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Abstract

The PRE-DISposal management of radioactive waste (PREDIS) project is the outcome of the EURATOM NFRP-2019-2020-10 RIA call "Developing predisposal activities identified in the scope of the European Joint Programme in Radioactive Waste Management" (September 2019). The project started on 1st of September 2020 and has a four-year duration. The consortium includes 47 partners from 18 Member States.

This report presents a Strategic Research Agenda (SRA) for PREDIS. The first issue of this document focussed on the consolidation of the existing published SRAs of major European and worldwide stakeholder groups (where available) and described the scientific and technical domains and sub-domains and needs of common interest in Predisposal. This earlier report fulfilled the PREDIS project milestone M2.3 Draft SRA for consultation (Month 12 of the project).

Following establishment of the baseline document, this second issue SRA document has been developed based on the needs of PREDIS and the End User Group (EUG), as identified through consultation with the project partners and wider stakeholder community. The initial work during year 2 of the project involved the project team considering the best engagement approach and the subsequent development of a survey/questionnaire to collate the needs and priorities from the stakeholder community. The engagement approach was devised by the PREDIS delivery team between December 2021 and February 2022. The aim of the survey was to develop an understanding of the stakeholder priorities for research and the drivers behind these priorities.

The survey found that there are seven key technical topics of interest, in descending order as follows:

- Characterisation
- Waste Acceptance Criteria (WAC)
- Conditioning & Packaging
- Treatment & Processing
- Inventory
- Technology Selection
- Optimisation

These seven priority topics were then discussed in more detail at a series of focus webinars, attended by the end-users, stakeholders, PREDIS partners and selected experts. The intention of the focus sessions was to elicit further information on each of the technical areas to understand the purpose behind the drivers, the specific Research and Development (R&D) activities required and the urgency of each activity. The output from these sessions was collated and forms the basis of the technical content in Section 4 of this document. The remaining technical topics have been included at a commensurate level of detail in the document, informed by the output from the user survey and input from the PREDIS partner organisations.

A key theme that emerged from the development of the SRA and engagement with the communities was the need for an **integrated waste management** approach, to enable optimisation of the whole waste

lifecycle and to facilitate **waste minimisation** and the drive to a **circular economy**. This can be aided using state-of-the-art approaches such as **Life Cycle Assessment (LCA)**. This is consistent with the United Nations sustainable development goals and European strategy.

The main findings for each of the seven key technical topics can be summarised as follows:

Sub-area	Proposed Activities
Characterisation	
Waste classification	Common system for the classification of wastes based on physico-chemical properties to support standardised management of these wastes
	Characterisation and classification of legacy wastes based on physico-chemical and radiological properties, to help determine suitable approaches for its re-treatment and re-conditioning to meet storage and disposal acceptance criteria.
Technology selection	Assuring method fitness for purpose; defining optimised threshold values; how to adapt procedures.
Isotope vector and scaling factor	Scaling methods and scaling factors in different facilities; scaling factor development also in view of heterogeneity/changing vectors as function of time/etc.; scaling factor development for decommissioning wastes, contaminated pieces, etc.
	Impact on and treatment of uncertainty/ conservatism using these approaches;
	Improving the understanding of distribution/spreading of radioisotopes in nuclear facilities to improve the knowledge on isotope vectors in waste forms
	Scaling factor development for both radioactive and non-radioactive components
	Validation of computer calculations used for isotopic vectors
In situ characterisation and segregation	Remote, integrated and automatic technologies for (in situ) waste characterisation and segregation
	Exchange and dissemination of best practices for on-line characterisation during remediation and clean-up
	Exchange and dissemination of best practices on characterisation of underground remaining structures
	In situ characterisation for inaccessible areas
Radiological characterisation challenges of (conditioned) radioactive waste (packages)	Development of new radiological and non-radiological characterisation approaches; non-destructive methods; analytical methods for specific nuclides; quick operative, reliable, robust, efficient and economic characterisation methods
	Share experience, knowledge and case studies from more advanced programmes
	Characterisation of heterogeneous (metallic) waste items or containers (also inside cemented packages)
	Solid organic waste characterisation/characterisation of historic or legacy wastes to reduce the need for sorting and segregation
	Characterisation of fissile material inside waste drums/materials (also to manage criticality risk)
	Sampling techniques (in cemented waste packages). Optimise sampling strategy using statistical methods approach and sampling representativeness. Improvement of existing sample analysis technologies.
	Characterisation of large/dense (cemented) waste packages (active and passive neutron detection, transmission and emission tomography using high energy X-rays, photofission, angular gamma scanning)
	Mobile monitoring or characterisation systems. Improvement of mobile systems and integrated technologies for containerised RW and unconventional legacy waste
	Need for more/better accuracy in radiological measuring techniques, e.g., by combining different techniques
	Characterisation for security/safeguard purposes, e.g., related to transport of nuclear materials
Non-radiological properties and inventory of radioactive waste	Improving the understanding of the non-radiological properties and inventory of radioactive waste, e.g., presence of (toxic) chemical species and/or material characterisation inside a waste package, for example by neutron activation analysis
	Non-destructive testing for/characterisation of the physico-chemical content and properties (leachability, compressive strength, internal swelling pressure)
	Improved data and understanding of organic materials and complexants (behaviour) that affect the release of radionuclides and chemical species following disposal
	Monitoring changes in waste forms/packages that happen over time
	Detection of gasses (such as hydrogen) and outgassing monitoring (using Cavity Ring-Down Spectroscopy (CRDS)); gas transport in/around waste drums/packages
Developments or improvements of characterisation technology	Coupling gamma spectrometry and tomography
	Fast, affordable and straightforward methods for difficult to measure radionuclides (DTM), including in situ alpha and beta measurements and automation
	Enhance the use of robotics including drones, submersible ROVs and sensors, allowing also the characterisation and/or sampling of difficult to access.

	Demonstration pre-condition information and final package information regarding DTM or impossible to measure (ITM) nuclides. Develop specific algorithms for the assignment of waste package inventories and fingerprints based on historic records information and/or for corroboration of package inventories based on limited measurement data.
	Efficient metal type recognition in hot-cell conditions
	Gamma camera technology
	Alpha measurement on organic liquids (oils)
	X-ray for small volumes of cemented waste content
	Graphite characterisation
	Radiation-tolerant devices
	Neutron coincidence counting with alternatives to 3He detectors (now too expensive)
	Active neutron interrogation to measure the fissile mass in high-level waste
	Automation of measurements – combine on-site measurements with external analysis
Digitalisation and data management	Characterisation data handling and (measurement) uncertainty management (e.g., through Bayesian approaches)
	Improved interpretation of characterisation results using artificial intelligence (AI) or machine learning (e.g., for attenuation correction) methods or geostatistical methodology techniques
	Evaluate the regulatory implications of using advanced technologies including robotics, automated site mapping and digital twin technology. Alignment and harmonisation based on European Union (EU) standards for an efficient benchmarking of best available techniques being used in similar conditions
	Characterisation for clearance/release of materials
Release/clearance methodology	Automated characterisation technologies for structures and land areas for final status surveys and release (clearance of surfaces and structures). Indoor positioning system development and demonstration. Subsurface radionuclide contamination detection.
	Identify opportunities to improve the exchange of experiences and identification of Member States' regulatory differences regarding clearance criteria. Advantages and disadvantages for harmonised regulations.
	Sharing of experiences with respect to clearance of difficult to measure items (such as fire water hoses in controlled areas)
Competence development	Implementation of educational and training programmes to ensure sufficient and skilled staff are available for the sector with focus on the use of new technologies
	(Improve access to) Facilities and infrastructures equipped to measure large items
Quality control	Appropriate reference materials (standards) and inter-comparison exercises/benchmarking to support expanding programmes in characterisation
Waste Acceptance Criteria (WAC)	
Good practice in development of WAC	Harmonisation – benchmarking exercise
	Reducing conservatisms
	Non-rad, hazardous and chemotoxic – good practice
WAC for specific waste types	How to meet WAC and/or safety case requirements for more innovative waste forms (e.g. geopolymers) – guidance
Demonstrating compliance with WAC	Study to develop decision process for dealing with non-compliant wastes
Data and understanding of long-term behaviour under disposal conditions	Research to understand the evolution and chemistry of wasteforms in specific disposal environments and hence how this informs WAC requirements.
Conditioning & Packaging	
Optimisation of existing conditioning solutions (linked to WAC and disposal capacity)	Optimise conditioning material properties. Waste loading, mechanical resistance, compatibility with the environment, long-term behaviour.
	Increase waste loadings, mixing wastes
	Exchange & harmonisation of best practices, interactions Waste Management Organisations/waste generators
New conditioning solutions for strategic waste addressing safety, technical and economic aspects	Development of innovative emerging solutions
	Use of recycled/innovative materials
Long term behaviour and performance of existing and new conditioning matrices	Durability demonstration under irradiation conditions (gamma and alpha)
	Control hydrogen generation and release
	Impact of heavy metals on conditioning practices
	Matrix performance (compressive strength, chemical reactions causing swelling or cracking, corrosion, etc.)
	For all of above – simulation models
Containers	Use of reusable/recyclable/new types of materials
	Long term durability behaviour for safety
	Non-destructive control techniques for efficiency of performance evaluation
	Simulation models to support understanding of stability/performance over long term.
Broken packages	Develop approaches for package remediation, including raw waste that has been in long-term storage. Such research may involve development of techniques for package repair or reinstatement (e.g., package over-packing, application of repair grouts and/or the application of surface coatings).
	Guidance to improve management of damaged and/or broken packages

Secondary waste	Develop approaches to optimise processes that reduce or remove generation of secondary wastes, promoting waste hierarchy.
Treatment & Processing	
Flexible decontamination and treatment processes (including modular and mobile systems)	Treatment solutions for different quantities, dimensions, characteristics, waste routes and regulatory requirements
	Benchmarking for decontamination technologies and approaches (good efficiency and minimised secondary waste production)
	Promote international sharing of facilities
Management of problematic waste	Graphite mixed waste
	Organic materials: Research activities related to alternative thermal treatment technologies. Develop alternative solutions for ^{14}C
	Reactive metallic waste, including dust (hydrogen in disposal environment)
	Liquid waste with specific contaminants
	Hazardous and toxic materials (e.g. asbestos and Polychlorinated Biphenyls (PCBs))
Recycling and reuse	Benchmarking of technologies
	Regulatory requirements for release
	Societal engagement for recycling
	Harmonise good practices in recycling of released materials
New and emerging solutions	High efficiency and reduction of secondary waste
	Industrialisation of lab scale solutions
	Information Technology (IT) tools and other emerging technologies to manage waste flows from production to disposal
	Solutions for new fuel types and advanced reactors/fuel cycles
Inventory	
Non-radiological, hazardous and chemotoxic materials	Guidance on good practice in inventory development for these materials
Legacy and problematic waste inventories	Knowledge management regarding existing data and case studies of best practices
Future wastes and inventories (new fuels and advanced fuel cycles)	Guidance on defining future wastes and inventories associated with new reactors/fuel cycles to inform development of a waste management plan
Assessment, recording and management of inventory data	Accuracy, conservatisms, assumptions
Technology Selection	
Selection of technologies for (existing or future) waste streams where no WAC are present at the moment (no industrially mature waste disposal route available) Optimal technology for existing and planned waste streams.	Definition of WAC criteria (link to WAC topic area)
	Review of technologies / develop case studies
Comparison of technologies at different levels of maturity including cost-benefit ratio and availability with focus on NDT	Analysis of technologies in a new R&D project
	Selection of most suitable technology
	Link to case studies activity above
Supporting innovation and reducing environmental impact of radioactive waste management	Establish network of experts with focus on environmental issues
	Consider environmental impact (LCA implementation)
	Consider societal impact and support development of accessible communication materials
Digitalisation and data management	Develop best practices and guidelines on the implementation of digital technologies to improve key tasks in the decommissioning
	Evaluate the regulatory implications of using advanced technologies including robotics, automated site mapping and digital twin technology.
	Benchmarking to EU standards of best available techniques being used in similar conditions
Optimisation	
Design	Optimisation of waste characterisation & conditioning considerations versus repository design/sizing
	Implementing new technologies with respect to existing techniques, infrastructure, etc.
	Cost-benefit analyses, providing sound methods/tools for decision making
	Learning from previous implementation efforts, knowledge transfer from more advanced programmes to earlier stage programmes
Performance	Heuristic evaluations over full life cycles to find global optimums for the entirety of predisposal radioactive waste management
	evaluations, i.e., LCA & Life Cycle Design (LCD), new geoscience models, process models, numerical simulation, digital twins.

A further phase of the SRA document will be developed, with the final PREDIS SRA (planned for spring 2024) taking into account the findings of PREDIS technical achievements (in ongoing work packages, WP4 to WP7).

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Glossary of Terms

Terms

AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Management
CRDS	Cavity Ring-Down Spectroscopy
CT	Computed Tomography
D&D	Development & Demonstration
DA	Destructive Analysis
DQA	Data Quality Assurance
DQO	Data Quality Objectives
DR	Digital Radiography
DTM	Difficult-To-Measure (radionuclides)
ERDO	Association for Multinational Radioactive Waste Solutions
ETM	Easy-To-Measure (radionuclides)
EU	European Union
EUG	End User Group
EURADSCIENCE	A Network of Research Organisations for Radioactive Waste Management Science within Europe
HIP	Hot Isostatic Press
HLW	High Level Waste
IAEA	International Atomic Energy Agency
IAEA IDN	IAEA International Decommissioning Network
IGD-TP	Implementing Geological Disposal of radioactive waste Technology Platform
ILW	Intermediate Level Waste
IMF	Inert Matrix Fuel
ISDC	International Skills Development Council
IT	Information Technology
ITM	Impossible-To-Measure (radionuclides)
KM	Knowledge Management
LCA	Life Cycle Assessment
LCC	Life Cycle Costing

LCD	Life Cycle Design
MR	Mixed Reality
NDA	Non-Destructive Analysis
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Techniques
NEA	Nuclear Energy Agency
NEA RWMC	NEA Radioactive Waste Management Committee
NEA CDLM	NEA Committee on Decommissioning of Nuclear Installations and Legacy Management
NUGENIA	Nuclear Generation II & III Alliance
PAN	Polyacrylonitrile
PCB	Polychlorinated Biphenyls
PPE	Personal Protective Equipment
QC	Quality Control
QMS	Quality Management System
R&D	Research and Development
RCMS	Radiological Characterisation & Monitoring System
RD&D	Research, Development and Demonstration
RE	Research Entity
RFID	Radio Frequency IDentification
ROV	Remotely-Operated Vehicle
SITEX	Sustainable Network for Independent Technical Expertise on Radioactive Waste Management
SNETP	Sustainable Nuclear Energy Technology Platform
SRA	Strategic Research Agenda
SS	Strategic Study
TRL	Technology Readiness Level
TSO	Technical Support Organisation
VR	Virtual Reality
WAC	Waste Acceptance Criteria
WMO	Waste Management Organisation
WP	Work Package

International or European Commission (EC) Project / Task Name Acronyms

CARBOWASTE	Treatment and Disposal of Irradiated Graphite and Other Carbonaceous Waste (EC Project, 2008-2013)
CHANCE	Characterization of conditioned nuclear waste for its safe disposal in Europe (EC Project 2017-2022)
EMOS	Development of a Mobile and Automated Optical System for the Inspection of Radioactive Waste Drums
EURAD	The European Joint Programme on Radioactive Waste Management (EURAD). Also referred to as the 'Joint Programme'.
HARPERS	Harmonised Practices, Regulations and Standards in Waste Management, and Decommissioning (EC Project, 2022-2025)
INSIDER	Development and validation of an improved integrated characterisation methodology based on new statistical processing and modelling
JOPRAD	Towards a Joint Programming on Radioactive Waste Disposal (EC Project 2015-2019)
MICADO	Model uncertainty for the mechanism of dissolution of spent fuel in a nuclear waste repository (EC Project, 2006-2009)
PREDIS	Predisposal management of Radioactive Waste (EC Project, 2020-2024)
ROUTES	Waste Management Routes in Europe from Cradle to Grave (Work Package of EURAD-1)
THERAMIN	Thermal treatment for radioactive waste minimization and hazard reduction (EC project, 2017-2020)

1 Introduction

This report presents a Strategic Research Agenda (SRA) for the predisposal management of radioactive waste, developed for the European Union (EU) project "PRE-DISposal management of radioactive waste" (PREDIS). The first issue of this document in August 2021 focussed on the consolidation of the existing published SRAs of major European and worldwide stakeholder groups (where available) and described the scientific and technical domains and sub-domains and needs of common interest in predisposal. This earlier report fulfilled the PREDIS project milestone M2.3 Draft SRA for consultation (August 2021, Month 12 of the project).

This second issue SRA document has been developed based on the needs of PREDIS and the End User Group (EUG), as identified through consultation with the project partners and wider stakeholder community.

A further phase of the SRA document will be developed, with the final PREDIS SRA (planned for spring 2024) taking into account the findings of PREDIS technical achievements (in ongoing work packages (WP), WP4 to WP7).

2 Background

The PREDIS project is the outcome of the EURATOM NFRP-2019-2020-10 RIA call "Developing predisposal activities identified in the scope of the European Joint Programme in Radioactive Waste Management" (September 2019). The project started on the 1st of September 2020 and has a four-year duration. The consortium includes 47 partners from 18 Member States.

Figure 1 shows the PREDIS project in the context of two other major European Projects, namely SHARE[1] , which addressed issues of decommissioning nuclear facilities, and EURAD[2], which addresses radioactive waste management and disposal issues. It should be noted that both SHARE and EURAD touch on predisposal waste management topics and indeed collaboration with these projects is a key element of the PREDIS programme.

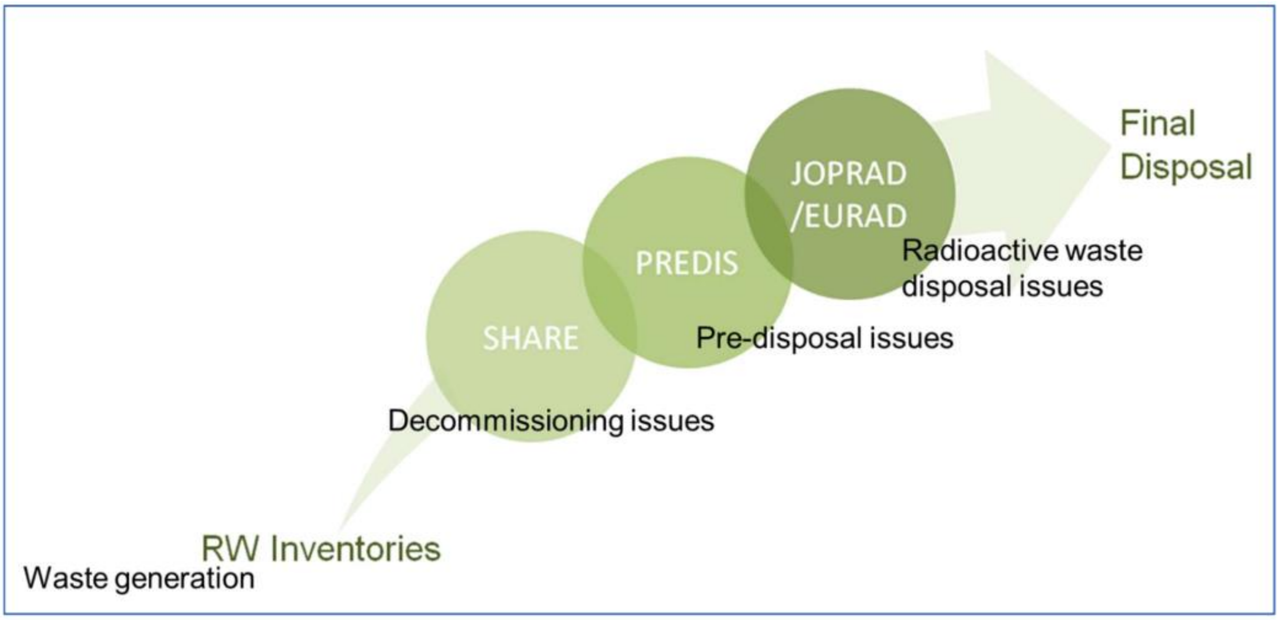

Figure 1 – PREDIS project interfaces with upstream and downstream domains

[1] SHARE: StakeHolders-based Analysis of Research for Decommissioning (EC Project 2019-2022) https://share-h2020.eu (See Appendix 3)
[2] EURAD: European Joint Programme on Radioactive Waste Management (EC Project 2019-2024) https://www.ejp-eurad.eu (See Appendix 3)

The PREDIS project develops and increases the Technology Readiness Level (TRL) of treatment and conditioning methodologies for (low and intermediate level) wastes for which no adequate or industrially mature solutions are currently available, including metallic materials, liquid organic waste and solid organic waste. The PREDIS project also develops innovations in cemented waste handling and predisposal storage by testing and evaluation. The technical Work Packages align with priorities formulated within the Roadmap Theme 2 of EURAD and with those identified by the project's industrial EUG. PREDIS will produce tools guiding decision-making on the added value of the developed technologies and their impact on the design, safety and economics of waste management and disposal.

