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Final project report on innovations in cemented waste handling and pre-disposal storage

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Abstract

This report provides a comprehensive overview of the PREDIS project's Work Package 7 (WP7), which targeted innovations in the handling, monitoring, and pre-disposal storage of cemented radioactive waste, aiming to improve storage operations, reduce costs, enhance safety, and provide a better understanding of waste characteristics before final disposal. The report is structured to cover the objectives, approach, deliverables, and outcomes of each of the technical tasks within WP7.

Task 7.2 “State of the art in packaging, storage, and monitoring of cemented wastes” involved compiling a comprehensive report on the current methods and procedures for managing cemented waste packages. A questionnaire was distributed to gather information on cemented waste management practices across Europe. The responses highlighted the widespread use of cement grouting and the common use of metallic drums and prismatic concrete containers. The work in Task 7.2 also identified key degradation phenomena such as corrosion, cracking, and Alkali-Silica Reaction (ASR), and recommended a reference package for further study in WP7.

Task 7.3 “Innovative integrity testing and monitoring techniques” focused on developing and testing various monitoring technologies for cemented waste packages. These technologies included SciFi and SiLiF for radiation monitoring, Acoustic Emission for measuring ASR, non-contact ultrasonic scanning for detecting package defects, RFID embedded sensors for measuring temperature, pressure, and humidity, Sensorised Long-range Radio wireless sensor network for radiation monitoring, and muon tomography for inspecting package contents. These technologies demonstrated potential for continuous remote monitoring and early detection of anomalies, though future work is required to further develop and validate the technologies in real-world end-user facilities.

Task 7.4 “Digital Twin” aimed to develop a proof of concept for certain aspects of Digital Twin (DT) technology in the pre-disposal management of radioactive waste packages and demonstrate the use of machine learning algorithms to predict the geochemical and mechanical evolution of waste package over time. A DT dashboard was developed, providing real-time monitoring and decision support. The task also explored the use of surrogate models and Bayesian inference methods to improve computational efficiency and accuracy in parameter estimation.

Task 7.5 “Data handling, processing and fusion” established a framework for secure data management and processing. It involved developing a comprehensive data management system, translating monitoring data into engineering parameters, and integrating multi-method monitoring data for informed decision-making. The study explored the potential use of Non-Fungible Tokens and machine learning for long-term data management.

Task 7.6 “Demonstration and implementation of monitoring, maintenance, and automation/digitalisation techniques” aimed to demonstrate the viability of the developed technologies in a real storage environment. Selected technologies were tested in a storage configuration at UJV, Czech Republic, and other locations at the National Nuclear Laboratory (NNL, UK) and the National Institute for Nuclear Physics (INFN, Italy) using a set of mock-ups. The demonstrations confirmed the feasibility of the technologies for continuous monitoring and data transmission.

Finally, Task 7.7 “Dissemination and Reporting” focused on disseminating the findings of the project through various channels, such as conferences, workshops, and publications. This task also involved conduct of a value assessment to evaluate the economic, environmental, and safety impacts of the developed technologies in comparison to current practices. This process involved close collaboration between technology developers and the End Users Group (EUG) through a series of workshops to discuss the outcomes of the value assessment and incorporate EUG feedback into the project deliverables.

Keywords

Radioactive waste, cemented waste, pre-disposal management, monitoring technology, waste storage, integrity testing, digital twin, data management, automation, digitalisation, non-destructive evaluation, sensor technology, value assessment, package degradation, safety and maintenance, innovation

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Notification

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2) LIST OF ACRONYMS

AE	Acoustic Emission
AI	Artificial Intelligence
ALARA	As Low As Reasonably Achievable
ANN	Ansaldo Nucleare SpA (Italy)
ARM	Azure Resource Manager
ASR	Alkali-Silica Reaction
BAM	Bundesanstalt für Materialforschung und -prüfung (Federal Institute for Materials Research and Testing in Germany)
BFS	Blast Furnace Slag
BZL	Swiss Federal Interim Storage Facility
DT	Digital Twin
EC	European Commission
ENSI	Swiss Federal Nuclear Safety Inspectorate
EUG	End User Group
EURAD	European Joint Programme on Radioactive Waste Management
GSL	Galson Sciences Limited; UK
IAEA	International Atomic Energy Agency
IFE	Institute for Energy Technology (Norway)
ILW	Intermediate Level Waste
INFN	Istituto Nazionale di Fisica Nucleare (National Institute for Nuclear Physics; Italy)
IT	Information Technology
KIT-INE	Institute for Nuclear Waste Disposal of the Karlsruhe Institute of Technology; Germany
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LLW	Low Level Waste
LoRa	Long-range Radio
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
Mu-Tom	Muon Tomography
NDA	Nuclear Decommissioning Authority
NDE	Non-destructive Evaluation
NFT	Non-Fungible Token
NNL	National Nuclear Laboratory; UK
NRG	Nuclear Research and Consultancy Group; Netherlands
OLAP	Online Analytical Processing
OPC	Ordinary Portland Cement
PREDIS	Pre-Disposal Management of Radioactive Waste
PSI	Paul Scherrer Institute; Switzerland
R&D	Research and Development
RCA	Recycled Concrete Aggregate
RFID	Radio Frequency Identification
SciFi	Scintillating optical Fibre
SCK CEN	Studiecentrum voor kernenergie (Belgian Nuclear Research Centre)
SiLiF	Silicon Lithium Fluoride

SoTA	State of the Art
TRL	Technical Readiness Level
UJV	Ústav Jaderného Výzkumu (Institute of Nuclear Research in Řež, Czech Republic)
UNIPI	University of Pisa; Italy
VTT	VTT Technical Research Centre of Finland Ltd
WP	Work Package

1 Introduction

1.1 Background to the PREDIS Project

The pre-disposal management of radioactive waste (PREDIS) project was a four-year (2020-2024) programme of research and development (R&D) targeting the development and implementation of activities for pre-disposal treatment and management of radioactive waste streams other than nuclear fuel and high-level radioactive waste. The project was funded by the European Commission's (EC's) Euratom Research Programme [1].

The project was structured around the following seven Work Packages (WPs):

- WP1 – Management and dissemination.
- WP2 – Strategic implementation.
- WP3 – Knowledge management.
- WP4 – Innovations in metallic waste treatment and conditioning.
- WP5 – Innovations in liquid organic waste treatment and conditioning.
- WP6 – Innovations in solid organic waste treatment and conditioning.
- WP7 – Innovations in cemented waste handling and pre-disposal storage.

The relationship between the WPs and the overall PREDIS project structure are shown in Figure 1-1. WPs 4 to 7 comprise the primary technical topics within PREDIS. The overall strategy is considered in WP2 and is informed by the technical topics. WP3 concerns knowledge management and includes designing and defining training programmes covering the content of WPs 4 to 7, gathering the state-of-the-art on pre-disposal activities and interfacing with the European Joint Programme on Radioactive Waste Management (EURAD) project to ensure consistency. WP1 concerns project management and dissemination and spans all of the WPs.

The PREDIS consortium included 47 partners from 18 Member States, as well an End Users Group (EUG), which specifically targeted radioactive waste producers as a separate group within the radioactive waste management community. PREDIS also encompassed the wider European Community, allowing cross-fertilisation and interaction between different national programmes.

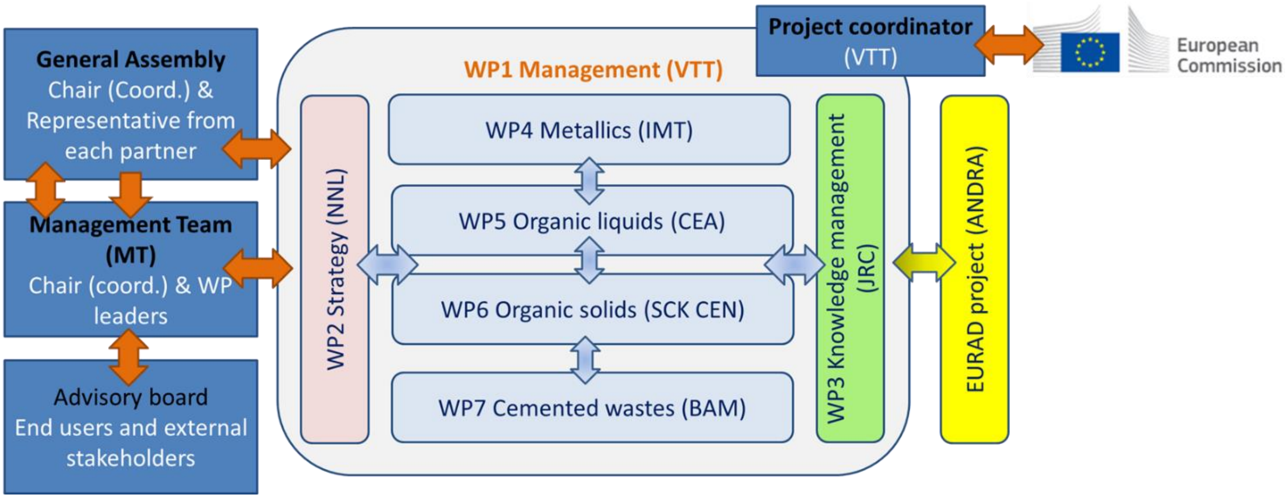


Figure 1-1: The organisational structure of the PREDIS project and relationship between its WPs. The lead organisation for each WP is shown in brackets.

