS	*Space inside the interim storage is needed, cost for storage should be considered *No cost for export of the sources *No cost for disposal	*Possibly lower cost option than to export the short-lived sources. Costing should be performed (including costs for decay storage, security means, inspections, clearance measurements, disposal of conventional waste	*Minimization of waste by clearance
Export for recycling or disposal	*Radiological discharges in case of leakage from a damaged source during dismantling *Non-radiological discharges metals including lead from dismantling of radioactive devices (recycling of metals is the best option)		*Reduce risks (dispersion of radioactivity, internal dose for personnel in case of leakage) due to low amount of DSRS in storage *Reduction of external dose for personnel due to the reduction of dose rate inside the storage facility	*Level of security of the storage facility can be lower due to low amount of DSRS in storage *Increased number of transports for DSRS → lower security	*Positive psychological effect for community due to lower amount of sources in storage *Negative psychological effect due to increased number of transports for DSRS	*Lower costs for security due to low amount of DSRS in storage *Lower cost for storage *High cost for export / return to producer	*Minimization of waste and needs for disposal

Appendix C. Assessment of metals from decommissioning

Table 22 – Evaluation of management options for metals by utilizing the NDA Value Framework

Metals	**Environment**	**Health & safety**	**Risk / hazard reduction**	**Security**	**Socio-economic impacts**	**Lifetimes costs**	**Enabling the mission**
Cementation	*No radiological discharges *Non-radiological discharges for cement production (green-house emissions) *Non-radiological discharges (minimization principle, interim storage and clearance of material)	*Non-radiological exposition of personnel due to Inhalation of dust during cementation (in case of malfunction of ventilation system) *External dose to the personnel in case of manipulation of high activity metals during cementation	*Reduction of dose rate *Reduction of potential dispersion *Reduction of long-term corrosion in drums and leakage	*Theft of material complicated (high weight)	*Implications, if area has nature values (big interim storage that takes space from animals) *Psychological effect of big interim storage facility versus small interim storage facility for neighbours *Within construction phase: impact of neighbours due to transport, handling and building *Mobile facility for conditioning and testing: advantage regarding socio-economic	*Low cost of asset and support facilities *High cost for long term interim storage *High cost for disposal (if price by volume)	*Possible non-compliance with the future WAC due to non-compaction (maybe not relevant for SIMS due to low total amount of waste) *Innovative research on chemical composition of cementitious materials in order to improve its properties for future compliance *R&D are on-going to develop and qualify new conditioning matrices (geopolymers, magnesium phosphate cements) that may be used as alternative to cement based matrices not only for reactive metals, but also for other metals.
Thermal treatment	*No discharges because of outsourcing *High energy demand (CO2 release) *Discharge of H-3 at melting facility	*Radiological and non-radiological exposition of personnel during sampling *External dose to the personnel in case of manipulation of high activity metals during	*There is not loose contamination on completion of the intervention *Secondary waste (e.g., sludges, filters) to be treated and	*Risk in transport to and from melting facility (e.g., Studsvik) then to waste producer / treatment facility for secondary waste	*No treatment unit needs to be built in case of outsourcing. Otherwise melting facility (including control zone) needs to be build, operated & decommissioned (as	*No cost for construction, maintenance and decommissioning of treatment facility in case of outsourcing *Significant cost for characterization	*Homogeneous activity distribution and accurate characterization of the metallic waste, WAC easier to meet *Robust metallic

Metals	Environment	Health & safety	Risk / hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
		characterization *Thermal cutting of metal components causes release of radioactive aerosols, measures for radiation protection of workers in case of thermal cutting (special ventilation system)	disposed of according to waste type		nuclear facility) *Smaller interim storage due to waste minimization by clearance *Higher waste volume in other waste streams due to secondary wastes (including activity concentration)	equipment and specialised personnel for characterization *The cost for transport of raw waste and outsourcing the treatment should be considered	matrix, WAC easier to meet
Super-compaction	*Liquid discharges *Potential dust production	*Noise during compaction *Radiological and non-radiological exposition of personnel during sampling *External dose to the personnel in case of manipulation of high activity metals during characterization	*Reduction of potential dispersion *Reduction of long-term corrosion in drums and leakage	*Good due to heavy waste form	*Amount of waste will be minimised: low storage place needed	*Super-compaction is an expensive technique *Maintenance expensive *Decommissioning not expensive due to low contamination of the asset	It is a method to enhance the potential to meet (future) WAC
Recycling / reuse	*Radiological discharges during decontamination (liquids or gas through filters) *Non-radiological discharges during decontamination (decontamination chemicals)	*Radiological and non-radiological exposition of personnel to aerosols during sampling for characterization as well as during decontamination *External dose to the personnel in case of manipulation of high activity metals during characterization as well as during decontamination *Noise during mechanical decontamination	*Reduction of dose rate *Reduction of potential dispersion *Reduction of long-term corrosion in drums and leakage	*Reduction of security level because of minimization of waste (lower volume, lower activity)	*Small storage place is needed because the amount of waste is minimised *Implications, if area has nature values (big facility for characterization, decontamination and clearance that takes space from animals) *Psychological effect of big facility for neighbours *Within construction phase: impact of neighbours due to transport and building *Use of material for other purposes (circular economy)	*Significant cost for purchase and maintenance of characterization equipment and specialised personnel for characterization *Significant cost for purchase, maintenance and decommissioning of the decontamination equipment	*Lower amounts of RW for disposal *Better inventory of metallic waste due to characterization *Reuse of material for other purposes