It is noted that the alignment of the PREDIS SRA with the needs of EURAD and, particularly, the EURAD SRA, means that the PREDIS SRA has not necessarily been restricted to the scope of the PREDIS project. The EURAD SRA also covers some predisposal issues relating to spent fuel and High Level Waste (HLW), and technical areas over and above PREDIS's technical scope WPs (WP 4–7).

To deliver these aims the PREDIS project has 7 WPs, as illustrated in Figure 2. The technical WPs (WP4–7) focus on developing solutions (methods, processes, technologies and demonstrators) for future treatment and conditioning of waste across a number of Member States, making significant advances in TRL during the course of the PREDIS project. The WPs address issues associated with metallic (WP4), organic liquids (WP5), organic solids (WP6) and cemented wastes (WP7). These subjects were identified during the proposal phase as described in the PREDIS Gap Analysis report, Deliverable 2.2 [1].

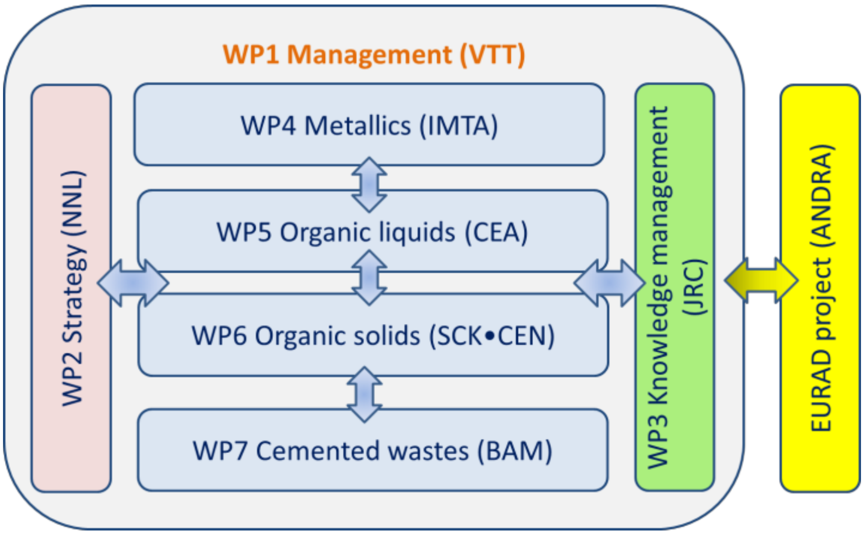

Figure 2 – PREDIS Project Work Packages (WP lead organisation in brackets)

Work Package 2, (Strategy), aims to enhance the strategic implementation of the PREDIS project and focus future predisposal collaborative programmes through extensive engagement of stakeholders across Member States and international bodies.

Within WP2, **Task 2.2 of PREDIS is the development of an SRA specific to the needs of predisposal activities**. The intention is to build on available existing research agendas developed by European and worldwide nuclear waste management organisations, forums and governing bodies, engaging and discussing with the wider PREDIS project and user community, to identify topics and themes pertinent to the predisposal management of radioactive waste.

This work will lead to the publication of the PREDIS SRA in April 2024 (Month 44 of the project).

3 Development of the PREDIS SRA – The Plan

The development of the SRA comprises of 3 phases (Figure 3), which are detailed below by PREDIS project year.

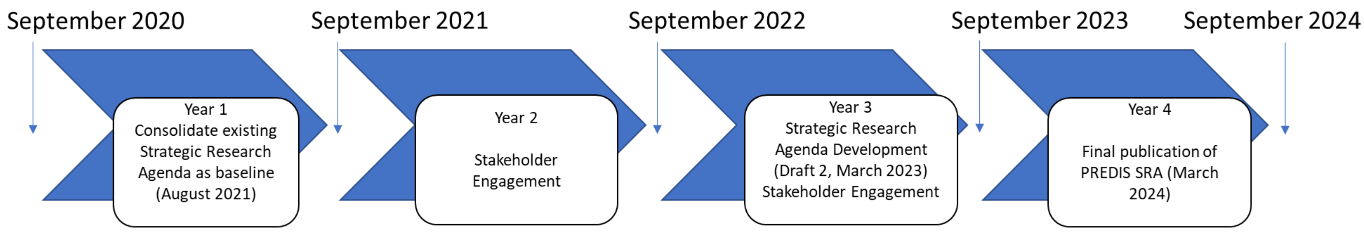

Figure 3 – Schedule for the development of the PREDIS Strategic Research Agenda (PREDIS Task 2.2)

Year 1 - focused on the consolidation of existing SRAs.

- Many stakeholder groups had already declared their interest in the predisposal waste management subject either because they are directly involved, or are operating at the interfaces; consequently, many of these groups have already published documents (in many cases SRAs) which consider predisposal activities (e.g. Nugenia[3], EURAD etc). Some initial work was undertaken in 2019, when originally preparing the PREDIS project proposal, to review existing SRAs to consider what has already been flagged as important needs. This assisted in developing a focused list of topics and SRA documents for review.

- Key themes from these published documents were consolidated into the baseline for the subsequent development of the PREDIS SRA.

Years 2 and 3 – focused on the development of the PREDIS SRA through stakeholder engagement

- PREDIS aimed to produce an informative long term, future focussed SRA based on a holistic lifecycle philosophy, of both relevance and use to the Commission and different stakeholders. The PREDIS SRA should complement the updated EURAD SRA 2023 and, ideally, contain the same structure and types of information.
- Engagement with the relevant stakeholder communities is key to achieving this aim and build a comprehensive Predisposal SRA.
- It should be noted that there are many stakeholders and interfaces involved in Predisposal, as illustrated in Figure 4. Key interfaces are with
  - the legacy waste owners, nuclear operators, and decommissioners, who are the inputs to the predisposal waste management operations,
  - waste treatment and waste management organisations, who treat the waste (predisposal) and develop new treatment and/or processing technologies, also implementing the waste management hierarchy,
  - waste management organisations (WMOs) who store and ultimately dispose the waste.
- Mixed methods have been used to facilitate this engagement, including for example stakeholder workshops, on-line surveys, in session quick polls, facilitated discussion groups, one-to-one stakeholder interviews, engagement with other relevant projects (e.g. SHARE, EURAD) and relevant stakeholder organisations (e.g. Sustainable Nuclear Energy Technology Platform (SNETP), International Atomic Energy Agency (IAEA), Nuclear Energy Agency (NEA) etc).
- Inclusion of the output from the PREDIS Gap Analysis Task 2.6 Deliverable D2.2 [1] and the relevant predisposal elements of the SHARE SRA [2] and roadmap [3].
- This document is the second iteration of the PREDIS SRA.

Year 4 – focuses on peer reviewing, finalising and publishing the PREDIS SRA

- Incorporation of findings from the PREDIS project technical WP results (WP4–WP7).
- Horizon scanning to identify emerging technologies.
- External peer review of the SRA document will be undertaken.
- Final version of the SRA will be published, (April 2024, PREDIS project Month 44)
- Dissemination activities implemented (e.g. journal publication, conference presentation.

[3] Nugenia: The Nuclear Generation II & III Alliance. https://snetp.eu/nugenia

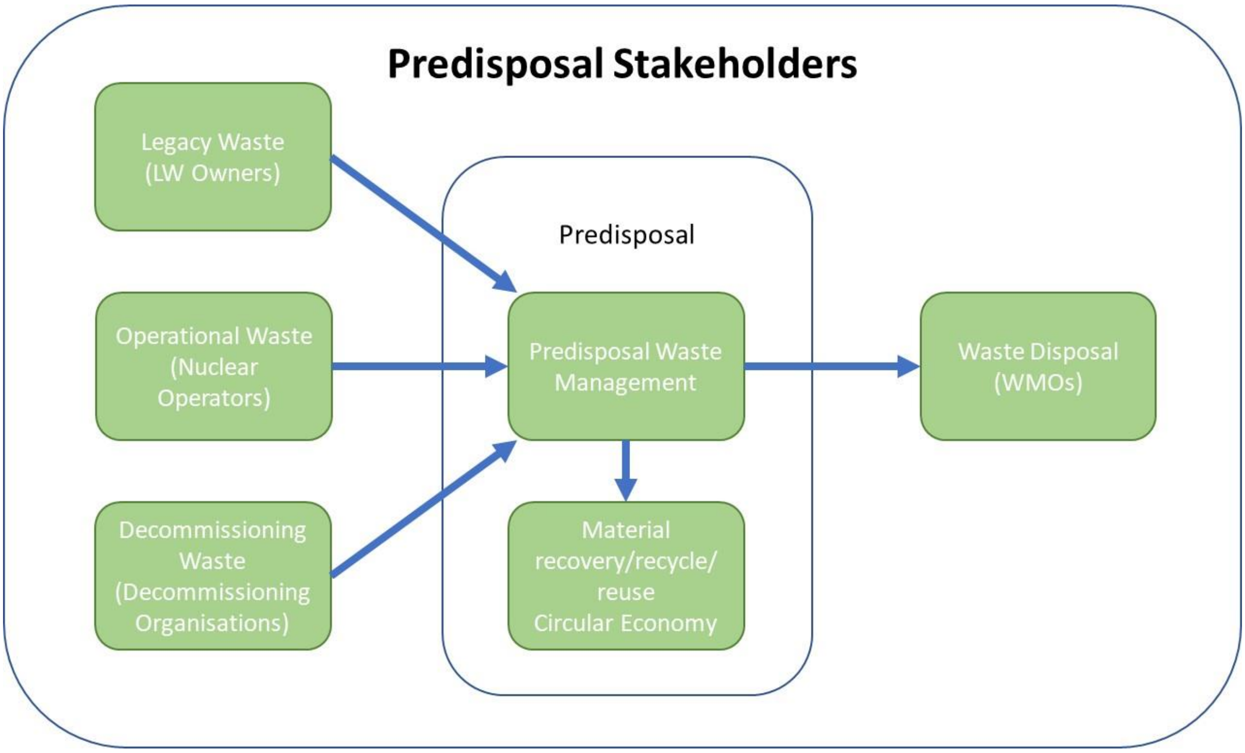

Figure 4 – Predisposal Stakeholder and 'waste management interfaces

The methodologies for development of both the baseline SRA document (2021) and this 2023 SRA edition are detailed in Appendix 1.

4 PREDIS Strategic Research Agenda

This SRA spans a wide range of predisposal activities from waste generation through to preparing waste packages suitable for final disposal The PREDIS SRA fits into the EURAD Roadmap [4], which covers the holistic radioactive waste management programme, as Theme 2 (Predisposal). The PREDIS SRA and the EURAD Roadmap Theme 2 are structured according to three predisposal thematic areas, which are based on the IAEA classification of predisposal waste management programme activities [5]. The three thematic areas and corresponding sections of this SRA are:

- Planning (Section 4.1) – inventory, waste acceptance criteria, technology selection, cost-estimating & funding, waste hierarchy.
- Implementation (Section 4.2) – characterisation, treatment & processing, conditioning and packaging, storage, transport, deployment options.
- Operations (Section 4.3) – quality & management systems, commissioning, optimisation, secondary waste management.

4.1 Planning

This initial Planning section of the SRA covers:

- Inventory (Section 4.1.1).
- Waste acceptance criteria (Section 4.1.2).
- Technology selection (Section 4.1.3).
- Cost estimating & funding (Section 4.1.4).
- Waste hierarchy (Section 4.1.5).

It covers areas relating to the planning phases of predisposal management to support hazard reduction, reduce volumes for storage and disposal, and help reduce costs.

4.1.1 Inventory

Evaluating the sources and quantities of waste generated and in existing storage (waste material types, radioactivity, volume, location) accounting for anticipated future waste generation and evolution.

4.1.1.1 Introduction

For states and organisations responsible for the management of radioactive wastes and residues to demonstrate they have control of their waste stocks and arisings, it is necessary in the first instance to demonstrate that there is an appropriate level of knowledge of the inventory. This knowledge includes: waste volumes and how these will change over time; the locations of waste stocks; radioisotope fingerprints and activity levels and the physicochemical properties of the waste.

This necessitates the generation of large high-quality datasets and therefore an additional consideration is the appropriate management of these data, including methods of collection, storage and assessment. Effective data are required to support and inform decision-making at every stage of the waste management lifecycle, and as such there are clear links between the topic of inventory and several other key topics covered in this SRA, including Characterisation, Waste Acceptance Criteria, Waste Hierarchy, Treatment & Processing and Conditioning & Packaging.

Following the collection and analysis of information from the PREDIS SRA survey and other engagement activities, specific sub-areas were identified as being most important for future improvements through Research and Development (R&D), Strategic Studies (StSt) and Knowledge Management (KM) activities. The main gaps and issues and the associated activities are summarised below according to sub-area.

4.1.1.2 Non-radiological, hazardous and chemotoxic materials

There is a recognition that large amounts of waste produced from nuclear processes are non-radioactive, but amongst these there are also chemically-aggressive and thermotoxic wastes to consider, and it needs to be demonstrated that these wastes can meet the needs of differing regulations for both radiological and non-radiological aspects of materials. Linked to characterisation, there is a need to understand and record the amounts of specific non-radiological materials of interest – e.g. cellulose, nitrate, concrete, etc.

This theme was also highlighted within the JOPRAD[4] project [6] and by IGD-TP[5] [7] with areas including:

- Understanding the quantities and nature of the chemotoxic components of common decommissioning wastes (low and intermediate level wastes) and their implications for disposability [6].
- Improving data and characterisation methods for chemical species in long-lived intermediate level waste (ILW) [6], [7].
- Understanding the effects of organic materials and species in the wastes and their impact, including complexing agents from degradation of cellulose and PAN (polyacrylonitrile) [7].
- Developing a common, systematic approach to characterising and classifying waste based on physico-chemical properties [7].

4.1.1.3 Legacy/problematic wastes

There is a need to understand the form of legacy wastes and associated radioactivity, whether liquids are present, any materials to promote corrosion, gas generation etc. in order to develop and validate processes for downstream treatment, conditioning, packaging and disposal of such wastes. Particular wastes highlighted in existing SRAs include graphite wastes, mixed wastes, organic wastes, tritiated wastes [8], and small inventories of fuel from research reactors [7].

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[4] JOPRAD: Towards a Joint Programming on Radioactive Waste Disposal (EC Project 2015-2017) http://www.joprad.eu (See Appendix 3)
[5] Implementing Geological Disposal of radioactive waste Technology Platform (IGD-TP) (https://igdtp.eu)

There is a significant amount of work that has already been undertaken in this area and as such the remaining gap is primarily that of KM and the sharing of best practice.

4.1.1.4 Future wastes

For research into new fuel types, there is a tendency to concentrate on the fuels themselves but other wastes arising from its use and management are often overlooked; e.g. new coolants that are activated, impact on filter efficiency, etc. There is a need to convey this to nuclear engineers so that they take into account waste produced during operation and maintenance.

There is a need to understand the inventory and decommissioning wastes from Advanced reactors and future Small Modular Reactors (SMRs), due to the different characteristics of the fuels and wastes compared with those from current reactors, to inform strategies for treatment and disposal of their waste streams. Reactors will not be licensed unless wastes and their management are understood and a strategy is in place.

Methodologies as well as relevant good practices are needed to be implemented across Member States, to allow designers and operators to give consideration to what waste is being produced from these new technologies, in early phases before R&D and further investigation commence.

Particular areas highlighted in existing SRAs include:

- Understanding inert matrix fuels (IMF) and dispersion fuels, in terms of their properties, stability as a wasteform and suitability for disposal [9].
- Minor actinide (Np, Am, Cm) bearing fuels for use in Light Water Reactors and Gen IV fast reactors [9], where a particular issue is the quantity of helium generated that may be problematic for long term storage and disposal.

4.1.1.5 Assessment, recording and management of data

There is a need to understand the sensitivity of safety case calculations to uncertainty in inventory data and hence determine the effort required in gathering and recording inventory data. The levels of precision required will be dependent on the data needed, and subsequently this should inform the methods of data collection (links to characterisation) and storage such that effort to reduce uncertainty is placed where it is warranted.

Identifying good practice in the assessment, recording and management of inventory data has been raised in several existing SRAs [10], [7], [6], [11]. This includes use of targeted, fit-for-purpose assay [6], use of radionuclide vectors, characterising waste forms, addressing uncertainties in radionuclide properties databases [11], remote and in situ technologies [8], measurement and modelling [7].

4.1.1.6 Activities of common interest

The activities of common interest within the Inventory topic are summarised in the following table. For each sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

Table 1 – Activities of common interest in Inventory

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
Non-radiological, hazardous and chemotoxic materials	Guidance on good practice in inventory development for these materials	StSt, KM	Meet regulations for non-rad/hazardous materials Knowledge of any effects on radionuclide/waste form/container/repository behaviour	Short term – need to know now, in order to make decisions on how to deal with the wastes
Legacy and problematic waste inventories	Knowledge management regarding existing studies	KM	Understanding wastes that are not currently well characterised and are without identified waste routes	Short term

Future wastes and inventories (new fuels and advanced fuel cycles)	Guidance on defining future wastes and inventories associated with new reactors/fuel cycles to inform development of a waste management plan.	StSt	Take full account of all wastes produced (and therefore to be dealt with) Understanding future wastes for disposal (implications for facilities)	Short term
Assessment, recording and management of inventory data	Accuracy, conservatisms, assumptions	KM	Reduction in uncertainty, removal of excessive conservatism that affects treatment/routing decisions Acquire right data to allow use of waste routes	Short term

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.1.1.7 Summary of past and ongoing EU activities/projects in this topic area

A large body of work has been completed historically. Most recently, focus has been on benchmarking and best practice, with the following two projects highlighted:

- EURAD – The EURAD ROUTES WP has been evaluating needs as well as best practices for addressing efficient waste management of 'challenging' wastes [12] (i.e. legacy and problematic wastes).
- EC Directorate-General for Energy (DG-ENER) – Published and presented a report on 'Benchmarking analysis of member states approaches to definition of national inventories radioactive waste and spent fuel' [13].

4.1.2 Waste Acceptance Criteria (WAC)

Identifying the parameters and metrics (radiological, mechanical, physical, chemical and biological characteristics) for waste acceptance criteria through the whole life cycle, accounting for national policy and regulations. Includes understanding the suitability and safety of a waste form/package for storage and disposal and its behaviour within these environments, to determine the implications for treatment, conditioning and packaging designs prior to disposal.

4.1.2.1 Introduction

Final disposal or interim storage of radioactive wastes imply in advance developing and implementing actions that allow their acceptance in the planned repository. WAC are therefore required for the establishment of procedures of waste production that fulfil the acceptance process.

WAC has always been a matter of discussion among countries and entities, which have been trying to harmonise or standardise their use, but up to now it has been difficult to carry out this kind of harmonisation. There are some main features/actors that make this process difficult, like variations in national policy or regulatory guidance, different types of disposal/storage, waste classification, or stakeholder requirements, that could change the final WAC to apply significantly and therefore move the process away from its standardisation.

It is necessary to develop a good understanding of the overall WAC implications to better facilitate their development from a solid basis. The aim is not to try and provide WAC themselves but to produce the capability for building a Waste Acceptance System from which WAC is a logical consequence.