1.2 Scope and Objectives of PREDIS WP7

Within the PREDIS project, WP7 focused on innovations in cemented radioactive waste handling, monitoring, and pre-disposal storage. For many decades, grouting/cementation has been recognised and deployed as a suitable treatment route for the immobilisation of radioactive waste streams in most member states. Therefore, innovation in this area will have significant impact in terms of improved storage operations, including cost and safety (for example, in reducing intervention and repackaging), and improved understanding of the characteristics of the waste prior to final disposal. The objectives of WP7 as outlined in the PREDIS grant agreement [1] were to:

- Compile information about the state of the art (SoTA) of current methods and procedures for cemented waste management with specific focus on monitoring and long-term storage.
- Perform a gap analysis to assess the technology readiness, technology gaps, urgency and important of technology developments during the first year of the project.
- Identify, evaluate, and demonstrate store and package quality assurance (mainly Non-destructive Evaluation (NDE)) and monitoring technologies.
- Adapt and demonstrate Digital Twin (DT) technology.
- Develop and demonstrate methods for data handling.
- Develop and demonstrate a digital decision framework.
- Identify opportunities for increased store automation, reducing human exposure to radiation.
- Identify options for post treatment of packages and potential approaches to improve package design, construction, and maintenance.

To achieve the above objectives, WP7 was split into the following tasks:

- Task 7.1: WP management.
- Task 7.2: SoTA in packaging, storage, and monitoring of cemented wastes.
- Task 7.3: Innovative integrity testing and monitoring techniques.
- Task 7.4: Digital twin.
- Task 7.5: Data handling, processing, and fusion.
- Task 7.6: Demonstration and implementation of monitoring, maintenance, and automation / digitalisation techniques.
- Task 7.7: Dissemination and reporting.

1.3 Objective of this Report

This report aims to summarise the work completed within WP7 of the PREDIS project. For each technical task within WP7, the following information is provided: objectives, approach followed and deliverables produced, and the main outcomes of the work, including any potential future needs and opportunities if identified.

1.4 Structure of this Report

This remainder of this report is structured as follows:

- Section 2 provides a summary of the work completed within Task 7.2 of WP7.
- Section 3 presents the work completed in Task 7.3.
- Section 4 describes the work completed in Task 7.4.

- Section 5 describes the work completed in Task 7.5.
- Section 6 discusses the demonstration work in Task 7.6.
- Section 7 summarises the dissemination and reporting activities in Task 7.7, including interactions with the EUG.
- Section 8 presents the conclusions of the report.
- Section 9 lists the references used in this report.

2 Task 7.2: SoTA in Packaging, Storage, and Monitoring of Cemented Wastes

2.1 Objectives

The objectives of Task 7.2 of WP7 were to compile a SoTA report on the packaging, storage, and monitoring strategies for cemented waste packages, identify a reference package and degradation mechanisms for consideration in subsequent activities in WP7, and provide necessary data from WP7 for use in WP2 of PREDIS on the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) activities.

The SoTA collation involved reviewing and recording information on the cemented packaging systems, storage systems, storage management procedures, waste acceptance criteria (WAC) and monitoring techniques in use at the start of the PREDIS project, with the aim of providing a starting point for performing a gap analysis and enabling a comparison between the state of knowledge at the start and end of the PREDIS project.

Task 7.2 was subdivided into three sub-tasks: gap analysis and SoTA report (T7.2.1); identification of reference package evolution, degradation scenarios, and monitoring techniques (T7.2.2); and preliminary strategic assessment of developments and results, providing data for WP2 assessments on LCA/LCC (T7.2.3).

2.2 Approach and Deliverables

The approach followed to undertake Task 7.2 and achieve its objectives involved close cooperation of several organisations including Galson Sciences Limited (GSL, UK), SOGIN (Italy), National Nuclear Laboratory (NNL, UK), Federal Institute for Materials Research and Testing (BAM, Germany), Paul Scherrer Institute (PSI, Switzerland), Orano (France), and Institute of Nuclear Research (UJV, Czech Republic).

2.2.1 Gap Analysis and SoTA Report

Within the scope of PREDIS WP2, a gap analysis for the entire PREDIS project was conducted in two separate phases. The first phase aimed to evaluate industry and stakeholder needs for research, development and demonstration in pre-disposal waste management technologies, which also served to initially define the scope of the PREDIS project. The second phase involved further reviewing, refining and prioritising project plans against identified needs, as well as identifying any additional requirements. WP7 partners, especially those involved in Task 7.2 and the WP7 lead, contributed to this gap analysis and analysed the results with a focus on WP7. The methods, data and conclusions are reported in Deliverable D2.2 of WP2 [2]. The outcomes of the WP7 gap analysis are summarised in Section 2.3.1.

For the SoTA report, the approach involved using a questionnaire to collect information on the methods and procedures used in cemented waste management across Europe. The questionnaire was distributed to the registered EUG members of PREDIS. The questionnaire aimed to:

- Identify common waste package types used in long-term storage.
- Identify the adopted storage configurations and waste package handling procedures.
- Record the main degradation phenomena observed/considered by store operators and material conditions that may lead to the initiation of ageing mechanisms during long-term storage conditions.
- Understand the monitoring and data collection systems put in place by EUG members.

Information in the questionnaire was structured around four topics:

- General information on the respondent.
- Storage system: waste streams to be stored (existing and foreseen); description of the main waste package typologies; package handling system, storage configuration.
- Storage management strategy: monitoring strategy; long-term storage monitoring strategy.
- Parameters and data collection systems currently used for monitoring package normal and degradation scenarios: relevant parameters currently monitored; data transmission/archiving; data analysis; anomalies; quality assurance and control.

Questionnaire responses were received from eleven organisations in the following countries: Belgium, Czech Republic, Denmark, Estonia, Finland, France, Italy, Spain, Sweden, and Switzerland. The responses were analysed and formed the core of the SoTA report (Deliverable D7.1 [3]). A summary of the key outcomes of this analysis is provided in Section 2.3.2.

2.2.2 Reference Package and Degradation Mechanisms

The SoTA report [3] and other documents from the UK Nuclear Decommissioning Authority (NDA) [4,5] were used to identify trends and common characteristics of cemented waste packages being used in Europe and the key evolution and degradation mechanisms observed for these packages. Based on this information, a reference package and degradation mechanism were recommended for consideration in further WP7 activities. This work was compiled into a technical memorandum to meet MS50 of PREDIS [6]. A summary of the recommended reference package characteristics is provided in Section 2.3.3.

2.2.3 LCA/LCC Data

Data to support WP2 assessments of environmental and economic impacts for two case study technologies in WP7 were collated and shared with WP2 partners. To facilitate this, meetings between WP7 and WP2 partners were held to discuss the context and the requirements of the WP2 assessments. It was determined that relatively high technology readiness level (TRL) techniques would be considered to ensure sufficient data availability. This led to the choice of radiation monitoring technologies that use external sensors, developed by WP7 partners at the National Institute for Nuclear Physics (INFN, Italy) and the University of Pisa (UNIPI, Italy). The requested information included data on materials, energy, waste, and costs for use in assessments of environmental and economic impacts of these technologies. More details on the LCA and LCC methodologies can be found in the WP2 note titled “LCA and LCC protocol guidance” [7].

A report was produced to form the basis for meeting Milestone MS50 of PREDIS [8], which contains tables of data provided by UNIPI and INFN for their respective monitoring technologies developed in PREDIS.

2.3 Outcomes

2.3.1 Gap Analysis

The gap analysis for WP7 highlighted the need to adapt the WP7 work plan to address several actions as far possible. The recommendations from the gap analysis are listed below, most of which have been addressed:

- *“WP7, T7.3: The list of the parameters to be measured by embedded and externally attached sensors should be appended with “internal corrosion” (of a metallic container)” and “external corrosion (of a metallic container)” as well as “pressure within a waste package, potentially damaging the container”. These parameters can potentially be measured by the RFID systems to be developed by VTT/BAM”.*

As reported later in this document (Section 3.3.6), a pressure sensor was added to the BAM/VTT Embedded Radio Frequency Identification (RFID) sensing system. The issue of external corrosion was discussed in the context of the NNL visual inspection system (Section 3.3.4). An internal corrosion system can be added to the BAM/VTT system in future work.

- *"WP7, T7.3: The parameter "condensation" should be added to the external RFID sensing system (UNIPI), at least in a sense that the potential of adding an appropriate sensing module is explored."*

  The UNIPI system (Section 3.3.2) is capable of integrating a variety of other sensors. However, the integration of a condensation sensing system was discarded due to time and budget constraints.

- *"WP7, T7.4: The work program of the digital twin technology should take the potential of measured data into account, which will be delivered by systems such as those developed in CHANCE, MICADO as well as data, coming from commercially available sensing systems."*

  The work on digital twins considered data inputs from a variety of sources, extending beyond the sensors developed in Task 7.3.

- *"WP7, T7.5: The database should include a prototype of additional (non-PREDIS) sensing systems."*

  The WP7 database, developed by the Technical Research Centre of Finland Ltd (VTT) and other partners, can store and exploit various types of data. The methods are detailed in Deliverable D7.5 [9].

- *"WP7, T7.6: The demonstration task should explore the possibility of joint demonstrations of certain sensing systems from MICADO, CHANCE and PREDIS (e.g. muon imaging)."*

  The muon imaging system used in PREDIS (Section 3.3.5) is the same as that used in CHANCE, with improvements. However, since the other demonstrations were performed in nuclear facilities, adding other technologies or granting access to partners outside of PREDIS was not feasible.

- *"The potential of robotic/mobile deployment of technologies should be assessed."*

  The robotic deployment of visual and ultrasonic technologies was demonstrated by NNL and is reported in Deliverable D7.3 [10].

2.3.2 SoTA Report

Analysis of the questionnaire responses from EUG members highlighted that cement grouting is widely used for waste streams such as sludges, fine particulates, rubble, and metals, with a high percentage classified as Intermediate Level Waste (ILW), indicating the need for long-term storage. The conditioning processes adopted by many organisations are categorised into two main classes: 'homogeneous conditioning' for liquid/fluid waste and 'heterogeneous conditioning' for solid waste. Various containers are used for storing waste, with a preference for metallic drums for liquid/fluid waste and prismatic concrete containers for solid waste. Most waste package types are certified for transport and are stackable, with remote-operated and semi-automated handling systems being the most common.