Metals	**Environment**	**Health & safety**	**Risk / hazard reduction**	**Security**	**Socio-economic impacts**	**Lifetimes costs**	**Enabling the mission**
Welded into steel capsules filled with argon	No discharges	*Beryllium is a high toxicity material which might harm seriously workers health *Welding might harm workers health	*Lower risk for storage			*Low cost for purchase and maintenance of equipment	*Safe for interim storage *The waste is retrievable
Solidification in specific matrices	*No radiological discharges *Non-radiological discharges for cement production (green-house emissions) *Non-radiological discharges (minimization principle, interim storage and clearance of material)	*Non-radiological exposition of personnel due to Inhalation of dust during cementation (in case of malfunction of ventilation system) *External dose to the personnel in case of manipulation of high activity metals during cementation	*Reduction of dose rate *Reduction of potential dispersion *Even more reduction of long-term corrosion in drums and leakage than in case of use of common cement	*Theft of material complicated (high weight)	*Implications, if area has nature values (big interim storage that takes space from animals) *Psychological effect of big interim storage facility versus small interim storage facility for neighbours *Within construction phase: impact of neighbours due to transport and building *Mobile facility for conditioning and testing: advantage regarding socio-economic	*Low cost of asset and support facilities *High cost for long term interim storage *High cost for disposal (if price by volume)	*Possible non-compliance with the future WAC due to non-compaction (maybe not relevant for SIMS due to low total amount of waste) *These innovative matrices aim to ensure a waste form that could be compatible with disposal conditions
Solidification in magnesium brucite based cement	*No radiological discharges *Non-radiological discharges for cement production (green-house emissions) *Non-radiological discharges (minimization principle, interim storage and clearance of material). *Waste volume increase by conditioning.	*Non-radiological exposure of personnel due to Inhalation of dust during cementation (in case of malfunction of ventilation system) *External dose to the personnel in case of manipulation of high activity metals during cementation	*Reduction of dose rate through radiological shielding provided by the cement matrix *Reduction of potential for dispersion of radionuclides and chemical contaminants, potentially over longer time periods than for conventional cement formulations. *Potential for reduced long-term corrosion in drums and leakage than in the case of more conventional cement formulations.	*Theft of material complicated (high weight)	*Surface footprint required for additional cementation facility; implications if area has nature values. *Visual and noise impact of facility for neighbours, particularly during construction. *A mobile facility for conditioning and testing would be advantageous from a socio-economic, as well as cost perspective.	*Low cost of asset and support facilities *High cost for long term interim storage (dependent on waste volume) *High cost for disposal (if price by volume).	*These innovative matrices aim to ensure a waste form that could be compatible with disposal conditions. *Main issue is uncertainty in their performance, give the much less extensive body of research underpinning their use, compared to that of more conventional cement formulations