The need for development of WAC issues in the future is mainly related to:

- More realistic scenarios, avoid conservativeness.

- Chemicals to be considered and their influence on short and long term timescales.
- Impact due to non-radiological aspects, e.g. chemo-toxics, how to build similar scenarios to the radiological ones that quantify the health risk.
- New aspects that could significatively influence the disposal evolution.

4.1.2.2 Activities of common interest

The activities of common interest within the WAC topic are summarised in the following table. For each sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

Table 2 – Activities of common interest in WAC

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency
Good practice in development of WAC	Harmonisation – benchmarking exercise	StSt	Guidance provided to support organisations, particularly those with less developed programmes.	Short term
	Reducing conservatisms	StSt/KM		
	Non-rad, hazardous and chemotoxic – good practice	StSt/KM	Good practice guidance for organisations	
WAC for specific waste types	How to meet WAC and/or safety case requirements for more innovative waste forms (e.g. geopolymers)	StSt	Enable new waste forms to be developed and disposed Enable new waste routes for certain waste types (e.g. liquid organics) Accelerate regulatory acceptance Accelerate hazard reduction	Short term
Demonstrating compliance with WAC	Study to develop decision process for dealing with non-compliant wastes Case studies on how to deal with this issue of non-compliant wastes	StSt KM	Increasing waste owner confidence in waste routes	Short term
Data and understanding of long-term behaviour of wasteforms under disposal conditions	Research to understand the evolution and chemistry of (new/novel) wasteforms in specific disposal environments and hence how this informs WAC requirements.	RD&D	Reduction of uncertainty and conservatisms in developing WAC Understanding differences relating to disposal system/environment	Short/Medium term

4.1.2.3 Summary of past and ongoing EU activities/projects in this topic area

The following previous activities and proposals for future activity are highlighted:

- EURAD [14] – WAC has been considered within the ROUTES WP, including current use of WAC, sharing experience on waste management with or without WAC, and identifying R&D needs and opportunities.

- JOPRAD - Recommended the development of good practice guides for the derivation of WAC, accounting for waste characteristics and uncertainties, the disposal concept, and local site conditions [6].
- THERAMIN[6] - Developed a generic approach for the production of WAC for thermally-treated products to ensure that characterisation requirements are identified. A recommendation from THERAMIN was to enable development of context-specific rather than generic disposability criteria, accounting for specific disposal concepts and disposal environments [15].

4.1.3 Technology Selection

Assessing the potential technologies suitable for each category of waste, for the implementation phase, considering the cost-benefit ratio and availability of concepts and technologies.

4.1.3.1 Introduction

Technology selection is a complex process that involves assessing the technical feasibility, economic viability, regulatory compliance and societal acceptability of current and future available technologies.

Given that many predisposal facilities are in operation across Europe, and the maturity of existing technology routes is typically high, RD&D for predisposal is primarily on items that will lead to a major technology change and/or step changes in technical readiness level (TRL). Considering the multi-generational character of some of these sites (e.g., extended long term interim storage of spent fuels and other long-lived radioactive waste), joint needs for KM continue to be important in some areas. Several areas are key, including continuing to improve understanding of problematic wastes and novel solutions for small inventories (i.e., research reactor fuels), particularly mobile treatment facilities and new approaches for waste characterisation, treatment and processing, including options for handling mixed wastes and implementing more environmentally friendly materials.

The following subsections focus on the specific issues raised and highlighted through the stakeholder and end-user engagement process.

4.1.3.2 Selection of technologies for (existing or future) waste streams where no WAC are present at the moment (no industrially mature waste disposal route available)

Small waste streams are often outside the scope of accepted treatment procedures. They might have a previously unknown or uncommon composition and it is difficult to find guidance about the treatment. There might be reports describing treatment options, but there may be difficulties in finding or accessing such documentation. KM is the key factor here to overcome these difficulties. In the UK there is an initiative to develop a toolkit for problematic waste across a larger range of wastes. However, this activity needs to be continued over a longer time and it is important to include any knowledge that has been gained anywhere and which might be important. In this context it would be very helpful to carry out case studies and systematically compile all information that comes together during the process.

Case studies are generally considered a very good way to test new technologies for their effectiveness. By applying them, one learns which difficulties were not considered beforehand (lack of knowledge, unexpected difficulties, unsatisfactory technology). If this is evaluated comprehensively and competently, valuable conclusions can be drawn to improve the technologies. Another very important aspect, however, is the acceptance of new methods, if it can be proven beyond doubt in the experiment or study that they fulfil their purpose and that a clear added value (cost, safety, information gain) is achieved.

It is important that each case study is subjected to a comprehensive evaluation. As many aspects as possible should be considered here, i.e., costs, environmental impact and expected acceptance in addition to feasibility.

[6] THERAMIN: Thermal treatment for radioactive waste minimization and hazard reduction (EC Project 2017–2020) http://www.theramin-h2020.eu (See Appendix 3)

4.1.3.3 Comparison of technologies at different levels of maturity including cost-benefit ratio and availability

The cost/benefit ratio of new technologies is difficult to assess, and it is often unclear in the beginning how costs might scale up if the technology is brought into a larger scale, after it has been developed in a smaller research environment.

To establish new technologies, it is usually necessary to overcome a certain inertia among end users, as the hurdles are quite high. It is therefore necessary to highlight the benefits of new technologies. Firstly, however, it is necessary to prioritise the problems to be solved before then launching appropriate research activities.

In terms of future research projects, this means identifying and prioritising the most urgent problems. Then there should be a series of new, specific RD&D projects in which these solutions can be transferred into established technologies. Finally, there should be a link to appropriate case studies to demonstrate the effectiveness of the technologies to the relevant communities. Only in this way can the necessary persuasion be achieved.

4.1.3.4 Supporting innovation and reducing environmental impact of radioactive waste management

Environmental and societal impacts are nowadays crucial topics that have a great influence on the whole theme of treatment and storing of nuclear waste. Whilst recognising that there are several other factors to consider besides environmental impact, it is noted that this is a particularly fast emerging space and there is a huge diversity of approaches and models used across nuclear and other industries.

If new technologies are developed, the environmental impact of the process must be considered from the outset. Should this be negative, it may be assumed that the technology will not be accepted, especially by the public. This is then a political-social aspect that is very difficult to assess.

Life Cycle Assessments (LCA) (see section 4.1.5.2) should accompany the technology development and selection process from the outset and should consider both environmental and socio-political aspects. To this end, a network of experts should be formed to evaluate precisely these two aspects. At the same time, however, communication must also be improved and adapted. It is necessary to establish comprehensible communication and to provide suitable material for this purpose.

4.1.3.5 Digitalisation and data management

Rapidly-emerging technologies that are anticipated to improve and optimise the development and operation of waste management systems include digitalisation, modelling and simulation. Specifically, amongst these, Building Information Management (BIM) systems and Digital Twins have been identified as adding value in the acceleration of decommissioning programmes. Best practices and guidelines on the implementation of digital technologies to improve key tasks in the decommissioning should be developed and shared to assist in appropriate selection.

Adoption of advanced digital technologies such as robotics, automated site mapping and Digital Twins may have regulatory implications and these need to be assessed and understood prior to any selection process. There is also a benefit to seeking alignment and harmonisation based on EU standards for an efficient benchmarking of best available techniques being used in similar conditions.

4.1.3.6 Activities of common interest

The activities of common interest within the Technology Selection topic are summarised in the following table. For each sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

Table 3 – Activities of common interest in Technology Selection

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
Selection of technologies for	Definition of WAC criteria (link to WAC topic area)	RD&D	See WAC topic area	Short term

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
(existing or future) waste streams where no industrially mature waste disposal route available Optimal technology for existing and planned waste streams	Review of technologies / develop case studies	StSt, KM, RD&D	Case studies accessible for decision-makers	Medium term
Comparison of technologies at different levels of maturity including cost-benefit ratio and availability	Analysis of technologies in a new R&D project	KM	Means of prioritisation of technologies for development	Medium term
	Selection of most suitable technology	StSt		Short term
	Link to case studies activity above	StSt		Short term
Supporting innovation and reducing environmental impact of radioactive waste management through technology selection	Establish network of experts with focus on environmental issues	StSt	Community of practice group established	Short term
	Consider environmental impact (LCA implementation)	StSt / KM	Improved understanding of environmental impact and costs	Short term
	Consider societal impact and support development of accessible communication materials	StSt / KM	Support to national programmes on societal aspects and acceptance	Short term
Digitalisation and data management	Develop best practices and guidelines on the implementation of digital technologies to improve key tasks in the decommissioning	KM	Knowledge sharing	Short term
	Evaluate the regulatory implications of using advanced technologies including robotics, automated site mapping and digital twin technology.	StSt	Harmonisation of practices	Short term
	Benchmarking to EU standards of best available techniques being used in similar conditions	StSt		

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.1.3.7 Summary of past and ongoing EU activities/projects in this topic area

- SHARE - The SHARE project included identification of existing and emerging technologies, solutions and best practices for decommissioning, employed across the nuclear industry, to meet current and future needs [16].
- World Nuclear Association provides information on a selection of technologies for waste treatment and disposal to meet decommissioning strategy [10].

4.1.4 Cost-estimating & Funding

Estimating costs (procedures and tools) for the predisposal management of radioactive wastes, accounting for uncertainties, including due to long programme timescales. Planning investments for infrastructure and for competencies required for implementation.

Identifying and specifying funding mechanisms to ensure that adequate financial and human resources are available when needed for the implementation of predisposal management of radioactive waste.

4.1.4.1 Introduction

Fundamental to the planning of predisposal management of radioactive wastes is the accurate assessment of future costs and the provision of adequate financial resources. A key principle is to ensure that future generations are not burdened with liabilities associated with activities carried out by previous generations. Additionally, the 'polluter pays' principle means that waste generators are required to cover the cost of waste management and disposal.

Cost estimation requires procedures, tools, data and assumptions, to assess the costs of infrastructure, resources and competencies associated with different stages and components of the predisposal management of wastes. Funding relates to the approach to payment of the costs of predisposal management, which will be based on the national legislative framework. It may involve direct financing from waste generators for some predisposal activities, state funding (e.g. for managing some legacy wastes) or a pre-collected fund for managing long-term liabilities.

A cost estimation process is needed to ensure that the costs of predisposal waste management are identified, understood and accurately estimated using reliable methods, while taking account of uncertainties and risks. Given the long timescales often associated with waste management activities where the final endpoint is disposal, it is necessary to ensure that cost estimates and associated funding requirements are regularly reassessed and updated. The cost estimation and funding models for predisposal management of radioactive wastes need to meet national requirements and legislation but, overall, the general principles to be met should be common. It is also important that the cost estimation and assessment process is transparent, clearly documented and available for review and audit.

Further information on cost estimation and funding is available in the 2022 EURAD study on cost assessment and financing [17] and its references.

4.1.4.2 Activities of common interest

From the PREDIS questionnaire responses, no activities of common interest were identified relating to Cost Estimating and Funding. However, there were responses from single organisations relating to:

- Developing baseline costs for each lifecycle stage using real data from existing Member State organisations for use in technology selection exercises.
- Standardised cost estimation methodologies to increase stakeholder confidence.

In addition, the SHARE project's SRA [2] has identified several areas relating to Cost Estimating (in the context of decommissioning):

- Methodologies and guidance for cost estimation, e.g. improving and broadening guidance on cost estimation methodology to deal will all costs and all types of nuclear facilities; establishing working groups for cost estimation for various facility types; guidance for determining the significant cost drivers per project; coordination on public case studies of costing; dissemination of ISDC guidelines.
- Methodologies and software tools for comparison of alternative strategies and components, e.g. development of available tools for cost estimation for application of risk and uncertainty analysis; development of methodology to define unknowns and the associated uncertainty.
- Development of mechanisms for cost benchmarking, e.g. improvement in approaches and data sharing for cost benchmarking; further development of cost benchmarking methodology.

4.1.4.3 Summary of past and ongoing EU activities/projects in this topic area

- EURAD - Guidance has been developed on cost assessment and financing schemes of radioactive waste management programmes [17]. This guidance has a focus on geological disposal programmes but the principles can be applied to other programmes, including predisposal issues.

- SHARE [2] [3] – The SHARE project has identified further development of cost estimation in the context of decommissioning activities as an area of urgency, as described in their SRA [2] and Roadmap [3]. Further details of the activities identified in the SHARE projects are provided in Section 4.1.4.2.

- IAEA and NEA have produced reports on cost estimation (e.g. [18] [19]), mainly relating to disposal of radioactive waste and decommissioning rather than predisposal management.

4.1.5 Waste Hierarchy

Developing the waste management strategy and evaluating options to apply the waste hierarchy to minimise waste volumes at higher impact inventory disposal levels. This requires an understanding of existing storage facilities and the available waste management routes and disposal options.

4.1.5.1 Introduction

European legislation and national policies in many countries adopt the concept of the waste hierarchy and require development, review and updating of waste management plans as part of the overall waste management strategy. The waste hierarchy sets out a priority order to support delivery of the best overall environmental option: prevention, preparing for re-use, recycling, other recover (e.g. energy recovery) and disposal (Figure 5).

Figure 5 – Waste Management Hierarchy

The hierarchy must not be seen as a succession of preparatory phases but rather a succession of functional phases. Then, whilst the approach encourages waste minimisation and sustainability, sometimes it may be necessary for the management of certain waste streams to divert from following the waste hierarchy. Where this is the case, it needs to be justified based on consideration of the impacts throughout the lifecycle and aspects such as technical feasibility, economic viability and environmental protection.

Development of a waste management strategy should consider the full lifecycle of a facility and the processes that may produce waste, from construction through to operation and decommissioning phases. A waste management strategy applies the waste hierarchy through evaluating options for minimising waste volumes for disposal and seeking to ensure that waste, where generated, is kept to the lowest classification possible. This strategy needs to account for the available treatment and processing options, waste management routes, storage facilities and disposal options. Early planning presents an opportunity to minimise waste generation and implement processes to optimise waste treatment, recycling of materials and packing in containers for disposal. Effective planning and strategy development should also mitigate the need for future re-conditioning of waste packages and limit disposal of mixed wastes, which could be sorted for treatment, free release, re-use or recycle.

Clearly, the opportunities for applying the waste hierarchy differ for new facilities in the design phase, compared with existing facilities and wastes that may already have undergone treatment and/or conditioning. For new facilities there should be greater opportunity for waste prevention and re-use or recycling.

Nevertheless, existing facilities can apply the waste hierarchy through review of waste management plans and implementing good practice for the operational and decommissioning phases to reduce wastes generated and adopt the best management solution.

The waste hierarchy topic area is strongly linked with other topic areas, in particular, characterisation (due to the need for accurate characterisation and classification of materials to support treatment, re-use and recycling) and treatment & processing (to undertake sorting and segregation and for decontamination of materials).

Following the collection and analysis of information from the PREDIS SRA survey and other engagement activities, specific sub-areas were identified as being most important for future improvements through R&D, SS and KM activities. The main gaps and issues and the associated activities are summarised below according to sub-area.

4.1.5.2 Life Cycle Assessment (LCA) for waste management strategy

For new facilities, there is a need to consider, at the design and planning stages, how wastes are generated and managed throughout the lifetime of the facility, including any new waste types (from a radiological and commodity point of view) that may have different properties and challenges compared with current wastes. It is usually a requirement to develop waste management plans and decommissioning plans as part of the regulatory approvals process. The production of guidance and specifications on the development of waste management strategies to address the full life cycle of a facility will support implementation of the waste hierarchy and the adoption of sustainable resource management, thus minimising waste volumes at higher inventory disposal levels.

LCA is a methodology used to evaluate the environmental impact of a product, process or service over its entire life cycle, from the extraction of raw materials, through production, use and disposal. In the context of radioactive waste management, LCA can be applied to assess the environmental impact of various waste management options, taking into account the energy and material inputs, emissions and secondary wastes produced at each stage of the life cycle. Tools and data to support these life cycle analyses and to assess waste management options are also required. The PREDIS project has already progressed developments in this area (specifically within the task on LCA and Life Cycle Costing (LCC)) and is helping identify specific future activities of importance, which will be further detailed at the end of the project in the final SRA.

As highlighted earlier, management of certain wastes may divert away from the waste hierarchy as the decision making also needs to consider a range of factors including safety, cost, environment, socio-economic, etc. It is advisable that "management routes" are first defined according to the characteristics of the waste (including the amount) and therefore the possibility of being able to send it, for example, to recycling or disposal (with the various management processes that precede this phase). One area where this may be the case is if an option is considered for retention of materials in situ, either to allow for decay, or for in situ disposal, where this can be demonstrated to provide an overall benefit (and is possible under national policy). This will be dependent on the intended future use of a site. In this case, it would be useful to address how such options and decisions are made, accounting for experience in this area. This could include how to account for the effects of non-radiological and hazardous components as well as radioactive components.

4.1.5.3 Recycling of materials

Improved understanding of good practice in recycling of materials will support more sustainable management of facilities. This might include understanding the characterisation needs to determine the nature and location of activity (e.g. on the surface, within a certain depth of the surface, locally or dispersed throughout) to enable its removal and also the availability of treatment and processing techniques, plus routes for reuse and recycle. Attention must also be paid to the chemical and conventional characterisation. Materials highlighted in the engagement activities are:

- metallic waste, where quality controls to enable future use are linked to being able to adequately characterise, handle and segregate materials.
- concrete, where large volumes will arise from decommissioning activities – the potential for recycling and use of recycled concrete aggregate, use of measures at the construction phase to limit contamination and later decontamination requirements, e.g. applying coatings to surfaces.

A Strategic Study to consider the issues associated with societal and stakeholder acceptance of recycling and the reuse of materials is proposed. Addressing this will provide benefits from a perspective of sustainable use of resources, reduction in wastes for disposal, reduction in transport of materials (if used locally), and reduction in costs.

4.1.5.4 Waste tracking

To support implementation of the waste hierarchy improvements in tracking wastes and materials throughout their management is needed. This could include software and hardware systems to incorporate all relevant information and characterisation data associated with the materials throughout their management. Examples include Information Technology (IT) tracking software systems and hardware such as barcodes and radio frequency identification (RFID) tags.

4.1.5.5 Activities of common interest

The activities of common interest within the Waste Hierarchy topic are summarised in the following table. For each sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

Table 4 – Activities of common interest in Waste Hierarchy

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
Life Cycle Assessment (LCA) for waste management strategy	Develop specifications/guidance for the design of new facilities to cover waste management strategy and sustainable resource management for the full life cycle from construction and operation through to decommissioning and remediation/reuse	StSt	Improved and more sustainable management of future facilities and projects to minimise wastes and implement the waste hierarchy from the design stage onwards. Drivers: Protection of citizens and environment	Short term
	Identify/develop tools to support LCA of facilities and projects	RD&D	Improved analysis capability to assess options and underpin decisions regarding waste management strategy. Supports better communication of strategy. Drivers: Processes, products and services; Protection of citizens and environment	Short term
	Assess when options such as leaving materials in situ are appropriate and how they can be justified.	StSt		Short term
	Defining the management route of the waste	StSt		Medium term
Recycling of materials	Identify good practice in recycling of materials	StSt / KM		Short term
	Identify good practice relating to recycled concrete aggregate	KM	Minimise use of new resources Reduce volumes for disposal	Short term

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
	Identify good practice in recycling of metals by meeting quality requirements - linked to characterisation and handling and segregation of materials	KM	Minimise use of new resources Reduce volumes for disposal	Short term
	Societal acceptance of policy of recycling and reuse of material	StSt	Improved stakeholder engagement and buy-in. Reduced costs and transport movements from recycled materials being available for local use.	Short term
Waste tracking	Improve and develop approaches and tools to support waste/materials tracking, e.g. IT tracking software systems, hardware including barcodes and RFID tags	RD&D	New or improved methods of tracking wastes and materials Increased confidence in the provenance of materials	Short / Medium term

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.1.5.6 Summary of past and ongoing EU activities/projects in this topic area

- SHARE [16] – The SHARE project highlighted work undertaken to identify/employ characterisation techniques and decontamination technologies for radioactive concrete and metal wastes that enable separation of the waste into component streams for re-use/recycling, in line with principles of the Waste Hierarchy.
- Application of the Waste Hierarchy is covered in the World Nuclear Association's Methodology to Manage Material and Waste from Nuclear Decommissioning [10].