Waste packages are often identified by single labelling and stored in ventilated and controlled areas. The survey on monitoring strategies revealed that no EUG members employ sampling or instrumented waste packages. Instead, the majority employ visual monitoring on a periodic basis to identify metal corrosion, cracks, external contamination, swelling, leakage, and deformation of lifting features (see Figure 2-1 for an example of results obtained from responses to the questionnaire). Almost half of the respondents collect information about gas emissions from packages.

Data collection is mainly manual, with semi-automated systems used by half of the respondents. Digital systems are often used for data transmission and archiving, with Expert System applications being the most common for data analysis.

The SoTA report also provided an analysis considering the normal and abnormal thermo-mechanical, hydro-chemical, and biological processes that occur within cemented waste packages, which can lead to degradation during extended storage. The report also examined the impact of the storage system and external environment on waste package behaviour and degradation. Most store operators have observed degradation phenomena such as internal and external corrosion, damages linked to the handling of the package, Alkali–Silica Reaction (ASR), leakages, and swelling. Consequently, they are implementing preventative and remedial measures for the extended storage of the waste packages.

The SoTA report concluded that the innovation technologies investigated in WP7 and applied to monitoring of cemented waste packages during short- and long-term storage will significantly impact all waste producers by improving storage operations, including cost efficiency and safety.

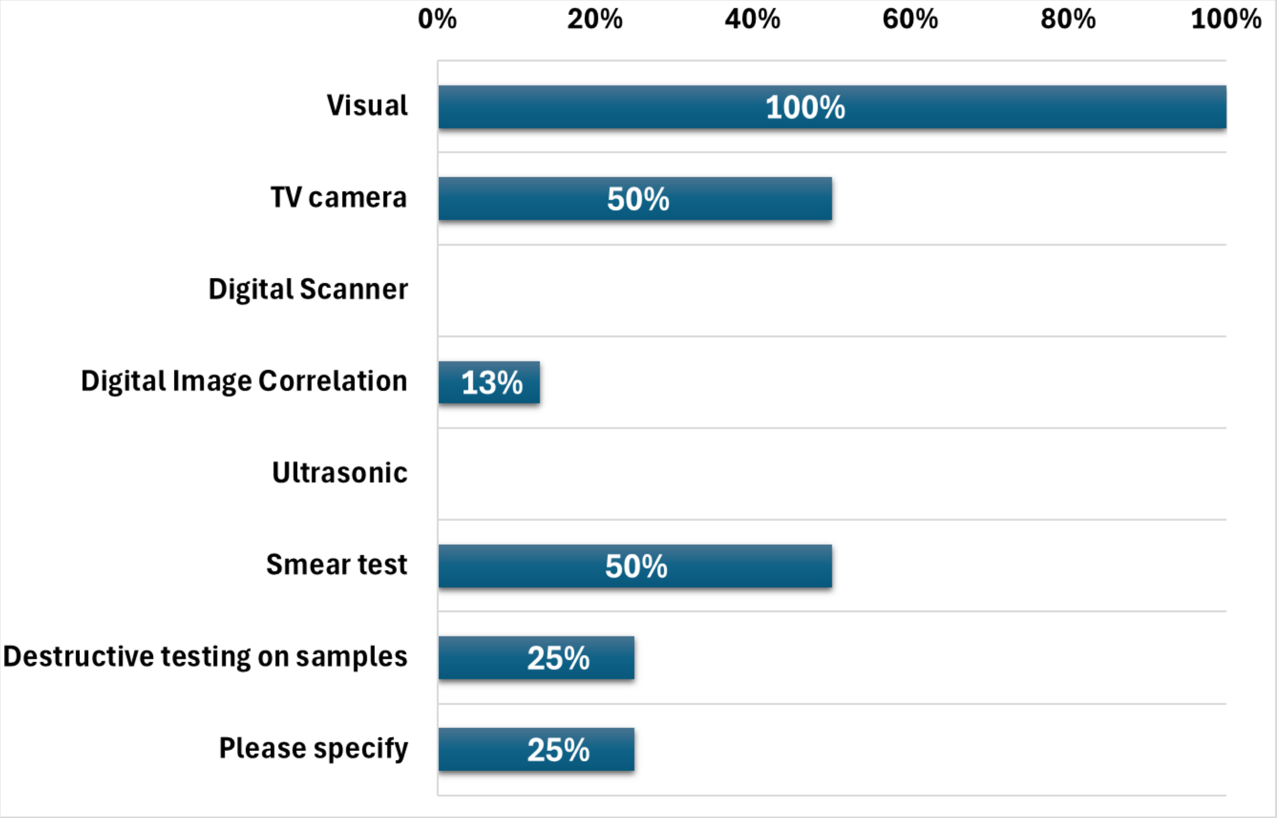


Figure 2-1: Cemented waste package monitoring techniques, as an illustrative example of output from the responses to the questionnaire developed in Task 7.2 of WP7 [3].

2.3.3 Reference Package and Degradation Mechanisms

The collected data in the SoTA report and other sources, mentioned in Section 2.2.2, were used to develop a cemented waste package to be used as a point of reference throughout the rest of WP7. For this reference package, details such as geometry, grout matrix, and waste container material were provided (see Table 2-1 below). For degradation of the grout matrix and package, corrosion of reactive metals, in particular Magnox or magnesium metal, was selected as a reference degradation mechanism. Additionally, several key areas where variants may be investigated were identified, including:

- Use of aluminium metal instead of Magnox. could be used to investigate corrosion mechanisms.
- Use of a prismatic geometry instead of the cylindrical form. For the prismatic geometry, a concrete container may be used instead of steel.
- Pure Portland Cement could be used instead of a Blast Furnace Slag (BFS) and Ordinary Portland Cement (OPC) blend for the grout matrix. Adding a large-sized component, such as graded limestone, to the grout formulation may also be considered to improve grout performance by increasing resistance to cracking.

Table 2-1: Summary of the reference package details [6].

Criteria	**Single Skin**
Geometry	Cylindrical
Size	200 L (60 cm diameter, 90 cm height)
Construction material	Austenitic stainless steel (300 grade, 1.2 ± 0.2 mm thickness)
No. of skins	One
Closing system	Concrete layer between wasteform and lid. Stainless steel (300 grade) lids. Suggested this be vented. Closing system can be screw, clamp or bolted.
Wasteform grout formulation	>3:1 wt/wt BFS: OPC blended mix, 0.35-0.5 w/s, no additives, sand, aggregate or superplasticisers
Waste type	Magnox metal (or magnesium). Large discrete pieces or small bits evenly distributed throughout the grout matrix. Recommended use 62kg of Magnox (or magnesium).
Storage environment	0-20 ºC, relative humidity <50%, controlled air change and controlled chloride content (<100 μgCl.cm^{-2})

3 Task 7.3: Innovative Integrity Testing and Monitoring Techniques

3.1 Objectives

The objectives of Task 7.3 of WP7 were to select suitable conventional and innovative NDE/monitoring techniques and adapt them for use under typical storage conditions. This included their implementation into individual waste packages and the testing of wireless data transmission and wireless energy supply for some technologies. The task also involved testing the relevant technologies using full-scale package mock-ups to help advance their TRLs and provide measurement data to Tasks 7.4, 7.5, and 7.6 of WP7.

Task 7.3 was subdivided into three sub-tasks: external sensing technologies (T7.3.1), embedded sensing technologies in instrumented packages (T7.3.2), and preliminary system testing and optimisation (T7.3.3).

3.2 Approach and Deliverables

The approach followed to undertake Task 7.3 and achieve its objectives of testing and improving cemented waste monitoring systems involved close cooperation between several organisations including BAM (Germany), INFN (Italy), Magics (Belgium), NNL (UK), UJV (Czech Republic), UNIPI (Italy), and VTT (Finland). The work focused on developing and adapting advanced monitoring techniques suitable for storage conditions and included innovations in wireless data transmission and energy supply. Full-scale package mock-ups with real cementation technology were tested at UJV and other locations, providing critical insights into the readiness of these technologies for comprehensive monitoring and guiding their deployment and automation.

Table 3-1 lists the technologies developed and tested within Task 7.3 of WP7. The functionality and performance of each technology were thoroughly evaluated and documented, providing valuable insights into their effectiveness. These developments made within the WP7 for integrity testing and monitoring of waste drums highlight the readiness of these technologies for practical implementation.

Table 3-1: List of all the technologies developed and tested within the WP7.

Technology	Technology developers
Scintillating optical Fibre (SciFi) gamma radiation monitoring	INFN, Italy
Silicon Lithium Fluoride (SiLiF) neutron radiation monitoring	
Sensorised Long-range Radio (LoRa) wireless sensor network	UNIPI, Italy
Acoustic Emission (AE) for measuring ASR	Magics, Belgium
Non-contact ultrasonic scanning	NNL, UK
RFID embedded sensors	BAM, Germany VTT, Finland
Muon tomography (Mu-Tom)	INFN, Italy

The results of Task 7.3 were comprehensively documented in Deliverable D7.3 [10], which provides a detailed account of the technologies developed and tested in the project and highlights the substantial progress made, including testing of several technologies in both virtual and laboratory environments. Two journal publications [11, 12] were also produced and summarised in Deliverable D7.2 [13]. A summary of the achievements of Task 7.3 for each technology is given in Section 3.3.

3.3 Outcomes

3.3.1 SciFi (gamma) and SiLiF (neutron) radiation monitoring

SiLiF neutron counters and SciFi gamma ray counters are designed as compact flux detection devices, suitable for external installation around waste drums (Figure 3-1). These devices were optimised and assessed in WP7 of PREDIS by INFN. The SiLiF neutron counter contains a semiconductor detector in the form of a silicon diode with a neutron converter layer of ^{6}LiF on each side. The SciFi gamma ray counter contains a scintillating fibre with a silicon photomultiplier at each end, all contained within an aluminium tube. Variations in neutron and gamma counts measured on the external surface of a waste package are expected to reflect variations in the internal structure of the waste package. The proposed monitoring method involves attaching a set of four SciFi and SiLiF sensors to the cemented drum for continuous monitoring throughout the pre-disposal phase. Before and after its full characterisation, each drum would be monitored for any possible anomalies that might arise while awaiting disposal.

