

Predisposal Radioactive Waste Management (PREDIS) Project Final Achievements and Impacts Overview

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Abstract. The PREDIS project on Predisposal of Radioactive Waste has succeeded in developing and implementing new methods, processes and technologies for treatment of challenging low-level waste (LLW) and intermediate level waste (ILW) streams. Over the 4-year duration, this Euratom project of 47 partners from 17 Member States has worked in close collaboration with 25 End User industrial members to advance the technologies associated with predisposal issues. This has included characterisation followed by treatment, conditioning and processing of metallics, liquid organic and solid organic wastes as well as with digitalization technologies for assessing performance of concrete waste packages and pre-disposal storage. Long-term modelling and performance testing have been done to verify the safety and effectiveness of the new or enhanced solutions. Value Assessments were done for some of the new solutions to ensure implementors would have sufficient tools for making choices about the potential implementation. This included life-cycle assessment of quantitative sustainability indicators and life cycle-costing for economic indicators. This project addressed new guidance on Waste Acceptance Criteria and contributed with a revised Strategic Research Agenda to guide future predisposal activities, complimentary to the holistic waste management programme. Knowledge Management actions were also an integral part of the whole project to foster competence development and capturing knowledge. Actions included training, mobility, and guidance especially through online forums such as webinars and digital training. This paper provides a snapshot of some of the key outcomes and impacts from the project, from technical as well as strategic and knowledge perspectives.

1 Introduction

The PREDIS project “Predisposal management of radioactive waste” aimed at effectively developing and implementing new methods, processes, technologies and demonstrators for the pre-disposal treatment of challenging low-level waste (LLW) and intermediate-level waste (ILW) streams. The consortium of 47 organizations from 17 European countries brought together expertise and innovation from leading researchers in nuclear technologies to form a programme underpinned by ambition and excellence. The project outcomes targeted to benefit many Member States, where low-level and intermediate-level waste makes up a large fraction of the total waste pro-

duced. Large volume savings can be made utilizing waste hierarchy principles and finding solutions to such waste with no present waste route. The waste hierarchy refers to minimizing the waste going to final disposal by implementing upstream earlier actions of waste prevention, followed by waste minimisation, re-use of materials and recycling. The technical scope of work for ILW and LLW predisposal activities included material characterisation, processing, treatment, storage and acceptance of waste streams for final disposal, with a focus on metallics, organics and concrete waste packages including digitalization technologies. Knowledge management and strategic implementation holistic actions were also included in the project.

PREDIS [1,2] had close synergy with the European Joint Partnership on Radioactive Waste (EURAD,

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Project #847593, 2019-2024) [3], with the aim to supplement the reinforce the scope of predisposal within their Roadmap by also integrating the research challenges, best practices and knowledge of the waste producers. Complementary engagement took place with other existing and emerging networks of international parties, including SNETP (Nugenia), IGD-TP, SITEX, EuradScience, IAEA, NEA and multiple EC-funded projects.

There were five main objectives of the PREDIS project, as:

- applying multi-disciplinary and multi-scale scientific approaches to demonstrate new solutions
- addressing project drivers from the end user's point of view
- fostering deeper cooperation between experts from many EU Member States
- training new experts in the field of predisposal waste management technologies, and
- updating and revising predisposal guiding documents.

How these objectives were met by the Key Performance Indicators is elaborated on in the next section, followed by the more concrete examples the subsequent section.

2 Overall Key Performance Indicators

The final outcome of how Key Performance Indicators (KPIs) were achieved linked to the project objectives are summarised in Table 1 below. This summary table is taken from the project's final periodic report, similar to as was reported in the final conference with supporting proceedings [4].

Towards the first objective of applying multi-disciplinary and multi-scale scientific approaches to demonstrate the new solutions, at least 14 increases of Technology Readiness Level (TRL) and innovations were achieved in Work Packages (WPs) 4–7, at least 45 technical or scientific open access journal publications were published and 23 were either submitted and under review or to be submitted, and 3 patents or invention notifications (pre-patent) were generated. In addition to the scientific papers, the project has produced a wealth of knowledge at varying level of details, including 66 deliverable reports, 8 summary newsletters, 4 case studies, 3 blogs, and over 100 conference presentations, most of which can be downloaded from the project web page [1]. The project embraced the online and virtual environment, hosting 20 webinars with over 500 individual participants from over 40 countries, where the videos are available for further knowledge sharing and lectures can be used as training modules.