4.2 Implementation

This intermediate Implementation section of the SRA covers:

- Characterisation (Section 4.2.1).
- Treatment & Processing (Section 4.2.2).
- Conditioning & Packaging (Section 4.2.3).
- Storage (Section 4.2.4).
- Transport (Section 4.2.5).
- Deployment Options (Section 4.2.6).

4.2.1 Characterisation

Identifying the characteristics of the wastes (physical, mechanical, chemical, radiological and biological properties) in order to sort, classify and quantify radioactive waste in accordance with the requirements established or approved by the regulatory body. Characterisation of wastes applies throughout the life cycle (e.g. for processing, storage, transport and disposal).

4.2.1.1 Introduction

Radioactive waste can originate from different generators such as nuclear power plants, research facilities, nuclear medicine, etc. In order to classify the waste and select appropriate waste management strategies, it needs to be characterised. Thus, characterisation lies at the basis for radiation protection measurements, protecting man and environment from any potential harmful effects, and directly influences planning and costing of waste management facilities needed to mitigate these effects. Characterisation is relevant in all phases of the life cycle of a nuclear installation with different levels of detail and with differing objectives. In the context of final radioactive waste disposal, the purpose of radioactive waste characterisation is generally to verify that the waste (packages) complies with the acceptance criteria of the licensed disposal facility. These criteria differ depending on the form and type of radioactive waste and on the different (country-specific) regulations that apply for these facilities. Appropriate control procedures to ensure the compliance with these criteria are necessary for quality control. These procedures can take place at different stages of the waste management strategy, including during decommissioning of nuclear facilities.

Characterisation of nuclear waste or nuclear waste packages is performed through both non-destructive and destructive measurement methods, allowing access to the physical (density, volume, shape, position of the waste and embedding matrices, mechanical toughness, cracking, diffusion coefficient, gas release, thermal power, etc.), chemical (elemental composition, content of toxic or reactive substances, etc.) and radiological characteristics (dose rate, α and β activity, isotopic composition and mass of nuclear materials, etc.) [20].

4.2.1.2 Techniques

Destructive analysis (DA) provides the most accurate and unbiased activity determination, since pure alpha and beta emitting radionuclides or those emitting gamma or X-rays with a too small intensity or energy are extremely difficult to measure in already conditioned waste packages. Chemical and radiochemical treatment of the primary waste or waste form allows measurements to be performed that assure the traceability of the determined activity. This is not the case with non-destructive analysis (NDA) methods, which typically use standards calibration or modelling. As a consequence, there is greater uncertainty with NDA in terms of determining activity.

Non-destructive techniques (NDT) are used in order to minimise the radiation dose to personnel, to avoid secondary radioactive waste production and to minimise costs. Furthermore, with destructive testing, there is always the essential question of taking a representative sample, especially for heterogeneous waste [21]. However, many radionuclides whose characterisation is important for long-term waste management are difficult to measure (DTM) from the outside of a waste package. Within the context of waste characterisation, the relationship between some key easy-to-measure (ETM) nuclides, such as certain gamma emitters, and DTM nuclides is used to derive information on the DTM nuclides of interest.

Several non-destructive methods for quality checking of radioactive waste packages have been developed and tested. Reference [21] distinguishes these by the measured quantity, and their operation mode. Passive methods are based on the detection of neutrons and gamma-rays spontaneously emitted by the nuclides of interest. Such methods are easy to implement, but also impaired by the low intensity of radiations or self-attenuation inside the packages (e.g., in the case of low-energy gamma-rays emitted by actinides). To overcome these impairments, active methods may be employed. These methods are based on fission processes and on the detection of particles emitted after such processes [22].

Apart from radiological measurements, other characterisation efforts are also pursued. Imaging, for example, can be a powerful tool allowing the physical characterisation of waste drums, including waste identification, density measurement, and integrity check of the package. Using X-rays, digital radiography (DR) and computed tomography (CT) can be performed on either small sub-samples or on entire waste drums.

A complete state of the art on non-destructive measurements can be found in the CHANCE[7] project [23].

4.2.1.3 Activities of common interest

The activities of common interest within the Characterisation topic are summarised in the following table. For each sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency. Characterisation emerged as the key topic from the stakeholder and end-user engagement work undertaken to determine areas of interest for future research, and hence a large number of sub-areas and activities were identified.

[7] CHANCE: Characterization of conditioned radioactive waste for its Safe Disposal in Europe (EC Project 2017-2022) https://www.chance-h2020.eu/ (See Appendix 3)

Table 5 – Activities of common interest in Characterisation

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
Waste classification	Common system for the classification of wastes based on physico-chemical properties to support better management of these wastes	StSt	Waste classification has mainly focussed on radiological characteristics, but chemical/ chemotoxic characterisation is also an important aspect	Medium term
	Characterisation and classification of legacy wastes based on physico-chemical and radiological properties, to help determine suitable approaches for its re-treatment and re-conditioning to meet storage and disposal acceptance criteria.	StSt	Reduce uncertainties	Medium term
Technology selection	Assuring method fitness for purpose; defining optimised threshold values; how to adapt procedures.	StSt	Harmonisation of practices; improve efficiency	Short term
Isotope vector and scaling factor	Scaling methods and scaling factors in different facilities: e.g., when working with a variety of different radionuclide vectors (e.g., in research facilities); scaling factor development also in view of heterogeneity/changing vectors as function of time/etc.; scaling factor development for decommissioning wastes, contaminated pieces, etc.	StSt	Development of guidance to remove inconsistencies across waste streams and sites; documenting and sharing of best practice	Short term
	Impact on and treatment of uncertainty/ conservatism using these approaches	RD&D/ StSt	Uncertainty and conservatism reduction	Short term
	Improving the understanding of distribution/spreading of radioisotopes in nuclear facilities to improve the knowledge on isotope vectors in waste forms	RD&D/ StSt	Uncertainty and conservatism reduction	Short term
	Scaling factor development for both radioactive and non-radioactive components	RD&D	Better inventory; uncertainty and conservatism reduction	Short term
	Validation of computer calculations used for isotopic vectors	StSt	Benchmarking/better quality management	Medium term
In situ characterisation and segregation	Remote, integrated and automatic technologies for (in situ) waste characterisation and segregation	RD&D	improvement of existing technologies, active demonstration to increase the technology readiness and demonstrate maturity	Short term
	Exchange and dissemination of best practices for on-line characterisation during remediation and clean-up	KM	Knowledge sharing	Short term

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
	Exchange and dissemination of best practices on characterisation of underground remaining structures	KM	Knowledge sharing	Medium term
	In situ characterisation for inaccessible areas	RD&D	Better inventory; uncertainty and conservatism reduction	Medium term
Radiological characterisation challenges of (conditioned) radioactive waste (packages)	Development of new radiological and non-radiological characterisation approaches; non-destructive methods (as alternative to destructive techniques); analytical methods for specific nuclides; quick operative, reliable, robust, efficient and economic characterisation methods (e.g., in D&D projects, legacy waste inventory, etc.)	RD&D	Improve safety, efficiency and economics, reduce uncertainty and conservatism	Short term
	Share experience, knowledge and case studies from more advanced programmes	KM/ StSt	Knowledge sharing	Medium term
	Characterisation of heterogeneous (metallic) waste items or containers (also inside cemented packages)	RD&D	Identification of materials and better characterisation of radiological inventory	Short term
	Solid organic waste characterisation/characterisation of historic or legacy wastes to reduce the need for sorting and segregation	RD&D	Identification of materials and better characterisation of radiological inventory	Short term
	Characterisation of fissile material inside waste drums/materials (also to manage criticality risk)	RD&D	Demonstration of conformity/ Reduction of uncertainty	Short term
	Sampling techniques (in cemented waste packages). Optimise sampling strategy (using statistical methods approach, Data Quality Objectives method) and sampling representativeness (result precision, ascertain degree of uncertainty and heterogeneity). Improvement of existing sample analysis technologies (rapid, cheap, and straightforward methods including automated methods). Benchmarking.	RD&D /StSt	Demonstration of conformity/Reduction of uncertainty	Medium term
	Characterisation of large/dense (cemented) waste packages (active and passive neutron detection, transmission and emission tomography using high energy X-rays, photofission, angular gamma scanning)	RD&D	Identification of materials and better characterisation of radiological inventory	Medium term
	Mobile monitoring or characterisation systems. Improvement of mobile systems and integrated technologies for containerised RW and unconventional legacy waste	RD&D /StSt	Technology improvement/economics	Medium term
	Need for more/better accuracy in radiological measuring techniques, e.g., by combining different techniques (gamma spectroscopy and calorimetry)	RD&D	Demonstration of conformity/Reduction of uncertainty	Medium term

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
	Characterisation for security/safeguard purposes, e.g., related to transport of nuclear materials (what leaves a facility and arrives at destination)	RD&D /KM	Improve safety, exchange of best practices	Medium term
Non-radiological properties and inventory of radioactive waste	Improving the understanding of the non-radiological properties and inventory of radioactive waste, e.g., presence of (toxic) chemical species and/or material characterisation inside a waste package, for example by neutron activation analysis	RD&D	Demonstration of conformity/Technology improvement	Short term
	Non-destructive testing for/characterisation of the physico-chemical content and properties (leachability, compressive strength, internal swelling pressure, …) – also during interim storage (changes occurring during storage)	RD&D	Demonstration of conformity/Technology improvement	Short term
	Improved data and understanding of organic materials and complexants (behaviour) that affect the release of radionuclides and chemical species following disposal	RD&D	Reduce uncertainty and conservatism, improve safety	Medium term
	Characterisation of ageing effects in cemented waste drums (or, more generally, monitoring changes in waste forms/packages that happen over time; especially difficult when there is shielding in place).	RD&D	Demonstration of conformity	Medium term
	Detection of gases (such as hydrogen) and outgassing monitoring (using Cavity Ring-Down Spectroscopy (CRDS)); gas transport in/around waste drums/packages	RD&D	Technology improvement, improvement of safety	Medium term
Developments or improvements of characterisation technology	Coupling gamma spectrometry and tomography	RD&D	Reduction of uncertainties in radiological inventory	Medium term
	Fast, cheap and straightforward methods for difficult to measure radionuclides (DTM), including in situ alpha and beta measurements (e.g., H-3, C-14, Ni-63) and automation	RD&D	Improve efficiency and economics	Short term
	Enhance the use of robotics including drones, submersible ROVs and sensors, also allowing the characterisation and/or sampling of difficult to access areas (e.g., within cells, vessels, pipelines, ponds, etc.).	RD&D	Demonstrators to increase the technology readiness and demonstrate the maturity of new technology	Short term
	Demonstration pre-condition information and final package information regarding DTM or impossible to measure (ITM) nuclides. Develop specific algorithms for the assignment of waste package inventories and fingerprints based on historic records information and/or for corroboration of package inventories based on limited measurement data.	StSt/ RD&D	Demonstration of conformity	Short term
	Efficient metal type recognition in hot-cell conditions	RD&D/ StSt	Technology improvement	Medium term
	Gamma camera technology	RD&D	Technology improvement /economics	Medium term
	Alpha measurement on organic liquids (oils)	RD&D	Technology improvement	Medium term

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
	X-ray for small volumes of cemented waste content	RD&D	Technology improvement	Medium term
	Graphite characterisation	RD&D	Technology improvement	Short term
	Radiation-tolerant devices	RD&D	Technology improvement	Short term
	Neutron coincidence counting with alternatives to 3He detectors (now too expensive)	RD&D	Improve economics, Technology development	Medium term
	Active neutron interrogation to measure the fissile mass in high-level waste (high gamma irradiation and high neutron emitters like curium isotopes	RD&D	Improve safety	Medium term
	Automation of measurements – combine on-site measurements with external analysis	RD&D	Technology improvement	Medium term
Digitalisation and data management	Characterisation data handling and (measurement) uncertainty management (e.g., through Bayesian approaches)	RD&D/ StSt	Reduce uncertainty and conservatism, improve safety, harmonisation of practices	Short term
	Improved interpretation of characterisation results using artificial intelligence (AI) or machine learning (e.g., for attenuation correction) methods or geostatistical methodology techniques	RD&D	Reduce uncertainty and conservatism, improve safety, harmonisation of practices	Short term
	Characterisation for clearance/release of materials	StSt/ KM	Improved economics and sustainability in waste management	Medium term
Release/ clearance methodology	Automated characterisation technologies for structures and land areas for final status surveys and release (clearance of surfaces and structures). Indoor positioning system development and demonstration. Subsurface radionuclide contamination detection.	RD&D	Reliable, adequate characterisation methods	Short term
	Identify opportunities to improve the exchange of experiences and identification of Member States' regulatory differences regarding clearance criteria. Advantages and disadvantages for harmonised regulations.	StSt	Harmonisation of practices	Short term
	Sharing of experiences with respect to clearance of difficult to measure items (such as fire water hoses in controlled areas)	StSt	Harmonisation of practices	Medium term
Competence development	Implementation of educational and training programmes to ensure sufficient and skilled staff are available for the sector with a special focus on the use of new technologies for characterisation	KM	Education & training	Short term
	(Improve access to) Facilities and infrastructures equipped to characterise and measure large items	KM	Improved access to best available technology	Medium term
Quality control	Appropriate reference materials (standards) and inter-comparison exercises/benchmarking to support expanding programmes in characterisation (e.g., in view of D&D)	KM	Improved quality control; international standardisation	Short term

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.2.1.4 Summary of past and ongoing EU activities/projects in this topic area

- CHANCE [24] – This project developed an understanding of current conditioned radioactive waste characterisation schemes and considered specific innovative characterisation technologies of calorimetry, muon tomography and CRDS. The project identified the main characterisation needs associated with radiological content, chemical properties, physical properties and mobile systems to perform non-destructive analyses, and also identified important R&D challenges that still need to be overcome [23].

- SHARE [2] [3] – The SHARE project considered characterisation during the transition phase, main decommissioning phase (including decontamination), for environmental remediation and to support the end-state study for site release. Stakeholders rated 94% of the thematic sub-areas related to characterisation as being of medium and high importance, with half of them considered to be of high urgency. The project highlighted opportunities for further development of existing technologies in terms of automation, remote control and integrated systems; active demonstration of new technologies; and fast, cheap and straightforward methods for DTM.

- MICADO[8] – This project has provided a proof of concept system for non-destructive characterisation of nuclear waste and the associated digitisation and management of the data. The results from MICADO have highlighted the need for improved characterisation methods and usage of such data.

- INSIDER[9] – The INSIDER project considered the development of an improved integrated characterisation methodology coupled with analytical and measurement methods, in the context of decommissioning, post-accident land remediation and nuclear facilities under constrained environments. Activities included sampling and strategy, radiochemical measurement techniques and in situ measurement.

4.2.2 Treatment & Processing

Minimising waste quantities and volumes and/or changing the characteristics of the waste to improve safety and/or economy. This includes pre-treatment (e.g. collection, segregation, chemical adjustment and decontamination) and treatment (e.g. volume reduction, removal of radionuclides from the waste, change of composition).

4.2.2.1 Introduction

Radioactive wastes produced from the operation and decommissioning of nuclear facilities and from the application of radionuclides in industry, medicine and research, must be processed in a manner that protects human health and the environment, now and in the future, without imposing undue burdens on future generations. Waste processing includes pre-treatment, treatment and conditioning and is intended to produce a waste form compatible with the selected or likely disposal option.

Pre-treatment may include operations such as waste collection, segregation, chemical adjustment and decontamination with the aim of reducing the amount of radioactive waste and/or adjusting its characteristics to make it more amenable to additional processing and disposal.

Treatment of radioactive waste includes, when necessary, removal of radionuclides, reduction of volume and change of composition (for example, through thermal treatment) with the aim of reducing the potential hazard of the waste and enhancing safety in the short term (by making immediate improvements in the characteristics

[8] MICADO: Measurement and Instrumentation for Cleaning And Decommissioning Operations (EC Project 2019-2023) https://www.micado-project.eu (see Appendix 3)
[9] INSIDER: Improved Nuclear Site characterisation for waste minimisation in Decommissioning and Dismantling operations under constrained EnviRonment (EU project 2017-2021) https://insider-h2020.eu (See Appendix 3)

of the waste) and in the long term (as one of a series of steps contributing to the safe predisposal management of radioactive waste).

Radioactive waste is diverse and varied in nature and it encompasses a broad range of radionuclides, half-lives, activity concentrations, volumes and physical and chemical properties. Other than radionuclides, the waste may contain other hazardous elements (i.e. asbestos).

Due to this variety of composition, the choice of process(es) to be used for waste treatment is quite complex and dependent on the level of activity, the type (form and characteristics) of waste and the overall strategy for waste management. Each country's nuclear waste management policy and its national regulations also influence the approach taken.

Following the collection and analysis of the data deriving from the survey and the focus sessions, specific sub-areas (within the Treatment & Processing topic) were identified as most important for future improvements through R&D, SS and KM activities and they include:

4.2.2.2 Flexible decontamination and treatment processes

Strategic Studies that include benchmarking for decontamination technologies and development of new technology might help to select the optimised solutions for decontamination with the main goal of reducing the amount of secondary waste.

The development of mobile or modular waste treatment facilities, that can be easily transported and adapted to the needs of a specific site and tasks, will give invaluable advantages in terms of flexibility for different quantities, dimensions, waste routes and regulatory requirements. They might support services as site operations run down at decommissioning sites and help to provide up-to-date and best-available technologies.

Strategic Studies to highlight the opportunities and challenges for shared solutions/facilities can support less advanced/small programmes (in particular when small quantities of waste need to be treated).

4.2.2.3 Management of problematic waste

Some wastes (e.g. organics or metals) react with encapsulants, causing problems with waste form integrity (cracking) and transport and disposal (hydrogen generation).

R&D activities are needed to enable waste routes for organic materials where currently not available. They mainly include the development of alternative thermal treatment technologies (considering also the issues related to the release of ^{14}C).

Solutions should be developed to passivate/inhibit corrosion of reactive metallic materials (including dust) to prevent or limit the hydrogen production.

Graphite contains long-lived highly mobile radionuclides such as ^{14}C, ^{36}Cl and ^{3}H that pose a challenge for conditioning and long-term sequestration of encapsulated graphite wastes. Strategic Studies are needed to enable a generally accepted approach for graphite waste treatment/conditioning and disposal.

Challenges are present for the treatment of liquid waste with specific contaminants and hazardous and toxic materials (e.g. asbestos and Polychlorinated Biphenyls (PCBs)). KM and R&D activities are needed to enable waste routes, to provide solutions to remove specific contaminant from liquid waste (e.g. Cl, F, ^{14}C, ^{3}H, etc.) and to improve safety and reduce costs.

4.2.2.4 Recycling and reuse

A lot of materials, by-products or some components of waste generated during operation and decommissioning of the nuclear fuel cycle facilities have a potential value and may be recycled within the original process or reused outside, either directly or after appropriate treatment.

Minimisation of waste arisings and the practice of recycling and reuse can improve process economics and minimise the potential environmental impact.

Benchmarking of technologies might help to identify technologies and approaches for recycling and reuse. Development of new technologies for recycling and reusing of materials will increase efficiency, reduce volume of waste to be disposed and reduce costs.

Strategic Studies are needed to promote and facilitate the implementation of the recycling and reuse of materials. Applying the principles of circular economy to nuclear decommissioning and waste management will improve environmental sustainability and create opportunities at the international level for recycling.

In general, it was highlighted that there is scope for much greater harmonisation in terms of clearance of materials for recycling and reuse, and application of good practices in recycling of released materials. The need for societal engagement for recycling was highlighted too.

4.2.2.5 New and emerging solutions

Although treatment and decontamination technologies have reached a certain level of maturity (high TRLs), further technological development work is required, particularly aiming at improving performances, safety, waste minimisation and cost reduction.

