Deliverable D 9.22: ROUTES - Summary report on analysis, assessment and evaluation of disposal options for SIMS (taking into account both potential disposal options and predisposal routes) including Annex: Case studies on typical waste pathways.

Work Package ROUTES

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Disclaimer

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Executive Summary

The generation of radioactive waste might be significantly different depending on the development status of a nuclear program. 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 SIMS, Subtask 8.1 evaluated different predisposal processing options within LIMS for selected waste types and identified 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 (see Deliverable 9.21). In addition, this report includes the results of Subtask 8.2, which aims at analysing qualitatively the existing disposal options for SIMS, based on the input of two workshops held in March 2022 (M34) [MS260] and October 2022 (M41) [MS284], and includes two selected case studies, based on the input of one workshop held in February 2023 (M45) [MS294].

Four challenging waste types relevant for SIMS were selected in Subtask 8.1: Spent ion exchange resins (SIERs), disused sealed radioactive sources (DSRS), metals and concrete from decommissioning. Disposal options for these waste types were analysed and assessed qualitatively in the frame of the workshops, with the aim of providing a basis for future comparison with regards to the applicability of four disposal options for managing small amounts of waste: i) “on-surface option”, consisting in a long term storage followed by clearance, ii) near surface disposal, iii) geological disposal and iv) borehole disposal. Based on the “NDA Value Framework” methodology, the analysis of these disposal options included major factors such as the effects on the environment, risk/hazard reduction, health & safety, security, socio-economic impacts, lifetime cost, as well as the facilitation of the mission. Additionally, the achievability of the disposal 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 disposal routes for SIMS and the availability of shared solutions.

Additionally, this deliverable encompasses the R&D recommendations discussed during the workshops and both case studies.

Usual advantages and drawbacks of the disposal options considered have been highlighted during this analysis:

- The on-surface option (long term storage followed by clearance) is feasible if only short lived (SL) nuclides are present in the waste. This option might lead to radiological discharges, as well as to an exposure of workers during storage. An advantage is the easy retrievability of the waste. Climate change can have an impact on the safety of the waste, as containers or buildings can degenerate faster. In addition, there are no intrinsic security measures, and this option can have a psychological impact on the public. The costs are low for construction but might be high for maintenance over long periods.
- Near surface disposal should only be considered if the amount of long lived (LL) nuclides in the waste is small. This disposal option can have an impact on the environment and public due to nuisance during construction. It offers higher security compared to on surface facilities and the exposure of workers will be lower than for on surface options as waste will be emplaced in disposal vaults. Climate change and its consequences must be considered, as well as costs

that are higher than for on surface options. The visual impact on the neighbourhood is lower, but the psychological effects can be higher.

- Geological disposal has an impact on the environment from excavation, is energy intensive and has a high CO_2 output. The safety is increased, and security enhanced. The costs are higher compared to the first options. The advantage is that in this type of facility all radioactive waste types can be disposed of. Geological disposal might be of interest for intruders if resources were mined at the facility in former times, and the resources become of interest again.
- Borehole disposal has less impact on public and workers than the other options. The exposure is low due to short operational times. The security is enhanced and quick closure possible. The costs are low, as standard drilling equipment can be used. However, this option is only applicable for small amounts of waste and is only suitable for DSRS amongst the waste forms studied within Subtask 8.2.

In addition, this analysis has allowed to highlight specificities regarding the different disposal options to the studied waste forms:

- Concrete from decommissioning could be used as stabilization or backfill material for other waste types.
- The on surface option (long term storage followed by clearance or export) is a valuable option for DSRS, that must be sent back to the producer since 2018.
- Near surface disposal is an available technology for DSRS. There is a risk of Rn-222 leakage from Ra-226 sources, as well as H-3.
- On surface options (long term storage followed by clearance) and borehole disposal have a limited suitability for SIERs due to the waste volume, depending on the selected predisposal route.
- Regarding the disposal of SIERs, near surface disposal facilities may implement a fixation of the waste in a matrix.
- Regarding on surface disposal, attention must be given to non-radiological hazards, such as from heavy metals.
- The hydrogen explosion risk that might occur in challenging wastes needs to be mitigated when considering the disposal of metals for decommissioning in near surface disposal facilities.

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Glossary abbreviations

DGF – Deep Geological Facility

DSRS – disused sealed radioactive source

EW – exempt waste

HASS – high activity sealed radioactive source

HLW – high level waste

ILW – intermediate level waste

LILW – low and intermediate level waste

LIMS – large inventory member states

LL – long-lived

LLW – low level waste

MS – member states

NORM – naturally occurring radioactive material

NPP – nuclear power plant

NSDF – near surface disposal facility

PSE – personal safety equipment

RAW – radioactive waste

RR – research reactor

SF – spent fuel

SIER – spent ion-exchange resin

SIMS – small inventory member states

SL – short-lived

SMR – small modular reactor

SRA – strategic research agenda

TENORM – technologically enhanced NORM

TRL – technological readiness level

URT – Uranium / Radium / Thorium

VLLW – very low level waste

WAC – waste acceptance criteria

1 Introduction

The generation of radioactive waste might be significantly different depending on the development of 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 a small number of nuclear power plants (NPP). These countries have small amounts of waste from research reactors and from medicine, industry, and research, and/or a small volume from nuclear power plants.

In the framework of ROUTES Task 8, aiming to qualitatively analyse possible waste management solutions for Member States with less advanced programmes, especially without waste acceptance criteria (WAC) and with small inventories, the Subtask 8.2 compares different disposal options of selected waste types in LIMS and determines opportunities for sharing in case national solutions are not adaptable to small amounts of waste or cannot be implemented for other reasons.

After a presentation of the methodology used in this work in Chapter 2, Chapter 3 describes the general boundary conditions for SIMS regarding disposal options. These boundary conditions of member states (MS) were discussed during the second workshop [MS284] and include available host rocks and the status of the disposal implementation in the participating states. In a second step, a ranking for the resource requirements regarding human, technological and financial resources was performed by participants. Additionally, retrievability of radioactive waste in repositories and the aspects public acceptance, legal and regulatory aspects, ethical aspects, long term monitoring and cost considerations and safety and security aspects were discussed.

Chapter 4 is dedicated to a guidance for SIMS in form of several decision trees to screen out non-credible disposal options. In total, eight significant questions have been elaborated, addressing the applicability of on surface, near surface and geological disposal options. In the following, Chapter 5 discusses the combinations of disposal options for SIMS.

Chapter 6 discusses the assessment of disposal options, including the results of the workshops held within Subtask 8.2. During the workshops held in Subtask 8.2, four challenging waste types for SIMS, initially selected in ROUTES Task 4 and Task 5.2 were analysed: 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, which is presented in Chapter 2 of this report. For each waste type, the implications of a predisposal waste management option on the following factors are discussed:

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

The R&D recommendations emanating from ROUTES Task 8 can be found in Chapter 7. The last chapter, Chapter 8, of this report summarises the results of this deliverable.

Finally, two case studies are presented in Annex. Based on the results of ROUTES Subtask 4.2, Subtask 5.2, as well as Task 6, and new information from IAEA about predisposal management and WAC, it was noted that the IAEA had already published (2022) a document on “Management of Disused Radioactive Lightning Conductors and Their Associated Radioactive Sources (NW-T-1.15)“ [1] and therefore it was decided to change the second case study "Lighting rods containing radioactive sources“. The final selection of case studies was made by Task 8 participants via an online survey. The two case studies presented in Annex are thus related to activated control rods from research reactors (Appendix A) and metal scraps contaminated with NORM (Appendix B).

2 Methodology

ROUTES Task 8 extends the evaluation of the possible waste management solutions carried out in Task 5 for Member States without WAC and / or SIMS. Three of the Task 8 objectives 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, an assessment framework was chosen, and the predisposal and disposal options were analysed accordingly. The evaluation of disposal options in Task 8 is based on the input of Task participants in the framework of two workshop in in March 2022 [MS260] and October 2022 [MS284] . The participants represented a total of 13 countries and 17 organisations, from research entities, waste management organizations and technical support organisations as well as civil society representatives. Therefore, this report is a synthesis of the arguments and assessments of the participants. All arguments were discussed to reach consensus, but the arguments and statements in this report do not necessarily reflect the technical opinion of each contributor or author.

The assessment of the disposal 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 respective 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: SIERs, DSRS, metals (from decommissioning) and concrete (from decommissioning). The chosen disposal options were defined in D9.10 [3]. The selection of waste types is based on Milestone 151 “Workshop predisposal routes for the disposal options for SIMS (T 5.2)” [4].

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

- The environment (i.e., the potential to generate radiological and non-radiological discharges),
- health & safety (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),
- risk/hazard reduction (the risk or hazard reduction after the implementation of an option and on completion of the intervention),
- security (threats such as theft, sabotage and in case of disposal options also isolation),
- socio-economic impacts (social, economic, and environmental well-being of the 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).

Additionally, it was discussed if the disposal option is at all achievable, regarding necessary waste form characteristics, as well as other relevant information or comments.

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

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

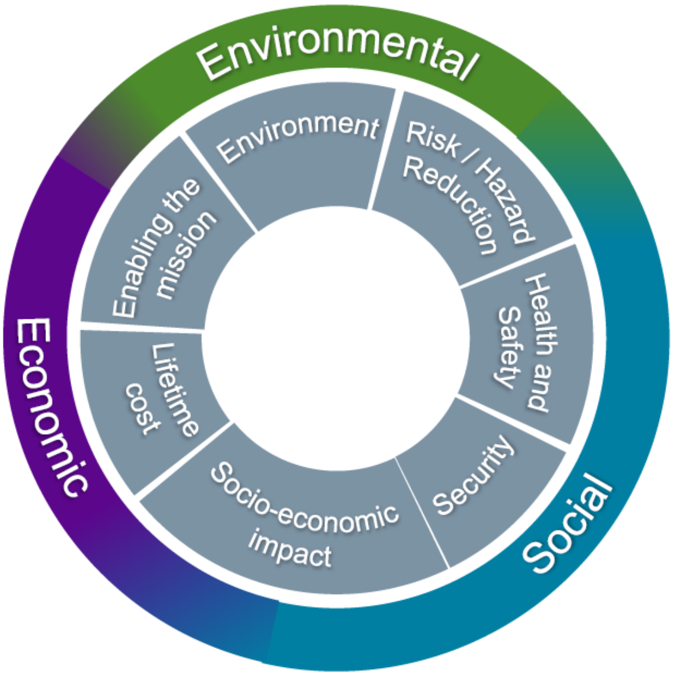


Figure 1 – NDA Value Framework and the three pillars of sustainability and social value [2]

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.

Additional to the assessment of the disposal options, this report includes two selected case studies, based on the input of one workshop held in February 2023 (M45) [MS294] and as a synthesis of the arguments from the general waste type discussions.

3 General boundary conditions for final disposal options in SIMS

In order to further evaluate available disposal options for SIMS and generate best practice strategies on the selection of disposal options, during the second workshop of ROUTES Task 8.2 possible boundary conditions for each disposal option have been analysed. Additionally, preconditions of SIMS have been discussed and evaluated. The participants were also informed about the current progress in EURAD WP 12, "Knowledge management" during the workshop. The authors refer readers towards publications of WP 12 for best practice strategies or guidelines on the implementation of disposal facilities. Examples mentioned hereafter are country specific examples and cannot necessarily be generalized.

3.1 Status quo and current developments in SIMS on radioactive waste disposal

First, the current situation in SIMS was addressed. The SIMS present at the workshops of T 8.2 stated the current technological and political situation regarding disposal of RAW in their country. In addition, the so-called EU "Green Deal" was also discussed based on the question, if the legislation will have an impact on the disposal strategy or energy policy in the respective country. This deal makes it legally binding for countries to reduce their greenhouse gas emissions by 55 % until 2030. To facilitate financial support in the nuclear sector, the Member State must have operational final disposal facilities for all very low (VLLW), low (LLW) and intermediate level (ILW) radioactive waste [5].

Additionally addressed was the availability of host rocks, and if a selection of a host rock has already been done. The results are displayed below per country. Countries not listed did not provide any information during or after the workshops.

3.1.1 Austria

There is currently no existing or planned disposal facility and there is no timeline fixed for a disposal facility in Austria. The "Entsorgungsbeirat", a committee, is currently investigating the next steps towards a disposal facility in Austria. The EU has started infringement proceedings regarding the EURATOM 2011/70 directive [6] against Austria as the provided national programme was handed in too late and no timeline was provided.

Impact of the EU "Green Deal": There is no expected impact from the EU "Green Deal".

Available host rocks: Austria has granite, salt, and sedimentary host rock possibilities. No selection of a host rock has been done.

3.1.2 Greece

The design proposal for VLLW and LLW is a near surface disposal facility (NSDF). The site selection has not been finalized but might be within the NCSRD campus site. For ILW a borehole is proposed to host the research reactor (RR) control rods and DSRS.

Impact of the EU "Green Deal": There is no expected impact from the EU "Green Deal".

Available host rocks: Greece has clay, granite, and sedimentary host rock possibilities. The host rock at the proposed site is a fractured schist covered by a weathering zone and scree.

3.1.3 Netherlands

The Netherlands will store their waste for over 100 years above ground. There is no selection of a site for disposal.

Impact of the EU "Green Deal": The impact from the EU "Green Deal" is currently unknown.

Available host rocks: The Netherlands has clay and salt as host rock possibilities. Both rock types are currently under investigation for the disposal. All types of waste will be disposed of in a deep geological disposal facility. In addition, shared solutions are under discussion.

3.1.4 Poland

Poland has a disposal facility for low and intermediate level waste (LILW) in operation [7], it is however almost full, and a new facility is currently under consideration for short-lived (SL) radioactive waste. The timeline for new disposal facilities is roughly 50 years. The closure of the current disposal facility will be a milestone in order to demonstrate the closure system and the monitoring system.

Impact of the EU "Green Deal": The EU "Green Deal" will lead to the construction of new NPPs in Poland.

Available host rocks: Poland has clay, magmatic and salt as host rock possibilities. All rocks are currently under investigation for a disposal facility for high level waste (HLW). Poland is also an ERDO member and investigates shared solutions.

3.1.5 Portugal

Portugal has currently no existing or planned disposal facilities. There is no timeline for the disposal facility. The EU has started infringement proceedings against Portugal regarding the EURATOM 2011/70 directive [6] as the provided national programme was handed in too late and no timeline was provided.

Impact of the EU "Green Deal": The impact from the EU "Green Deal" is currently unknown.

Available host rocks: Portugal has clay, granite and sedimentary as host rock possibilities. Clay and granite are under study at research level, there is no decision on a regulatory level. The disposal facility will be for LILW.

3.1.6 Slovenia

Slovenia has a construction license for a silo type disposal for LILW. This facility is for the Slovenian LILW only, coming from Slovenia's NPP (current operation and future decommissioning) and all small producers. For HLW there is a strategy available comprising of a dual track option with national geological disposal or a multistate repository. The envisaged timeline is until 2100. This facility might employ borehole disposal.

The timeline has been adopted to have the LILW facility operational until the end of 2020ies, and for HLW until the end of the century.

Impact of the EU "Green Deal": The lawsuit against the EU "Green Deal" might impact the proposed timeline.

Available host rocks: Slovenia has granite in 500 m depth, and sedimentary rocks. The host rock for the HLW disposal facility has not been chosen. For the LILW disposal facility it will be a disposal in a sandy material based in underground water-river sediments.