For addressing the second objective of steering the project from the end users' point of view, and the third objective of cooperation, 25 organisations participated to End User Group (EUG), and at least four demonstrations of new technologies took place (WP4–7) within the partner organisations. The adoptions or refining of national Waste Acceptance Criteria (WAC) based on project guidelines (WP2) was not able to quantify during the project, but over 250 EUG/stakeholders from over 20 different

countries participated to the three webinars on WAC and the WAC documents have been widely disseminated. PREDIS has also actively participated in discussions with Small Inventory Member States (SIMS) to understand their needs and hopefully uptake of results, including WAC, in the future. Fostering deeper cooperation between experts from many EU Member-states succeeded well, as at least 9 countries outside PREDIS consortium participated to the workshops and there were over almost 200 individual subscribers from 29 countries to the project newsletter.

KPIs on training new experts in the field of pre-disposal waste management technologies were exceeded: 51 PhD and Postdoc students were part of the project, 65 mobilities were performed between partners and 8 training modules were produced (WP3), in cooperation with EURAD. For updating and revising pre-disposal guiding documents, feedback from EUG to the Strategic Research Agenda (SRA) [5] was received in three webinars with over 150 participants from EUG/stakeholders and project feedback from EUG members at annual workshops was excellent (range from 4.2 to 4.9 out of 5 by different groups of participants, with a score of 5 being highest approval).

Producing cooperative deliverables with EURAD programme was achieved through production of 12 domain insights to support EURAD's Roadmap [6] of Theme 2 as part of Knowledge Management. Close collaboration was also performed with Waste Acceptance Criteria work between PREDIS and the EURAD ROUTES Work Package. Over 20 partner institutes were active in both projects, and there were multiple joint publications and presentations given at conferences, especially on issues of joint knowledge management activities and the common strategic research agenda where PREDIS contributed to the Theme 2 Predisposal portion of the EURAD Strategic Research Agenda [5,7].

3 Example Key Results and Impacts

The following sections provide a short overview of the key resulting impacts from each of the work packages in the project, with the first two being more holistic topics and the later four being more technical. More detailed results can be found from the project's final conference proceedings [4] and various project deliverable reports.

3.1 Knowledge management

The knowledge management (KM) programme included training, mobility and production of guidance documents. The objectives were to generate and capture knowledge, especially for the next generation of experts in radioactive waste management. One specific targeted aspect was integration of knowledge management in all PREDIS activities (student group, project management and R&D WP) as well as avoiding work duplication by aligning PREDIS KM activities with EURAD, IAEA and OECD/NEA [8]. At the outcome of the project, PREDIS had contributed with:

Table 1. The KPIs as identified in the project proposal, with the right column indicating the self-assessment status of the relevant KPIs at the end of the project.

Project's specific objective	KPI as measure of success	Targets, by project end	Achievement, at the project end	
Applying multi-disciplinary and multi-scale scientific approaches to demonstrate the new solutions	Increase of TRL and innovations, WP4–7	At least +1 TRL level increase for 10 or more innovative solutions		≥ 14
	Technical/scientific journal publications (open access)	At least 25 submitted		≥ 45
	Generate invention notifications (pre-patent)	At least 4 submitted		3
Addressing project drivers from the end users' point of view	Participation of industry to EUG	At least 20 at start, 30 by project end		25
	Demonstration or trial deployment of new technologies (WP4–7)	At least 3 by EUG members, in different Member states		4, at partner institutes
	Adoption or refining of national WAC based on project guidelines (WP2)	At least 8 EUG members implement		still to be seen
Fostering deeper cooperation between experts from many EU Member-states	Engagement of other countries, beyond PREDIS membership	Participants from at least 5 other countries to workshops		≥ 9
	Individual subscribers to project newsletter (WP1)	At least 200, from over 25 countries		About 200, 29 countries
Training new experts in the field of pre-disposal waste management technologies	Number of PhD and Postdoc students (see Table 3.4c)	At least 15		51
	Number of mobility between partners (WP3)	At least 20		65
	Number of training modules produced (WP3), in cooperation with EURAD	At least 6		8+12
Updating and revising pre-disposal guiding documents	Producing cooperative deliverables with EURAD	At least 5		12 Domain Insights
	Completed feedback from EUG for SRA (WP2)	At least 20		≥ 150 participants in the process
	Project feedback from EUG members at annual workshops	Average score 9.6 out of 10 (survey questions)		4.2-4.9, out of max 5