R&D activities for the demonstration and industrialisation of lab scale solutions and technologies (e.g. thermal waste treatment processes like vitrification or hot isostatic pressing (HIP)) might solve specific issues and optimise specific activities. A further opportunity highlighted the potential for IT tools and other emerging technologies to manage waste flows from production to disposal to enable optimisation (e.g. in data collection and integration).

A number of projects and studies have been launched worldwide to further develop nuclear energy technology in the near future (15–25 years) and beyond. For new fuel types and advanced reactors/fuel cycles some waste types will be either new or known to be problematic. Strategic Studies and R&D activities are needed to identify challenges and enable future waste routes.

4.2.2.6 Activities of common interest

The activities of common interest within the Treatment & Processing topic are summarised in the following table. The highest importance sub-areas are those raised by multiple organisations/countries during the PREDIS survey and included also in other SRAs (e.g. H2020 SHARE project). For each sub-area, the suggested activities (RD&D, StSt and KM) are reported together with the expected outcomes/impacts and urgency, as they were discussed and consolidated with the wider community during specific focus session and workshops.

Table 6 – Activities of common interest in Treatment & Processing

Sub-area	**Activities**	**Type of Activity**	**Expected Outcome & Impact**	**Urgency***
Flexible decontamination and treatment processes (including modular and mobile systems)	Treatment solutions for different quantities, dimensions, characteristics, waste routes and regulatory requirements	RD&D	Facilitated treatment of different types of waste, including owners of small quantities of waste Flexible, modular treatment solutions	Short term
	Benchmarking for decontamination technologies and approaches (good efficiency and minimised secondary waste production)	StSt / KM	Optimised solutions for decontamination Better understanding of decontamination mechanisms (e.g. gels and foams) Reduction of secondary wastes when using decontamination agents	Short term
	Promote international sharing of facilities	StSt	Support to less advanced/small programmes Costs optimisation Sharing of best practices and skills	Short term

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
Management of problematic waste	Graphite mixed waste	StSt	Enable a generally accepted approach for graphite waste conditioning and disposal	Medium term
	Organic materials – Research activities related to alternative thermal treatment technologies. Develop alternative solutions for ^{14}C	RD&D	Enable new waste treatment routes where currently not available	Short term
	Reactive metallic waste, including dust (hydrogen in disposal environment)	RD&D	Provide a solution to passivate/inhibit corrosion	Short term
	Liquid waste with specific contaminants	RD&D	Provide a solution to remove specific contaminant from liquid waste (e.g. Cl, F, ^{14}C, ^{3}H, etc.)	Short term
	Hazardous and toxic materials (e.g. asbestos and PCBs)	RD&D / KM	Enable waste treatment routes where currently not available. Improve safety and reduce costs in hazardous and toxic materials management	Short term
Recycling and reuse	Benchmarking of technologies	StSt/ KM/ RD&D	Identify technologies and approaches for recycling and reuse Development of new technologies for recycling and reuse of materials. Increase efficiency, reduce volume of waste to be disposed and reduce costs	Short term
	Regulatory requirements for release	StSt	Reduce waste disposal burned	Short term
	Societal engagement for recycling	StSt	Promote recycling and reuse of released materials Public/societal acceptance	Short term
	Harmonise good practices in recycling of released materials	StSt/ KM	Improve environmental sustainability Create opportunities at the international level for recycling	Short term
New and emerging solutions	High efficiency and reduction of secondary waste	RD&D	More efficient treatment and decontamination technologies Flexible and cost-effective solutions Optimisation of volume of waste to be disposed	Medium term
	Industrialisation of lab scale solutions	RD&D	Increase TRL and demonstration for new treatment processes	Medium term
	IT tools and other emerging technologies to manage waste flows from production to disposal	RD&D	Improvements in data collection and integration	Medium term
	Solutions for new fuel types and advanced reactors/fuel cycles	StSt/ RD&D	Identify challenges Enable future waste treatment routes	Medium term

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.2.2.7 Summary of past and ongoing EU activities/projects in this topic area

EURAD - Deliverable D9.12 “Studies and plans for developing shared solutions for radioactive waste management in Europe” [25] summarises the knowledge and approaches regarding the sharing of technology and facilities between countries in different steps of the waste lifecycle. This has included exploring shared R&D work and the use of technologies and facilities for treatment of wastes.

CARBOWASTE[10] [26] - Research undertaken as part of this project led to the development of techniques for separating coated particles from moderator graphite of high-temperature reactor fuel as well as the identification of thermal, chemical or microbiological treatments that can remove a significant proportion of contamination in irradiated graphite. The feasibility of recycling and reuse of irradiated graphite was also highlighted, although there is unlikely to be a sufficient market for significant quantities of irradiated graphite.

THERAMIN [15] – The project identified which thermal treatment technologies were under development, demonstrated the applicability of different thermal treatment technologies (incineration-vitrification: SHIVA process; vitrification: In-Can Melter and GeoMelt®; thermal gasification; HIP) to a range of waste groups, and identified areas of further work (see Appendix 3).

HARPERS[11] - The project will be considering the benefits and added value of harmonisation of practices, standards and regulatory frameworks relating to decommissioning and waste management. Topics to be examined could include cross border services and treatment facilities, treatments for reuse and recycle of materials to promote a circular economy, and advanced waste treatment technologies.

4.2.3 Conditioning & Packaging

Stabilising the waste by conditioning it (e.g. conversion of the waste into a solid waste form). Preparing the waste/waste form for safe handling, transport, storage and disposal by packaging it in a suitable container.

4.2.3.1 Introduction

Conditioning includes all operations consisting of introducing the waste, possibly pre-treated, into a container where it can be blocked or incorporated into a matrix to form a waste package. The choice of container and immobilisation matrix is mainly related to the radiological and physico-chemical characteristics of the waste. It also aims to optimise the conditioned volume of the waste and to comply with the acceptance criteria applicable to storage and disposal facilities.

The conditioning of radioactive waste stabilises the waste (e.g. by transforming it into a solid waste), in order to prepare it for safe handling, transport, storage and disposal by conditioning it in an appropriate container. This step is mandatory for all radioactive waste, whether it arises from the operation of fuel cycle facilities (industrial and research) or from the decommissioning and dismantling (D&D) of end-of-life nuclear facilities.

The main drivers identified by PREDIS stakeholders for future research activities on conditioning and packaging are: society (protection of citizens and the environment), professional performance of industry players (safe and efficient processes, products and services) and scientific excellence (quality of science and increased development or optimisation of technologies).

In addition, it was found that packaging is a priority within the European scientific community. Data collected during the PREDIS surveys show that packaging is the third most important R&D topic to be addressed in the nuclear industry in the coming years, after waste characterisation and waste acceptance criteria.

As a result of the collection and analysis of data from the survey and discussion sessions, specific sub-areas (within the Packaging and Conditioning theme) were identified as the most important for future improvements through R&D activities, strategic studies and knowledge management:

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[10] CARBOWASTE: Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste (EC Project 2008-2013) (see Appendix 3)

[11] HARPERS: HARmonised PracticEs, Regulations and Standards in waste management and decommissioning (EC Project 2022–2025) https://www.harpers-h2020.eu (See Appendix 3)

4.2.3.2 Optimisation of existing conditioning solutions

The largest volume of radioactive waste comes from the nuclear industry, mainly from plant operation and fuel cycle operations. Although the pathways for conditioning most of this well-known waste are established, new technological developments will improve technical and economic performance as well as safety and environmental aspects.

Over the last 50 years, thousands of cubic metres of nuclear wastes from R&D and industrial activities have been immobilised. The performance of conditioning matrices over the long period is crucial for their acceptability to disposal. Optimised encapsulation matrices will enable safe and efficient disposal activities.

Optimisation can result in the mixing of different wastes in the same matrix, thereby increasing the waste load. This can reduce the pressure on the space required for waste packaging and thus improve the environmental impact of disposal sites.

Optimising current conditioning matrices will also help to meet new or modified waste acceptance criteria at disposal sites.

National strategies can differ considerably across Europe, so it is important to ensure exchange and harmonisation of best practice.

As key stakeholders, WMOs and waste generators should be consulted and fully involved in R&D and knowledge management activities.

4.2.3.3 New conditioning solutions

Projects for decommissioning nuclear installations are progressing significantly across Europe, and therefore it is critical to be efficient in identifying suitable waste management routes for these decommissioning wastes. The same applies to new fuels that could be used in the nuclear industry in the future (molten salt, SMR fuels, etc.). These wastes still need to be qualified and conditioning solutions identified.

Some difficult or strategic wastes also require specific conditioning solutions that have not yet been developed or need TRL increase. This may be the case for ashes, reactive materials, reactive metals, non-incinerable organic materials, sludge, chemotoxic substances. The methods for converting or transforming these wastes into accepted waste forms still need to be studied. Studies to share knowledge between the owners of these wastes or to pave the way for common solutions need to be conducted.

New conditioning solutions can refer to the development of new innovative materials, such as geopolymers or ceramics. Even if the first studies have shown promising results (e.g. PREDIS), some technical aspects such as scale-up, standardisation of solutions and qualification as well as long-term durability of these matrices remain to be demonstrated. Developing effective matrices will allow demonstration of waste conditioning performance to regulators according to WACs.

Strategic Studies are needed to promote and facilitate the implementation of materials recycling and reuse. Applying circular economy principles to nuclear decommissioning and waste management will improve environmental sustainability and create recycling opportunities internationally.

4.2.3.4 Long term behaviour

Long-term behaviour is critical to provide safety demonstration for storage and disposal. The durability of the conditioning matrix must be demonstrated under various conditions taking into account the impact of irradiation.

Long-term behaviour requires experimentation over long periods of time, to support understanding of the expected evolution after disposal, sometimes over a few hundred years or more. The use of modelling simulations is necessary to help understand the long-term stability and performance of conditioning matrices.

Other R&D activities will build on the progress made in the PREDIS project. For example, to demonstrate the relevance and safety of direct conditioning for RLOW using new conditioning solutions (e.g. geopolymers or alkali-activated materials as a replacement of traditional cement binders alone).

4.2.3.5 Other

The package is the first of the successive barriers between the radioactive elements and the environment. In the perspective of long-term management of packages, the quality of this barrier must therefore be assessed over time. In particular, corrosion and waste/container interface reactions are important to study especially in case of a long-term storage period. Indeed, the container integrity must be preserved to ensure the safety of transport and disposal activities. R&D activities are needed for non-destructive control techniques and to develop simulation models to support understanding package stability/performance through both long term storage and final disposal in a repository.

The use of reusable/recyclable or new types of materials in the composition of containers will also allow the application of the principles of the circular economy. This will create opportunities to enhance their technical performance and improve the economics of their production.

Finally, the orientations to improve the management of broken or damaged waste packages and to optimise the management of secondary waste will rely on both KM and R&D activities to provide support to the community.

4.2.3.6 Activities of common interest

The activities of common interest within the Conditioning & Packaging topic are summarised in the following table. For each sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

Table 7 – Activities of common interest in Conditioning & Packaging

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
Optimisation of existing Conditioning solutions (linked to WAC and disposal capacity)	Optimise conditioning material properties: Waste loading, mechanical resistance, compatibility with the environment, long-term behaviour	RD&D	Meet WACs related to disposal facilities	Short/ medium term
	Increase waste loadings, mixing wastes	RD&D	Reduction of wastes for disposal	Long term
	Exchange & harmonisation of best practices, interactions WMOs/waste generators	KM	Exchange of knowledge on optimised solutions	Short / Medium term
New conditioning solutions for strategic waste addressing safety, technical and economic aspects	Development of innovative emerging solutions	RD&D / StSt	Identify routes for wastes that do not have existing routes	Short term
	Use of recycled/innovative materials	RD&D/ StSt	Demonstrate – depends on the WACs in comparison with the raw material financial & environmental impact	Medium term
Long term behaviour and performances of existing and new conditioning matrices	Durability demonstration under irradiation condition (gamma and alpha)	RD&D	Demonstrate – depends on the WACs	Short term
	Control hydrogen generation and release	RD&D	Demonstrate – depends on the WACs	Short term
	Impact of heavy metals on conditioning matrices	RD&D	Demonstrate – depends on the WACs	Medium term
	Matrix performance (compressive strength, chemical reactions causing swelling or cracking, corrosion, etc.)	RD&D	Demonstrate – depends on the WACs	Short term

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
	For all of above – simulation models	RD&D / StSt	Demonstrate to regulators behaviour/performance of waste form	Short term
Containers	Use of reusable/ recyclable/ new types of materials	RD&D / StSt	Demonstrate to regulators behaviour and performance (containment and confinement capability)	Medium term
	Long term durability behaviour for safety	RD&D / StSt	Demonstrate long term behaviour/performance	Short term
	Non-destructive control techniques for efficiency of performance evaluation	RD&D / StSt	Develop new or increase TRL of non-destructive control techniques	Short / Medium term
	Simulation models to support understanding of stability/performance over long term	RD&D / StSt	Demonstrate predictive capability of modelling	Short Term
Broken packages	Develop approaches for package remediation, including raw waste that has been in long-term storage. Such research may involve development of techniques for package repair or reinstatement (e.g., package over-packing, application of repair grouts and/or the application of surface coatings).	RD&D	Produce solutions to handle failed waste packages.	Short term
	Guidance to improve management of damaged and/or broken packages	KM	Exchange of best practices (criteria, re-pack)	Short term
Secondary waste	Develop approaches to optimise processes that reduce or remove generation of secondary wastes, promoting waste hierarchy.	RD&D	Handling optimisation	Short term

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.2.3.7 Summary of past and ongoing EU activities/projects in this topic area

- EURAD [27] – Under the EURAD WP ROUTES, an overview of the issues related to challenging waste has been prepared, highlighting conditioning processes under investigation by Member States and future needs and potential R&D research topics.
- SHARE [16]– Assessed different waste route options, including conditioning.

4.2.4 Storage

Safely storing wastes/packages in a facility that provides for their containment, prior to transport and deposition. Includes decay storage, interim (short-term) storage and long-term storage.

4.2.4.1 Introduction

Radioactive waste may be subject to storage at a number of stages during its management and, therefore, may be stored in processed and unprocessed forms for varying periods of time. Storage is a temporary measure in which radioactive waste is held in a facility that provides for its containment, with the intention of retrieval. Extended storage periods are generally only required for radioactive waste for which no disposal option is yet available.

Low- and intermediate-level wastes are commonly processed to produce volume-reduced, solid waste forms and the converted wastes are enclosed and/or over packed in containers. These resulting waste packages are often stored in above-ground storage buildings or in shallow near-surface storage structures, and facility operators generally use a combination of engineering design features, operating procedures and monitoring programmes to achieve safe handling and storage. Low- and intermediate-level wastes are typically stored in metal containers, but a number of different types of materials have been used for the fabrication of waste containers.

While in storage, radioactive waste should be expected to retain its form and suitability for transport and disposal for a predetermined period of time without subsequent reconditioning. This expectation is met through the interaction of three sets of criteria: the WAC, the waste form and container specifications, and the design and operating requirements of the storage facility.

In designing an interim storage facility, the following factors should be considered:

- passive safety.
- multiple barrier containment.
- robust storage facilities with adequate storage capacity.
- appropriately established waste acceptance criteria for storage.
- effective storage facility maintenance, inspection and retrieval.
- records management.

Radioactive waste is stored in physically and chemically stable forms to achieve passive safety that minimises the need for active safety control systems. These waste forms should exhibit good resistance to leaching, corrosion, as well as predictable behaviours during the intended storage period, which are important to retain radionuclides and hazardous waste constituents under normal and accident conditions.

Radioactive waste has been stored safely and securely in many countries for decades. However, operators continue to face challenges in maintaining good quality storage.

Challenges include:

- the management of historic and legacy waste and in particular of non-conforming stored packages and existing storage facilities.
- the ageing behaviour of radioactive waste during long storage periods.
- the continual ageing of storage components and structures.
- the changing of regulations over the storage time.
- lack of public support and confidence.
- effective management of knowledge and records.

The maintenance of safe storage often relies on continuous monitoring programmes and procedures, ageing management programmes to monitor degradations of storage structures and components, execution of remediation projects if necessary and continual research and development work to address safety and degradation of storage facilities and components, particularly to determine how long storage may be technically feasible.

Overall, a moderate level of interest was found on the topic of storage from the PREDIS SRA Survey as it placed just out of the top half of weighted priority scores. Storage was identified as being of interest by five respondents. Survey results also indicated that the decision to perform research and development work related to storage considerations will be driven by needs regarding protection of citizens and the environment, public trust and confidence and performance improvement.

Specific sub-areas regarding the topic of optimisation in predisposal radioactive waste management were identified though the collection and analysis of information from the PREDIS SRA survey and other engagement activities. The sub-areas in this research topic were related to performance in storage environments, monitoring and optimisation.

4.2.4.2 Activities of common interest

The identified activities of interest within the Storage topic are summarised in the following table. For the sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

Table 8 – Activities of common interest in Storage

Sub-area	Activity	Type of Activity	Expected Outcome & Impact	Urgency*
Performance in storage environments	Establish the likely performance of waste in storage environments to include long-term storage.	RD&D	Research in this area should be able to inform judgements about waste treatment and conditioning routes and understanding if/when product failure might occur.	Short term
	Predicting how waste properties may evolve against relevant product quality criteria over time.			
	Understanding and minimising corrosion of metallic waste containers.			
	Understanding waste form leach rates or gas generation rates.			
Monitoring	Develop remote techniques and approaches to assess the chemical evolution of stored raw waste, the physical degradation of packages and environmental discharges. Such monitoring may involve visual and non-destructive methods. Package monitoring may involve use of remote activity mapping (e.g., detect localised hotspots), laser profiling techniques (e.g., to confirm or monitor dimensional parameters) and monitoring of package seal performance and internal pressure. Approaches to package monitoring might also involve the development and application of statistically based sampling regimes to ensure adequate coverage of the package population and to help define sampling frequencies.	RD&D	Promotes understanding of waste package evolution and (early) detection of product failures.	Short term
	Develop guidance on standard approaches for monitoring over extended storage periods.	KM		
Optimisation	Identify the potential for waste to be decay stored and subsequently re-categorised and diverted to alternative routes within the waste hierarchy.	StSt	Promotes cost savings and circular economy considerations.	Short term
	Enable more efficient use of storage infrastructure and resources.			

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.2.4.3 Summary of past and ongoing EU activities/projects in this topic area

- THERAMIN [15] – The project provided: demonstration of thermal treatments to produce wasteforms suitable for ongoing storage, e.g. HIP, vitrification; characterisation of products from thermal treatment processes to demonstrate the removal of volatile components, organic complexants and water, to reduce the potential for gas generation and corrosion of storage containers; a value assessment exercise including the impact of volume reduction through thermal treatment on life cycle storage costs.

- PREDIS – Ongoing work is considering innovations in cemented waste handling and predisposal storage.

4.2.5 Transport

Transporting wastes between facilities at different stages of predisposal management, in accordance with regulatory requirements.

4.2.5.1 Introduction

The transport of radioactive material by land, water or air has been ongoing for decades. Such practices have well established guidelines which comply with applicable regulations and stakeholder expectations from both domestic and international perspectives. Consignments are typically transported by specialised organisations that carry distinct certifications. Often, purpose-built vehicles/ships and multi-purpose containers designed for storage and transport are used. The level and nature of radioactivity will control the safety assessment and regulatory oversight demands.

New technologies that are being implemented or might be applicable to the predisposal management of radioactive waste and may have an impact on transport include:

- the use of robotics and autonomous vehicles.
- new multi-purpose cask and container designs.
    - package/basket innovations.
    - new materials providing added safety features such as better shock absorption and dampening, and cask components with greater impact protection overall.
- integration of sensors to packages and transport vehicles for quality control of waste form behaviour, package integrity and safety assessment evaluation.
- tracking of thermal load monitoring during transport.
- utilisation of digital technologies for transport route planning to aid efficiency and reduce hazards based on real-time conditions, including traffic and weather.

Overall, relatively little interest was found on the topic of transport from the PREDIS SRA Survey as indicated by its placement in the bottom quintile of weighted priority scores. Transport was identified as being of interest by only two respondents.