3.2 Impact of Small Modular Reactor (SMR) research on waste management

This section summarises the discussion about the impact of SMR research on the waste management and disposal strategies in the MS:

- As already stated above, the EU "Green Deal" could have an impact on the employment of a disposal facility, as a disposal facility in operation is a prerequisite for the "Green Deal".

- The research on SMRs could have an impact on the timeline of the disposal implication – for LLW it could accelerate the process, for a HLW disposal the process could be further delayed as additional waste would need to be disposed of.
- The waste inventory would change, and therefore the choice of the disposal type. It would also shift considerations regarding criticality and security.
- There would also be a strong impact on the legal framework, which might be changed (new waste categories included).

3.3 Resource requirements of disposal options

Human, technological, and financial resources for “on surface” (long term storage & clearance), “near surface” (NSDF, cavern & bunker, tunnel & galleries, silo) and “geological” (converted mine, new mine-type facility, deep cavern, drift mining into hillside, borehole) [8] disposal facilities were ranked according to a high / medium / low scheme including potential boundary conditions. This included the amount of human resources and the respective complexity of human expertise needed, the complexity of the necessary technology involved, the necessary financial resources and the technical implementation time scale. Similar to resources, the expected time scales for the different disposal options were ranked from short to long and costs for the different disposal options are ranked from low to high. To facilitate a distinction between different disposal options of the same category, on surface / near surface and geological disposal options are discussed separately. In Figure 2 to Figure 5 the results are graphically represented.

3.3.1 On surface facilities, long term storage and clearance

Amount of human resources or complexity of human expertise: Resources needed are low, but the staff needs to be highly trained for the clearance process.

Complexity of necessary technology: Medium.

Financial Resources: For LILW the needed resources are low. For HLW, clearance is not an option, and subsequent disposal is necessary.

Technical implementation time scale is short, and the costs are low to medium. The long term storage is only relevant for specific waste streams.

3.3.2 Near surface disposal facilities

3.3.2.1 NSDF

Amount of human resources or complexity of human expertise: Medium. Know how to approve the safety case is needed.

Complexity of necessary technology: Medium.

Financial Resources: Medium to high. Resources needed depend on the complexity of the solution and which parts of the safety case calculation can be outsourced.

Technical implementation time scale is short to medium, the costs are low to medium. This might change if engineered barriers are needed.

3.3.2.2 Cavern & bunker

Amount of human resources or complexity of human expertise: Medium. Know how to approve the safety case is needed.

Complexity of necessary technology: Medium to high.

Financial Resources: Medium to high. It depends on the complexity of the solution and which parts of the safety case calculation can be outsourced.

Technical implementation time scale is medium to long, and the costs are medium to high.

3.3.2.3 Tunnel & galleries

Amount of human resources or complexity of human expertise: Medium. Know how to approve the safety case is needed.

Complexity of necessary technology: Medium to high.

Financial Resources: Medium to high. Resources needed depend on the complexity of the solution and which parts of the safety case calculation can be outsourced.

Technical implementation time scale is medium to long, and the costs are medium to high.

3.3.2.4 Silo

Amount of human resources or complexity of human expertise: Medium. Know how to approve the safety case is needed.

Complexity of necessary technology: High.

Financial Resources: Medium to high. Resources needed depend on the complexity of the solution and which parts of the safety case calculation can be outsourced.

Technical implementation time scale is medium to long, and the costs are medium to high.

3.3.3 Geological facilities

To facilitate a distinction between different disposal options of the same category, geological disposal options are discussed separately from on surface / near surface disposal options. Therefore, the categorisation of complexity and resources in the following section cannot be compared directly with the categorisation of the previous section.

3.3.3.1 Converted mine

Amount of human resources or complexity of human expertise: Medium. Know how might still be available, depending on the mining history of the country.

Complexity of necessary technology: Medium.

Financial Resources: Low.

Technical implementation time scale is long, and the costs are high. Converted mines need to be chosen with care due to previous excavations. The advantage is that the infrastructure, such as shafts are already available, however there might be many unknown factors.

3.3.3.2 New mine-type facility

Amount of human resources or complexity of human expertise: Medium to high.

Complexity of necessary technology: Medium.

Financial Resources: High.

Technical implementation time scale is long, and the costs are high.

3.3.3.3 Deep cavern

Amount of human resources or complexity of human expertise: Medium.

Complexity of necessary technology: Medium.

Financial Resources: Medium.

Technical implementation time scale is long, and the costs are medium to high.

3.3.3.4 Tunnel

Amount of human resources or complexity of human expertise: Low to medium.

Complexity of necessary technology: Medium.

Financial Resources: Low to medium.

Technical implementation time scale is medium to long, the costs are medium to high.

3.3.3.5 Borehole (shallow and deep)

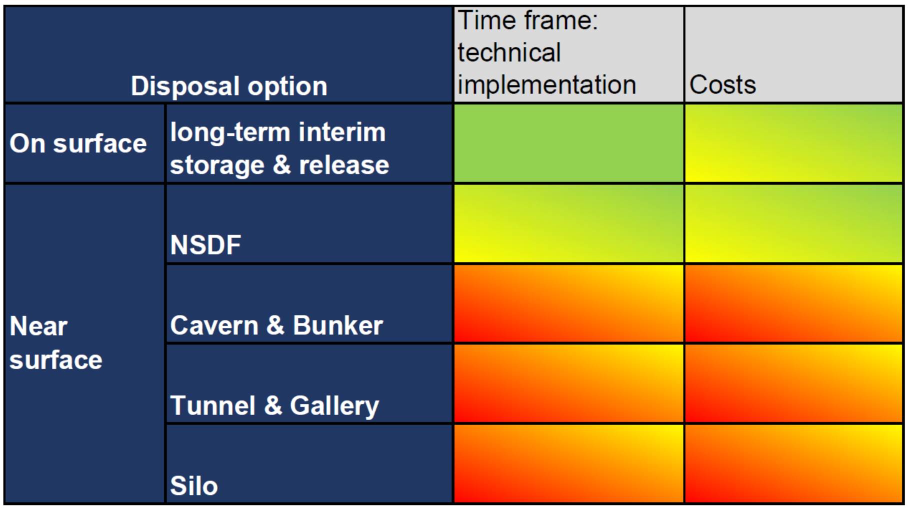
Amount of human resources or complexity of human expertise: Low.

Complexity of necessary technology: Medium up to 100 m, high up to a few 1000 m. IAEA support is possible.

Financial Resources: Low up to 100 m, unknown up to a few 1000 m.

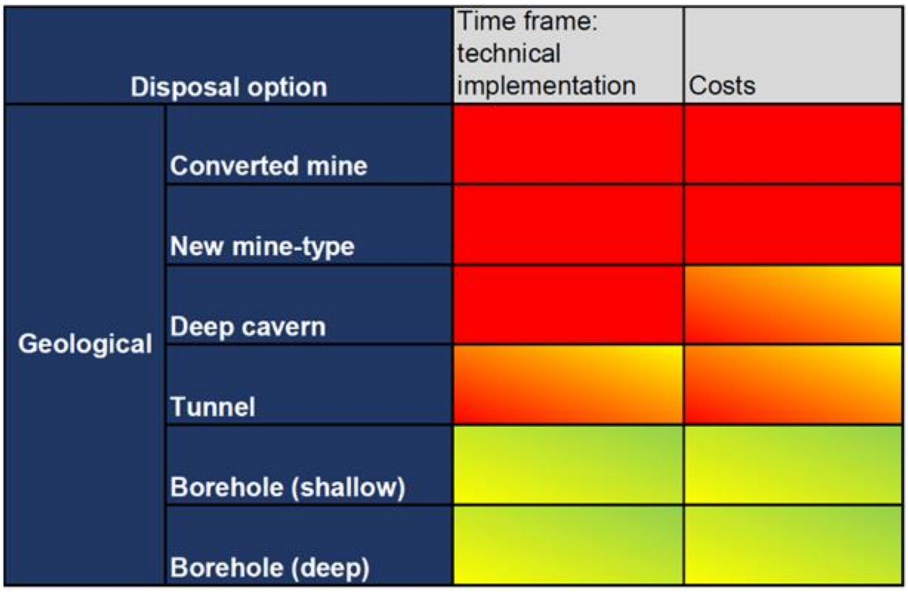
Technical implementation time scale is short to medium, the costs are low to medium. It depends strongly on the number of boreholes.

Other: Current issues for borehole disposals are retrievability, emplacement of waste package, and the dependence on amount of waste and available host rock.



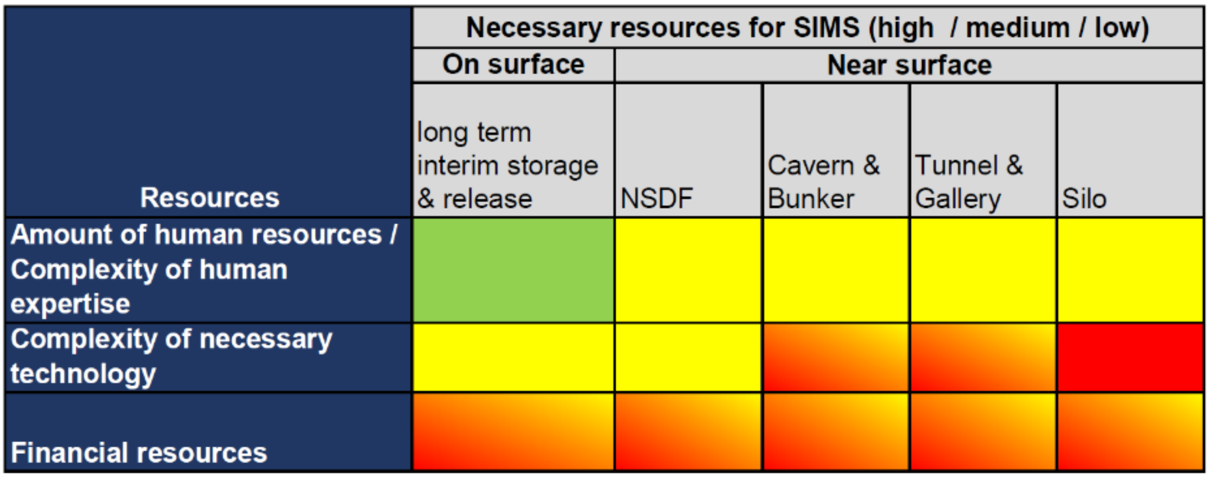
Disposal option		Time frame: technical implementation	Costs
On surface	**long-term interim storage & release**	🟩	🟨🟩
Near surface	**NSDF**	🟨🟩	🟨🟩
	Cavern & Bunker	🟥🟨	🟥🟨
	Tunnel & Gallery	🟥🟨	🟥🟨
	Silo	🟥🟨	🟥🟨

Figure 2: Ranked time scale and cost for on surface and near surface disposal options in SIMS, red high, yellow medium, green low, split cells indicate a "from – to" ranking.



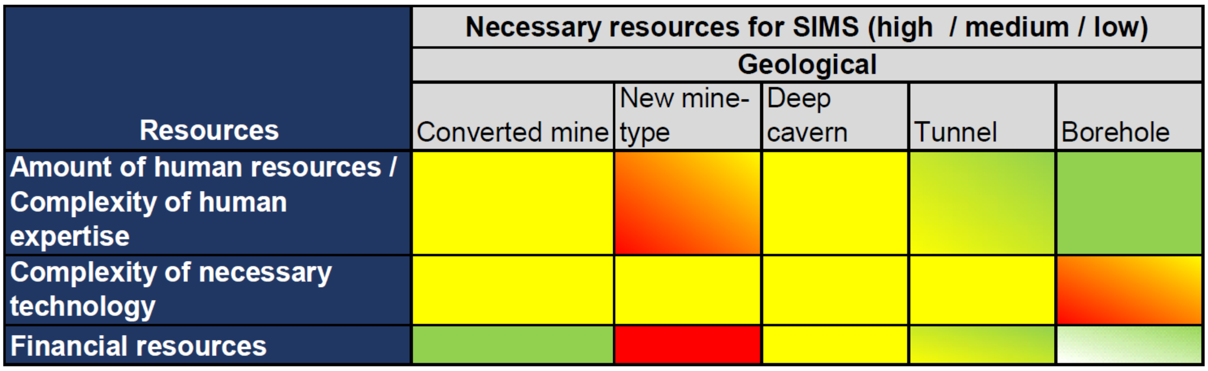
Disposal option		Time frame: technical implementation	Costs
Geological	Converted mine	🟥	🟥
	New mine-type	🟥	🟥
	Deep cavern	🟥	🟥–🟨
	Tunnel	🟥–🟨	🟥–🟨
	Borehole (shallow)	🟨–🟩	🟨–🟩
	Borehole (deep)	🟨–🟩	🟨–🟩

Figure 3: Ranked time scale and cost for geological disposal options in SIMS, red high, yellow medium, green low, split cells indicate a "from – to" ranking



Resources	Necessary resources for SIMS (high / medium / low)				
	On surface	Near surface			
	long term interim storage & release	NSDF	Cavern & Bunker	Tunnel & Gallery	Silo
Amount of human resources / Complexity of human expertise	🟩	🟨	🟨	🟨	🟨
Complexity of necessary technology	🟨	🟨	🟥–🟨	🟥–🟨	🟥
Financial resources	🟥–🟨	🟥–🟨	🟥–🟨	🟥–🟨	🟥–🟨

Figure 4: Ranked resources for on surface and near surface disposal options in SIMS, red high, yellow medium, green low, white unknown, split cells indicate a "from – to" ranking.



Resources	Necessary resources for SIMS (high / medium / low)				
	Geological				
	Converted mine	New mine-type	Deep cavern	Tunnel	Borehole
Amount of human resources / Complexity of human expertise	🟨	🟥–🟨	🟨	🟨–🟩	🟩
Complexity of necessary technology	🟨	🟨	🟨	🟨	🟥–🟨
Financial resources	🟩	🟥	🟨	🟨–🟩	⬜–🟩

Figure 5: Ranked resources for geological disposal options in SIMS, red high, yellow medium, green low, white unknown, split cells indicate a "from – to" ranking.

3.4 Evaluation of retrievability options

This section discusses the advantages and disadvantages of retrievability. Discussions on retrievability of radioactive wastes tends to focus on deep geological disposal, as proposed for either high level waste (HLW) or spent nuclear fuel, although several countries propose some form of co-disposal of long-lived intermediate level waste (ILW or transuranic radioactive waste in the USA).[1]

Retrievability is being investigated in a number of countries in studies, in repository designs and in experimental demonstration work. For example, Sweden, France, Belgium, and the United States have paid particular attention to how retrievability is included in their disposal systems.

The issue of minimizing burdens on future generations versus maximizing their freedom to choose was also discussed and it was concluded that for some disposal systems there is no contradiction, whereas in other cases a conflict may exist between the two objectives. The extent to which one can satisfy both these premises is an important issue.

The implementation of the retrievability option will also influence the repository siting and layout, method (the sealing techniques, the choices of backfill, buffer, and waste packaging) and/or phasing of closing individual disposal chambers, tunnels or boreholes as well as the entire repository.

Provisions designed to facilitate retrievability can decrease the reliability of isolation barriers and thus be counterproductive in respect to overall safety, but this assumption is not necessarily valid in all cases. Certain features - such as long-lived containers - are advantageous for both.

Retrievability is always possible but costs and risks are affected by when and how it is done. Current technology is considered sufficient, but demonstration would be useful, even if not required.