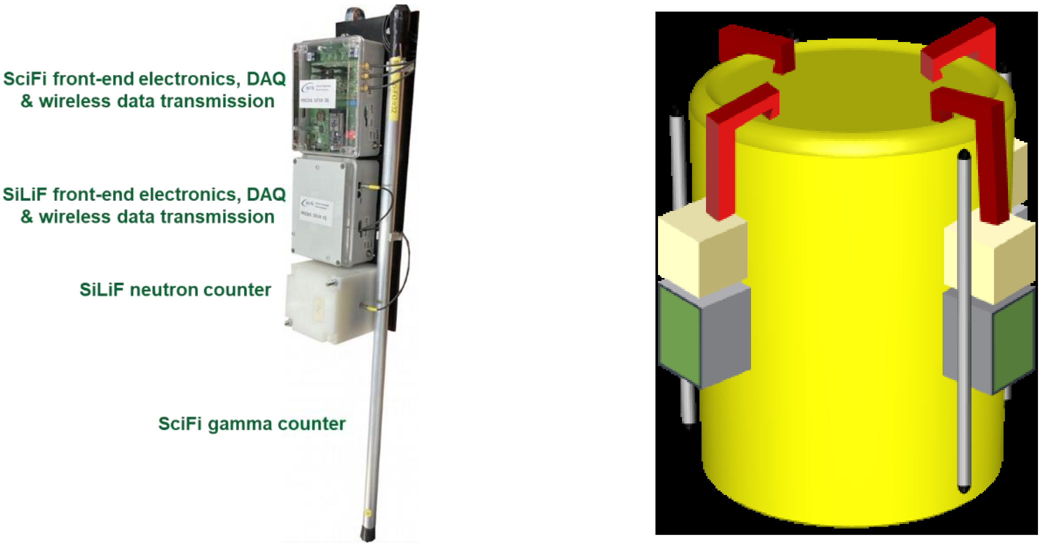


Figure 3-1: Left – Complete monitoring unit consisting of one SiLiF detector and one SciFi detector with the related electronics. Right – A possible arrangement of four radiation monitoring units on a cemented drum during its pre-disposal phase [10].

The feasibility of medium-to-long term monitoring using radiation sensors positioned around radioactive waste drums was evaluated in PREDIS through preliminary laboratory tests, computer simulations, and a two-month data collection period. This demonstration involved a cemented mock-up drum containing a 165 MBq ^{137}Cs gamma source. Separately, the feasibility of neutron measurement was assessed using a PuBe neutron source. The potential for periodic automatic monitoring of radiation levels around radioactive waste drums offers significant added value in terms of safety and security. It is judged that this monitoring technique could soon become a valuable tool for early detection of anomalies or potential tampering with drums during their pre-disposal phase in real industrial environments.

3.3.2 Sensorised LoRa Wireless Sensor Network

UNIPI developed and tested an innovative platform to assess the durability of wasteforms in storage and repository conditions. This platform integrates LoRa technology to enable long-term monitoring of radiological levels in radioactive waste packages, evaluating surface radiation intensity and internal structural integrity. This method uses passive gamma and neutron counting and provides continuous monitoring. By examining fluence variations over time, structural changes in the waste matrix can be identified, minimising inconsistencies and human errors common in waste package management.

The proposed Wireless Sensor Network consists of three integrated levels as presented in Figure 3-2. The first layer comprises LoRa Nodes responsible for package identification and radiation data collection from within the waste package, facilitating monitoring of the structural condition of the waste package. The second layer, LoRa Gateways, manages the LoRa traffic and forwards the data to local storage or cloud-based applications, employing a Message Queuing Telemetry Transport (MQTT) broker. These gateways also synchronise all nodes using acknowledgment radio payloads to prevent data transmission collisions. Finally, the third layer is a cloud-based platform, implemented through an Azure Internet of Things (IoT) central application, facilitating remote access and data processing.

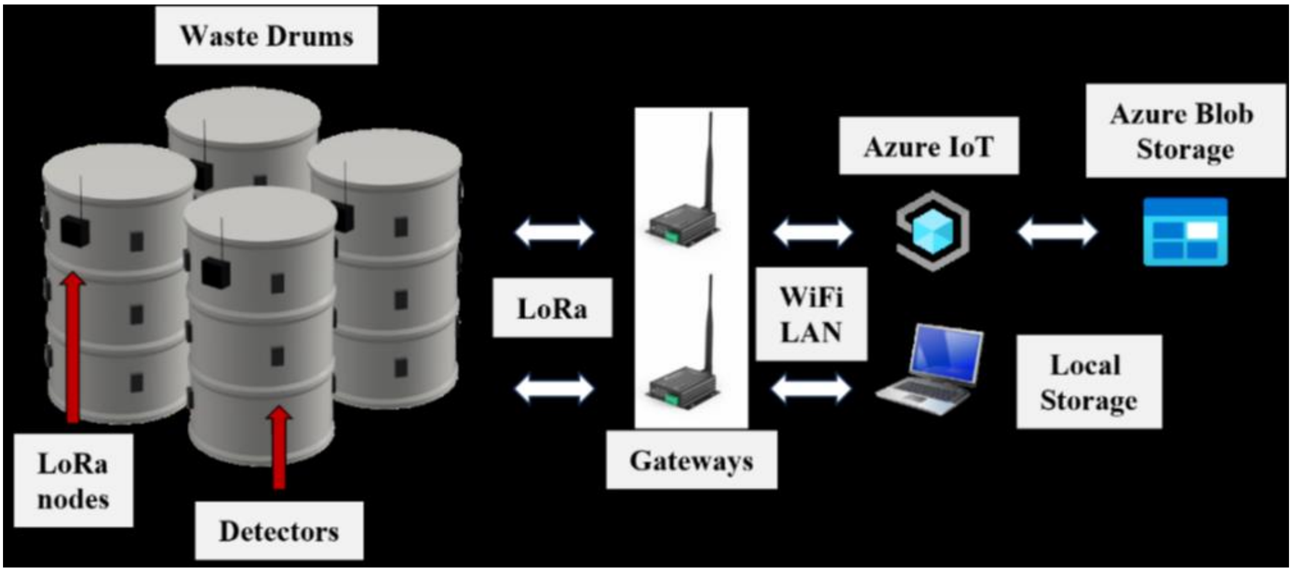


Figure 3-2: LoRa radiation monitoring framework for radioactive waste drums [10].

The developed system, utilising LoRa technology for its energy efficiency, cost-effectiveness, and long-range capabilities, was initially characterised at UNIPI's Laboratory of Nuclear Measurements facility, and subsequently underwent field trials at Nucleco site in Rome and a three-month demonstration at UJV as part of the PREDIS project.

These tests validated the capability of this technology for detailed activity monitoring and anomaly detection within containers, demonstrating its suitability for remote, automated monitoring without internet connectivity. Key aspects assessed included the accuracy of radiation detectors, wireless data transmission reliability, battery life, and the system's ability to detect structural changes within the drum matrix, proving its effectiveness for long-term radioactive waste drum surveillance and its adaptability to different operational needs.

The durability of the platform is under evaluation through radiation hardness tests for its applicability in managing low-level waste (LLW) and ILW. This includes studying material ageing and other factors that influence detection accuracy and effectiveness. Furthermore, the economic and regulatory feasibility of the technology is being analysed to ensure its cost-effectiveness and sustainability.

Efforts are also being made to improve data management with the creation of intuitive dashboards and analytical tools for enhanced decision-making by users and stakeholders. Moreover, research into standalone units with LoRa transceivers is underway to remove the reliance on wired connections. This is complemented by advancements in sensors capable of identifying various gamma energy levels, facilitating edge computing for immediate integrity analysis while accounting for gamma emitter decay, thus refining waste drum monitoring techniques.

3.3.3 Acoustic Emission for measuring ASR

AE technology is a non-destructive monitoring technique developed by Magics and used to assess the integrity of waste drums. An example process that might induce disturbances in a waste drum is ASR in cemented packages, which leads to the formation of a gel-like substance that swells and causes stress development and potential cracking of the concrete. AE uses highly sensitive piezoelectric sensors (Figure 3-3) at the surface of a package. When a crack occurs, the elastic stress wave propagates through the material and can then be recorded by an AE sensor. To detect such AE events, processing is needed on the continuous waveform. Given the detected events, a cumulative event count could be generated as a function of time. Further details about this technique are provided in the D7.3 report [10].

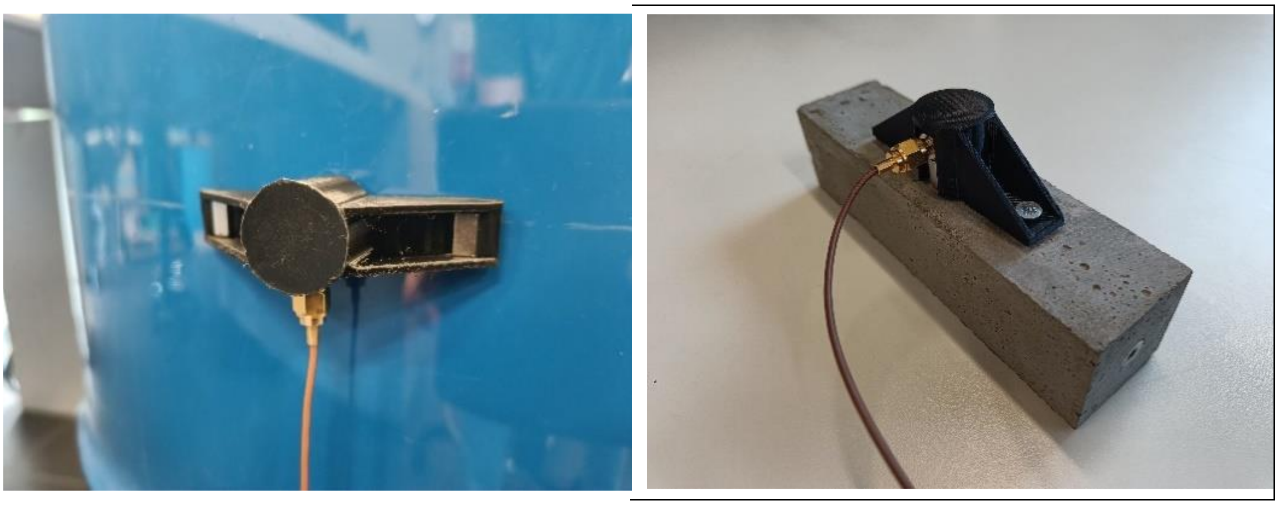


Figure 3-3: AE sensor attached to a waste drum (left) and placed on top of a concrete sample for testing (right) [10].