4.2.5.2 Activities of common interest

Only one activity of interest within the Transport topic was identified and it is summarised in the following table. For the sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

Table 9 – Activities of common interest in Transport

Sub-area	**Activity**	**Type of Activity**	**Expected Outcome & Impact**	**Urgency***
Continuing transportability of loaded and stored packages	long-term operations	StSt KM	Incorporation of an appropriate ageing management programme for the design lifetime of a package ranging from the design stage until the end of usage. After the application of ageing management procedures with positive results it should be possible to ensure safe transport of loaded multi-purpose casks or storage canisters even after several decades of storage.	Short- to long-term, depending on desired start of extended storage operations

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.2.5.3 Summary of past and ongoing EU activities/projects in this topic area

No recent projects have addressed transport issues, likely due to the current best practices and non-urgency of implementing new solutions.

4.2.6 Deployment Options

The development and assessment of alternative scenarios for selection and deployment of operational activities. Option selection and evaluation for different strategic approaches such as in situ/ex-situ, remote handling, robotics, etc.

4.2.6.1 Introduction

Several challenges for safe facility operation need to be addressed when considering alternative deployment scenarios. In particular, these will include physical and radiological safety (for example, the potential radiation exposure experienced by workers and the public), the stability and integrity of the waste and waste packages and how these may be impacted by the approach to be taken, compliance with regulatory and legal requirements, economic feasibility, and public perception and acceptance. In general, it is preferable, where at all possible, to remove or reduce worker contact with the waste, and hence the use of remote handling and robotic technology is a focus for this topic. However, the effectiveness and safety of emerging remote and automated systems need to be assessed carefully.

4.2.6.2 Considerations for Deployment

It is generally agreed that movement both of untreated material and final packages must be minimised. In situ treatment is not possible in almost all scenarios and for all technologies. However, treatment should happen on site where possible to avoid unnecessary transport of untreated material. Only if the amount and activity of material is so small that on site treatment is inefficient and transport risks are limited, ex situ treatment is acceptable. However, on site treatment equipment has already been developed for conventional treatment technologies. Thus, deployment of the whole waste management predisposal facility encompasses all technologies that demonstrate the efficiency of the process from robotics to automated systems to transport, sort and classify materials and/or packages and then sensors and data collection systems to verify their performance.

The major objectives of deployment implementation include radiation safety in general, health and safety of the staff on site and minimisation of the risk of accidents when moving packages. Options for the deployment of equipment for waste package handling, inspection and monitoring or for the collection of data include:

- Permanently (e.g. sensing/monitoring technology inside or outside the packages).
- Manually (equipment is applied by workers at each instance of use).
- Robotically (processes are fully automated and isolated from workers).

The first option avoids movement of equipment and packages almost completely (only first-time installation and potential maintenance activities are required). However, the installation procedures for the technologies developed for a waste handling facility (especially where technology is integrated into packages) would have to be optimised and, if possible, automated (through future research on integration into automated treatment equipment).

Should in situ operations not be possible due to limitations proscribed by the storage facility, waste packages may have to be retrieved and brought to a dedicated site. If it can be foreseen that a large number of packages need to be moved during the service life of a facility, automated package handling is to be preferred, which would involve e. g., robots, cranes, automated vehicles, conveyor belts.

The stakeholder and end-user engagement activities highlighted automation as a key topic area for research. In particular, the assessment of existing and established automated technologies from non-nuclear industries (such as the construction industry) for their use in nuclear applications. Specific areas covered included:

- Robotics and heavy lifting equipment.

- Various forms of Virtual Reality (VR) that allow workers to experience a virtual 3D presence in facilities whilst maintaining safe distance.
- Building Information Management (BIM) systems, enabling the digital representation of physical and functional characteristics of facilities, and how this may be linked to automated radiation protection measures.

4.2.6.3 Activities of common interest

Activities of common interest within the Deployment Options topic are summarised in the following table. For this sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

Table 10 – Activities of common interest in Deployment Options

Sub-area	Activity	Type of Activity	Expected Outcome & Impact	Urgency*
Technology application to dismantling/decommissioning associated with efficiency of waste handling e.g., robotics, technology transfer from the construction industry (e.g., heavy lifting equipment) Extended reality (Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR)), in situ measurements)	Assessment of existing technologies for deployment in dismantling operations	RD&D, StSt	Technologies both within and currently outside of the nuclear industry that could assist in dismantling/ decommissioning processes will be assessed and selected. Impact will be hazard reduction, improved safety and decreased timescales for completion of activities.	Short to medium term
Automated radiation protection measures	Linking BIM and radiation protection	StSt	Consideration of automated radiation protection measures within building design and management.	Medium term

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.2.6.4 Summary of past and ongoing EU activities/projects in this topic area

- SHARE [28] – The SHARE project provides a detailed compilation of the different technologies and techniques available for various radioactive waste management applications including sampling, characterisation, decontamination, dismantling, size-reduction, remediation, modelling and analysis, etc. The report sets out the relative benefits of each technology and discusses deployment including options for in situ, on-site and off-site deployment.
- EMOS (Development of a Mobile and Automated Optical System for the Inspection of Radioactive Waste Drums) - EMOS is a mobile and automated inspection unit that remotely handles and scans the entire drum surface optically, including lid and bottom, analytically evaluates and electronically stores, as well as output the results in an inspection report. In this way, periodic inspections of the drum stock of an interim storage facility can be completed under always the same test conditions.

4.3 Operations

This final section of the SRA covers:

- Quality Management Systems (Section 4.3.1).
- Commissioning (Section 4.3.2).
- Optimisation (Section 4.3.3).
- Secondary Waste Management (Section 4.3.4).

4.3.1 Quality Management Systems (QMS)

Implementing quality systems and management systems to ensure accurate detailed records of wastes, processing undertaken and package characteristics (e.g. radiological, physico-chemical, stability, durability) over their lifetime, from production until disposal. Includes records management and monitoring required throughout the lifetime of the wastes/packages.

4.3.1.1 Introduction

The effective management of nuclear waste requires a systematic, integrated and standardised approach to quality assurance and control. A QMS is a set of integrated policies, procedures and practices aimed at ensuring that products, processes and services meet customer and regulatory requirements. In the context of radioactive waste management, a QMS is essential for ensuring the safety, reliability and quality of operations related to handling and treatment of the waste through its life cycle. QMS will need to evolve to adapt to the emerging new wastes and novel treatment technologies. There is also an increasing role in digital technology in enhancing the efficiency and effectiveness of QMS implementation.

Very little interest was found on the topic of QMS from the PREDIS SRA Survey, as indicated by its low placement in the weighted priority scores. Quality Assurance is a very mature area, and the proposed activities reflect this in terms of developing guidance and assessing the use of existing digital technologies. There are clear links to the activities proposed against the Deployment Options topic (Section 4.2.6), where the potential use of BIMs is discussed for the digital management of waste and associated facilities.

4.3.1.2 Activities of common interest

The activities of common interest within the Quality Management Systems topic are summarised in the following table. For each sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

.Table 11 – Activities of common interest in Quality Management Systems

Sub-area	Activities	Type of Activity	Expected Outcome & Impact	Urgency*
Identify systems for Quality Control	Develop guidance on: Properties to assess and criteria to assess against Technology selection Methodology to apply	KM	Enumerate different valid techniques/approaches for Quality control Clear guidance on methodology	Short term
Digital Technology for QMS	Assessment of impact of digital technology on QMS	StSt	Understanding of potential impact of introducing digital technology in QMS for information management, maintenance etc.	Short term

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.3.1.3 Summary of past and ongoing EU activities/projects in this topic area

- SHARE [28] – Data Quality Assurance (DQA) and Data Quality Objectives (DQO) – cross-references US EPA (2006) Guidance on Systematic Planning Using the Data Quality Objectives Process, EPA QA/G-4 [29].

4.3.2 Commissioning

The steps undertaken to commission facilities and plants required to support the implementation activities. These steps might include logistics, scheduling, competencies, reduction of risks, quality control, regulatory permissions and sharing of operational experience.

4.3.2.1 Introduction

Commissioning of a building or plant is used to ensure that all process systems have been properly constructed, are operational, and are verified to perform according to the design intent and the user's operational needs. The main objective of commissioning is to confirm that the design intent of the components, the systems, and the plant as a whole are achieved. Experience has shown that a successful commissioning process takes considerable upfront planning at the design phase of the project to be successful.

Very little interest was found on the topic of commissioning from the PREDIS SRA Survey, as indicated by its placement in the bottom quintile of weighted priority scores. In fact, this topic was identified as being of interest by only one respondent.

4.3.2.2 Activities of common interest

The activity of interest within the Commissioning topic identified by a single respondent is summarised in the following table. For the sub-area, the suggested activities (RD&D, StSt and KM) are reported, together with the expected outcomes/impacts and urgency.

Table 12 – Activities of common interest in Commissioning

Sub-area	Activity	Type of Activity	Expected Outcome & Impact	Urgency*
Commissioning planning	Proper timing of facility commissioning	StSt KM	Improved decision making Ensured operability and maintainability	Short- to long-term depending on desired start of operations

* Urgency: Short term (up to 5 years), Medium term (5–10 years), Long term (>10 years)

4.3.2.3 Summary of past and ongoing EU activities/projects in this topic area

None identified.

4.3.3 Optimisation

Evaluating the potential for improving and optimising implementation phases taking account of both new and existing technologies, to improve costs and environmental impact while maintaining safety and accounting for potential risk scenarios.

4.3.3.1 Introduction

Optimisation is the process of obtaining the most suitable solution to a given problem. For a specific problem only a single solution may exist, and for other problems there may exist multiple potential solutions. Optimisation should find the 'best' solution, where 'best' implies that the solution is not necessarily the optimal solution but is a sufficiently superior optimum relative to a starting or baseline configuration. Optimisation is often associated with technical and economic aspects but, particularly in the radioactive waste management space, concerns operational and long-term safety as well. In principle any step in the predisposal management of radioactive waste (e.g., characterisation, processing, storage) can be optimised over any or all of its attributes.

Future needs and activities in the optimisation of predisposal radioactive waste management will be influenced by the outcomes of such pursuits in other areas. For example, a decision to optimise the formulation of immobilisation matrices may have been made possible by research and development in waste conditioning. On the other hand, a decision to optimise the formulation of immobilisation matrices may itself lead to research and development in waste conditioning.

In addition to possibilities for optimising ongoing predisposal operations, future developments in waste generating activities (reactors and fuel cycles) and waste management activities (handling of uncertainties, treatment and conditioning technologies) will likely necessitate further changes and adaptations in design and implementation. Therefore, optimisation efforts (from a longer-term perspective) should also consider future technology advancements in the nuclear sector and, furthermore, could take a more holistic view.

Ultimately, any optimisation process should answer three basic questions:

1. What is being optimised?
2. Why is it being optimised? (i.e., what are the aims of this optimisation? what is the benefit of this optimisation?)
3. How will it be optimised?

According to the results of the PREDIS SRA Survey, the decision to optimise predisposal radioactive waste management activities will be performance-driven, innovation-driven, or protection-driven.

Specific sub-areas regarding the topic of optimisation in predisposal radioactive waste management were identified through the collection and analysis of information from the PREDIS SRA survey and other engagement activities. The sub-areas in this research topic were related to making decisions with respect to design, performance or systems in varying level of detail. Optimisation activities related to systems are not covered specifically in this section but are highlighted within other topic areas in this SRA, such as Treatment Processing, Conditioning & Packaging and Storage.

4.3.3.2 Activities of common interest

Optimisation efforts of common interest in predisposal radioactive waste management are summarised in the following table. Optimisation categories (design, decision or system) are given first followed by sub-areas (as activities), type of activity (RD&D, StSt and KM), expected outcomes and impacts and urgency.

Table 13 – Activities of common interest in Optimisation

Sub-area	Activities	Type(s) of Activity	Expected Outcome & Impact	Urgency*
Design	Optimisation of waste characterisation & conditioning considerations versus repository design/sizing Implementing new technologies with respect to existing techniques, infrastructure, etc. Cost-benefit analyses, providing sound methods/tools for decision making Learning from previous implementation efforts, knowledge transfer from more advanced programmes to earlier stage programmes	StSt KM	Improved decision making More adaptive and flexible designs Cost reductions	Short term
Performance	Heuristic evaluations over full life cycles to find global optimums for the entirety of predisposal radioactive waste management Developing ideas and tools for full life cycle evaluations, i.e., LCA & Life Cycle Design (LCD), new geoscience models, process models, numerical simulation, digital twins	RD&D	Improved underpinning for safety cases Improved data management and process performance More economical, sustainable and environmentally friendly waste conditioning practices	Short term

* Urgency: Short term (up to 5 years), Medium term (5-10 years), Long term (>10 years)

4.3.3.3 Summary of past and ongoing EU activities/projects in this topic area

- SHARE [28] – The SHARE project covers optimisation of characterisation/sampling methods, radiological protection of workers undertaking waste management operations, and centralisation of waste processing facilities. The report highlights specific waste management facilities (e.g. Spain: Jose Cabrera, Italy: SiCoMoR) developed to optimise the use of materials and minimise production of primary/secondary radioactive waste.

- THERAMIN [15] – The work programme provided a vehicle for coordinated EU-wide research and technology demonstration designed to provide improved understanding and optimisation of the application of thermal treatment in radioactive waste management programmes across Europe, improving the technology readiness level to accelerate industrial implementation.

4.3.4 Secondary Waste Management

Managing secondary waste streams produced during initial processing of the primary wastes, for a life cycle approach.

Secondary wastes are those produced during the processes employed to manage primary wastes; e.g. during handling, size-reduction, decontamination, segregation and packaging/treatment processes. This topic is principally linked to Technology Selection (4.1.3), Waste Hierarchy (4.1.5) and Optimisation (4.3.3). In general, following the principles of the Waste Hierarchy (Figure 5) it is desirable to reduce the quantity of any wastes, whether primary or secondary, to a minimum, but with consideration of other influencing factors such as radiological and conventional safety, timescales, costs, etc. Any secondary wastes produced should be managed in the same manner as primary waste streams.

Considerable volumes of low and very low-level secondary waste and effluents can arise from the following:

- Deployment of specific size-reduction and cutting technologies, such as wire or oxy-acetylene cutting,
- Deployment of specific decontamination techniques, such as water jetting or sand blasting,
- Personal Protective Equipment (PPE) and other laundry waste associated with normal operation and decommissioning of reactors and other associated nuclear facilities.

Careful selection of appropriate technologies in the management of primary wastes is therefore of key importance to minimising secondary wastes. The SHARE project [28] provides a detailed compilation of the different technologies and techniques available for size-reduction and decontamination and sets out the relative amounts and types of secondary waste to be expected from the deployment of each one. The ways in which these volumes can be reduced will have major benefits. One specific example of such technologies is the use of material coveralls which can be dissolved in hot detergent solutions, resulting in liquid waste streams that can be cleaned up and safely discharged to the environment [8]. A less obvious area relates to the further development of simulation software to optimise maintenance scheduling and the logistics of operations leading to a reduction in the number of man hours spent working in active environments. This in turn can reduce the volume and activity levels of the required PPE and tooling [8].

No specific areas were raised in the SRA survey/questionnaire or stakeholder discussions for secondary wastes. However, related areas of common interest can be found in Table 3 (Technology Selection), Table 4 (Waste Hierarchy) and Table 13 (Optimisation).

5 Further considerations

5.1 Socioeconomics and legislation

In addition to technical considerations, it is recognised that the different Member States have differing political, legislative and socio-economic contexts, and these need to be taken into account in the development of a strategic research programme. Where Member States have significantly different or challenging socio-economic and/or legislative arrangements that may impact on the ability to implement aspects of the PREDIS SRA, these need to be identified such that mitigating actions can be proposed if necessary.

5.2 Knowledge Management

Knowledge Management (KM) encompasses the development and transfer of knowledge and competence across stakeholders and end users up to the level of Member States national programmes, to preserve knowledge transfer for coming generations. Specific activities may include the development of knowledge management programmes, collection and documentation of the state of knowledge, and the implementation of training and mobility modules.

It is clear that KM is a key activity type suggested as being the action to deal with some of the gaps that were provided during the survey and focus sessions. Some examples of this can be found explicitly within the SRA as individual activities in the Characterisation, e.g. Isotope vector and scaling factor, Radiological characterisation challenges of (conditioned) radioactive waste (packages) and Inventory, e.g. Legacy and problematic waste inventories, topic areas.

KM was also drawn out as being a key activity consideration in the following topic areas:

- Waste Acceptance Criteria – to help build a Waste Acceptance System
- Technology Selection – for (existing or future) waste streams where no WAC is present, for problematic waste where identification of case studies would be valuable and also further development of advanced technologies (geopolymers, ultra & nano filtration, selective sorption) due to the technologies being used in completely different contexts and to aid understanding on how results can be transferred to other areas, ahead of application.
- Conditioning & Packaging – New conditioning solutions, enabling commonality.
- Treatment & Processing Management of problematic waste, the treatment of liquid waste with specific contaminants and hazardous and toxic materials (e.g., asbestos and PCBs), to provide solutions to remove specific contaminant from liquid waste (e.g., Cl, F, ^{14}C, ^{3}H, etc.) and to improve safety and reduce costs.
- Quality Management Systems – different existing techniques of measurement for the aspects/properties to control.

As suggested in the Conditioning & Packaging topic area, one method to deliver this is that key stakeholders including WMOs and waste generators should be further consulted and continue to be fully involved in R&D programmes and KM activities.

Furthermore, a specific example in the Storage topic area suggests that effective management of knowledge and records is a priority enabler.

Other recent relevant projects and programmes that have highlighted KM as a key area of focus include SHARE and EURAD (including EURAD ROUTES WP).

Table 14 summarises the KM activities identified for each of the technical topic areas and indicates which type of activity is proposed. The seven activity types identified are briefly defined as follows:

- **Study**: An analysis of resources, capabilities, and environment to determine the most effective strategy for achieving set goals.
- **Case Study**: An in-depth analysis of specific projects or situations to determine the key learning points.

- **Guidance**: Provision of recommendations, practices, or interpretations of regulations or technical requirements aimed at helping stakeholders understand and comply with standards.
- **Networking**: The establishment and maintenance of relationships between individuals and groups to exchange information, resources, and support.
- **Good Practice**: Recommended practices and procedures for achieving outcomes aimed at improving quality, efficiency, and effectiveness.
- **Benchmark**: The process of comparing the performance, processes or practices of an organisation against those of other similar organisations or industry standards, to identify areas for improvement.
- **Training**: The provision of practical and/or classroom-based work experience in a relevant topic or setting, to pass on skills and industrial knowledge.

It should be noted that some Member States may highlight different technical topics where they specifically need more guidance or training, depending on their programme's maturity and resource pool.

Table 14 – Summary of KM activity types identified in the SRA

Technical Topic	Proposed Activity	Study	Case Study	Guidance	Networking	Good practice	Benchmark	Training
Inventory	Non-radiological, hazardous and chemotoxic materials			X				
	Legacy and problematic waste inventories				X			
Waste Acceptance Criteria	Good practice in development of WAC				X	X		
	Demonstrating compliance with WAC	X						
Technology Selection	Selection of technologies for (existing or future) waste streams where no industrially mature waste disposal route available		X					
	Supporting innovation and reducing environmental impact of radioactive waste management				X			
	Further development of advanced technologies	X						
Waste Hierarchy	Recycling of materials					X		
Characterisation	In situ characterisation and segregation				X			
	Radiological characterisation challenges of (conditioned) radioactive waste (packages)		X					
	Digitalisation and data management			X		X		
	Competence development							X
	Quality control						X	
Conditioning & Packaging	Optimisation of existing conditioning solutions				X		X	
	Treatment of damaged packages			X				
Storage	Monitoring			X				
Treatment & Processing	Flexible decontamination and treatment processes (including modular and mobile systems)						X	
	Recycling and reuse						X	
Optimisation	Design Optimisation of waste characterisation & conditioning considerations versus repository design/sizing				X		X	
	Implementing new technologies with respect to existing techniques, infrastructure, etc				X		X	

There is no doubt that radioactive waste management is under continuous development and improvement and what results is an increase in the knowledge base with time. Capturing all the knowledge generated is a complex process, considering the existing interdependencies between predisposal systems themselves and also with disposal processes. In the light of the continuous improvement of the process and systems, substantial optimisations are implemented, which implies that safety and implementation goals need to be evaluated. A possible future focus should be on creating sustainable knowledge management systems to handle large and complex data flows (e.g. techniques, methodologies and uncertainties, quantifiable and qualitative decision-making) possibly using artificial intelligence.