When discussing retrievability, the following aspects should be included [9]:

- Public acceptance;
- Legal and regulatory aspects;
- Ethical aspects;
- Long term monitoring and cost considerations;
- Safety and security aspects

3.4.1 The R-scale

The R-scale (International Understanding of Reversibility of Decisions and Retrievability of Waste in Geological Disposal [10]) of the OECD-NEA was used as a basis for the discussion of the specific reasons and characteristics of retrievability.

The idea behind the generic scale of retrievability is to align the effort of retrieving the waste or waste packages depending on the status of the geological disposal facility. OECD-NEA therefore discriminates between six stages of the waste lifecycle.

- Stage 1: Waste package in storage
- Stage 2: Waste package in disposal cell
- Stage 3: Waste package in sealed disposal cell

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[1] The French National Assessment Agency (CNE) has suggested there could be little or no justification for development of a retrieval capability in the case of low-level waste (LLW), because of the lack of any re-usable resource value, but did accept the fact that it might ultimately prove necessary because of public concerns [17]. Indeed, proposals have also been made recently in various LLW Compacts in the USA regarding development of so-called ‘Assured Isolation Facilities’ following the intense public reaction to plans for near surface disposal of these wastes. [9]

- Stage 4: Waste package in sealed disposal zone
- Stage 5: Waste in closed repository
- Stage 6: Distant future evolution

With each further step, the ease of retrieval declines while the costs of retrieval increase. Similarly, the safety assurance shifts from active controls to passive safety.

When discussing retrievability, one always must take into account the upsides and downsides of delaying, moving the repository into the next stage or speeding this process up.

With respect to safety assurance, this “as soon as possible” movement into the next stage of the waste lifecycle reduces, e.g., the risk of proliferation. This is especially relevant for wastes containing specific radionuclides such as Plutonium or Uranium.

If retrieval of one or more waste packages due to renewed state of the art knowledge supports the long term safety of the repository, e.g., reconditioning of waste or other steps is possible with lower costs for retrieval in earlier stages. This possibility might as well boost public acceptance of the disposal site.

3.4.2 Public acceptance

Retrievability – A matter of public acceptance?

- The perceived risk is very important. It is difficult to convey actual risk or calculated risk to the public. In any case, broad public support is required. The level of transparency is very important.
- Retrievability options could facilitate the decision-making process, as the public might endorse the facility at the specific site. However, it can also be seen as detrimental, as the possible easier access to the waste could be seen as a counter argument.
- “A step-by-step” approach – with a possibility to reverse each step – may be the best way to achieve public acceptance. Early and continuous public participation is essential.

3.4.3 Ethical aspects

There are very different views on ethical aspects related to retrievability.

- Sweden: “We have to act now and our action must be based on the knowledge that is available today.” There is always some degree of uncertainty, which is unavoidable.
- Netherlands: There are fundamental differences in view of the ethics regarding disposal of radioactive waste between the regulator (representing the official position) and the representatives of environmental organisations. In one view it is considered ethical to emplace the waste in a (retrievable) underground repository in order to create a fail-safe situation. In the other view it is found more ethical if each successive generation would decide for itself what the best disposal method is, manage the waste such as to keep all options open and pass on the know-how, the technology, and the resources to enable that.

3.4.4 Long term liability and cost considerations

- It is necessary to deal with issues of liabilities, responsibilities, financial commitments, etc. when discussing different options. Generally, after closure of the repository, according to most present legislation the operator will be released from further responsibility. With the option for a future retrieval of the waste, questions on continued responsibility, costs, and funding need to be taken care of.

3.4.5 Safety and security aspects

Safety has the highest priority and shall not be compromised by retrievability or anything else. Safety comprises radiological and conventional (mining) safety. Also, it is necessary to distinguish between safety during the operational phase (regarding the staff as well as members of the public) and post-operational safety. The safety case for “full retrievability” has not yet been fully assessed, neither theoretically nor practically, for example, in demonstration experiments in laboratories, pilot plants or underground research laboratories.

The IAEA lists a number of factors which can potentially influence the ease with which emplaced wastes (in this case specifically spent fuel) could be recovered [9]. These include:

- Host rock
- Depth of emplacement
- Repository design and layout
- Type of backfill material used
- Type of container used
- Temperature in the repository
- Special measures to aid recovery or hinder human access

4 Identification of non-credible options

This section describes decision trees that have been developed to deal with radioactive inventories, not taking into account other physical and chemical properties besides radioactivity. It should provide guidance for SIMS to screen out non-credible disposal options based on the evaluation of their needs and boundary conditions. In total, eight significant questions have been elaborated, addressing the applicability of on surface, near surface and geological disposal options. In the following paragraphs, only questions that were discussed during the second workshop are described.

4.1 On surface facilities – Long term storage followed by clearance

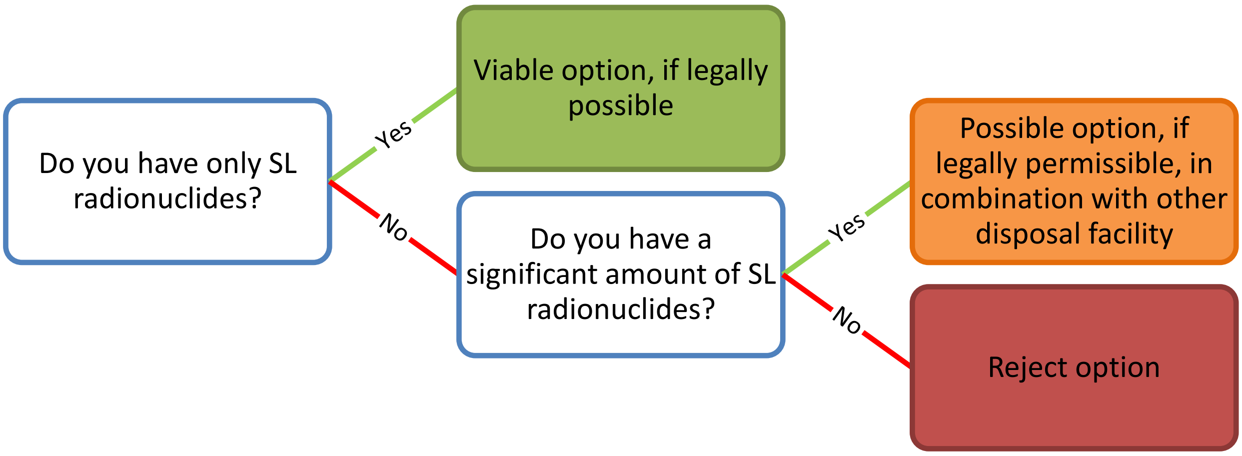

Figure 6: Decision tree for on surface facilities: Long term storage followed by clearance

The decision tree in Figure 6 starts with the question about the half-life of the radionuclides present in the radioactive waste. If the radionuclides are only SL, an on surface option is viable. If not, the second question is about the amount of SL radionuclides. If their amount is significant, it could be a viable option in combination with another disposal facility. If the amount is not significant, and LL radionuclides are present in significant amounts, this option is not viable and needs to be rejected.

4.2 Near surface disposal facilities

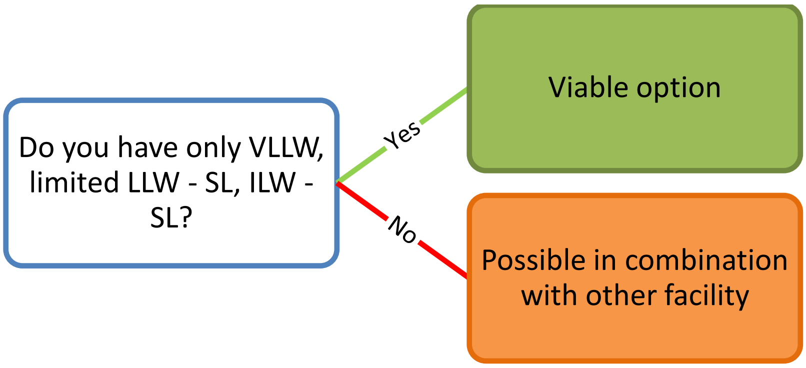

Figure 7: Decision tree for near surface disposal facilities

For NSDF, caverns & bunkers, tunnels & galleries, and silos the decision tree is simple, as shown in Figure 7. This option is viable, if the radioactive waste consists only of VLLW, or limited LLW – SL or ILW – SL. If there are other waste types, this option is only feasible in combination with another disposal option, which should be geological.

4.3 Geological disposal facilities

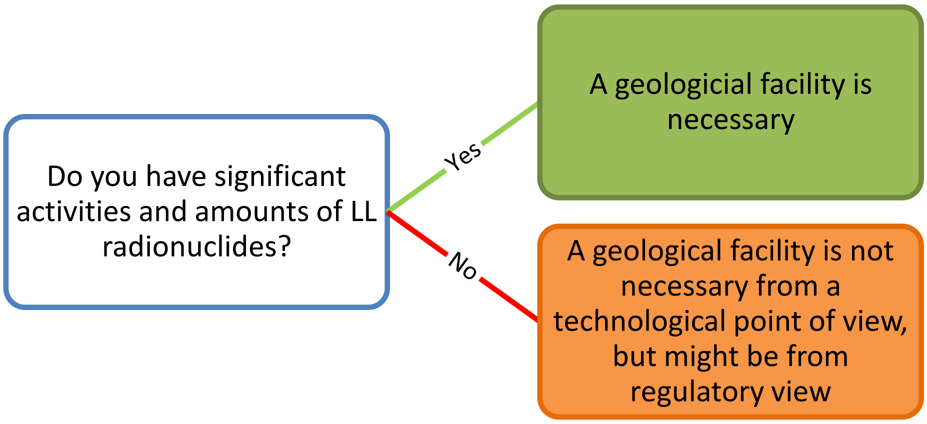

Figure 8: Decision tree for geological disposal facilities

The general question regarding geological disposal option is shown in Figure 8. A geological disposal is a viable option if there are either significant activities of radionuclides present or there is radioactive waste that is LL. If this is not the case, it can still be a viable option if the regulator demands a geological disposal facility.

4.3.1 Converted mine

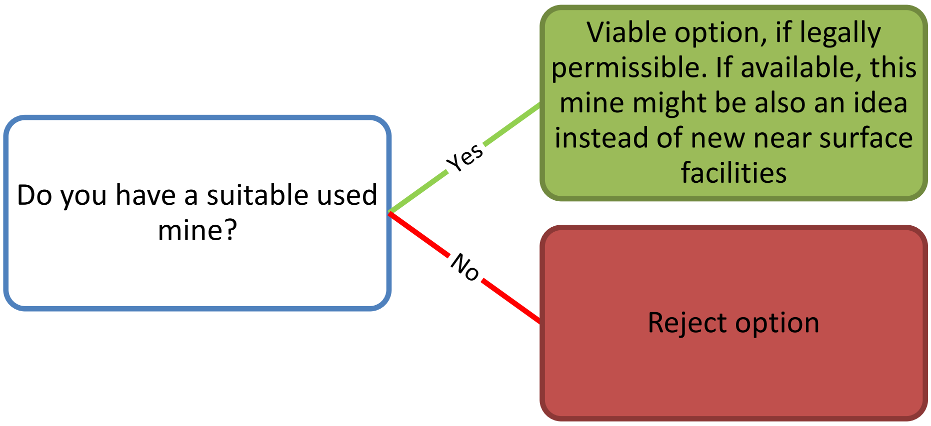

Figure 9: Decision tree for converted mines disposal facilities

For converted mines as geological disposal facility, the first question is if the country has a suitable mine that could be converted into a disposal facility, as shown in Figure 9. If yes, it is a viable option if it is legally permissible. It could also be an option instead of a planned near surface facility. If there is no suitable existing mine in the country available that can be converted into a disposal facility, the option has to be rejected.

4.3.2 New mine-type facility and deep cavern

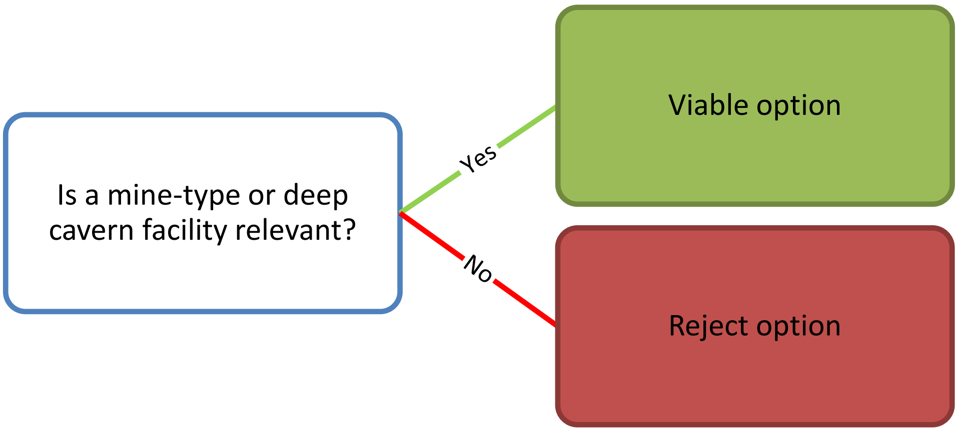

Figure 10: Decision tree for new mine-type facilities and deep caverns

For new mine-type facilities or deep caverns, the decision tree is shown in Figure 10. The question elaborates towards the relevance of topics like the amount of waste, the retrievability vs. reversibility, the type of inventory, the available funding, and the operation period.

4.3.3 Drift mining into hillside / tunnels

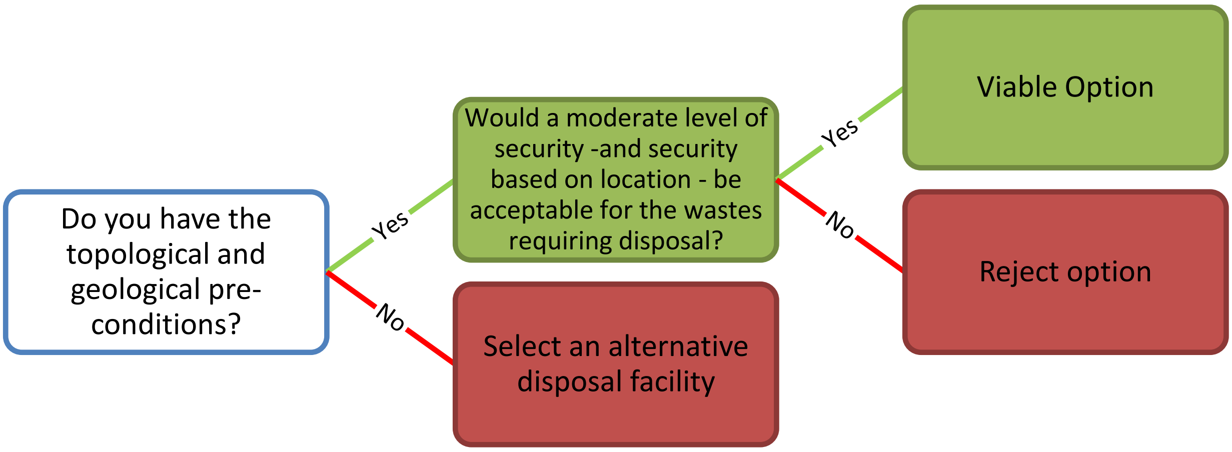

Figure 11: Decision tree of drift mining into hillside / tunnels

For geological tunnels the decision tree is shown in Figure 11. The first question is if the country has the topological and geological pre-conditions for this facility option. If this is not the case, an alternative disposal facility needs to be chosen. If the topological and geological conditions fit, the second question directs towards the security of the location. If a moderate level of security is acceptable, this option is viable as disposal option. If not, another geological facility needs to be chosen.