The feasibility of AE for monitoring concrete expansion was demonstrated through laboratory-scale experiments in PREDIS. Initial findings suggested a correlation between cumulative acoustic events and expansion under specific concrete compositions and environmental conditions. However, distinct expansion signals were not observed in the drum-scale experiments. Consequently, a decision was made to postpone the processing and analysis of the collected AE data until observable changes occurred.

Further research is essential to refine AE monitoring techniques on a larger drum scale. This includes exploring additional concrete mixtures, environmental variables, and refining sensor placement to enhance sensitivity and accuracy. Continuous monitoring and analysis will be crucial to detect and understand any eventual changes in drum-scale experiments. Using this continuous approach will make AE technology effective for reliable and early detection of structural changes in concrete, contributing to improved management and safety practices in waste storage and disposal facilities.

3.3.4 Ultrasonic Inspection

The aim of this monitoring technology is to detect swelling in the drums and provide screening for discontinuity defects such as cracks, dents, and corrosion cavities. The collected measurements are also expected to provide an indication of pressure build-up inside the drums and possibly also indicate moisture content. This technology was tested in PREDIS by NNL.

Air-coupled ultrasonic transduction offers a non-contact, non-destructive, and non-invasive means of inspection. To perform the required measurements using this technology, a longitudinal ultrasonic wave is emitted by the transmitter at a specific angle normal to the drum's circumference to create a Lamb wave in the drum's shell (Figure 3-4). This Lamb wave then travels around the drum circumference, emitting longitudinal waves along its path, which are used to detect the time of flight of the Lamb wave around the drum. The pattern and angle of the Lamb waves detected by the transducer indicate the presence of defects across the circumferential direction of the package.

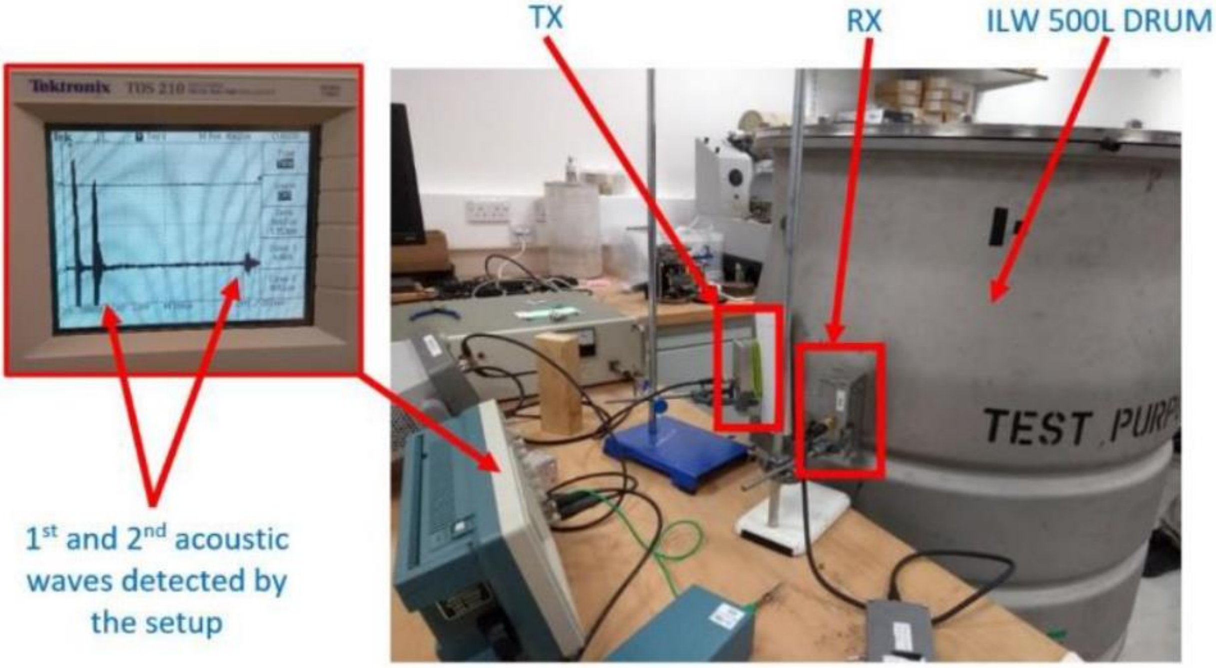


Figure 3-4: Air coupled transmitter (TX) and receiver (RX) setup generating and receiving a wave on / through the surface of an empty 500 L drum sample and an oscilloscope view of the acoustic waves (left) detected by the receiver during the successful wave generation/detection [10].

Physical tests have proved the feasibility of using non-contact air-couple ultrasonic transducers to measure the circumferential cross section of an ILW 500 L drum via a restricted access point. The ultrasonic transducers were able to detect hairline cracks in samples manufactured using the same material and dimensions as that of the ILW drums.

NNL have access to an experimental set of 500L Magnox Encapsulation Plant (MEP) drums that had been used for encapsulation testing of MAGNOX swarf. These drums were over 30 years old and thus provided an excellent test case for this measurement method. Testing on these drums offered significant advantage over the testing of the reference package, as the MEP drums directly replicated the waste containers used in the UK.

The validation of ultrasonic circumferential measurements using real, full-scale filled/encapsulated drum samples, as within this work, represents a critical step in enhancing inspection capabilities. The inspection process aims to ensure accuracy and reliability in detecting discontinuities and defects within the drum structure.

Future work beyond PREDIS will focus on inducing controlled defects into these samples to further refine and validate the defect detection process. Additionally, calibrating the system will help promote the pressure build up screening process into a pressure measuring process. Automation of the ultrasonic transducer locating and alignment process will speed up and improve the transduction process, ensuring consistent and efficient data collection. Integrating ultrasonic readings with real-life point cloud scans will enable the creation of a measured DT of full-scale real ILW drums. This fusion of data will provide a comprehensive and accurate representation of drum conditions, facilitating improved monitoring and management strategies.

Overall, these advancements aim to strengthen the capabilities of ultrasonic technology in assessing and monitoring ILW drums, paving the way for enhanced safety, efficiency, and reliability in waste management practices.

3.3.5 Muon Tomography

The Mu-Tom technique is an interesting and promising method for investigating the internal composition of cemented drums in a non-destructive manner. It was tested in PREDIS by INFN. This technique uses muons produced by cosmic rays, which are highly penetrating particles capable of traversing matter without being absorbed. The interaction of muons with matter through Multiple Coulomb Scattering affects their trajectories. The distribution of the diffusion angles depends on the density; the atomic number and the thickness of the materials being traversed. By analysing the scattering angles, Mu-Tom allows exploration of the inner contents of radioactive waste drums without the need for destructive intervention. The system consists of two muon detectors placed about 3 m apart from each other (Figure 3-5). The technique is capable of producing 3D images and scanning the objects at different horizontal layers using a 3D reconstruction algorithm (although the current apparatus has not been optimised for the vertical coordinate). Further details are provided in the D7.3 report [10].