Another field of knowledge management activities that is of interest in a revised SRA, is to develop technologies and methodologies for creation of efficient networks (also including Community of Practices), connecting people to people, independently if between experts, experts-newcomers, between students or radioactive waste management organisations (WMO, Technical Support Organisation (TSO) or research entities (REs)) to public. Methodologies from other disciplines could be studied if they are suitable in the field of radioactive waste management and for long-term interactions of decades. This must be accompanied by proper training design, to ensure that the basics are transferred in a solid fashion to newcomers and generations.

Harmonisation of regulations between countries seems to be a challenge that should be overcome. Several reports concerning international cooperation in decommissioning and radioactive waste management claim that the lack of regulatory harmonisation is making multinational approaches more difficult. Regulatory discrepancies prevent stakeholders from benchmarking the efficiency of decommissioning and waste management strategies between countries, making it difficult for them to identify the best available techniques. This could also have an impact in public risk perception and public acceptance. The enhance use of robotics including drones and sensors is highlighted from both standardisation and regulatory implications points of view, in addition to the regulatory differences regarding clearance criteria.

Finally, in terms of education and training activities as well as the development of competences, the implementation of educational and training programmes to ensure sufficient and skilled staff are available for the sector with a special focus on the use of new technologies is identified.

5.3 Stakeholder Engagement

Stakeholder Engagement was another key activity type that was suggested as being the action to deal with some of the gaps that were provided during the survey and focus sessions. Some examples of this can be found explicitly as individual activities in the WAC topic area where a range of stakeholders have an influence and input into the process, be it country policy, type of disposal/storage, waste classification, regulatory bodies, that could have an impact on the final WAC. Also, in the Waste Hierarchy topic area with respect to Recycling of materials, undertaking an engagement exercise to help further determine societal and stakeholder acceptance of recycling and the reuse of materials, in particular metals and concretes, would be beneficial. This was also found in the Treatment & Processing topic area, again in the context of recycling and reuse, where the need for societal engagement was highlighted to promote and develop societal acceptance.

Other recent relevant projects and programmes that have highlighted Stakeholder Engagement as a key area of focus include SHARE and HARPERS, which are both stakeholder-focused projects.

Stakeholder engagement has been key to the development of the PREDIS SRA, particularly in the identification and understanding of key technical topics for inclusion (see Appendix 1). For the subsequent strategic research programme to be implemented successfully following publication of the SRA, engagement with relevant stakeholders remains highly important, notably with SNETP. Establishing links and engagement between PREDIS activities and other ongoing initiatives and programmes will ensure activities are coordinated, avoid duplication and maximise impact for the end-user community.

6 References

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APPENDIX 1: METHODOLOGY FOR SRA DEVELOPMENT

Methodology for SRA Development

Establishing the baseline

The first activity was to establish a baseline SRA document from which to develop the PREDIS-specific SRA over the duration of the project. The starting point was to undertake a review of existing SRAs, strategic roadmap documentation and or Research Needs' documents from a range of sources and identify the sections relevant to PREDIS activities. These would then be extracted and placed into the draft PREDIS SRA structure for further analysis and development. The SRA structure was developed from IAEA guidance and in line with the structure used for the JOPRAD/EURAD SRAs. It is noted that whilst this structure was utilised for the initial baseline SRA assessment, the structure evolved in future iterations of the PREDIS SRA report in line with new IAEA guidance.

The list of existing SRA or other strategic outputs from previous and current projects or organisations was developed through consultation with the PREDIS partners. Table 15 shows the list of identified source documents, with weblinks where available, and provides a brief description for each of these. The exercise to review these SRAs and identify pertinent sections was also undertaken by the PREDIS partner organisations, with reviewers assigned to identified sources according to their knowledge and experience, and in the main reviewing the documents they had identified. Table 15 also shows a short summary of the outcome of the review. The PREDIS partner organisations involved in the SRA review work included BAM, CEA, ENRESA, NNL, SCK CEN, SOGIN and VTT.

Table 15 – Summary of outcome of reviews

Area	Aims of the SRA/Outputs	Summary of Outcome
H2020 CHANCE	To address the characterisation of conditioned radioactive waste by means of non-destructive analytical techniques and methodologies, encompassing both physicochemical and radiological characterisation. https://www.chance-h2020.eu/public-deliverables	Reviewed and sections identified
H2020 Micado	To propose a cost-effective solution for non-destructing characterisation of nuclear waste, implementing a digitisation process that could become a referenced standard facilitating and harmonising the methodology used for the in-field Waste Management and Dismantling & Decommissioning operations. https://www.micado-project.eu/publications/	Reviewed and sections identified
H2020 Metrodecom	To provide nuclear site operators with measurement techniques that can be used to measure radioactivity for planning decommissioning, for segregating and checking waste materials during demolition, and for monitoring the condition of waste packages in radioactive waste repositories. http://www.decommissioning-emrp.eu/?page_id=1388	Reviewed and sections identified
H2020 Pleiades	To provide a new digitally enhanced methodology for improving current D&D operations, defining good practices for digitalisation and facilitating higher standardisation required for international application. https://pleiades-platform.eu/results/	Reviewed and sections identified
IAEA IDN	IAEA International Decommissioning Network. The mission is to raise skills and expertise levels to facilitate safe decommissioning of nuclear facilities through collaboration, training and sharing of knowledge and information.	Predisposal topics addressed in IPN
NEA RWMC	The Radioactive Waste Management Committee (RWMC) systematically identifies its activities by focusing on three main aspects of radioactive waste management: 1) environmental; 2) economic; and 3) societal. These aspects are considered in the context of three frameworks: legislative, organisational and regulatory.	Too general to identify appropriate PREDIS sections
NEA CDLM	The Committee on Decommissioning of Nuclear Installations and Legacy Management provides a forum for experts, authorities, operators, service providers, research institutes and other relevant stakeholders to exchange experience and information on decommissioning and dismantling of nuclear facilities and development of practical guidance on regulating and managing legacy waste, sites and releases of legacy sites.	No document identified for review
WNA	To promote a wider understanding of nuclear energy among key international influencers by producing authoritative information, developing common industry positions, and contributing to the energy debate. Within WNA, the Waste Management and Decommissioning Working Group monitors trends in waste management strategies on both the international and local level, and seeks to establish a consensus for a more effective system of nuclear waste management and decommissioning. https://world-nuclear.org/getmedia/e81d115f-70c2-4c47-b208-242acc799121/methodology-to-manage-material-and-waste-report.pdf.aspx	Reviewed and sections identified

Area	Aims of the SRA/Outputs	Summary of Outcome
SNETP	An R&D platform to support and promote the safe, reliable and efficient operation of Generation II, II and IV civil nuclear systems. The international membership base of the platform includes industrial actors, research and development organisations, academia, technical and safety organisations, SMEs as well as non-governmental bodies. https://snetp.eu/wp-content/uploads/2020/06/Strategic-Research-Agenda-May-2009.pdf	Reviewed and sections identified
Nugenia - Global Vision	Hosted within SNETP and dedicated to the research and development of nuclear fission technologies, with a focus on Gen II & III nuclear plants. The NUGENIA Global Vision Document provides a detailed description of the technical and scientific content of the technical areas while addressing the main inherent R&D objectives, recalling their general scope and state of the art and outlining the main R&D challenges in the medium and long term. https://snetp.eu/wp-content/uploads/2020/10/Global-vision-document-ves-1-april-2015-aa.pdf	Reviewed and sections identified
Nugenia Technical Area 5B V. 2014	A NUGENIA sub-area is focused firstly on safe the management of nuclear plant operational waste and decommissioning "waste", and secondly the decommissioning/dismantling step in the nuclear plant lifetime. The aim is to minimise the arising waste through good design and operational practices, and to develop new technical solutions through focussed R&D on waste management and decommissioning.	Reviewed and sections identified
IGD-TP	The IGD-TP Vision 2040 SRA considers the next steps that must be taken to achieve the industrialisation of radioactive waste disposal in Europe by 2040; its scope covers RD&D supporting progress towards achieving final geological disposal, as well as RD&D relating to predisposal issues such as waste acceptance criteria, waste characterisation and waste treatment in support of disposability. https://igdtp.eu/document/2020_igd-tp_strategic-research-agenda/	Reviewed and sections identified
H2020 Theramin	To provide improved safe long-term storage and disposal of ILW and low level waste (LLW) suitable for thermal processing. Work carried out within the project aimed to identify radioactive wastes that could benefit from thermal treatment, which treatment technologies were under development in participating countries, and how these could be combined to deliver a wide range of benefits. http://www.theramin-h2020.eu/downloads/THERAMIN%20D5_4%20Project%20Synthesis%20Report.pdf	Reviewed and sections identified
H2020 Mind	A multidisciplinary project with the goal of addressing key microbiology technical issues that must be tackled to support the implementation of planned waste disposal across the EU. The project addresses the influence of microbial processes on organic waste forms and their behaviour and on the technical and long-term performance of repository components. https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwi4i9uWnNbxAhWbRUEAHWcsAF0QFnoECAUQAA&url=https%3A%2F%2Fec.europa.eu%2Fresearch%2Fparticipants%2Fdocuments%2FdownloadPublic%3FdocumentIds%3D080166e5c7a215bd%26appId%3DPPGMS&usg=AOvVaw31lMpoG58-oQlXvgAelJ-N	Reviewed and sections identified
EURAD-SCIENCE	The first international network of research entities established to unite the work of national research organisations on radioactive waste management from cradle to grave, and to drive scientific excellence in the field over the next decades. The EURADSCIENCE network links research-oriented organisations to EURAD, the 1st European Joint Programme on geological disposal of radioactive waste.	No document identified for review
EC EURATOM	Facilitate the establishment of a nuclear-energy industry on a European rather than a national scale. Other aims of the community were to coordinate research in atomic energy, encourage the construction of nuclear-power installations, establish safety and health regulations, encourage the free flow of information and the free movement of personnel, and establish a common market for trade in nuclear equipment and materials	No document identified for review

Area	Aims of the SRA/Outputs	Summary of Outcome
H2020 EURAD	Describes the scientific and technical domains and sub-domains and knowledge management needs of common interest between EURAD participant organisations. Developed in a stage-wise manner and taking over entirely the scope developed within the EC JOPRAD Project enhanced with a small number of additional needs identified by ongoing EC projects. The SRA scope is structured by scientific themes broadly relating to infrastructure and resources, fundamental science, engineering & technology, and applied science and integration. https://www.ejp-eurad.eu/sites/default/files/2020-01/2._eurad_sra.pdf	Referred to JOPRAD as it has same structure and content as EURAD but with a greater level of technical detail.
H2020 JOPRAD	To prepare a proposal for the setting up of a "Joint Programming on Radioactive Waste Disposal" to bring together at the European level those aspects of R&D activities implemented within national research programmes where synergy from Joint Programming is identified. The aspects of R&D activities brought together concern geological disposal of spent fuel and other high activity long lived radioactive waste, including waste management aspects linked with their disposal and accompanying key activities (Education and Training, as well as Knowledge Management). http://www.joprad.eu/fileadmin/Documents/JOPRAD_Deliverables/JOPRAD_D4.3_JOPRAD_meeting_on_Programme_Document_report_v1.pdf	Reviewed and sections identified
ERDO	Multinational working group to study the feasibility of implementing a shared geological repository in Europe. http://www.erdo-wg.com/documents/ERDO%20Strategy%20Document.pdf	Reviewed but no appropriate sections identified
EDRAM	An association of well-established organisations from eleven countries with responsibility for management of radioactive wastes in their respective countries. Two meetings are held every year to discuss the progress of work worldwide and the most recent developments in the different member countries, to support national efforts towards site selection and implementation of long-term disposal strategies and to promote a common understanding of waste management issues and the internationally recognised principles which apply thereto.	No SRA document available. Referred to work cited in IGD-TP Vision
WENRA	The Association of Regulators of Western Europe is an association of agencies or regulatory agencies in the field of nuclear countries of Western Europe with the intention of acting as a European network of chief regulators of EU countries with nuclear power plants to improve nuclear safety. http://www.wenra.eu/sites/default/files/publications/2019_wenra_strategy_2019-2023_final.pdf	Reviewed but no appropriate sections identified
EUR organisation	To develop common specifications for new designs to be proposed by Vendors in Europe and its promotion of harmonisation in requirements across Europe and worldwide. The EUR Organisation brings together thirteen Utilities which represent the major European electricity producers. The purpose is to present a clear, complete statement of utility expectations for Generation III NPPs. https://www.europeanutilityrequirements.eu/Portals/0/Documents/Courses/2014/EUR%20roadmap%202019-2021%20-%20Executive%20summary%20fin.pdf	Reviewed and sections identified

Area	Aims of the SRA/Outputs	Summary of Outcome
ENEF	A platform for a broad discussion about the opportunities and risks of nuclear energy, linked to the energy challenges faced by the EU and its Member States and in particular to the role of nuclear energy within the strategic framework for the energy union. ENEF gathers all relevant stakeholders in the nuclear field: governments of EU countries, European institutions including the European Parliament and the European Economic and Social Committee, representatives of the nuclear industry and regulators, electricity consumers, and civil society. https://ec.europa.eu/info/sites/default/files/enef2019conclusions_0.pdf	Reviewed but no appropriate sections identified
SITEX Network	Sustainable network for Independent Technical Expertise on radioactive waste management. To enhance and foster cooperation at the international level to achieve a high-quality expertise function in the field of safety of radioactive waste management. https://igdtp.eu/wp-content/uploads/2019/09/SITEX-II-D1.1_SRA_final.pdf	Reviewed and sections identified
IAEA - NEFW	This Section supports Member States to identify and apply safe, prompt and cost-effective solutions to manage all forms of radioactive waste resulting from the nuclear fuel cycle and nuclear applications	Projects reviewed but no publicly-available documentation identified
IAEA - IPN	A forum for the sharing of practical experience and international developments on radioactive waste management activities before disposal.	
IAEA - CRP T13017	Coordinated Research project under topic "Spent fuel management options". Covers management of wastes containing long-lived alpha emitters: Characterisation, processing and storage.	
IAEA Disponet	To enhance efficiency in sharing international experiences to ensure the application of safe and sustainable solutions in the disposal of low and intermediate level waste.	
IAEA - Labonet	International Network of Laboratories for Nuclear Waste Characterisation. Purpose is to increase efficiency in sharing international expertise on characterisation of low and intermediate level wastes.	

Each document review was carefully recorded in a purpose-built audit trail template (APPENDIX 1) where the reasoning behind each identified section could be captured or, conversely, if no pertinent text was identified this could be recorded to show that the document had been reviewed but discounted as not relevant to PREDIS.

Following extraction, the relevant SRA paragraphs were consolidated into a single draft PREDIS SRA document. Table 16 shows how the sections extracted from the various reviewed SRAs have been mapped to the appropriate sections in the PREDIS SRA. Whilst some SRA documents, such as EURAD, have content in most or all areas, others cover only one or two sections. The broad coverage of EURAD is expected as it covers all the areas of waste management & disposal and has also been used as the basis for the PREDIS structure. Importantly, Table 16 illustrates that relevant paragraphs have been identified in at least one existing SRA document for all of the PREDIS sections.

Table 16 – Mapping of SRAs to PREDIS areas

Areas	Nugenia Global Vision [9]	Nugenia Technical Area 5B [8]	IGD-TP-Vision 2040 [7]	MIND [30]	SNETP [31]	THERAMIN [15]	JOPRAD [6]	EUR [32]	SITEX II ToR [33]	SITEX II SRA [11]	WNA [10]
Methodology for identifying the SRA											
Predisposal Management - Waste generation											
Predisposal Management - Processing											
Predisposal Management - Storage & Transport											
Disposability Management - Disposability Assessment											
Disposability Management - WAC											
Way forward - Knowledge Management											
Way forward - Stakeholder Engagement											

A broad review of the extracted text highlighted a significant amount of duplication of topics across the different source SRAs. The next step therefore was to rationalise the text to eliminate this duplication. The text was reviewed, and several common themes topics were identified that could be assigned to keywords based on the PREDIS SRA sections, as shown in Table 17. In future iterations of this SRA, it is intended that these keywords will be refined to align with the WP3 Glossary of predisposal keywords.

Table 17 – Keywords assigned to SRA common topics

SRA Section	Keyword	Description
Waste generation	Planning	Waste management strategy, waste hierarchy, waste routes, technology selection
	Inventory	Sources and quantities of waste generated and in existing storage, future waste generation
	Classification	Characteristics of wastes in order to sort, classify and identify waste types
Processing	Treatment	Pre-treatment and treatment to minimise waste quantities and volumes
	Conditioning	Stabilise waste by conditioning
	Packaging	Containers and packaging for future transport, storage and disposal
Storage & Transport	Storage	Safe storage of wastes/packages including decay storage, interim storage and long-term storage

SRA Section	Keyword	Description
	Transport	Transport of wastes between facilities at different stages of predisposal management
Disposability Management	Disposability	Suitability of wasteform for disposal, behaviour within a disposal environment, implications for treatment, conditioning and packaging
WAC	WAC	Parameters and metrics for waste acceptance
Cross-cutting	Characterisation	Characterisation of wastes throughout the lifetime of wastes/packages
	Optimisation	Optimisation of the different phases of predisposal management
	Quality & Management	Quality and management systems, records management and monitoring required throughout the lifetime of the wastes/packages

The PREDIS SRA text was then reviewed again with reference to the keywords in Table 17, with up to four keywords assigned to each paragraph depending on relevance. It was then possible to use the assigned keywords to sort the text into groups of common topics, with the next step then being to remove duplication through the development of a single section of discussion for each topic, ensuring links are made to original SRA through references.

Following development of the PREDIS SRA structure and the list of topics and themes for consideration within the SRA, a workshop was held with the PREDIS partner organisations that had undertaken the initial SRA reviews to present the findings and obtain buy-in for the proposed structure and identified priority themes. The outcome of this workshop was a positive acceptance of the structure and themes, and it was recognised that the topics and themes identified from the review of existing SRAs were largely in line with those identified in a similar exercise undertaken for the Gap Analysis task 2.6 [1]. This provided good confidence that both the SRA and gap analysis were focusing on the appropriate topics.

Determining topics of common interest

Following establishment of the baseline document, the PREDIS SRA has been further developed through interactions with the PREDIS End User Group and wider stakeholders. The initial work during year 2 of the project involved the project team realigning the baseline document with the structure and needs of EURAD Theme 2 and considering the best engagement approach and the subsequent development of a survey/questionnaire to collate the needs and priorities from the stakeholder community. The engagement approach was devised by the PREDIS SRA delivery team between December 2021 and February 2022. The aim of the survey was to develop an understanding of the stakeholder priorities for research and the drivers behind these priorities.

The end users were asked to rank their five most important technical topics, and in addition to identify the three most significant drivers; the survey template is shown in Figure 6 with the technical topics on the vertical axis and the drivers on the horizontal axis. The survey was launched in March 2022 at an online meeting with the end user group. The list of drivers is consistent with those developed by the SHARE project.