4.3.4 Borehole disposal facilities

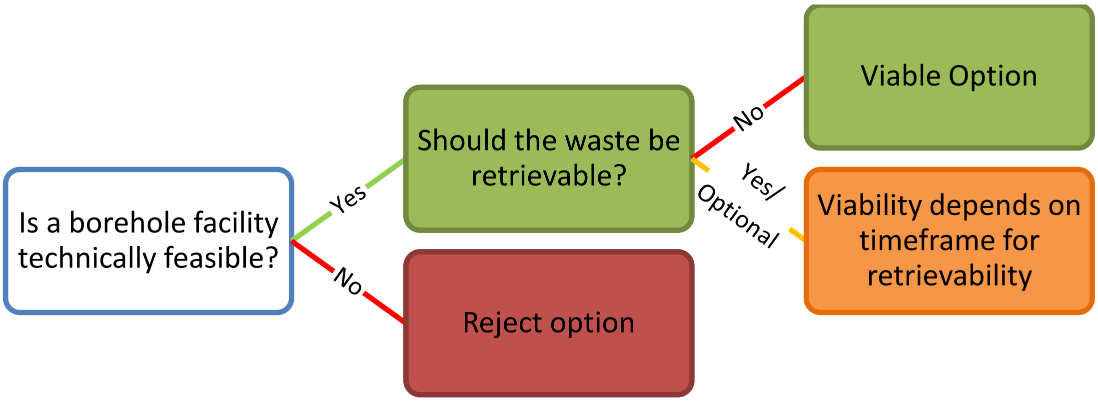

Figure 12: Decision tree for borehole disposal facilities

In Figure 12 the decision tree for borehole disposals is shown. The first question is if the borehole facility is technically feasible. If this is not the case, an alternative disposal facility has to be chosen. If it is technically feasible, the next question is if retrievability is needed. If it is not needed, a borehole disposal facility is a viable option. If it is needed after the closure of the facility, it is not a viable option. If it is only needed during placement of the waste packages, it might still be a viable option (see also Chapter 3.4 on retrievability).

5 Combinations of disposal options for SIMS

5.1 Two facilities of same type

This option can be necessary if there are either legislative limitations in size or activity at the disposal facility, or if there is more radioactive waste than originally anticipated (e.g., due to the construction of additional nuclear facilities). It might also be that the first facility is already closed and there is still radioactive waste that needs to be disposed of.

Another possible reason to have two facilities of the same type would be to avoid long distance transports of radioactive waste. However, this would indicate that the country has the respective treatment facilities at or in the vicinity of the disposal sites.

5.2 Combination of different disposal type facilities

5.2.1 Long term storage and near surface facilities

This practice is in operation for LILW in countries like Poland, Czech Republic, or Hungary. Material that can be cleared in the mid-term future is currently stored for clearance, while the other waste goes into the disposal facility. This option could be a feasible solution for large volumes of waste that does not need to be disposed of in geological facilities but has activities or half-lives of contained nuclides that require a disposal.

This combination can reduce the size of a needed geological facility, e.g., for HLW. The costs of implementation and operation are also lower than those of a geological facility.

The disadvantage of this combination is the need of an additional third type of facility if a geological facility is needed.

5.2.2 Long term storage and geological facilities

This practice is either planned or in operation in several countries (e.g., Poland – planned, the Netherlands – planned, Slovenia – planned, UK – in operation). In general, this combination will be in practice before a disposal facility is operational and will be a working model until the stored material is transferred to the disposal facility.

For a combination of a mine-type facility with long term storage, the Netherlands plan this kind of option in about 100 years. An exclusion criterion could be that this option is cost-intensive, especially for SIMS.

For a combination of tunnels with long term storage, the advantage is that it is probably cheaper and the technological readiness level (TRL) is higher than a borehole disposal, if there is no spent fuel (SF).

5.2.3 Near surface facility and geological facilities

This combination could be a possibility for LLW-SL and LILW-LL waste.

For a combination of a near surface facility with a new mine-type facility an exclusion criterion could be the high costs, especially if the waste volume is low.

For a near surface facility combined with a tunnel the advantage is that it is probably cheaper and the TRL is higher than for a borehole disposal, if there is no SF. An exclusion criterion could be the high costs, especially if the waste volume is low.

For a near surface facility combined with a borehole disposal the advantage would be that it is probably the cheapest solution. It is a good option for small amounts of waste that are not suitable for near surface disposal.

6 Assessment of disposal options

The following chapter discusses the different disposal options for four challenging waste types, selected in [11]. The discussed disposal options are:

- **On surface long term storage**: Long term storage enables the subsequent clearance of previously radioactive waste if the radionuclides are of short half-life.
- **Near surface:** Near surface disposal facilities are from ground level down to a depth of a few tens of meters. These facilities can contain VLLW, LLW and partly ILW.
- **Geological:** Geological disposal facilities are built in suitable geological formations. Radioactive wastes up to HLW can be disposed in these facilities.
- **Borehole:** Borehole disposal facilities can reach a depth of up to a few kilometres. These boreholes can contain radioactive waste up to HLW but are of limited suitability for larger amounts of waste.

6.1 General Evaluation

The evaluation used the methodology of the NDA Value Framework, described in Chapter 2. As a significant number of statements apply to a specific disposal option independent of the waste type, these are summarized in the sections below. In the next chapter, the general evaluation points that are only applicable for the individual waste types are described. The disposal option borehole disposal is only applicable to DSRS and in parts to SIERS and will be discussed in the specific chapter dedicated to these waste types. A detailed analysis of shared solutions is available in [12].

6.1.1 Evaluation of on surface storage followed by clearance

Environment: The appropriate measures for elimination or reduction of radiological risks should be applied. Monitoring is necessary.

Health & safety: There is the possibility of an exposure of workers during the wastes extended storage duration. Radiological monitoring is needed. Active monitoring in connection with ensuring safety, both operational, i.e., during the storage of radioactive waste, and long term, after the closure of the facility is needed.

Risk/hazard reduction: The storage of these waste types might lead to a radiological risk for the staff operating the facility. There is a possible radiological risk for the public. Due to climate change material might degrade faster.

Security: There are no intrinsic security measures or human intrusion diversion measures if not installed. Disposal or storage facilities are a possible threat target during crisis time. There is no possibility for a quick closure of the facility.

Socio-economic impacts: The storage building might have psychological effects on the public and neighbours. The disposal facility represents an intergenerational burden and transfers responsibility to future generations. It is important to maintain the technology, the knowledge, and the capabilities. A good public engagement and information is necessary. The construction of the facility may have an impact on the original spatial development plans of the area and should be in line with the spatial development plans of the area.

Lifetime costs: The construction costs can be relatively low; however, the operation of the storage is over a long period. The maintenance costs are high, as well as monitoring and inspection costs.

Enabling the mission: The advantage of long term storage is easy retrievability of disposed materials.

6.1.2 Evaluation of near surface disposal options

Environment: During the construction phase there will be an environmental impact on the surroundings. There can also be a hydrological impact during construction and operation phase.

Health & safety: During the construction phase there is the risk of dust, noise, or other nuisances for neighbours or the public. Active monitoring is needed in connection with ensuring safety, both operational, i.e., during the storage of radioactive waste, and long term after the closure of the facility. During operation, there is radiological risk for workers.

Risk/hazard reduction: The radiological risk to the public is lower than for long term surface storage, but strongly diverges between the different near surface disposal options discussed in [3].

Security: This disposal option has a higher intrinsic security compared to on surface storage. Disposal facilities are a possible threat target during crisis time. There is no possibility of a quick closure.

Socio-economic impacts: There is a lower visual impact on the neighbourhood compared to an on surface storage, as the facility is underground. The psychological effect of having a disposal facility in the vicinity might be higher compared to a storage facility. The construction of the facility may have an impact on the original spatial development plans of the area and should be in line with the spatial development plans of the area.

Lifetime costs: The costs are higher for building the facility, designing, and contracting it, compared to the on surface storage. The operational costs are also higher than for the on surface storage. After closure there are only costs for surveillance and inspection during a defined period.

Enabling the mission: There is a long operation time possible. The retrievability of waste is easy during operation phases of the facility and relatively easy after closure, however, ensuring the radiation safety of workers can be problematic.

6.1.3 Evaluation of geological disposal options

Environment: The “sealed system” does not correspond to a “normal life cycle” after closure. The material from the excavation has an impact on the environment and has to be stored in the vicinity (change of landscape). This option is, compared to the ones close to the surface, more energy intensive and has a higher CO_2 output.

Health & safety: There is the possibility of an exposure of workers during the transport and handling of the waste packages. There are general mining hazards for workers. There is less nuisance and less conventional hazards for the public than with near surface facilities. Monitoring in connection with ensuring operational safety is needed.

Risk/hazard reduction: After closure of this facility the safety is increased. The hazard of the waste is in general lower, this might be relevant for higher amounts of waste. In a clay host rock, the possibility of hydrogen release poses a threat.

Security: This disposal option has a higher intrinsic security compared to on surface storage and near surface disposal. Disposal facilities are a possible threat target during crisis time. There is no possibility of a quick closure.

Socio-economic impacts: The development and construction of a geological disposal facility is a long term project requiring a large amount of financial as well as well-educated human resources (e.g., scientists, technicians, and engineers) and involves several generations (the need to ensure the transfer of information, knowledge, and experience from generation to generation). Uncertainties on the date of availability of a disposal facility may lead to necessary decisions for extending the duration of interim storage.

Lifetime costs: The costs are higher for building the facility, designing, and contracting it, compared to the near surface facilities. The operational costs are also higher than for the near surface facilities. After closure there are only costs for surveillance and inspection during a defined period.

Enabling the mission: In this type of facility all waste types can be disposed of. The engagement and support of the government needs to be higher. There is a systematic approach needed. The predisposal routes need to produce containers for disposal. There is mining and material expertise necessary. The operation is possible for several decades.

Shared solutions: The compensation and responsibility need to be distributable.

6.2 Disposal of concrete

Possible options for concrete are on surface long term storage followed by clearance, near surface disposal and geological disposal. Borehole disposal is unsuitable due to the volume of the waste. A shaft disposal might be an option but is only under consideration in Norway.

In Table 1, the impacts of the discussed waste for each identified predisposal route on the disposal option is shown. The information was gathered from [11] and [12], and additional information about on surface storage including clearance was added.

Concrete	On surface	Near surface	Geological	Borehole
Big bag	If clearance is possible – suitable.	Suitable for VLLW.	Might not be suitable due to volume.	Not suitable due to volume.
Encapsulation in containers and cementation	Not suitable.	Suitable for low activity concentration if WAC are fulfilled.	Might not be suitable due to volume.	Not suitable due to volume.
Recycling / reuse	Suitable.	Suitable.	Suitable.	Not suitable due to volume.

Table 1 - Impacts of waste and predisposal route on disposal options for concrete

6.2.1 On surface – long term storage followed by clearance

Concrete has typically a high-volume waste stream, with the activity not being distributed homogeneously within the waste packages. A segregation into low- and intermediate level concrete is necessary prior to disposal. This option is only feasible for low amounts of waste due to storage space limitations. The technology is available. There are no special regulations for concrete. The long term storage might be an option for ILW concrete with SL-nuclides. The retrievability is easy.

Technological and resource prerequisites: A storage facility that has constant temperature and humidity levels is recommended. The disposal option can only be chosen if there are no long-lived nuclides present in the concrete.

Environment: On surface storage followed by clearance might lead to H-3 release if the waste packages are not kept in adequate facilities and their long term safety is not ensured. The large volumes of the waste might enhance the issue. Also, a contamination of soil is a risk for this option.

Enabling the mission: Depending on the conditioning method of the concrete, alkali-silica reactions could occur and influence maximum storage time.

6.2.2 Near surface disposal

This disposal option is suitable for concrete, e.g., in caverns, bunkers, tunnels and galleries. LILW concrete can be disposed of in silos. The option is more suitable for LLW or VLLW, in case of ILW mainly for short lived waste.

In France this disposal option is only for LILW-SL waste due to the current legislation. For LLW-LL this disposal facility is under discussion. The IAEA suggests disposing only low amounts of LL radionuclides in this kind of disposal facility [13] [14].

Risk/hazard reduction: There is the possibility of gaseous radionuclide leakages which might exceed the regulatory limits.

6.2.3 Geological disposal

Concrete could be used as stabilisation material for this disposal option. Another option is to use it as backfill material in converted mines, deep caverns, new mine-type facilities, or tunnels. It can therefore stabilise the mining structure. The volume of the concrete waste could have an impact on the disposability.

6.2.4 Borehole disposal

This option is currently not technically feasible due to the high volume of the waste stream.

6.3 Disposal of DSRS

The following paragraph discusses the disposal possibilities for DSRS. In Table 2 the impacts of the discussed waste for each identified predisposal route on the disposal option is shown. The information was gathered from [11] and [12], and additional information about on surface storage including clearance was added.

DSRS	On surface	Near surface	Geological	Borehole
Encapsulation and cementation in ordinary Portland cement	Not suitable.	Limited suitability due to lack of matrix and high activity concentration (WAC dependent suitability).	Limited suitability due to lack of matrix (WAC dependent suitability).	Suitable due to small volume of the waste. Specialised waste package necessary.
Welding into capsules (Ra-226 sources)	Not suitable due to longevity of Ra-226.	Limited suitability due to longevity of Ra-226 and its alpha-decaying properties.	Suitable (WAC dependent suitability).	Suitable due to small volume of the waste. Specialised waste package necessary.
Packaging with their shielding	Suitable, if clearance is possible.	Not suitable due to volume and non-conditioning.	Not suitable due to volume and non-conditioning.	Not suitable due to volume and non-conditioning.
Multiple HASS in specific container	Not suitable due to source activity and longevity of HASS.	Not suitable due to source activity and longevity of HASS.	Suitable (WAC dependent suitability).	Possibly suitable if conditioned and volume is suitable.

DSRS	On surface	Near surface	Geological	Borehole
Decay storage and clearance for SL-DSRS	Suitable, if clearance is possible.	Not suitable.	Not suitable.	Not suitable.
Export for recycling or disposal	Suitable	Not suitable.	Not suitable.	Not suitable.

Table 2 - Impacts of waste and predisposal route on disposal options for DSRS

6.3.1 On surface – long term storage followed by clearance

This option is only possible for smaller amounts of waste, as the storage will have space limitations at some point. The technology is available. In some countries (e.g., Austria or Greece) the export of DSRS for recycling of sources is highly recommended by legislation. This option could be the best solution for ILW DSRS with short half-lived nuclides. The retrievability is easy.

Sorting and categorization according to nuclides and half-lives is necessary for this option before putting the DSRS into storage in an adequate container. If the DSRS are dismantled, the storage volume is much smaller, as the one-by-one packaging requires more space.

Since 2018, a EU directive on the control of high-activity sealed radioactive sources and orphan sources [15] had to be implemented into national law which forces member states to have a legislation in place that, according to [15], “requires holders of sources to return each disused source to the supplier, place it in a recognized installation, or transfer it to another authorized holder without undue delay after it goes out of service, unless otherwise agreed by the competent authority”.