- involvement of 51 students,
- providing 65 mobility grants for collaboration between partners, especially among next generation experts,
- hosting 19 public webinars, including technical lectures and end user case studies, as well as discussion groups to foster collaboration and sharing,
- holding 8 training courses, both in-person, hybrid and on-line,
- knowledge capture with:
 - 4 blogs and 3 case studies,
 - 12 domain insight documents and one theme overview on predisposal topics, thus complementing the EURAD Roadmap [6],
 - 1 terminology glossary,

- dissemination of KM progress at 11 conferences, including various oral presentations, papers and posters.

Special attention was paid to monitor and evaluate the quality and fulfilment of trainees and mobility grantees expectations. Analysis of respondents' feedback showed an overall high satisfaction of trainings and mobility measures (between 4.2 to 4.8 on a scale up to 5, where 5 denotes excellent) [9].

3.2 Strategic implementation

The activities in this work package focused on strategic issues of importance in predisposal and more broadly

in the waste management lifecycle and delivered all of the expected impacts. One area of focus was the important issues of waste acceptance criteria (WAC) and waste acceptance systems for storage and disposal. Through a collaborative approach across the consortium a series of guidance documents were published based on international best practice and experience, to underpin these issues. The guides provide help to the different radioactive waste management programmes across Europe, particularly those at the early stages of development of their radioactive waste management and disposal solutions. This included key guidance documents on development of generic waste acceptance systems [10] and the formulation of generic waste acceptance criteria [11].

Life cycle assessment (LCA) and Life Cycle Costing (LCC) approaches have been developed and implemented across the PREDIS programme. An initial review of literature [12] confirmed that there was only a very limited use to date, particularly in the area of radioactive waste management (decommissioning, predisposal and disposal). However, LCA and LCC models were developed and utilised across the project to demonstrate the environmental sustainability and economic viability of technologies under development in PREDIS, and where possible to optimise the processes during R&D phases [13]. A protocol for these techniques has also been developed [14] and training delivered to aid the deployment of the techniques by others beyond the PREDIS consortium.

End users are vital if R&D is to translate into industrial impact. The project established strong and diverse End User and stakeholder networks from the start, in fact industrial end users were involved in the scoping of the project. This engagement continued throughout and played a significant role in the project [15] and in the development of the first SRA focussed specifically on predisposal waste management [5]. The SRA sets a direction for predisposal research, development and innovation in Europe, in the areas of greatest opportunity and impact based on end user priorities.

3.3 Metallic waste streams

This work package focused on new approaches to metal waste treatment and conditioning, which could potentially minimise waste volumes, increase recycling and offer new analytical techniques for difficult to measure radionuclides (DTM). Highlights of the work package included the optimisation of a chemical/gel decontamination methods of metallic waste with complex geometries, secondary waste effluents management, and development of new formulations for magnesium phosphate cements which could reduce costs of waste treatment compared with standard cements (e.g. replacing the expensive dead burnt MgO by reactive magnesia). A great success of the work package noted was the contribution towards the provision of raw materials by end users (for example, fly ash provided by EDF) demonstrating the value in completing the work as part of an international cooperation project.

An optimised chemical treatment process, Chemical Oxidation REDuction using nitric permanganate and

oxalic acid MIXture (COREMIX), has been developed. It involves the dissolution of the contaminated oxide layer formed on the metal surface. Based on a LCA/LCC study, optimisation included the use of less toxic chemicals (safer, more environmentally friendly and more cost-effective), reduction of treatment time (lower energy consumption, less CO₂ emission), and higher chemical and radiological compatibility with WAC for the conditioning/storage steps. Secondary waste effluents treatment advanced well and included oxide chemical precipitation, ionic liquids and electrochemical precipitation.

Inorganics have been tested successfully to decontaminate metallic waste (e.g., Ni-alloys and stainless steels) resulting in no secondary effluent (only solid waste which can be vacuumed for collection). A new gel formulation integrating magnetic particles has also been tested for remote application for difficult to access surfaces (applicable to low-level waste so no concern about activation of iron). Electrochemical gel decontamination (EASD) has been tested (advanced from TRL6 to TL7) and has proved a fast treatment ($\sim 0.5 \mu\text{m}/\text{min}$ removal for stainless steel) and can be deployed in-situ to target radiation hot spots.