			DRIVER											
			Societal			Actor Specific				Scientific		Financial		
	Technical Topic	Priority Topics (1 - 5)	Economic renewal & growth	Protect citizens & environment	Public trust & confidence	Processes, products & services	Improved performance	Contributes to competences and skills	Improve networks	Science quality and TRL	Innovation	Revenue, turnover	Investment	Sub-areas of key interest
Planning	Inventory	5		X	X		X							Understanding waste inventories from new fuel types.
	Waste Acceptance Criteria			X	X		X							
	Technology Selection					X	X				X			
	Cost Estimating		X									X	X	
	Funding		X									X	X	
	Waste Hierarchy	2		X	X		X							Waste tracking strategies. Waste segregation techniques.
Implementation	Characterisation	1			X		X				X			Remote characterisation. Physico-chemical characteristics
	Treatment Processing	4		X		X				X				Decontamination best practice.
	Conditioning & Packaging			X		X				X				
	Storage			X			X						X	
	Transport				X	X			X					
	Deployment Options		X	X				X						
Operations	Quality & Management Systems				X		X			X				
	Commissioning			X			X	X						
	Optimisation	3				X	X					X		Synergy between new and existing technologies
	Secondary Waste Management			X	X		X							
	R&D		X								X		X	
	Knowledge Management							X	X	X				
	Stakeholder Engagement				X		X		X					

Figure 6 – Illustration of the topic and driver matrix used in the survey

In total, there were 29 respondents to the survey, across a range of organisational types, as shown in Figure 7 below. It is noted that almost half the respondents were from waste management operator organisations, and this is reflected in the nature of the responses.

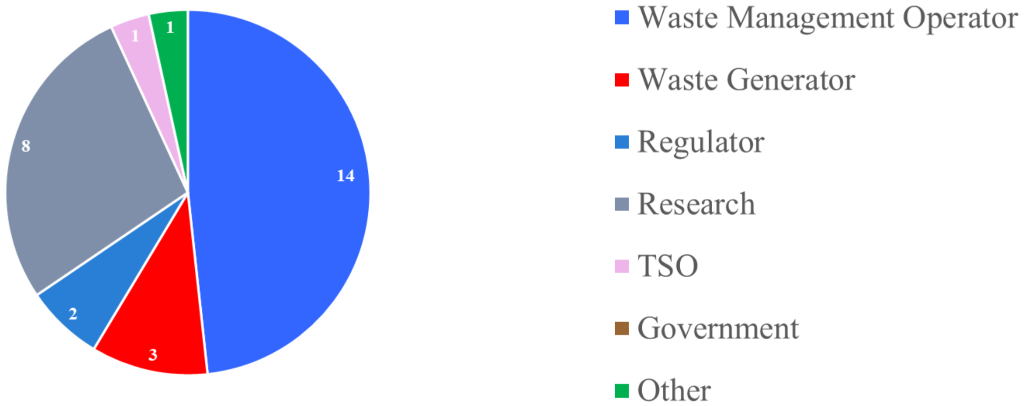

Figure 7 – Respondents to survey by organisation type

Figure 8 shows the 'heatmap' of responses on the selection of drivers for undertaking research in each technical topic area. The main drivers of interest are public and environmental protection, public confidence, improved performance, the development of products & services and the advancement of science & technology. As noted above, these results may reflect the respondent demographic being weighted towards waste management operators. The results of this survey were the basis for moving into a much wider programme of stakeholder engagement involving the whole predisposal community.

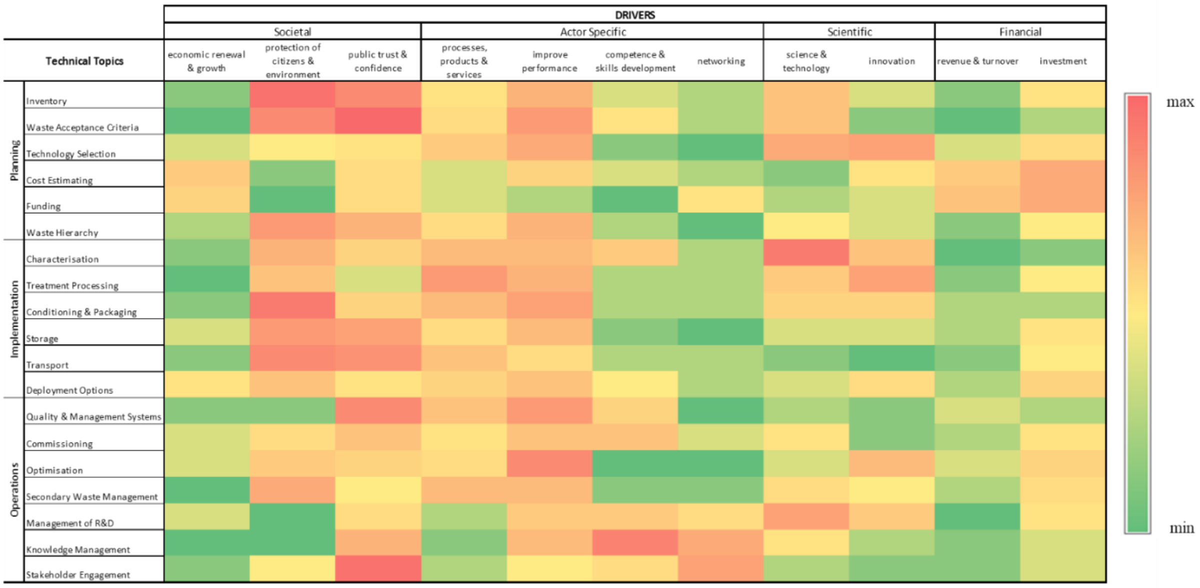

Figure 8 – Heatmap showing overall driver preferences given in the end-user survey

The final scores from the survey for the prioritisation of the technical topics are shown in Figure 9. There are seven key technical topics of interest, in descending order as follows:

- Characterisation
- Waste Acceptance Criteria (WAC)
- Conditioning & Packaging
- Treatment & Processing
- Inventory
- Technology Selection
- Optimisation

These seven priority topics were then discussed in more detail at a series of focus webinars, attended by the end-users, stakeholders, PREDIS partners and selected experts. The intention of the focus sessions was to elicit further information on each of the technical areas to understand the purpose behind the drivers, the specific R&D activities required and the urgency of each activity. The output from these sessions was collated and forms the basis of the technical content in Section 5 of this document. The remaining technical topics have not been discussed directly with the end-user group but are nevertheless included at a commensurate level of detail in the document, informed by the output from the user survey.

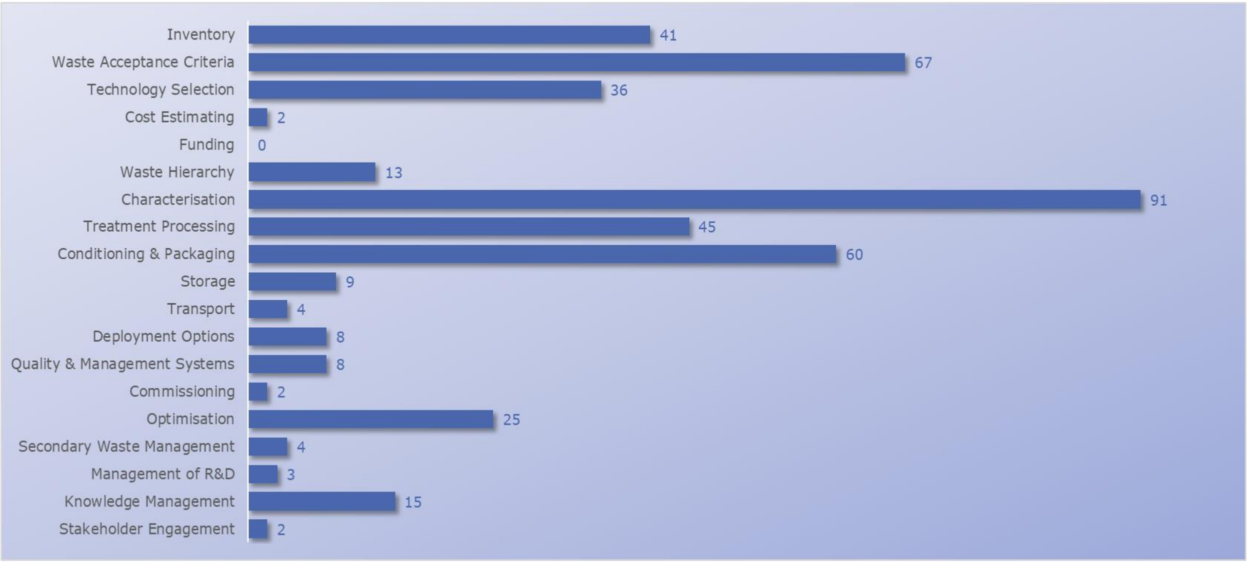

Figure 9 – Priority technical topics resulting from end-user survey

APPENDIX 2:

Audit Template used for SRA Document Review

PREDIS Strategic Research Agenda – Document review template

Document title	Document reference	Document type	Reviewer name	Reviewer organisation/affiliation	Date reviewed

Document section in initial report	PREDIS topics covered	Countries/States covered	Current or future view	Relevance score (Hi/Med/Lo)	PREDIS SRA section placed	Colour Code	Other comments

Guidance Notes

This template is to be used for the purposes of audit trail in reviewing the Strategic Research Agenda (SRA) documents. The reviewer should identify sections within the allocated SRA document(s) relevant to the PREDIS topic areas, extract these from the document and copy them into the accompanying PREDIS SRA template structure within the most appropriate section. Pasted text should be colour-coded within the PREDIS SRA structure using the highlighter tool to help identify which SRA document it has been extracted from. A separate audit template should be completed for each SRA document reviewed, with a separate entry being made in the audit template for each section extracted and copied. The fields above are to be completed as follows:

Document title: Enter the title of the SRA document being reviewed (e.g. Nugenia Technical Area 5B V. 2014).

Document reference: Enter the reference number of the document.

Document type: Enter the type of document being reviewed, e.g. SRA, roadmap, etc.

Reviewer name: Enter the name of the person reviewing the document.

Reviewer organisation/affiliation: Enter the name of the organisation for the person undertaking the review (e.g. NNL, VTT, etc.)

Date reviewed: Enter the start date of the review.

Document section in initial report: Enter the section number from the document being reviewed for the specific text being extracted.

PREDIS topics covered: Enter a brief summary of topic area covered in the text extracted (e.g. waste characterisation, asset management & care, etc.)

Countries/States covered: Enter the country or countries covered in the text if specific ones are covered. If not then enter N/A.

Current or future view: Enter ‘Current’ if the text reviewed is covering current technologies and/or practices, or ‘Future’ if it is covering future requirements.

Relevance score (Hi/Med/Lo): Enter ‘H’, ‘M’ or ‘L’ dependent on how relevant the text is to PREDIS requirements. This is a subjective assessment based on the opinion of the reviewer.

PREDIS SRA section placed: Enter the section number within the PREDIS SRA document that the text has been placed in.

Colour Code: Using the shading tool, fill in the cell with the colour being used to highlight the text pasted in the PREDIS SRA document to help identify it.

Other comments: Enter any other comments (e.g. further justification for the extracted text being selected).

APPENDIX 3:

Past and ongoing EU Activities/Projects Relevant to Predisposal Management of Radioactive Wastes

CARBOWASTE: Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste (EC Project 2008-2013) EC Grant agreement no: 211333 [26]

The Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste (CARBOWASTE) project focused on the development of guidelines and best practices to support the retrieval, treatment and disposal of irradiated graphite, both existing legacy waste and waste from graphite-based nuclear fuel from new reactors. The project considered methods for retrieval of graphite, decontamination and treatment technologies, and investigated the disposal behaviour of irradiated graphite wastes. Research undertaken as part of this project led to the development of techniques for separating the coated particles from the moderator graphite of high-temperature reactor fuel as well as the identification of thermal, chemical or microbiological treatments that can remove a significant proportion of the contamination. Overall, it was concluded that irradiated graphite waste can be safely disposed of in a wide range of disposal systems. However, in order to prove a safety case for any individual disposal facility, site-specific studies would be required. The feasibility of recycling and reuse of irradiated graphite was highlighted, although there is unlikely to be a sufficient market for significant quantities of irradiated graphite. A process for the evaluation and comparison of graphite waste management options for irradiated graphite was developed with multi-criteria decision analysis. Preferred options for different countries will vary depending upon specific national strategies, constraints and regulations. Overall, the key findings of the project were brought together into an integrated approach for the management of irradiated graphite.

CHANCE: Characterization of conditioned radioactive waste for its Safe Disposal in Europe (EC Project 2017-2022) EC Grant agreement no: 755371 (https://www.chance-h2020.eu/)

The CHANCE project aimed to address the specific issue of the characterisation of conditioned radioactive waste. The characterisation of fully or partly conditioned radioactive waste is a specific issue because unlike for raw waste, characterisation of conditioned waste is more complex and therefore requires more advanced non-destructive techniques and methodologies.

The first objective of the CHANCE project was to establish, at the European level, a comprehensive understanding of current conditioned radioactive waste characterisation and quality control schemes across the variety of different national radioactive waste management programmes. This was achieved based on inputs from end-user members such as Waste Management Organisations and storage operators.

The second objective of CHANCE was to further develop, test and validate techniques already identified that will improve the characterisation of conditioned radioactive waste, namely those that cannot easily be dealt with using conventional methods. Specifically, the work on conditioned radioactive waste characterisation technology focussed on:

- Calorimetry as an innovative non-destructive technique to reduce uncertainties on the inventory of radionuclides;
- Muon Tomography to address the specific issue of non-destructive control of the content of large volume radioactive waste;
- Cavity Ring-Down Spectroscopy (CRDS) as an innovative technique to characterise outgassing of radioactive waste.

EURAD: European Joint Programme on Radioactive Waste Management (EC Project 2019–2024) EC Grant agreement no: 847593 (https://www.ejp-eurad.eu)

The European Joint Programme on Radioactive Waste Management (EURAD) has been established to complement national programmes and enables effective use of resources by fostering and strengthening collaboration in RD&D and knowledge management. EURAD addresses all waste management-related topics, including predisposal and disposal. It is divided into WPs, tasks and sub-tasks consisting of RD&D activities, strategic studies and knowledge management activities.

Among the different WPs, WP9 ROUTES (Waste Management routes in Europe from cradle to grave) has the aim of describing and comparing the different approaches to characterisation, treatment and conditioning and to long-term waste management routes between Member States, to identify relevant R&D topics which could be collaboratively launched in the second wave of EURAD. Areas considered in ROUTES include categorisation/classification of radioactive wastes in different Member States; issues regarding the management and disposal of challenging waste; comparison of characterisation approaches; studies and plans for developing shared solutions for radioactive waste management in Europe; and Waste Acceptance Criteria and sharing of experience.

HARPERS: HARmonised PracticEs, Regulations and Standards in waste management and decommissioning (EC Project 2022–2025) EC Grant agreement no: 101060028 (https://www.harpers-h2020.eu)

The HARPERS "HARmonised PracticEs, Regulations and Standards in waste management & decommissioning" project has the overall goal of establishing and clarifying the benefits and added value of more aligned and harmonised regulations, practices and standards in decommissioning and radioactive waste management, including possibilities for shared processing, storage and disposal facilities between Member States. The project is focused on three main areas: (i) cross border services/facilities, (ii) circular economy, and (iii) advanced technologies. Obstacles and issues preventing implementation of a more common regulatory framework will also be identified. The high-level benefits of more aligned and harmonised regulations, practices and standards are related to 1) greater business opportunities, 2) better understanding between diverse groups serving wider markets, 3) improved cost efficiency, 4) waste minimisation and 5) improved final disposability of waste. Realisation of these high-level benefits would contribute to enhancing the overall safety and economics of the nuclear sector.

INSIDER: Improved Nuclear Site characterisation for waste minimisation in Decommissioning and Dismantling operations under constrained EnviRonment (EU project 2017-2021) EC Grant agreement no: 755554 (https://insider-h2020.eu)

The aim of the INSIDER project was to develop and validate an improved integrated characterisation methodology based on new statistical processing and modelling, coupled with present (and adapted) analytical and measurement methods, while taking into account sustainability and economic considerations, in the context of decommissioning. The project was aimed at improving the management of contaminated materials by proposing a methodology to define and select the best decommissioning and dismantling and remediation scenarios, and which produces well-characterised waste for which storage and disposal routes are clearly identified. In particular, this methodology would help to acquire characterisation data in a Medium and High radioactivity environment, which are the basis for decommissioning and dismantling scenario studies compliant with regulations in European countries. This would give access to a reliable vision of the radiological state of a facility (and/or its components) at a relevant confidence level, allowing the identification of the different decommissioning and dismantling scenario options. Three main case studies were considered: nuclear R&D facility, nuclear power plant and post-accident land remediation.

JOPRAD: Towards a Joint Programming on Radioactive Waste Disposal (EC Project 2015-2017) EC Grant agreement no: 653951 (http://www.joprad.eu)

The JOPRAD project had the aim of preparing a proposal for the setting up of a "Joint Programme on Radioactive Waste Disposal" to bring together at the European level those aspects of R&D activities implemented within national research programmes where synergy from Joint Programming was identified. The aspects of R&D activities brought together concern geological disposal of spent fuel and other high activity long lived radioactive waste, including waste management aspects linked with their disposal and accompanying key activities (Education and Training, as well as Knowledge Management). The project prepared a Programme Document listing key priorities along with a roadmap.

MICADO: Measurement and Instrumentation for Cleaning And Decommissioning Operations (EC Project 2019-2023) EC Grant agreement no: 847641 (https://www.micado-project.eu)

MICADO was aimed at improving waste management and Dismantling & Decommissioning (D&D) operations by proposing a cost-effective method for non-destructive characterisation of nuclear waste, defining the associated digitisation process and creating a database to manage the characterisation data. MICADO has provided a proof of concept system called the Radiological Characterisation & Monitoring System (RCMS) DigiWaste platform, with the aim of enabling i) faster execution of radiological measurements, ii) optimised characterisation of a nuclear waste package combining non-destructive methods and tools that are already used as reference, iii) accurate tracking and long-term monitoring of nuclear waste and iv) efficient digitisation of the full characterisation and logistical processes.

SHARE: StakeHolders-based Analysis of Research for Decommissioning (EC Project 2019-2022) EC Grant agreement no: 847626 (https://share-h2020.eu)

The goal of the SHARE project was to identify the technical and non-technical needs in the international stakeholder community to provide a roadmap for developments that will help reduce costs, minimise waste and the environmental impact, and improve worker safety in decommissioning projects. The needs were determined and consolidated together with the stakeholder community in an iterative and inclusive process based around the key thematic areas in the decommissioning process: safety and radiological protection, project management and costing, human resources, characterisation, site preparatory activities, dismantling and decontamination, material and radioactive waste management, and environmental remediation.

SHARE provided an SRA [2] and Roadmap [3] as a final outcome based on the valuable data generated during the project. Activities in the SRA and Roadmap were assigned to different categories: RD&D for activities that create knowledge including benchmarking and technology development, Knowledge Sharing for activities that demand dissemination, Harmonisation of Practices for activities that require at least the adoption of best practices but can include regulatory measures, and Education and Training for activities that aim at creating and developing workforce competencies. The categorised activities of common interest were prioritised according to the importance of the SHARE weighted survey reflecting the stakeholders' point of view.

THERAMIN: Thermal treatment for radioactive waste minimization and hazard reduction (EC Project 2017–2020) EC Grant agreement no: 755480 (http://www.theramin-h2020.eu) [15]

The Thermal Treatment for Radioactive Waste Minimization and Hazard Reduction (THERAMIN) project was aimed at providing improved safe long-term storage and disposal of ILW and LLW streams suitable for thermal processing. Work carried out within the project aimed to identify radioactive wastes that could benefit from thermal treatment, which treatment technologies were under development in participating countries, and how these could be combined to deliver a wide range of benefits.

The project successfully demonstrated the applicability of different thermal treatment technologies (incineration-vitrification: SHIVA process; vitrification: In-Can Melter and GeoMelt®; thermal gasification; hot isostatic pressing) to a range of waste groups representative of those identified in participating countries. The thermally treated products of these and other trials were characterised and these data used to undertake preliminary disposability assessments. Finally, THERAMIN developed a value assessment methodology that can be used to identify the benefits and challenges of thermal treatment compared to the baseline options, which can be used to inform strategic consideration of thermal treatment as the baseline for waste groups studied within the project.

The following areas of further work were identified during the project:

- Maintenance and development of the community of thermal treatment specialists developed through the THERAMIN project.
- Gathering of further information to support comparison of thermal treatment technologies against the baseline for specific waste streams.
- Optimisation of thermally treated product composition to increase waste loadings and/or improve wasteform performance.
- Development of waste acceptance criteria for thermally treated products.
- Understanding of the long-term behaviour and chemical durability of thermally treated products.