Environment: The necessary special conditions for elimination or reduction of radiological and non-radiological risks can be ensured due to the low amount of waste. There is no risk of damage to the waste package. Therefore, in general, the radiological and non-radiological discharges during long term storage as well as after clearance of material is low. However, monitoring is necessary.

Risk/hazard reduction: There is the possibility of gaseous radionuclide leakages which might exceed the regulatory limits.

Security: As DSRS are small, there is a higher risk for theft and a need for strict security.

6.3.2 Near surface disposal

The technology is available. There are regulations against near surface disposal of DSRS in some countries (e.g., Germany or Switzerland). Retrievability is easy during operation of the disposal facility and could also be feasible after closure.

The DSRS should be dismantled and collected in special containers prior to their disposal. If necessary, DSRS can be cemented or put into a polymer matrix for disposal. This disposal option is not recommended for HASS.

In France, DSRS with half-lives shorter than 5 years can be disposed of in near surface facilities. The IAEA defines requirements regarding the types of waste and special radionuclides that can be disposed of in near surface repositories (see [13] and [14]).

In Poland, smoke detectors containing americium or plutonium are dismantled and immobilized in 1 dm^3 metal boxes with polyester resin. The metal boxes are placed in a 50 dm^3 metal drum and grouted with concrete. Other parts of the smoke detectors in which plutonium contamination didn't exceed the clearance level are released from the radioactive material restrictions. Radium sources are immobilized with glass and placed into a brass container, which is put into storage containers and transported to the repository.

Sources are classified in addition to LLW, ILW and HLW according to categories from 1 to 5 [16].

Risk/hazard reduction: There is the possibility radionuclide leakage from sources, e.g., Rn-222 leakage from Radium sources. Regarding long term safety, the environmental safety case should include the risk of erosion. Therefore, there should be no discrete items with high and concentrated activity within the disposal site due to the higher risk of radionuclide transportation.

6.3.3 Geological disposal

The technology is available. In converted mines the leftovers of the original resource could enhance the intrusion possibility. In Germany, geological disposal is enforced through legislation. The retrievability is easy during operation in mines and tunnels, and difficult or nearly impossible due to stabilisation materials in caverns. After closure retrievability is difficult. There might be regulations in place regarding retrievability.

DSRS should be dismantled and collected in special containers prior to their disposal. If necessary, DSRS can be cemented or put into a polymer matrix for disposal.

Enabling the mission: The volume added by DSRS is low if the facility already exists.

6.3.4 Borehole disposal

The technology is available. It is recommended if waste that is disposed can also be disposed of in a borehole due to size. HASS cannot be disposed of in shallow, near surface boreholes (with depth of 10 m to 100 m), which are recommended only if the radioactive waste inventory consists of DSRS only.

Environment: For this disposal option only a small surface area is needed. Compared to other disposal options this option requires less energy and is probably cheaper as conventional drilling can be applied. Boreholes are situated at levels well below groundwater.

Health & safety: The borehole drilling will have less impact on the public than construction of a geological repository due to the smaller volume of excavated material and the limited transport of the necessary construction material. There will be no workers underground.

Risk/hazard reduction: The possible exposure is low due to short operational times. The waste is only handled shortly. There are technological risks during drilling. A safety assessment is necessary to evaluate risks during the emplacement.

Security: Disposal facilities are a possible threat target during crisis time. Due to higher isolation, there is in general a lower risk. A quick closure is possible. The intrinsic security is very high during the operational period as well as after closure. The retrievability is nearly impossible.

Socio-economic impacts: The public acceptance is possibly higher than for mine-type facilities.

Lifetime costs: The construction of a borehole for DSRS can use standardized equipment for drilling and sealing of the borehole. There are only low maintenance costs.

Enabling the mission: There is only a short operational time. It is not yet included in national disposal strategies, only in a few SIMS. The expertise is necessary, but licensing should be easier compared to a Deep Geological Facility (DGF).

6.4 Disposal of metals

The following paragraph discusses the disposal possibilities for metals from decommissioning. In Table 3, the impacts of the discussed waste for each identified predisposal route on the disposal option is shown. The information was gathered from [11] and [12], and additional information about on surface storage including clearance was added.

Metals	On surface	Near surface	Geological	Borehole
Cementation	Suitable if clearance is possible.	Suitable for low activity concentration if WAC are fulfilled.	Suitable also for higher activity metals if there is no volume restriction.	Not suitable due to volume.
Thermal treatment	Suitable if clearance is possible.	Suitable for low activity concentration if WAC are fulfilled.	Suitable also for high activity concentration if WAC are fulfilled.	Might be suitable, if drums/ capsules fit in borehole and meet the requirements of the safety analysis.
Super-compaction	Not suitable.	Suitable for low activity concentration if WAC are fulfilled.	Suitable also for high activity concentration if WAC are fulfilled.	Not suitable due to total waste volume.
Recycling / reuse	Suitable, if clearance is possible.	Not suitable.	Not suitable.	Not suitable.

Table 3 - Implications of waste and predisposal route on disposal options for metals

6.4.1 On surface – long term storage followed by clearance

This option is only possible for smaller amounts of metals, as the storage will have space limitations at some point. The technology is available. If recycling or reuse is possible, this should be the preferred option.

Metals are usually a high-volume waste stream. The activity distribution is not homogeneous. A segregation into low and high-active waste should be performed. Metals can be decontaminated through smelting if no Co-60 is present. To avoid galvanic corrosion, an inliner (e.g., from fibreglass) can be put into the container.

Retrievability is easy for this option. On surface long term storage has a very limited applicability for long-lived radionuclides.

Environment: There is a risk of radioactivity leakage due to hydrogen production. The long term storage is suitable only for metals contaminated by short-lived radionuclides.

Health & safety: There is the possibility of non-radiological hazards due to heavy metals (e.g., lead or beryllium).

Risk/hazard reduction: The possible hydrogen production in the waste containers could lead to a deformation of the containers.

6.4.2 Near surface disposal

The technology is available. There are regulations against near surface disposal of metals in some countries (e.g., Germany or Switzerland). Retrievability is easy during operation of the disposal and could also be feasible after closure.

Disposal in near surface facilities is suitable for metals (e.g., in caverns, bunkers, tunnels or galleries). The facilities are mainly dedicated to VLLW or LLW, sometimes also for ILW if there are only short-lived nuclides present.

France has this option only for SL radionuclides, both LLW and ILW, under the current legislation. LLW-LL material is currently under discussion.

The IAEA recommends placing only low amounts of LLW-LL in this disposal option.

Environment: There is the risk of heavy metal leakage.

Risk/hazard reduction: There is an explosion risk from hydrogen production that needs to be mitigated.

6.4.3 Geological disposal

The technology is available. In converted mines the leftovers of the original resource could enhance the intrusion possibility. In Germany, the geological disposal is enforced by legislation. Retrievability is easy during operation in mines and tunnels, and difficult or nearly impossible due to stabilisation materials in caverns. After closure, retrievability is difficult. There might be regulations in place regarding retrievability.

The possible production of hydrogen could be an issue.

Environment: The long term environmental assessment needs to take heavy metal leakage into consideration.

6.4.4 Borehole disposal

This option is currently not technically feasible due to the high volume of the waste stream. If the treatment leads to a significant reduction of the waste volume, borehole disposal might be an option.

6.5 Disposal of SIERs

The following paragraph discusses the disposal possibilities for SIERs. In Table 4 the impacts of the discussed waste for each identified predisposal route on the disposal option is shown. The information was gathered from [11] and [12], and additional information about on surface storage including clearance was added.

SIERs	On surface	Near surface	Geological	Borehole
Cementation	Not suitable.	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 limitation of the disposal site.	Suitable also for higher activity resins if no volume restriction. Possible WAC restrictions for organic resins due to radiolysis.	Not suitable due to volume.

SIERs	On surface	Near surface	Geological	Borehole
Polymer encapsulation	Not suitable.	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.	Suitable also for higher activity resins if no volume restriction. Possible WAC restrictions for organic resins and matrix due to radiolysis.	Not suitable due to volume.
Incineration and cementation	Not suitable.	Limited suitability due to activity concentration of the waste processing (WAC dependent suitability).	Suitable due to volume reduction of the waste processing and the absence of organic compounds in the waste.	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.
Incineration and super-compaction	Not suitable.	Limited suitability due to high activity concentration of the waste processing (WAC dependent suitability).	Suitable due to high volume reduction of the waste processing and the absence of organic compounds in the waste.	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.
(Hydro-) Pyrolysis and super-compaction	Not suitable.	Limited suitability due to high activity concentration of the waste processing (WAC dependent suitability).	Suitable due to high volume reduction of the waste processing and the absence of organic compounds in the waste.	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.

SIERs	On surface	Near surface	Geological	Borehole
Thermal compaction	Not suitable.	Limited suitability due to activity concentration of the waste processing (WAC dependent suitability).	Suitable due to volume reduction of the waste processing. Possible WAC restrictions for organic compound due to combustibility.	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.

Table 4 - Implications of waste and predisposal route on disposal options for SIERs

6.5.1 On surface – Long term storage followed by clearance

This option is only possible for smaller amounts of waste, as the storage will have space limitations at some point. The technology is available. Retrievability for this option is easy. Recycling of SIERs should be taken into account.

The waste volume of SIERs is usually small. It is necessary to characterize the waste regarding its radiochemical composition.

In Poland, SIERs with LL radionuclides are temporarily stored at ZUOP.

Environment: There is the possibility of a leakage of radionuclides and thus the long term safety of the packages.

6.5.2 Near surface disposal

The technology is available. There are regulations against near surface disposal of SIERs in some countries (e.g., Germany or Switzerland). Retrievability is easy during operation of the disposal and could also be feasible after closure.

SIERs can be cemented or fixed in a polyester matrix [12] to dispose of them in caverns, bunkers, tunnels, or galleries. For disposal in silos, they should be cemented, fixed in a polyester matrix, dried and/or incinerated. In the case of activated ion exchangers (resins) from water treatment (e.g., decontamination of water-cooled reactors), the use of molten salt oxidation technology to concentrate solid components and reduce their volume is also considered.

In Poland, short lived waste was conditioned by dewatering and solidification in a polyester matrix and packaging into standard metal drums. At present, research into advanced cement materials as well as Nochar polymers is ongoing.

In the case of the Czech Republic, the current national legislation only allows disposal of LLW and SL-ILW, and long term storage of LL- ILW and HLW intended for disposal in a future DGF (under specific WAC for long term storage) in the Czech NSDFs.

In France, only LLW and ILW containing short-lived radionuclides can be disposed of in near surface disposal facilities according to current legislation. The possibility of long-lived LLW disposal is under discussion.

The IAEA defines requirements regarding the types of waste and special radionuclides that can be disposed of in near surface repositories. Only a low amount of long-lived radionuclides should be disposed of in near surface disposal sites [13] [14].

6.5.3 Geological disposal

The technology is available. In converted mines the leftovers of the original resource could enhance the intrusion possibility. In Germany, this option is enforced through legislation. The retrievability is easy during operation in mines and tunnels, and difficult or nearly impossible due to stabilisation materials in caverns. After closure retrievability is difficult. There might be regulations in place regarding retrievability.

SIERs should be cemented or polymerized, dried, incinerated and/or super-compacted before placing them in converted mines, deep caverns, new mine-type facilities, or tunnels [11] [12].

The volume should be minimized before disposing the material. Specific WAC for geological disposal are needed.

6.5.4 Borehole disposal

This option is currently not technically feasible due to the high volume of the waste stream. If the treatment leads to a significant reduction of the waste volume, borehole disposal might be an option.

7 R&D recommendations

During the workshops held in Subtask 8.2, different aspects of restrictions in the applicability of the options presented in this report, as well as further concerns and envisioned developments were discussed. The following recommendations in this chapter have been classified depending on the type of project into “Strategic Study”, “Knowledge Management” and “R&D” and have been incorporated in the updated strategic research agenda (SRA) of the EURAD project in 2022.

Strategic Study recommendation – Impact of SMR development on pre-disposal and disposal strategies

The development of SMRs, promising faster and cheaper installation of nuclear power plants, currently arouses interest worldwide, but with low focus on the back end of novel reactor types. Indeed, the high variety of SMR design proposals make an estimation of the impact on current disposal strategies especially for SIMS complicated. In forecast of the potential impact of the so-called EU “Green Deal” on the intensification of SMR development, the impact on pre-disposal and disposal routes should be considered.

Expected outcomes and impact:

- Forecast on the impact of SMR implementation on potential pre-disposal and disposal strategies.
- Impact evaluation of SMR back-end on pre-disposal and disposal routes for SIMS.

Knowledge Management recommendation – Guidance and specifications on waste inventory dependent RAW management concepts

It is recommended to consolidate the processes of dissemination and sharing of information and experiences, identifying knowledge gaps, and developing a further understanding to address the following identified gaps:

- Development of methods for the inventory / quantification of the difficult to measure radionuclides and those that are important to transport, long term storage and operation and post-closure repository safety cases (e.g., long-lived radionuclides).
- Identification of good practices / approaches in the assessment, recording and management of inventory data (e.g., calculation, non-destructive analysis, destructive analysis, remote and in-situ technologies).
- Mapping / development of effective ways of using appropriate characterization methods and knowledge of waste inventories to support the development of a radioactive waste management strategy, including plant characterization and related analytical and visualization tools.

Expected outcomes and impact:

- Increased efficiency, cost effectiveness and safety of SIMS disposal strategies.

Strategic Study recommendation – Impact estimation of the EU “Green Deal” on LLW/ILW disposal facility development

A strategic study is recommended aiming at evaluating the effects of the so-called EU “Green Deal” on the RWM programmes in member states, emphasizing on:

- The need for legislation, a RWM policy and, strategy changes.
- Implementation of circular economy in the field of RAW (and SF) management in individual member states and at the European level (e.g., harmonisation of relevant requirements).
- Financial impact of the EU “Green Deal” on nuclear industry development and RAW/SF management programmes (incl. new disposal facility development).

Expected outcomes and impact:

- Improving the implementation of EU “Green Deal” requirements in the field of radioactive waste management and strengthening cooperation between stakeholders in this field at national and international level.
- Guidance on EU “Green Deal” implications for MS.

Knowledge Management recommendation – Guidance on EU “Green Deal” implications for MS

It is recommended to evaluate existing radioactive waste management programmes / strategies in terms of their potential impacts on various environmental areas, including circular economy and waste management, biodiversity, water systems and pollution, in the context of the EU “Green Deal” from the perspective of various stakeholders. This should include a stakeholders’ dialogue on the implementation of the EU “Green Deal” in RWM and nuclear energy development and its impacts.

Expected outcomes and impact:

- Improving the implementation of EU “Green Deal” requirements in the field of radioactive waste management and strengthening cooperation between stakeholders in this field at national and international level.

Strategic Study recommendation – Security & safeguard concepts for SMR from cradle to grave

With the on-going development of SMRs and their prospected world-wide deployment in high quantities, questions about their security and safeguard concepts for nuclear materials in SMRs arise. Studies suggest that the number of deployed SMRs might surpass the number of deployed conventional NPPs by some factors [17]. Additionally, SMRs are suitable for the deployment in remote, not easily accessible areas to provide power to smaller communities. Therefore, currently applied measures, e.g., for safeguarding, need to adapt to these changed boundary conditions.