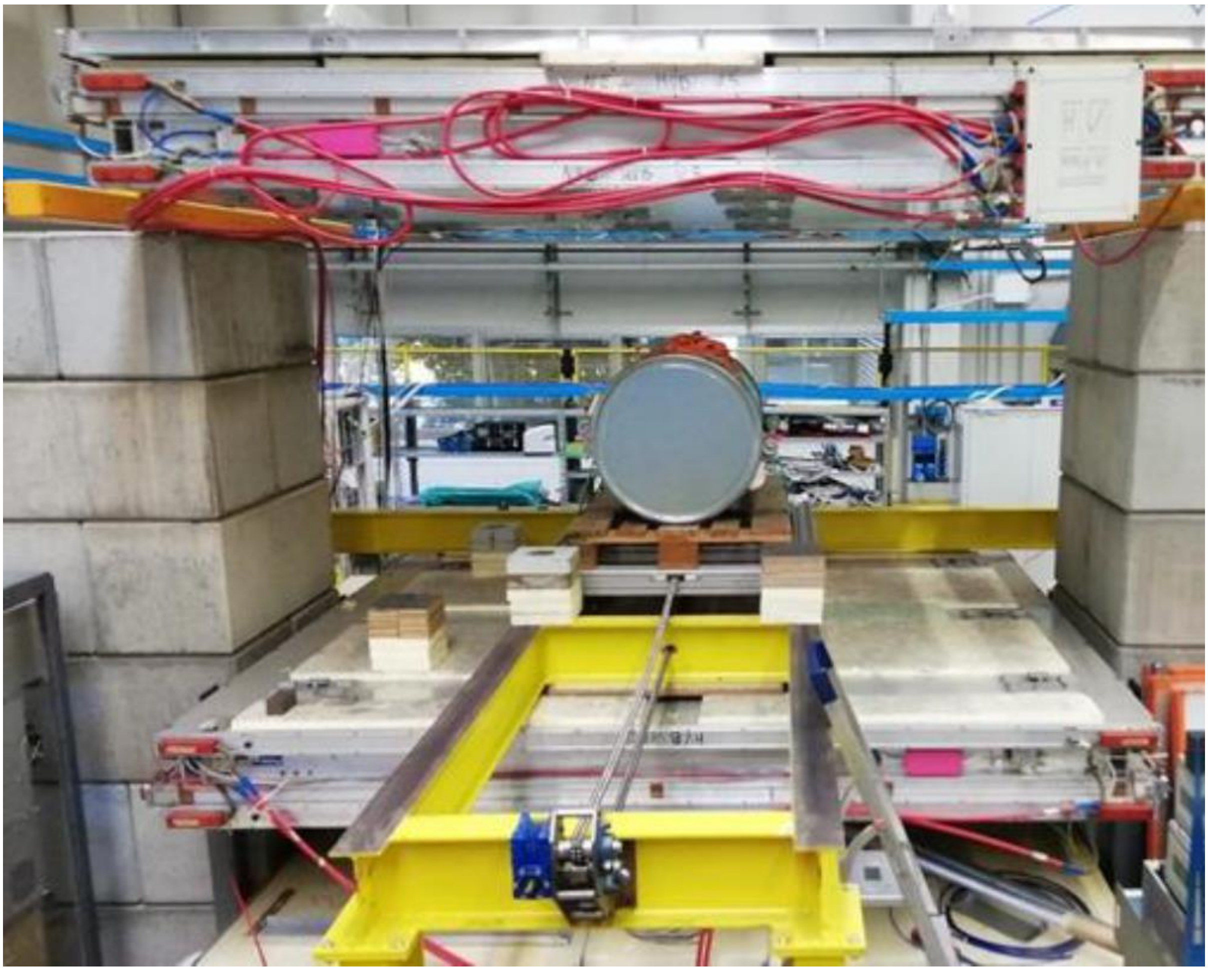


Figure 3-5: A picture of the mock-up produced by UJV and installed in the INFN Padova Mu-Tom demonstrator [10]. The two muon detectors are above and below the waste drum.

The tests in PREDIS considered a mock-up consisting of a cemented waste drum produced by UJV to simulate a real waste drum containing metallic structures embedded in concrete. The tests successfully demonstrated the capability of Mu-Tom to detect metallic objects embedded within large concrete blocks. This achievement marked a significant advancement in non-invasive inspection techniques for structural analysis. The next phase of this research will involve expanding the dataset to further quantify and optimise the performance of Mu-Tom. By collecting and analysing additional data, plans are to enhance the sensitivity and accuracy of the technology in detecting and characterising metallic objects within concrete structures.

Moreover, ongoing efforts are focusing on refining imaging algorithms and data processing techniques to improve resolution and reliability. This includes exploring different configurations and experimental setups to maximise the effectiveness of Mu-Tom in various operational environments.

Future work will consider the integration of advanced computational methods and Machine Learning (ML) algorithms to enable rapid interpretation of tomographic data and facilitate timely decision-making in critical applications, such as structural integrity assessments and nuclear waste management.

In summary, continued R&D in Mu-Tom is poised to further elevate its capabilities as a powerful tool for NDE. By advancing its performance and usability, Mu-Tom will contribute to enhanced safety, efficiency, and innovation in inspection technologies.

3.3.6 Embedded RFID Sensors

BAM developed an embedded RFID electronic measurement system to be placed inside a waste drum filled with concrete. The goal of this measurement system is to monitor the process of hardening and the evolution of the concrete over time to indirectly identify potential defects such as corrosion or cracking. The measured parameters in the PREDIS application were humidity, temperature, and pressure. In this regard, particular attention was given to the design of the electronic board’s enclosure, to allow the sensors to measure the state of the concrete without being in direct contact with it. In the scope of PREDIS, an innovative wireless technology developed by VTT was also applied to supply power to the battery-less sensors and transmit the data acquired by the sensors through the metallic waste drum.

The sensing system is made of a chain of small units, called SensorNodes (Figure 3-6). Each SensorNode includes two off-the-shelf sensors, with one for relative humidity and temperature and one for pressure and temperature. A SensorNode is designed to have a unique identifier to be connected to other units while being uniquely discoverable by a standard communication protocol. In this way, a distributed matrix of measurement points is created.

Figure 3-6: A SensorNode of the RFID sensing system developed by BAM [10].

The scope of work by VTT focused on enabling long-term operation and data readout of sensors embedded inside waste drums without compromising the integrity of the steel drums by avoiding perforations. To achieve this, VTT developed a wireless interface capable of both powering and reading data from the embedded sensors through the steel cover, addressing the need for an alternative powering method due to the constraints of battery exhaustion. Figure 3-7 shows the architecture of the PREDIS data acquisition system for embedded sensors in the drum. This wireless technology was designed to operate through a 1.5 mm thick ferromagnetic steel cover to be compatible with BAM's SensorNode for comprehensive monitoring. Additionally, the project explored extending this technology for condition monitoring of larger reinforced concrete containers in storage spaces, demonstrating the applicability of the wireless system in various storage environments by enhancing the wireless operation range. Further details are provided in the D7.3 report [10].

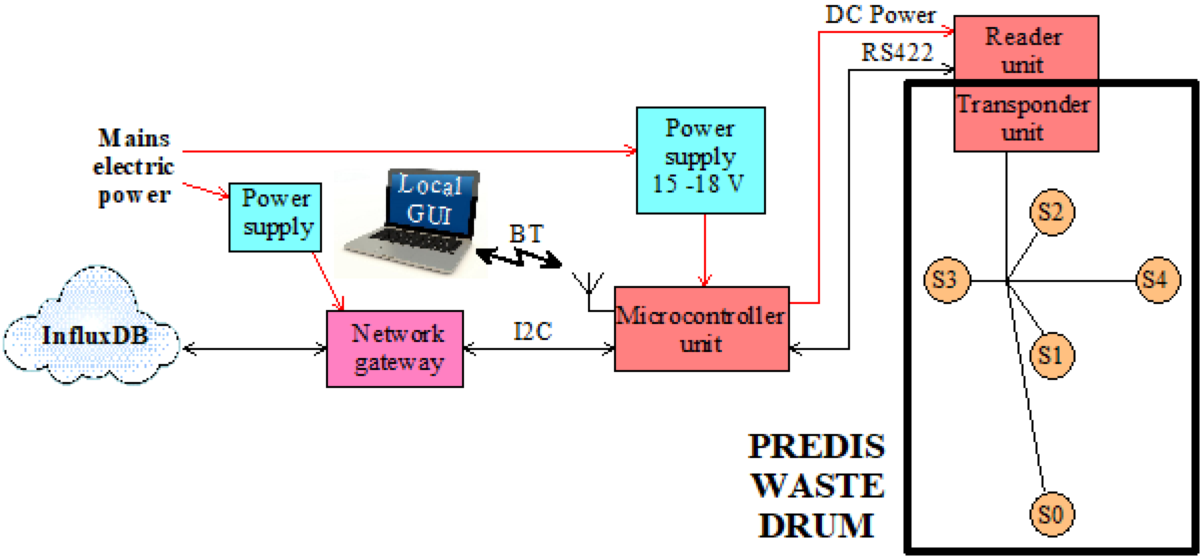


Figure 3-7: Architecture of the PREDIS data acquisition system for embedded sensors in the drum [10].

The feasibility of embedded concrete monitoring using a custom device was successfully demonstrated in PREDIS. Initial small-scale tests confirmed the effectiveness of the sealing technique in protecting electronic circuits during concrete hydration. However, to ensure long-term reliability, further experiments are essential to assess the durability of the materials and the consistency of measurements over extended periods. One of the primary challenges encountered during early-stage monitoring was the impact of moisture absorption by the dielectric insulator of the cables connecting the SensorNodes. This led to increased capacitance and communication protocol issues due to increased pulse rising times and inability of the communication protocol to decode them. Addressing this issue through the adoption of cables with lower moisture absorption and capacitance will be a priority for improving system performance.

Moreover, optimising the design of the SensorNode enclosure presents an opportunity to enhance system responsiveness. Reducing the internal air volume around the sensors can expedite equilibration with the external environment, thereby improving the system's time response and overall efficiency. Ongoing research aims to refine these aspects of the SensorNode design to maximise its effectiveness and versatility in embedded concrete monitoring applications. This includes exploring advancements in materials science and sensor technology to meet the evolving demands of structural health monitoring in diverse environmental conditions.

Although the PREDIS tests demonstrated the feasibility of powering and reading sensor data through 1.5 mm ferromagnetic steel lids, sporadic data message losses were observed due to timing skew caused by magnetic hysteresis. The development and successful testing of this data acquisition system for low-power battery-less sensors inside waste drums represents a significant advancement in waste management technology within the PREDIS project. Future improvements will focus on optimising modulation parameters to enhance tolerance to timing inaccuracies, thereby improving reliability across thicker layers of non-magnetic steel and other metals.

The developed technology holds promise beyond waste drum monitoring. Its successful adaptation for wireless monitoring of larger reinforced concrete containers in storage environments underscores its versatility and potential for broader industrial applications. Ongoing research aims to refine the system's performance characteristics, broaden its operational capabilities, and explore new applications in diverse settings. By addressing technical challenges and advancing the SensorNode system and wireless communication capabilities through dense materials, these technologies will contribute to enhanced safety, efficiency, and environmental sustainability in waste management practices.

4 Task 7.4: Digital Twin

4.1 Objectives

The objectives of Task 7.4 of WP7 were to develop a DT of a radioactive waste package based on ML algorithms describing the evolution of the geochemistry and the mechanical integrity of cemented waste packages, train the ML algorithms using the output from existing complex numerical models describing geochemical evolution, geo- and thermo-mechanical integrity, as well as NDE and monitoring data, and calibrate the numerical models with existing data from the experimental characterisation of conventional radioactive wasteforms and laboratory experimental data.