Pre-dismantling waste classification using a modelling approach combined with gamma spectrometry has been demonstrated (using neutron calculations and scaling factors methodology) leading to improve waste sorting (based on surface and volume activity determination for key radionuclides) which can be used to improve radiological characterisation on activated reactor components. The method allows determination of activities of Cs-137 and Co-60 at the level of clearance in 1–2 min (amount of metallic waste about 100 kg) (advanced from TRL3 to TRL5).

Difficult to measure radionuclides (DTM) studies included key isotopes $^{59}\text{Ni}/^{63}\text{Ni}$, ^{93}Zr and ^{41}Ca and involved the development of specific separation and purification protocols. Issues including calibration methodologies have been addressed and solved given the difficulties to procure certified standards of the isotopes of interest. Inter-comparison exercise will be held to validate the experimental results.

Magnesium Phosphate Cements (MPCs) formulations have been developed using alternative fillers to fly ash, offering an alternative encapsulant for specific metal wastes that are prone to corrosion in high pH cement matrices. Production tests indicate 15% cost reduction and better curing achieved if higher moisture used. Qualification tests of the new formulations completed for corrosion and irradiation resistance with a range of encapsulated reactive metals (aluminium, carbon steel and beryllium).

3.4 Liquid organic waste streams

This work-package focussed on testing (up to TRL 6) the use of a new class of mineral binders such as Geopolymers and related Alkali Activated Materials (AAMs) for conditioning of liquid organic wastes. Highlights of the work package included formulations for AAMs, which demonstrated a range of performance for different liquid organic wastes (for example, kerosene, liquid scintillation cocktail)

using alternative binders. A success of the work package was the improved understanding developed on the importance of the water to solid ratio (e.g., porosity of conditioning matrix) when conducting leaching experiments for samples exposed to irradiation, thermal and fire hazard conditions [16].

Data collected from across Europe indicates that the key reference radioactive liquid organic wastes are oils, solvents and scintillation cocktails, which can be directly mixed with raw materials and additives to formulate conditioned matrices (most common are Metakaolin, Blast Furnace Slag and Fly Ash). Optimised formulations using these three options have been developed within PREDIS. The most promising is Metakaolin-based geopolymer (now at TRL level 5/6). Further optimisation is required for Blast Furnace Slag-based geopolymer, which could not achieve the same percentage waste loading, and so no overall cost benefit for the approach compared to typical incineration and volume reduction. Leaching and waste release data for the formulations are also positive (with respect to long-term storage and disposal requirements) for oil mixes, but further work needed for solvents and scintillation cocktails.

The use of geopolymers has been tested at larger scale (50 litre and 100 litre drums with 35–45 minute mixing times, TRL 6) using a liquid organic radioactive waste surrogate (various weight % waste loadings) [17] and long-term performance data (for storage and disposability assessment) collected with embedded sensors to the drums including: thermal performance, homogeneity (e.g., extent of uniform distribution of materials within the geopolymer matrix) and compressive strength tests.

Application of a value assessment methodology was successfully used to analyse the performance of alternative waste management options for liquid organic wastes compared with the typical current waste management approach (i.e., baseline scenarios). The higher waste loading achievable with geopolymers in comparison with absorption/ cementation (oils and scintillation cocktails) leads to benefits in terms of safety, materials use and cost.

3.5 Solid organic waste streams

This work package addressed solid organic wastes, often those resulting from thermal treatment routes that are currently being considered to treat radioactive materials, including treatments by: plasma incineration, combined incineration/gasification, molten salt oxidation, wet oxidation and hot isostatic pressing. Highlights of the work package included formulations for AAMs, which demonstrated a range of performance for different liquid organic wastes (for example, kerosene, liquid scintillation cocktail) using alternative binders. Key successes of the work package include demonstrated matrix reliability for thermally treated products (data from short-term leaching experiments, characterisation of condition waste form and long-term durability tests) and feasibility of encapsulation using geopolymer and cement-based materials (proof of concept from TRL 2/3 to TRL 5).

This project showed that the IRIS process (pyrolysis/calcination) could be used to treat solid organics and ion exchange resins resulting in secondary waste ash which overall provides a significant waste volume reduction.