Expected outcomes and impact:

- Analysis of the prospected boundary conditions for safeguard measures in SMRs in contrast to conventional NPPs.
- Projection of necessary changes in the current safeguard regime with respect to SMR deployments in larger numbers.

R&D recommendation – Safety concepts for SMR spent fuels

Extending the existing databases to consider modern and advanced fuels with different properties (e.g., fuels with additives, higher burn-up fuels) is important to reduce the uncertainties about spent fuel properties (such as composition, impurities, burnup etc.) that affect their behaviour under (long term) storage / repository conditions and which require the development of more accurate data, appropriate methods, and guidelines.

- Identification/evaluation of the needs for the introduction of new legislative requirements and administrative controls allowing for RAW / SF disposal in relevant repository.
- Understanding inert matrix fuels and dispersion fuels, in terms of their properties, stability as a waste form and suitability for (long term) storage and disposal.
- Development / selection of suitable transportation and storage / disposal casks / containers.
- Evaluation of the impact of the emergence of new types of RAW / SF from SMR on the conceptual solution / design of the disposal facility.

Expected outcomes and impact:

- Improving the forecast on the impact of SMR implementation on potential pre-disposal and disposal strategies.
- Evaluation of SMR back-end impact on pre-disposal and disposal routes for SIMS.

8 Conclusion

The first part of this deliverable discussed the general boundary conditions for countries involved in ROUTES Subtask 8.2. Each country stated host rock options and the status quo (as of October 2022) of their disposals for radioactive waste. It was also discussed if changes in the legal framework, such as the so-called EU "Green Deal" will have an impact on the implementation of disposal facilities.

Human, technological, and financial resources for "on surface" (long term storage & clearance), "near surface" (NSDF, cavern & bunker, tunnel & gallery, silo) and "geological" (converted mine, new mine-type facility, deep cavern, drift mining into hillside, borehole) disposal facilities were ranked according to a high / medium / low scheme including potential boundary conditions. This was done for all identified disposal options. For on surface disposal options, the time scale and the costs were considered low, as well as the human resources. The technological complexity was considered medium and necessary financial resources medium to high. For near surface disposal options, the time scale was considered low to high, depending on the facility, and the costs were considered low to high (low: NSDF; high: silo). Human resources were considered medium. The technological complexity was considered medium to high as well as the necessary financial resources. For geological disposal options the time scale and costs were considered high, except for borehole solutions, which were considered low to medium. Human resources were considered medium, and low for borehole disposal. The technological complexity was considered medium. Financial resources were depending on the type – converted mines were considered as low, new mine-type facilities as high, deep caverns and tunnels as medium and boreholes as low or unknown.

The next part of the deliverable summarized the discussions about retrievability, that considered the aspects public acceptance, legal and regulatory frameworks, ethics, long term monitoring and cost considerations as well as safety and safeguards.

During the workshops several decision trees for non-credible options for SIMS were developed, to screen out disposal options that are not compatible with international recommendations. Queries include long-lived nuclides, amounts of waste, suitable facilities available, geological pre-conditions or the technical feasibility of boreholes.

The next chapter summarizes the discussions about combinations of disposal options for SIMS, which can be two facilities of the same type or different disposal facilities. The first option can come into effect after a legislative change, or a change in the anticipated waste amount. The second case summarizes state-of-the-art disposal options in countries, as waste might be disposed of in different disposal facilities depending on their type or waste class.

The last part of this deliverable focused on the assessment of different disposal options for the four challenging waste types selected in ROUTES Subtask 8.1.1. The NDA Value Framework was applied to perform this assessment. The outcome is summarized as follows:

Concrete from decommissioning

- For the disposal of concrete from decommissioning three options were discussed: on surface (long term storage followed by clearance), near surface disposal and geological disposal.
- The on-surface option (long term storage followed by clearance) might lead to radiological discharges, and an exposure of workers cannot be excluded. In addition, there are no intrinsic security measures, and this option can have a psychological impact on the public. The costs are low for construction but might be high for maintenance.
- Near surface disposal can have an impact on the environment and public due to nuisance during construction. It offers however higher security compared to on surface facilities and the

exposure of workers will be lower than in on surface options. The costs for building the facilities are however higher, as well as the operational costs.

- For geological disposal concrete could also be used as stabilization or backfill material for other waste types. The construction of this disposal option is more costly than the other options. The impact on the environment from excavation is higher, due to being more energy-intensive and a high CO_2 output. The safety and security of the waste are increased with this option.
- The choice of the disposal option will depend on the waste amount and the nuclides present. Concrete might not be disposed of as waste itself but used as secondary material.

Disused Sealed Radioactive Sources

- For the disposal of DSRS four disposal options were discussed.
- The on surface option (long term storage followed by clearance or export) is a valuable option as DSRS must be sent back to the producer since 2018. There is a risk of exposure of workers during storage, and the security of the waste packages must be ensured. Costs can be assumed to be relatively low if storage times are short.
- Near surface disposal is an available technology for DSRS. There is a risk of Rn-222 leakage from Ra-226 sources, as well as H-3. Climate change and its consequences must be considered, as well as costs that are higher than for on surface options. However, the visual impact on the neighbourhood is lower, but the psychological effects can be higher.
- Geological disposal has an impact on the environment from excavation, is energy intensive and has a high CO_2 output. The safety is increased, and the hazard of the waste is reduced, and security enhanced. The costs are higher compared to the first options. The advantage is that in this type of facility all waste types can be disposed of. Borehole disposal has less impact on the public and workers than the other options. The exposure is low due to short operational times. The security is enhanced and quick closure possible. The costs are low, as standard drilling equipment can be used.
- Borehole disposal can be a good choice if DSRS are the only waste type that needs to be disposed of. It has the lowest impact on the environment and high safety and security features.

Metals from decommissioning

- As metals are a high-volume waste stream, not all options are suitable for the waste type, and some options are only considered suitable if the waste volume is low.
- The on surface option (long term storage followed by clearance) is feasible if only SL nuclides are present in the waste. In addition, attention must be given to non-radiological hazards, such as from heavy metals. The security is low, and buildings can have psychological impacts on the environment. Construction costs are low, but operational and maintenance costs can be high. An advantage is the easy retrievability of the waste.
- Near surface disposal facilities should only be considered if the amount of LL nuclides in the waste is small. The hydrogen explosion risk needs to be mitigated. The security of this option is

higher than for the on surface option, the impact on the environment and during construction for the public can also be higher. The costs are higher for the construction, as well as for the operation of the facility.

- Geological disposal might be of interest for intruders if resources were mined at the facility in former times, and the resources become of interest again. It has an impact on the environment from excavation, is energy intensive and has a high CO_2 output. The safety is increased, and the hazard of the waste is reduced, and security enhanced. The costs are higher compared to the first options. The advantage is that in this type of facility all waste types can be disposed of. Borehole disposal is not considered due to the high amounts of waste.
- The choice of the disposal option will depend on the waste amount and the nuclides present. A high volume of waste excludes choices like borehole disposals.

Spent Ion Exchange Resins

- On surface options (long term storage followed by clearance) and borehole disposal have a limited suitability due to the waste volume, depending on the selected predisposal route.
- The on surface option (long term storage followed by clearance) might pose the risk of exposure of workers to radiological and non – radiological hazards. Climate change can have an impact on the safety of the waste, as containers or buildings degenerate faster. Costs for construction are relatively low, but maintenance costs can be high.
- Near surface disposal facilities implement a fixation of the waste in a matrix, and only low amounts of LL waste should be disposed of in such a facility. The security of this option is higher than for the on surface option, the impact on the environment and during construction for the public can also be higher. The costs are higher for the construction, as well as for the operation of the facility.
- Geological disposal might be of interest for intruders if resources were mined at the facility in former times and the resources become of interest again. It has an impact on the environment from excavation, is energy intensive and has a high CO_2 output. The safety is increased, and the hazard of the waste is reduced, and security enhanced. The costs are higher compared to the first options. The advantage is that in this type of facility all waste types can be disposed of.
- The choice of the disposal option will depend on the waste amount and the nuclides present. A high volume of waste excludes choices like borehole disposal.

Lastly, this report outlines gaps and gives recommendations on future strategic studies, knowledge management and R&D projects. Two main concerns highlighted in this report and therefore dominating the recommendations on further work were the effects of the so-called EU “Green Deal” on the RWM strategies in SIMS, as well as the impact on RWM in SIMS due to the development on SMRs and their potential future implementation in SIMS.

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Appendix A. Case study 1 – Control rods of research reactors

Control rods are essential for safe, reliable, and economical operation of a reactor. Usually, neutron absorbers consist of chemical elements like boron, cadmium, silver, hafnium, or indium. These elements can absorb multiple neutrons without undergoing decay themselves. Additionally, they have distinct neutron capture cross-sections for various neutron energies. There are many alloys and compounds used for the production of research reactor (RR) control rods. Steel with high boron content is one option but limited to RR. This is because the B-10 atoms are transformed to Li-7 and He-4 by an (n,α) reaction, which sends the Li- and He-atoms to interstitial positions and cause swelling of the control rods. This can lead to mechanical deficiencies and needs to be avoided. [18] [19]

The favourable material is usually an Ag-In-Cd alloy. Based on these components, the nuclide inventory consists of long-lived activation products in the neutron absorber and cladding material due to neutron capture during operation. Another aspect is surface contamination with fission products and alpha emitters .

Due to the fact that these are reactor core components that have been activated, it is classified as ILW-LL (long-lived intermediate-level RAW) [13]. A major advantage that can be taken into account is that there are only a few control rods per research reactor. Furthermore, the control rods can be separated and divided into higher- and lower activated parts, which reduces the ILW volume and influences further treatment.

In the following paragraphs the predisposal and disposal options discussed in [11] and this report are evaluated according to the NDA Value Framework [2] for control rods of research reactors.

Predisposal options

1. **Placement in special containers without matrix / solidification**

Environment: There are no radiological discharges. The impact on the environment depends on the performance and durability of the special container. There is no further environmental pollution due to conditioning (producing cement, etc.).

Health & safety: The staff might be exposed to high levels of radiation during conditioning if the work is not performed under water or in a hot cell. The waste requires further handling (e.g., transport to storage) which could involve additional exposure. Due to this fact, manual handling of the control rods has to be avoided. There are no non-radiological discharges due to no further pre-treatment.

Risk/hazard reduction: There is a reduction of dose rate, dispersion, and corrosion risk due to shielding, but not on the same level as with solidification.

Security: The control rods are easy accessible for further conditioning, as there is no encapsulation.

Socio-economic impacts: The construction of the facility may have an impact on the original spatial development plans of the area and should be in line with the spatial development plans of the area.

Lifetime costs: It is a low-cost option in production (no further conditioning required) and the waste volume will not be increased (cheaper if priced by volume).

Enabling the mission: There is a possible non-compliance with future waste acceptance criteria due to non-solidification. But an advantage is that this type of predisposal allows actions after storage and before disposal. In addition to that, a re-characterization and a re-description is quite easy, for example if the standards will change.

2. **Placement in special containers and solidification in specific matrices**

The intention of solidification is to transform gases and liquids into a physically stable solid form, making it easier to handle these hazardous materials. One way to achieve this goal is using geopolymers, which is a category of high-pH cement. If shared facilities are available, they can be used.

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 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.

Environment: There are no radiological discharges during the process of conditioning, but there is non-radiological discharge during cement production (greenhouse gases) and after decay storage and clearance the cemented waste can be released as non-radiological waste.

Health & safety: A non-radiological exposition of staff is possible in case of a malfunction of the ventilation system (inhalation of dust during cementation). Moreover, high dose rates for the staff might be conceivable, in case of manipulation of high activity control rods during conditioning out of designed environments as hot cells or under water.

Risk/hazard reduction: The utilization of certain matrices in conditioning results in decreased dose rates and potential dispersion of radionuclides and chemical contaminants. These effects might arise over extended time periods compared to standard cement matrices. Furthermore, long term corrosion within drums and leakage are reduced in comparison to standard cement formulations.

Security: Due to the increase in weight, there is also an improvement in security. A disadvantage is that the used conventional cement can contain water of crystallization, which can lead to corrosion.

Socio-economic impacts: Based on the better shielding and the resulting security increase, this pre-disposal possibility is expected to meet greater approval from the public. The construction of the facility may have an impact on the original spatial development plans of the area and should be in line with the spatial development plans of the area.

Lifetime costs: The plant and auxiliary equipment have low initial costs if already existing. If the equipment has to be installed, there are high costs for this treatment option. the absence of waste volume reduction could also result in high prices, especially if the waste is charged based on volume.

Enabling the mission: There is a possible non-compliance with future waste acceptance criteria due to non-compaction. 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.

3. Encapsulation in special containers and solidification in magnesium brucite based cement

Encapsulation entails the storage of solid waste materials, such as spent fuel, in a secure and stable container. The desired goal is to realize a stable matrix in the repository to be able to ensure safe storage of high-risk waste.

For waste with an aluminium concentration, research is mainly directed towards the development of a magnesium brucite based cement. This type of cement maintains an alkaline state, which helps to reduce corrosion rates and thereby hydrogen production over time.

Environment: There are no radiological or non-radiological discharges during conditioning, but there are non-radiological discharges during cement production, and after decay storage and clearance the cemented waste is classified as non-radiological discharge. Moreover, the waste volume is enlarged (larger facilities required).

Health & safety: A non-radiological exposition of staff is conceivable in case of a failure of the ventilation system (inhalation of dust). In addition to that, high dose rates for the staff are possible, in case of pre-treatment (fragmentation) of high activity control rods during conditioning.

Risk/hazard reduction: With the enhanced radioactive shielding of the advanced cement matrix, the dose rate and potential dispersion of radionuclides and chemical containments are reduced and maybe guaranteed for a longer period of time than conventional cement matrices. Moreover, a reduction in long term corrosion and leakage can be expected.

Security: Due to the increase in weight and volume, there is also an improvement in security (prevention of theft due to increased weight and size).

Socio-economic impacts: Because of the volume increase during conditioning, more space is needed. It follows that the facility has to be bigger which means a bigger surface footprint. Nevertheless, it is a very safe way to store or even dispose of radioactive waste. The construction of the facility may have an impact on the original spatial development plans of the area and should be in line with the spatial development plans of the area.

Lifetime costs: The facility and associated equipment have low initial costs if already existing. If the equipment has to be installed, there are high costs for this treatment option. In addition the long storage (depends on waste volume) and the disposal (if priced by volume) could be very expensive.

Enabling the mission: The objective of these advanced matrices is to ensure that waste forms fulfil the future WAC. One uncertainty is that there are still few long term studies or data on these matrices in comparison to conventional matrices.

Disposal options

1. Geological disposal

New or converted mines: The suitability of a converted mine as a disposal facility is not determined solely by its geological characteristics. More important for the suitability test is the previous use of the mine and the rock damage due to mining activities. These two requirements can be considered equally.

Identifying and eliminating these deficits takes a lot of time. In this respect, a rebuild is often more costly than a new construction [18]. Even if there is only a small amount of waste to deposit, the effort for a small mine-type facility is comparable and, in most cases, the same. The design of the deposit and the mining method to be used are essential issues, which have to be additionally adapted to the local requirements. The evaluation of the cavities, in terms of the condition of the rock, also play a central role in the evaluation process. A limited further use of the existing mines can serve as a possible compromise, in the form of e.g., shafts, which have been spared from rock deformations. An acceleration and simplification of the disposal of radioactive waste cannot be assumed, if a converted mine is used, because the use of a formerly operated extraction mine as a disposal facility requires the same tests as a newly constructed mine-type facility.