Task 7.4 was subdivided into three sub-tasks: geochemical evolution and mechanical integrity modelling (T7.4.1); model calibration and validation based on experimental data (T7.4.2); and development of a DT toolkit (T7.4.3).

4.2 Approach and Deliverables

The approach followed to undertake Task 7.4 and achieve its objectives of developing DT technology involved close cooperation of several organisations including PSI (Switzerland), Nuclear Research and Consultancy Group (NRG, Netherlands), BAM (Germany), Institute for Nuclear Waste Disposal of the Karlsruhe Institute of Technology (KIT-INE, Germany), Amphos21 (Spain), Belgian Nuclear Research Centre (SCK CEN, Belgium), and Magics (Belgium). The work focused on developing a DT model for cemented radioactive waste packages, using ML algorithms to predict their geochemical and mechanical evolution over time.

As the evolution of waste packages is most likely driven by a combination of chemical and physical-mechanical processes, the DT must integrate process models for all of these interactions. This can be approached in one of two ways: either model a single waste package in detail, using a reactive transport model discretised at the millimetre scale, combined with a mechanical module that describes physical behaviour based on local chemical conditions, or treat the waste package as a homogeneous, well-mixed cell, in which the main degradation processes are represented by changes in mineralogical and mechanical properties. The former approach requires a large set of input data and extensive calculations. The latter approach requires less input data and generally results in faster calculations. Therefore, the latter approach was adopted and implemented in a simplified manner. One drawback of this simplified approach is that it does not necessarily capture the main mechanisms driving chemical evolution in heterogeneous systems as these are determined by local conditions. Figure 4-1 represents a schematic overview of the processes in a DT.

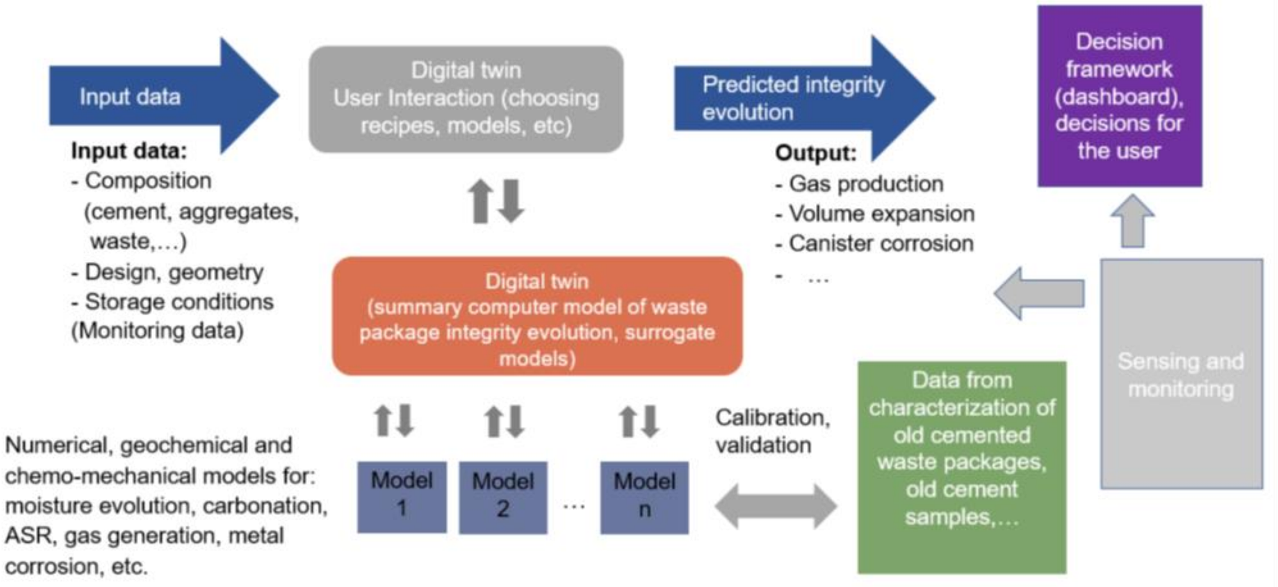


Figure 4-1: A schematic overview of the processes in a DT [9].

In addition to implementing a prototype DT, Task 7.4 also applied a real-life example of DT for ASR in waste packages. An integrated experimental-numerical programme was conducted. The insights gained from these experiments and models were then integrated into the PREDIS DT dashboard, a powerful tool for real-time monitoring and decision support.

As a potential input to future DT developments for cemented waste drums, a LLW cemented drum, stored since 1994 at the Swiss Federal Interim Storage Facility (BZL), operated by PSI, was also characterised as part of Task 7.4 by KIT-INE.

The results of Task 7.4 were comprehensively documented in Deliverable D7.5 [9], which provides a detailed account of the methodologies used, results obtained, and remaining challenges. In addition, three journal publications [14, 15, 16] on ML methods, neural network based model, and general DT and digitalisation technologies were produced and summarised in Deliverable D7.4 [17].

4.3 Outcomes

To achieve the principal objective of Task 7.4 of developing a proof of concept for certain aspects of DT technology in the pre-disposal management of radioactive waste, a DT dashboard was developed on the geoml platform (https://digitaltwin.geoml.eu/) where users can interact with different models related to cemented waste package degradation and produce data for different scenarios that could be then used in a decision framework for the suitability of the waste package. Key processes such as cement hydration and carbonation were successfully implemented and showcased through the DT dashboard, introducing the concept of a waste integrity parameter that could be applied to other processes. These models were implemented using different geochemical modelling codes and show the potential of having several tools running on the same platform that can be used to model different aspects.

The work within this task also highlighted the necessity of using metamodels to approximate complex systems and provide computational efficiency. The work in Task 7.4 demonstrated the use of a neural network-based ML surrogate model for organic degradation and metallic corrosion. Surrogate models are a specific type of metamodel, and they are built for using interpolation and regression methods to represent the relationships within the data. The surrogate model developed in Task 7.4 was trained using the complex geochemical model GEM-SELEKTOR and showed a significant gain in computational efficiency when carrying out sensitivity analysis on the rate of waste material degradation, running one million cases for global sensitivity analysis in under two seconds (compared to 79 days without the surrogate model).

Central to the DT framework is the development and implementation of appropriate multiphysics-based models. These models are typically phenomenological and may involve many primary variables such as temperature, pressure, and displacements to capture the relevant thermo-hydro-chemo-mechanical processes of the waste package. This leads to a significant number of material parameters that have to be estimated based on laboratory or *in situ* experiments. The work in Task 7.4 also highlighted Bayesian inference methods not only as a way forward for handling parameter estimation problems but also as a basis for the development of future metamodels.

Further, as part of Task 7.4, a real-life example of a DT application for waste packages was explored, focusing on ASR pathology. Such a pathology is a possibility if the right combination of alkali content, reactive silica and water occurs in the waste packages. This objective was met through a successful integrated experimental-numerical programme. Laboratory experiments and four drum-scale experiments on various cement recipes simulated the ASR process under natural and accelerated conditions, using a variety of sensors and data acquisition systems for real-time data management and analysis. The experiments identified a specific cement formulation using recycled concrete aggregate (RCA) as having the highest potential for ASR formation, although drum-scale tests primarily showed autogenous shrinkage due to slow ASR kinetics. The research suggested RCA may deplete free water, thus slowing ASR. Drum-scale experiments will continue beyond the PREDIS project. As part of the DT application, a coupled thermo-hydro-mechanical model for ASR was implemented, capable of simulating temperature and strain trends, although accurately capturing the hydration phase remains challenging. The PREDIS DT dashboard documents both experimental data and numerical predictions.

To provide information that can be used in the future to obtain more detailed DTs for cementitious waste drums, KIT-INE undertook characterisation of a LLW cemented waste drum stored at BZL for 30 years. After selection of a drum by the project partners and the approval of the Swiss Federal Nuclear Safety Inspectorate (ENSI), cement samples from four different locations in the drum (bottom, middle, upper, top lid) were collected by PSI. Initial visual inspection indicated dry cement samples, with unaltered cementitious backfill around the waste and a thin layer of calcite powder on top of the cementitious backfill within the steel drum. The dryness of the cement samples was further corroborated by failed attempts to extract cement pore water from the bottom part of the drum. No corrosion was observed on the steel drum. A thorough characterisation of the drum fragments was then conducted by KIT-INE using various techniques, including X-ray diffraction, thermogravimetric analysis coupled to differential scanning calorimetry, X-ray photoelectron spectroscopy, scanning electron microscopy and energy dispersive X-ray spectroscopy, and micro computed tomography. These methods confirmed the heterogeneity of the samples, with four main crystalline phases identified: quartz, portlandite, calcite and ettringite. Although no clear trends were identified along the drum, a systematic decrease in the overall Ca:Si ratio from the top to the bottom of the cemented drum was observed. Insights on the porosity of the material were obtained by micro computed tomography, with the identification of two main regions of different porosities. More details on the characterisation of this 30-year old cemented drum can be found in reference [18].

The outcomes of Task 7.4 highlight the impact of DT technologies within the PREDIS project, illustrating work from theoretical development to real-world application.

5 Task 7.5: Data Handling, Processing and Fusion

5.1 Objectives

The objectives of Task 7.5 of WP7 were to develop a conceptual model for secure and persistent data handling and storage, develop models and methods to translate NDE and monitoring data into engineering parameters, develop approaches for fusion of multi-method monitoring and other data in order to obtain adequate input for the decision framework, implement a plan for ensuring data integrity, and provide a database and software prototype for demonstration. The task collectively contributed to the overarching goal of innovation in the areas of degradation, prevention, early detection, and efficient handling of cemented waste.

Task 7.5 was subdivided into three sub-tasks: data handling, processing, and fusion platform (T7.5.1); ML and advanced signal processing (T7.5.2); and decision framework (T7.5.3). Figure 5-1 presents the three subtasks within 7.5 and the relationship of Task 7.5 to Tasks 7.3 and 7.4 of WP7.