Metals	Environment	Health & safety	Risk / hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
Conversion of Na waste into a thermally treated and stable product (glass)	*Gaseous discharges likely during high temperature treatment. These could require mitigation, potentially resulting in secondary waste streams (e.g., filters, scrubbers).	*High-temperature treatment of chemically hazardous material. Careful control of operating conditions essential.	*Reduction of dose rate through radiological shielding provided by the glass matrix *Significant reduction in chemical reactivity of the waste (essential to generate a disposable waste form). *Significant reduction in potential for corrosion in drums and leakage of waste during storage and disposal.	*Theft of material complicated (high weight)	*Surface footprint required for thermal treatment facility; implications if area has nature values. *Visual and noise impact of facility for neighbours, particularly during construction. *Energy-demanding high-temperature process. *Additional plant could provide employment to the local area.	*High cost associated with constructing and operating an additional processing facility; would likely only be cost-effective if the facility were also used to treat other waste streams (this has also been demonstrated).	*Durable waste form, ideal for disposal. *Batch process, more suited to relatively small volumes of waste, rather than large volume L/ILW streams. *In-container vitrification is relatively versatile and can also be applied to other waste streams.
Conversion of uranium from metallic to oxide form	*Depends on the process, but gaseous discharges, potentially including hydrogen, might be expected.	*High temperature, multi-step treatment of reactive metal requiring careful control of both radiological and non-radiological risks to workers.	*Conversion to a more chemically stable form, with significant associated reduction in: - Corrosion (leaching) rates, and oxidation via exothermic process. - Pyrophoricity. - Hydrogen and uranium hydride production.	*Converts material to a more passively safe form. *Requirements for security and safeguarding (and therefore desire for conversion and further conditioning) strongly linked to uranium enrichment level.	*Surface footprint required for additional processing facility. *Additional plant could provide employment to the local area.	*High cost associated with constructing and operating an additional processing facility.	*Significantly improved waste form for disposal, which is compatible with existing disposal concepts for spent uranium oxide fuel.

Appendix D. Assessment of concrete from decommissioning

Table 23 – Evaluation of management options for concrete by utilizing the NDA Value Framework

Concrete	**Environment**	**Health & safety**	**Risk / hazard reduction**	**Security**	**Socio-economic impacts**	**Lifetimes costs**	**Enabling the mission**
Transfer into simple Big Bags with no further conditioning (VLLW)	*No radiological discharges *Non-radiological discharges (minimization principle, interim storage and clearance of material - impact of corrosion not so high)	*Concrete might include heavy metals (disposal risk) *Vibration, noise and dust during crushing (better to use diamond cutting) *Radiological and non-radiological exposition of personnel due to Inhalation of dust during crushing of the concrete (in case of malfunction of ventilation system)	*Reduction of the possible dispersion compared to not using large bags	Not relevant	*Large volume of waste, large building for storage is needed *Implications, if area has nature values (takes space from animals) *Psychological effect of big interim storage facility for neighbours *Within construction phase: impact of neighbours due to transport, handling and building *As positive aspect is the fact of very low level of activity and related short time until clearance	*High amount of waste → costs for interim storage (better to directly bring it to disposal facility) *The cost for purchase and maintenance of radiological equipment is reasonable *Specialized staff required	*Due to the large volume, the disposal strategy should foresee the case of large amounts of VLLW
Transfer into special containers and cemented (ILW)	*Radiological and non-radiological discharges during conditioning *The necessity to ensure a sufficient volume of primary material for waste matrix (request for quarry which could indirectly affect environment) *Convenient properties as high chemical stability, which significantly reduces leachability and high strength	*Concrete might include heavy metals *Vibration, noise and dust during crushing, better to use diamond cutting *Radiological and non-radiological exposition of personnel due to Inhalation of dust during crushing of the concrete (in case of malfunction of ventilation system) *Radiological and non-radiological exposition of personnel due to waste form degradation (monitoring necessary)	*Reduction of dose rate *Reduction of potential dispersion	*Theft of material complicated (high weight)	*Large volume of waste, large building for storage is needed *Implications, if area has nature values (takes space from animals) *Psychological effect of big interim storage facility for neighbours *Within construction phase: impact of neighbours due to transport, handling and building	*The cost for purchase and maintenance of radiological equipment is reasonable *Specialized staff required	*Possible non-compliance with the future WAC due to non-compaction (maybe not relevant for SIMS due to low total amount of waste) *New special matrix for this type of waste could be developed with better physico-chemical characteristics
Recycling / reuse and minimization	*No radiological or non-radiological discharges in case of	*Concrete might include heavy metals *Vibration, noise and	*No identified risk / hazard reduction	*No identified security threats	*Benefit from minimization of waste (lower interim storage	*The cost for purchase and maintenance of	*Lower amount for disposal - lower cost

Concrete	**Environment**	**Health & safety**	**Risk / hazard reduction**	**Security**	**Socio-economic impacts**	**Lifetimes costs**	**Enabling the mission**
	recycling or reuse provided that the clearance regulations are complied with *Positive effect on environment due to lower use of "new" resources	dust during crushing, better to use diamond cutting *Radiological and non-radiological exposition of personnel due to Inhalation of dust during crushing of the concrete (in case of malfunction of ventilation system). This was already considered for normal workers during consideration of clearance levels			space needed) *Less transportation of radioactive waste (concrete) to disposal site needed, due to lower total amount of waste *Reuse of concrete is a high demand for conventional disposal of building rubble	radiological equipment is reasonable *Specialized staff required *A mobile facility for characterisation and crushing might be economical	for waste management