To assess the stability and durability of conditioned waste under experimental conditions that are as close as possible to the conditions expected for final disposal, a common protocol has been elaborated [18], taking into account the different national requirements and the proposal made within the framework of EURAD-ACED.

The assessment of economic, environmental and disposability impacts clearly shows that new treatment technologies generally offer benefits compared with current options (material environmental impact, package disposability and the disposal and storage costs for the product drums). Uncertainties remains associated to certain technology that are at lower TRL, but further development to the point where operating TRL 9 versions of these treatment facilities are available would remove or lessen many of the negatives or uncertainties, in which case they could in future become more sustainable, less costly alternatives [19].

3.6 Concrete packages and digitalisation

This work package specifically advanced cemented waste handling and storage, leading to improved operations, cost reduction, enhanced safety, and a deeper understanding of waste characteristics prior to disposal. The work started by analysing the current state of packaging, storage, and monitoring for cemented waste. It identified industry needs, guiding the work scope, and selected a reference package and degradation mechanisms for further study. Key findings included the common use of cement grouting, metallic drums, and concrete containers in Europe, with monitoring mostly through visual inspections. Major issues were corrosion, cracking, and alkali-silica reaction (ASR). The task recommended a reference package for testing and improvements in waste management practices. One of the tasks focused on advanced radioactive waste drum integrity testing with new technologies: gamma and neutron radiation monitoring (SciFi/SiLiF), acoustic emission for ASR detection, non-contact ultrasonic inspection, RFID sensors, a LoRa wireless network, and Mu-Tom imaging. These innovations show promise for continuous remote monitoring but require further optimization for better data reliability and accuracy. Future efforts will focus on validating and improving these technologies in real-world applications to enhance waste storage safety and effectiveness. Another task developed a proof of concept for using Digital Twin (DT) technology in radioactive waste management. The DT uses machine learning to predict the geochemical and mechanical changes in waste packages over time. The DT dashboard on the geoml platform enables real-time monitoring and decision-making. Future work will refine models and inference methods to improve prediction accuracy, using data from a 30-year-old low-level waste drum in Switzerland and ongoing experiments. These advancements aim to enhance radioactive waste storage management and safety.

This work package also established a secure data management framework for cemented radioactive waste. Key achievements include a comprehensive data system, translating NDE and monitoring data into actionable parameters, and integrating multi-method data for improved decision-making. It developed advanced models and techniques for data integrity and security, explored NFTs for digital traceability, and AI-based machine learning for property recognition. These innovations aim to enhance the reliability and efficiency of radioactive waste management.

The final actions in this work package were to demonstrate monitoring and automation technologies from WP7 in real storage environments (done at partner institutes at UJV, NNL, and INFN). Over three months, these technologies were tested for waste package monitoring, with a user-friendly dashboard for data integration and display. The demonstration highlighted their strengths and areas for improvement, with further industrial testing needed to validate practical usability and effectiveness for enhanced radioactive waste management.

4 Conclusion

During the 4-year implementation, the PREDIS project has successfully met its objectives of applying multi-disciplinary and multi-scale scientific approaches to demonstrate new solutions. Industrial end users' viewpoints were maintained through the technology development on treatment and conditioning of LLW and ILW metallic and organic waste streams, as well as digitalisation technologies for performance assessment of concrete package and storage conditions. Through knowledge management activities, extensive training of new experts was done and the whole project's engagement fostered deeper cooperation within EU Member States and worldwide. In addition to over a hundred technical reports and publications, there were also over a hundred of presentations and twenty online webinars and training sessions available for knowledge sharing. Over 500 persons were engaged in the project, including over 50 next generation experts (students). The synergies with the wider community were strengthened with over 2000 stakeholder individuals participating to free events, including those from the wider EURAD community to promote holistic waste management practices from generation toward disposal. Guidance was provided through an updated strategic research agenda, waste acceptance criteria and quantitative sustainability indicators of life cycle assessment and life cycle costing to help make informed choices during a value assessment prior to implementation of new solutions. This project will continue its momentum through contributions to the predisposal topics of collaboration within the new joint partnership of EURAD-2 for 2024–2029 period.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

Data associated with the results of this project can be provided upon request. The data is maintained by the Coordinator in accordance with the project's data management plan.

Author contribution statement

Writing – Original Draft Preparation Erika Holt; Writing – Review and Editing – all other co-authors.

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