Furthermore, the transport of waste in a shaft is easier than with boreholes, due to the larger space available.

Deep caverns: A cavern is designated as a large underground cavity created naturally or by mining activities, for example salt mining. In Germany, they are used commercially after salt extraction, for example, as storage for gas or oil, or are even built specifically for this purpose. [19]

To create a cavern, a borehole is drilled to approximately the planned depth of the cavern. Afterwards the salt is dissolved by flushing with a brine set and pumped to the surface. In this way, the cavern is created by expansion from the bottom up. The cavern has to be constantly filled with brine to remain stable. After completion, the brine is replaced by the storage medium, in order to stabilize the cavern.

Another option is that a smaller cavern could be realized, which is stable without counter-pressure. Furthermore, a tunnel can be constructed, where only minor rock deformation is expected.

Environment: In most cases, additional excavation work must be done. During this process heavy metals can be liberated, especially lead. To guarantee a smooth operation, ventilation systems, power systems, drainage systems and in some cases new areas have to be installed and protected (fence, guards). These steps are energy consuming and as a result they have a high CO_2 output. The visual nuisances for the public, is low, especially for converted mines.

Health & safety: Due to the fact that the facilities are often far from densely populated areas, the radioactive waste has to be transported there. The familiar risks of mining, for example heavy metal leakages, are also present for the workers. In some cases, the container with the radioactive waste must be manipulated. This results in a radiological risk for the workers, if the waste packages are not well shielded. Due to corrosion, hydrogen can be produced which results in an explosion risk.

Risk/hazard reduction: After closing the facility, it represents a well-isolated system, far off from populated areas, with a high intrinsic security. For example, after closure of a tunnel disposal facility, the lower parts will be backfilled with crushed rock. Moreover, the gap between the rock and constructed facility will also be filled with crushed rock and the lower part mixed with bentonite. At the end, tunnels and shafts will be plugged and closed with concrete at the ground surface). Compared to near surface facilities, geological facilities represent a better isolation of the waste from the environment. This lowers the potential hazard that could arise from the waste, which can be important for high amounts of waste, especially over long time periods.

Security: Quick closure might not be possible of this facility during crises times. However, the intrinsic security is higher, compared to near surface disposal facilities, regardless of whether during operation or after closure.

Socio-economic impacts: Due to more stable properties of these facilities compared to near surface disposal facilities, a long disposal period is possible. Based on the size of the project, many technicians, miners, engineers, and scientists are necessary. A great advantage of these facilities is the possibility to dispose of all types of waste, even in high amounts.

Lifetime costs: Due to the size and the energy demand, these types of facilities are cost intensive. In addition to that, the construction, design, and maintenance is also costly.

Enabling the mission: To realize projects like this, a high level of support from the government and from the public is needed. To get optimum results out of these projects, a systematic approach is essential. Hence, different kinds of expertise are relevant (mining, material sciences, engineering). There are special containers (pre-disposal route) for this disposal needed. Another important point is to distribute the responsibilities and the compensation.

2. Borehole disposal

Deep borehole disposal: By definition, deep boreholes have a depth of 100 m to 1000 m. They have not been used as final disposal facilities yet. As a result, there are still no techniques, procedures, and guidelines for the use of deep boreholes that can be used as a reference. Nevertheless, it is possible to draw on know-how from other industries, such as the oil and gas industry. These have to be summarized, checked for their suitability and finally tested. If necessary, they will then have to be adapted.

Very deep borehole disposal: Boreholes deeper than 1000 m are classified as very deep boreholes. The potential gain in radiological safety for the biosphere may compensate for the additional exploration and construction effort compared to deep boreholes. Since standard drilling technology from the oil and gas industry can no longer be used, the costs will be higher. Depths of two to three kilometres are being considered, although this is more a strategic matter and not a safety or technology requirement [18]. A "multi-barrier concept" is considered useful because it considers the waste and its container, the rubble, and the borehole casing, and, finally, the host rock. These successive barriers are intended to act as barriers against the transport of radionuclides to the biosphere.

Environment: The environmental impact is not as big and the amount of geological disruption is lower than for geological disposal facilities, because only limited boreholes have to be drilled into the ground and no additional excavation work has to take place.

Health & safety: Due to shorter interaction times with the radioactive waste and the fact that the drilling can be carried out from above ground, it is a safer option for the staff. Sealed systems, especially in a clay host rock can become a problem, as corrosion can lead to a possible hydrogen producing which leads to an a nuclide migration route.

Risk/hazard reduction: Borehole disposal presents a lower risk after closure due to simple and small concept compared to other disposal options.

Security: Fast and safe closure in times of crises can be guaranteed. Furthermore, a high degree of isolation can be ensured after closure.

Socio-economic impacts: The noise, dust and visual nuisance is less and extends over shorter periods of time than for geological disposal or near surface disposal. The effects and nuisances above ground are smaller and almost undetectable, but due to the small size of the borehole only small volumes, can be stored [20]. This can be an advantage or a disadvantage for the population.

Lifetime costs: Compared to geological disposal, borehole disposal is the less expensive option.

Enabling the mission: Due to the low volumes, this option is suitable for RR control rods in addition with small amounts of other radioactive waste. There are special containers (pre-disposal route) for the disposal needed. After final disposal in the borehole, retrievability is almost impossible (might be a problem with future WAC).

Pre-disposal of activated control rods	Environment	Health & safety	Risk/hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
Placement in special containers without matrix/solidification	No radiological discharges No non-radiological discharges Impact depends on performance of container	High dose rates for the staff during conditioning Avoidance of manual handling of control rods No non-radiological exposition	Reduction of dose rate Reduction of potential dispersion Reduction of corrosion risk due to placement in special containers	Fast investigation if needed (no encapsulation)	Facility may have impact on spatial development of area	Low-cost option during realization No increase of volume (cheaper if priced by volume)	Compliance with future waste acceptance criteria because of non-solidification and non-compaction Action after storage and before disposal possible Recharacterization easy to carry out (if standards change)
Placement in special containers and solidification in specific matrices	No radiological discharges Non-radiological discharges during cement production Cement can be released after decay and clearance	Non-radiological exposition of staff possible (inhalation of dust) High dose rates during manipulation of control rods for the staff	Reduction of dose rate due to solidification Reduction of potential dispersion because of better shielding (solidification matrices) Reduction of long term corrosion in comparison to common cement	Weight increase (difficult to steal) Water of crystallization in common cement poses a disadvantage, as it can lead to corrosion	Due to better shielding and long service life → potentially greater acceptance by the population Larger storage needed due to volume increase Facility may have impact on spatial development of area	Low cost for the plant and equipment High costs for long term interim storage and disposal (price per volume)	Possible non-compliance with future waste acceptance criteria due to non-compaction.
Encapsulation in special containers and solidification in magnesium brucite based cement	No radiological discharges Non-radiological discharges (cement production) Increase of waste volume due to cementation	Non-radiological exposition of staff (inhalation of dust) High dose rates during manipulation of control rods for the staff	Reduction of dose rate due to improved radiological shielding by matrix Reduction of potential dispersion potentially over a longer period Reduced long term corrosion and leakage in	Weight and volume increase (difficult to steal)	Larger facility required (volume increase during conditioning) Additional cementation facility required Safety performance can provide security for population	Low cost for the facility and equipment if already in place High costs for long term interim storage and disposal (price per volume)	The intention of these advanced matrices is, to fulfil future WAC Few data and studies available → insecurity with long term storage or disposal

Pre-disposal of activated control rods	Environment	Health & safety	Risk/hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
			comparison to conventional cement				

Disposal of activated control rods	Environment	Health & safety	Risk/hazard reduction	Security	Socio-economic impacts	Lifetimes costs	Enabling the mission
Geological disposal	Additional excavation of material from mine and cavern higher energy demand → higher CO_2 output Release of heavy metals during mining (lead) possible Less nuisance/ conventional hazards for public (than near surface facilities)	Transport of RAW necessary radiological risk for workers during the manipulation process of waste packages General mining risks and hazard for miners In clay host rock problem if hydrogen is produced due to corrosion → explosion risk	After closure: sealed system far away from biosphere with high intrinsic security Lower hazard (important for high amounts of waste)	Lower risk because of safe closure with high isolation factor During unstable situations (war, revolutions etc.) quick closure might not be possible Intrinsic security is high both during operation and after closure	Long interim storage period possible Big projects → many technicians, miners, engineers, and scientists necessary Possibility to store all waste types	High operational costs (energy demand, maintenance) Higher costs than near surface facilities due to size, design and construction as well as energy demand	High support of government and people (e. g. referendum) necessary Systematic approach is essential Lots of expertise necessary (material, mining, science) Special containers have to be produced (predisposal route) Shared solutions: Distributable compensation and responsibility
Borehole disposal	Lower geological footprint (than near surface and geological disposal) Less nuisance/ conventional hazards for public (than near surface facilities and geological disposal)	Transport of RAW necessary Shorter interaction times → less radiological risk for workers during the manipulation process of waste packages Work above ground without exception → lower risk for workers In clay host rock	After closure: sealed system far away from biosphere with high intrinsic security due to small concept	Lower risk because of fast and safe closure with high isolation factor during unstable situations (war, revolutions etc.) Intrinsic security is high both during operation and after closure	Lower noise/ dust/ visual impact on public (than near surface and geological disposal) due to fast realisation Long interim storage period possible Possibility to store all waste types	Lower costs compared to geological disposal	Special containers have to be produced (predisposal route) Low volumes → might only be suitable for specific types of RAW No retrieval possible after final disposal (possible non-

		problem if hydrogen is produced due to corrosion			Low volumes can be stored		compliance with future WAC)

Appendix B. Case study 2 – Scrap metal contaminated with NORM

Metals that are contaminated with NORM can arise from several different activities. One source is the piping of phosphoric acid production which is a part of the fertilizer industry. Here, technologically enhanced naturally occurring radioactive material (TENORM) deposits can be found. Another origin of NORM contaminated metal scrap is mineral scales inside piping from oil and gas extraction, which also contains TENORM. NORM contaminated metal scrap contains Ra-226 activities in the range from 200 Bq/g (in the stream coming from the fertilizer industry) up to 15,000 Bq/g (in the stream coming from oil or gas extraction). This radionuclide is predominant in most cases. However, elevated concentrations of Ra-228 and Pb-210 may also be found depending on the type of process leading to the scale formation, as well as other radionuclides. [17]

In this case study, different predisposal and disposal options are evaluated, considering the advantages and disadvantages that arise for metal scrap contaminated with NORM in each of these options. The different predisposal management and disposal options can be evaluated in terms of their effects on the environment, with consideration of risk and hazard reduction, health & safety, security, their socio-economic impacts, the arising lifetime costs as well as in terms of enabling factors of the mission.

Six different predisposal options will be discussed as well as three different disposal options. It should be noted that the predisposal options of solidification in specific matrices and solidification in magnesium brucite-based cement are useful especially when the metal is not only NORM contaminated but contains Co-60, since Co-60 does not precipitate during melting.

In the following paragraphs the predisposal and disposal options discussed in [11] and this report are evaluated according to the NDA Value Framework [2] for scrap metal contaminated with NORM.

Predisposal options

1. Decontamination, recycling, reuse, and minimization

Environment: Decontamination, recycling, reuse, and minimization have negative effects on the environment as radiological discharges might arise during decontamination. These can be liquid or gaseous. Also, non-radiological discharges like chemicals might arise. The volume of the waste however is smaller than for the other predisposal options reviewed here, which includes that the disposal facilities do not require as much space either.

Health & safety: Personnel may inhale dust, containing, e.g., heavy metal compounds. This means that radiological exposure as well as non-radiological exposure to aerosols is possible. Therefore, personal safety equipment (PSE) is required.

Risk/hazard reduction: Risks are reduced through the reduction of the dose rate in the decontaminated metal and the potential dispersion after the treatment. However, there is a concentration of the dose rate in the secondary waste.

Security: After decontamination the security is higher due to lower activity in the metal, but there is activity concentration in the secondary waste.

Socio-economic impacts: While minimization is usually received well by the public, this might not be true for recycling and reuse. The public might be sceptic of the impact recycling and reuse might have on them. As with all treatment facilities, these, too, might have a psychological impact on neighbours.

Lifetime costs: The costs of the decontamination equipment are significant. Meanwhile, the costs for storage and disposal are reduced.

Enabling the mission: Aspects that are enabling the mission are firstly, that the waste volume for which disposal is envisaged is reduced and secondly, that material can be reused instead of being disposed of. Provided legislation allows it, shared solutions are possible and facilitate the implementation.

2. Cementation

Environment: Cementation generates no radiological discharges. Its production however does include greenhouse gas emission.

Risk/hazard reduction: Risks and hazards are diminished, as cementation provides a barrier that not only reduces the dose rate but also potential dispersion after the treatment.

Health & safety: Regarding health and safety, this is a favourable option. External as well as internal dose rate during handling cannot be excluded but are unlikely. In contrast, mechanical accidents might be more severe due to the greater weight. For all these reasons PSE is required. Also, non-radiological dust inhalation cannot be excluded.

Security: Cementation might be advantageous in consideration of security, since cemented material is larger as well as heavier and is therefore more difficult to move.

Socio-economic impacts: The high carbon footprint of cement production is usually not perceived well by the public and the enlarged volume might be a disadvantage for storage and disposal. Also, an additional facility is needed. The construction of the facility may have an impact on the original spatial development plans of the area and should be in line with the spatial development plans of the area.

Lifetime costs: While the cementation facility itself has low costs, the interim storage creates higher costs due to the larger volume and disposal becomes more expensive as weight and volume increase, if disposal costs are priced by weight or volume.

Enabling the mission: There could be a possible non-compliance with future WAC due to non-compaction, as is the case in several other predisposal treatments discussed below. Altogether, it is an easy to implement option, even for small amounts of waste, if WAC are in place.

3. Thermal treatment (after decontamination or directly)

Thermal treatment either after decontamination or directly is another option for predisposal treatment. Beforehand decontamination might be required, which brings with it advantages and disadvantages of the decontamination option discussed above. Not all material is suited to undergo thermal treatment. For example, material contaminated with cobalt is not appropriate for smelting.

Environment: A positive effect when it comes to the environmental impact is that the interim storage can be smaller due to high volume reduction. A downside is the high energy demand which results in the production of large amounts of CO_2.

Risk/hazard reduction: During the treatment radiological discharge occurs and discharge of tritium might occur, so there is activity concentration in secondary waste. An advantage of this method is that there is no dispersion risk from the primary waste after the treatment, although secondary waste might disperse since it can be in the form of dust or sweepings.

Health & safety: Pre-sorting is also usually necessary. More handling equals higher risks.

Security: There is a risk in the transportation to the melting facility. This is the case for transportation of most radioactive materials. With thermal treatment however this becomes more important as the existing shared melting facilities are usually far away from the producer and the storage or disposal facility [17]. Also, EURATOM might need inclusion due to the concentration of nuclear material such as uranium and thorium in NORM contaminated metal scrap.

Socio-economic impacts: The risk of the transportation to the melting facility also has a socio-economic impact. Waste minimization means smaller interim storage, and both are generally received well by the public, reuse and recycling might not be, although reuse means less energy demand than a completely new product or material.

Lifetime costs: This shared solution reduces costs, although transportation becomes costlier if the facility is farther away. Without outsourcing costs of the thermal treatment would be high and it would only be viable for large volumes.

Enabling the mission: Waste acceptance criteria will be easier to prove since waste after thermal treatment has a homogeneous activity distribution. Furthermore, the WAC are more likely to be met since the waste is integrated into a robust metallic matrix. Another enabling factor is the availability of shared solutions (see [17]).

4. High-pressure compaction

Environment: There are no discharges that arise from high-pressure compaction, except for liquid discharges and the production of dust in some cases, although both are very unlikely.

Risk/hazard reduction: The dispersion risk is reduced. If the drums have a liner and there is no contact between aluminium and other metals, long term corrosion of drums and leakage do not become a problem. The treatment poses risks to personnel during handling (e.g., for characterisation) since they are exposed to radiation, measures to mitigate this risk shall be implemented.

Health & safety: It should be ensured that the staff has no direct access to the high-force compactor. In addition, it should be ensured that the treated metals cannot harm the staff.

Security: High-pressure compaction improves security by increasing the weight per volume.

Socio-economic impacts: The volume reduction leads to a smaller needed storage space.

Lifetime costs: The technology for super-compaction as well as its maintenance are expensive but costs for storage and disposal are decreased due to smaller waste volumes.

Enabling the mission: Shared solutions are possible which would most likely result in shared costs. Another enabling factor is that compacted metals generally will meet the WAC.

5. Solidification in specific matrices (e.g., geopolymers)

Environment: Solidification in specific matrices like geopolymers does not entail any radiological discharges.

Risk/hazard reduction: Dose rate and potential dispersion are reduced.

Health & safety: Inhalation of dust and external radiological exposure cannot be excluded. Handling is safer from a radiological perspective but because the waste is heavier, mechanical accidents are more severe and PSE is required.

Security: Mechanical accidents are more severe due to increased weight. Also, compared to melting or compaction the volume of the material is larger. For these reasons, transportation is more difficult.

Socio-economic impacts: An additional facility is needed which might not be received well by the general public. The construction of the facility may have an impact on the original spatial development plans of the area and should be in line with the spatial development plans of the area.

Lifetime costs: An additional facility is needed, although the cost of the facility is low while the cost of the matrix itself is higher compared to cementation. Not only is the weight enlarged but compared to melting or compaction the volume of the material is also larger. Therefore, the interim storage costs as well as disposal costs are higher if measured by weight or volume.

Enabling the mission: In terms of factors that might enable the mission, there is the possibility that solidification in specific matrices might not comply with future WAC because of the lack of compaction.

6. Solidification in magnesium brucite -based cement (e.g., for aluminium)

Environment: No radiological discharges occur from solidification in magnesium brucite based cement. However, cement production leads to CO_2 output. The matrix limits hydrogen production over time.

Risk/hazard reduction: Dose rate and potential dispersion are reduced.

Health & safety: Inhalation of dust and external radiological exposure cannot be excluded. Handling is safer from a radiological perspective but because the waste is heavier, mechanical accidents are more severe and PSE is required.

Security: Security is improved by the weight increase although mechanical accidents are more severe for the same reason.

Socio-economic impacts: The public might disagree with the need for an additional facility as well as the high greenhouse gas emission during the cement production. The construction of the facility may have an impact on the original spatial development plans of the area and should be in line with the spatial development plans of the area.

Lifetime costs: The cost of the facility is low whereas the costs of the interim storage are high if measured by weight.

Enabling the mission: There is the possibility that solidification in brucite based cement might not comply with future WAC because of the lack of compaction.

Disposal options

The same aspects of environment, risk / hazard reduction, health and safety, security, socio-economic impacts, lifetime costs and factors that play a decisive role in enabling the mission, can be used as pillars for the evaluation of disposal options of metal scrap contaminated with NORM.

The different disposal options that must be assessed are near surface disposal, geological disposal, and borehole disposal.

1. Near surface disposal (NSDF, cavern and bunker, tunnels and galleries, silo)

Environment: The construction greatly affects the environment at least during the construction phase, and they may have a hydrological impact on the environment. It has to be considered that a lead leakage might occur if the disposed metal contains lead.

Risk/hazard reduction: In the case of hydrogen production this leads to the risk of an explosion.

Health & safety: During the construction phase most likely a dust impact on neighbours and the public occurs.

Security: Near surface disposal ensures a higher intrinsic security than an on surface interim storage. However, there is a particular drawback to the near surface disposal facilities. During times of crisis, they can serve as threat target which poses a high risk, especially since a quick closure is impossible.

Socio-economic impacts: Near surface disposal has a visual impact. However, it is lower compared to an on surface long term interim storage. For near surface disposal as well as for all other disposal options, the psychological effect that the concept of disposal brings with it in contrast to storage has to be considered. The construction of the facility may have an impact on the original spatial development plans of the area and should be in line with the spatial development plans of the area.

Lifetime costs: Building, design, and construction of a facility underground implies higher costs than above ground, as is the case for long term interim storage. The same holds true for the costs during the operational period, whereas after closure the only costs that arise are from surveillance and inspection for a defined period of time.

Enabling the mission: Near surface disposal is not applicable to all types of waste, but might be an option for the discussed waste type. Later use of caverns and other used structures for different purposes would most likely be impossible.

2. Geological disposal (new or converted mine, deep cavern, tunnel)

Environment: Geological disposal after closure takes place in a sealed system far away from the biosphere. Nevertheless, the building process includes the excavation of material from the mine or cavern. Also, the building process is more energy intensive and as such brings on a higher CO_2 output. Heavy metals still require a long term environmental assessment before geological disposal can be considered as a disposal option.

Risk/hazard reduction: Geological disposal means lower hazard after closure compared to near surface disposal options, which might be significant for higher amounts of waste. However, building a sealed system especially in a clay host rock becomes a problem if hydrogen is produced through corrosion processes and lead to radionuclide migration processes. At the same time hydrogen production will lead to the risk of explosion.

Health & safety: Higher safety is ensured after closure. Transport of the radioactive waste is necessary, which is always connected with risks for workers as well as the public. The workers are not only exposed to radiological risks during the manipulation of different waste packages, but also to general mining hazards and risks. Conventional hazards for the public are lower.

Security: This type of disposal facilities still can be used as a threat object during war or revolution, but the risk is lower because of higher isolation but quick closure is usually not possible. In general, the high intrinsic security for the duration of the operational period as well as after closure is a great benefit of this disposal option.

Socio-economic impacts: Nuisance for the public is lower than for near surface disposal. Another socio-economic aspect is that a big project like the design, construction, operation, and maintenance of a geological disposal facility requires many scientists, technicians, and engineers.

Lifetime costs: Not only the costs of design and construction but also the operational costs are higher than for near surface disposal.

Enabling the mission: Engagement of and support from the government as well as a systematic approach are needed. Mining expertise and material expertise for the container production are needed. What makes the geological disposal option convenient is the fact that all other waste types can be disposed of in such a facility as well, in contrast to near surface disposal. Also, geological disposal is suited for a shared solution with distributable compensation and responsibility.

3. Borehole disposal

Environment: The environmental impact is not as great, and the method does not imply the same amount of geological disruption as geological disposal does.

Risk/hazard reduction: The risks and hazards are partly similar to those of geological disposal. Borehole disposal means lower hazard after closure. However, building a sealed system especially in a clay host rock becomes a problem if corrosion enables hydrogen production and facilitate radionuclide migration.

Health & safety: Safety is higher since the interaction time with waste packages is shorter. Furthermore, the risks due to borehole drilling are lower. Workers only work above ground.

Security: In case the borehole is used as a threat target in times of crisis, a quick closure is possible and after closure the degree of isolation is very high.

Socio-economic impacts: The dust, visual and noise impact on the public is smaller and lasts shorter than for either near surface or geological disposal. The effects above ground are smaller, but the volume that can be stored in a borehole is also smaller. This could be an advantage or a disadvantage for the public. The neighbours might feel safer with less radioactive waste close by but at the same time more boreholes are needed because of the small volume that is stored per borehole.

Lifetime costs: Cost-wise the borehole disposal is favourable compared to geological disposal.

Enabling the mission: Since it is not practical for large volumes, this option might only be applied to specific reactive materials and not the materials discussed. After the final emplacement in the borehole, retrievability is almost impossible.

Predisposal options of metal scrap	Environment	Risk/hazard reduction	Health & safety	Security	Socio-economic impacts	Lifetime costs	Enabling the mission
Decontamination & recycling/ reuse and minimisation	Radiological discharges during decontamination (can be liquids or gas) Also, non-radiological discharges like chemicals Less volume of waste results in less/smaller disposal facilities	Reduction of dose rate for decontaminated metal, but concentration of dose rate in secondary waste Reduction of potential dispersion after treatment	Radiological exposure of personnel during handling Possibly inhalation of dust, that may include lead → non-radiological exposure to aerosols (personal safety equipment (PSE) required)	Lower risk due to lower activity in metal Activity concentration in secondary waste	Recycling and reuse could have an impact on the public. Maybe facilities have psychological impact on neighbours Minimization generally received well by the public, same as recycling (for non-RAW)	Significant costs of decontamination equipment Reduced cost for storage and disposal	Reduced waste volume for disposal Shared solutions possible if legislation allows it Reuse of materials
Cementation	No radiological discharges GHG (greenhouse gas) emission / carbon emission during cement production	Reduction of dose rate Reduction of potential dispersion	Heavier, therefore mechanical accidents more severe (PSE) Non-radiological dust inhalation cannot be excluded External as well as internal dose cannot be excluded (unlikely but cannot be excluded. PSE required.)	More difficult to transport (heavier and larger) → advantage regarding security	Enlarged volume and weight (for storage and disposal) Carbon footprint of cement production Additional facility needed and should be in line with the spatial development plans of the area	Low-cost facility High costs of interim storage (volume) High costs of disposal (if priced by weight, volume)	Possible non-compliance with future WAC due to non-compaction Easy to implement, applicable also for small amounts if WAC are in place
Thermal treatment (after decontamination or directly)	High energy demand results in much CO_2 produced High volume reduction	If material is additionally cobalt-contaminated, not appropriate for smelting Decontamination beforehand might be required → see decontamination Pre-sorting is usually required Discharge of H-3 at melting facility	Radiological discharges possible during treatment Activity concentration in secondary waste	Risk in transport to and from melting facility EURATOM might need inclusion due to concentration of nuclear material such as uranium and thorium	Transport necessary → might be problematic with public acceptance Smaller interim storage due to waste minimization Reuse/recycle (might not be perceived positively by public)	Outsourcing leads to no construction costs Costs for transportation need consideration Without outsourcing high costs → only for large volumes	Homogeneous activity distribution → WAC are easier to prove since higher accuracy of characterisation Robust metallic matrix → WAC Shared option Reuse/recycle may be possible

Predisposal options of metal scrap	**Environment**	**Risk/hazard reduction**	**Health & safety**	**Security**	**Socio-economic impacts**	**Lifetime costs**	**Enabling the mission**
High-pressure compaction (super-compaction)	No discharges except for possible liquid discharge and dust production (unlikely)	Reduction of dispersion risk, long term corrosion of drums and leakage – can be avoided with inliner in drums	Radiological exposure of personnel during handling (e.g., for characterization)	Improved security due to increased weight per volume	Volume reduction leads to lower storage space The low compaction factor can have an impact on public as the effort is high compared to the results	Technology & maintenance of super-compaction expensive, but less costs for storage and disposal (less volume)	If shared solutions are used, costs will be lower Compacted metals generally meet the WAC
Solidification in specific matrices (e.g., geopolymers)	No radiological discharges	Reduction of dose rate, Reduction of potential dispersion prevents chemical reactions and radiolysis	Heavier, therefore mechanical accidents more severe (PSE) non-radiological dust inhalation cannot be excluded External as well as internal dose cannot be excluded (unlikely but cannot be excluded. PSE required)	More difficult to transport since heavier and larger	Enlarged volume and weight (for storage and disposal) Carbon footprint of geopolymer production Construction of facility may have impact on spatial development plans of the area	Low-cost facility, higher cost matrices (compared to cement) High costs of interim storage (volume) in comparison to melting or compaction.	Possible non-compliance with future WAC due to non-compaction research is ongoing (not much known about long term behaviour)
Solidification in magnesium brucite based cement (e.g., for aluminium)	No radiological discharges GHG emissions during cement production Matrix limits production of hydrogen over time	Reduction of dose rate Reduction of potential dispersion prevents chemical reactions	Heavier, therefore mechanical accidents more severe (PSE) Non-radiological dust inhalation cannot be excluded External as well as internal dose cannot be excluded (unlikely but cannot be excluded), PSE required	More difficult to transport since heavier and larger	Enlarged volume and weight (for storage and disposal) Carbon footprint of cement production Construction of facility may have impact on spatial development plans of the area	Low-cost facility High costs of interim storage (volume) High costs of disposal (if priced by weight, volume)	Possible non-compliance with future WAC due to non-compaction Easy to implement, applicable also for small amounts if WAC are in place

Disposal options for scrap metals	**Environment**	**Risk/hazard reduction**	**Health & Safety**	**Security**	**Socio-economic impacts**	**Lifetime costs**	**Enabling the mission**
Near surface disposal (NSDF, cavern & bunker, tunnels & galleries, silo)	Affects environment during construction phase Hydrological impact Lead leakage possible (for lead containing metals)	Hydrogen production → explosion risk through radiolysis / Al-crystal water reactions	During construction phase: dust etc impact on neighbours/public	Higher intrinsic security than for on surface interim storage Disposal facilities as threat objects during war, revolution etc high risk. No quick closure possible.	Lower visual impact on neighbourhood compared to long term interim storage, noise impact Higher psychological effect due to “disposal” instead of “storage”	Higher cost for design and contraction compared to long term storage Higher cost during operational period After closure, only surveillance and inspection costs (for defined time period)	Other use of caverns etc. later not possible, in case valuable materials should be found for example Not suitable for all types of waste (LL waste)
Geological disposal (new or converted mine, deep cavern, tunnel)	After closure sealed system far away from biosphere Excavation of material from mine/cavern More energy-intensive → higher CO_2 output Long term environmental assessment: heavy metals	Higher (intrinsic) safety after closure Lower hazard (might be significant for higher amounts of waste) In clay host rock problem if hydrogen is produced due to corrosion Hydrogen production → explosion risk	Transportation of metal waste to disposal site Radiological risk for workers (manipulation of different waste packages) General mining hazards/risk for workers	Disposal facilities as threat objects during war, revolution etc, higher isolation. Quick closure possible Intrinsic security higher (for operational period as well as after closure)	Longer interim storage period Big projects → many scientists, technicians and engineers needed Less conventional hazards for public than near surface facilities	Higher than near surface facility (design and construction) Operational costs are higher	All waste types can be disposed of in a geological disposal facility Higher engagement/ support of government needed Mining expertise necessary Material expertise needed Systematic approach needed Predisposal route needs to produce containers for disposal Shared solutions; distributable compensation and responsibility
Borehole disposal – only feasible for small amounts of waste	Lower geological footprint	Higher (intrinsic) safety after closure Lower hazard (might be significant for higher amounts of waste)	Short interaction time with waste Lower risk due to technology of borehole drilling (workers only on	In case of crisis quick closure possible, high degree of isolation	Lower dust/visual/noise impact on public than geological disposal	Significantly lower costs compared to geological disposal option	Not practical for large volume, maybe for specific reactive materials Suitable also for small amounts of waste

			surface level, not underground).				Almost no retrievability possible after final emplacement in borehole