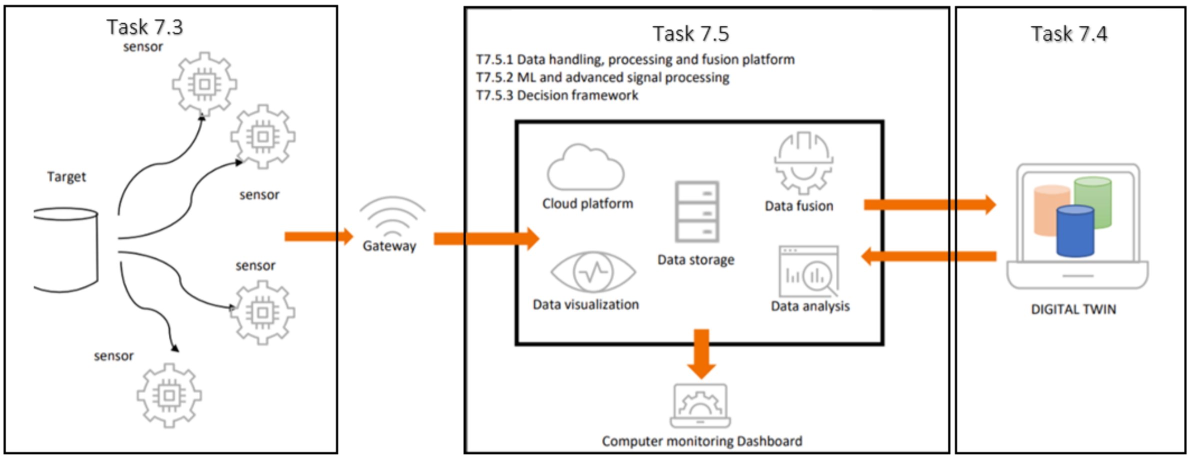


Figure 5-1: Scope of Task 7.5 and its relationship with Tasks 7.3 and 7.4 within WP7 (based on reference [19]).

5.2 Approach and Deliverables

The tools and methods developed within Task 7.5 are collectively referred to as the data management framework. The implementation of this framework was collaboratively achieved by several project partners, including VTT (Finland), Ansaldo Nucleare SpA (ANN, Italy), SCK CEN (Belgium), NNL (UK), NRG (Netherlands), BAM (Germany), and Institute for Energy Technology (IFE, Norway). The data management framework consists of a data platform, data processing and integration scheme, and decision framework. More details of the work performed, and the results achieved in Task 7.5 are provided in Deliverable D7.7 [19]. In addition, two journal publications [20, 21] were produced to disseminate some of the results of Task 7.5 on data management innovations; these publications were also presented in Deliverable D7.6 [22].

5.3 Outcomes

5.3.1 Data platform

The data platform is the central data repository of the data management framework, interfacing with the various data input and output flows. A reference metadata model, accessible as a web service, was set up by using a Django Virtual Environment in a local server on a site. In this metadata model, four database tables (waste packages, sensors, nodes, and images) were associated with the possibility of managing data by the administrator and user groups with the necessary permissions.

An SQLite3 Database was preliminarily filled (by using Django syntax) with the relevant data from the project. Once the waste packages were defined as a master table, any changes associated with them were automatically traced in a change history. Data was visualised in three different ways: admin mode, public mode (webpage), and other external open-source tools (i.e., HeidiSQL) to analyse the database structure and its consistency.

5.3.2 Data processing and integration

In Task 7.5, the Microsoft Azure cloud computing environment was tested to be suitable for performing the data processing and integration operations, and simple trials were performed with Azure artificial intelligence (AI) studio. While ML and advanced signal processing were considered to be part of the scope of Task 7.4, Task 7.5 focused on the other parts of the data-driven workflow: data collection, integration of the data management framework subsystems, and administration of the different development platforms.

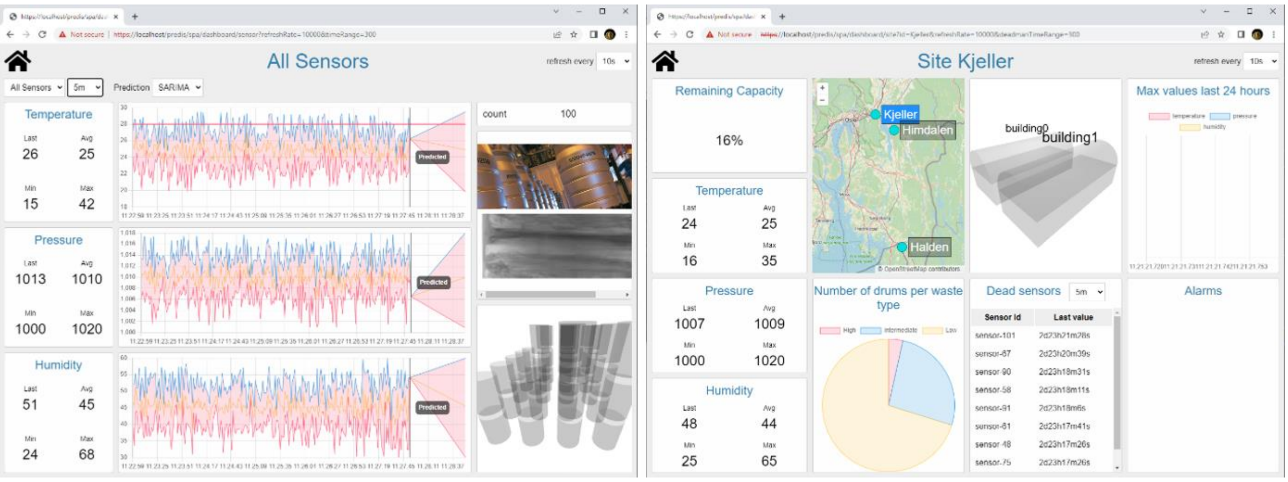
There are various options for modelling data. The possible use of ontologies in the context of the PREDIS project was studied. Potential benefits of ontologies, such as information integration, compatibility, and shared terminology, were described and considered within this task.

There are several types of data preprocessing methods for different purposes. Methods on data integration, data cleaning, handling of time series data and time-dependent sequences, labelling, and data transformation were examined. In addition, software libraries intended for data processing using the Python programming language were briefly considered and compared.

The data management framework was implemented in Azure. Automatic setup and management of this framework using scripts and Azure Resource Manager (ARM) templates was outlined. Several advantages achieved by using scripts and ARM templates were highlighted. In addition, a list of steps with which a partially corresponding system can be deployed was compiled.

5.3.3 Decision Framework

The Decision Framework is the user interface to the data management framework and aims to provide visualised information to end users to assist with the decision-making process based on information about the condition of the monitored packages and the predictions provided by the DT. As part of the decision framework initiative, a prototype for a decision platform was designed and implemented as a web application. This platform incorporated multiple dashboards, each tailored to present information from distinct perspectives, tailored to the specific needs of different users. Users can access 3D analysis views that facilitate the visualisation of the waste storage sites and containers. Example dashboards developed within this task are shown in Figure 5-2. Furthermore, the decision platform offers Online Analytical Processing (OLAP) analysis of radioactive waste and dose analysis reports (e.g., to support As Low As Reasonably Achievable (ALARA) based planning or briefing option). Additionally, the platform goes beyond presenting only the current situation by showcasing future predictions derived from a DT, which can be conveniently viewed on the dashboard. This comprehensive approach ensures that the decision platform not only addresses immediate needs but also provides valuable insights for long-term planning and management.



All Sensors

Temperature: Last 26, Avg 25, Min 15, Max 42

Pressure: Last 1013, Avg 1010, Min 1000, Max 1020

Humidity: Last 51, Avg 45, Min 24, Max 68

Site Kjeller

Remaining Capacity: 16%

Temperature: Last 24, Avg 25, Min 16, Max 35

Pressure: Last 1007, Avg 1009, Min 1000, Max 1020

Humidity: Last 48, Avg 44, Min 25, Max 65

Sensor Id	Last value
sensor-101	2d23h21m28s
sensor-67	2d23h20m39s
sensor-90	2d23h18m31s
sensor-58	2d23h18m11s
sensor-91	2d23h18m6s
sensor-61	2d23h17m41s
sensor-48	2d23h17m26s
sensor-75	2d23h17m26s

Figure 5-2. Example dashboards: dashboard for a single drum (left) and for a whole site (right) [19].

Utilising a decision platform that integrates ML and DT powered predictions and OLAP analysis holds the potential to significantly support informed decision-making. Through the integration of sensor data and other monitoring systems, the PREDIS platform provides immediate insights facilitating improved performance and safety in waste management processes. The real-time monitoring capabilities facilitate the instant detection of deviations from normal conditions and automated alerts upon the detection of irregularities for prompt corrective actions. The OLAP analysis empowers users to selectively extract and query data, allowing for analysis from various perspectives. This proactive approach ensures timely interventions, thereby minimising the likelihood of incidents/accidents or environmental impact.

5.3.4 Common showcase at UJV

To demonstrate the data management framework concept of Task 7.5 and its link to other WP7 tasks, a collaborative showcase between the different tasks and involving several partners was performed. This joint showcase demonstrated the advancements made in the project and the collaborative, iterative and integrative approach of the project.

Selected technologies were tested in a realistic environment in a storage configuration at UJV using a set of mock-ups. The commissioning of the UJV mock-up facility was completed in October 2023. Preliminary data collection tests were conducted locally at UJV to ensure seamless integration and data transmission to the Azure platform. Remote troubleshooting procedures were established for any potential issues during the three-month testing period, which concluded in January 2024.

The joint showcase produced data in the form of a metadata file, and the measured data from the sensing and monitoring systems were transferred to and stored on the cloud data platform through IoT applications. The data was processed and displayed to the end users through the decision framework. The final data connection with the DT of Task 7.4 may be subject of future work and the decision framework dashboard has capabilities to display the analysis data originating from the DT.

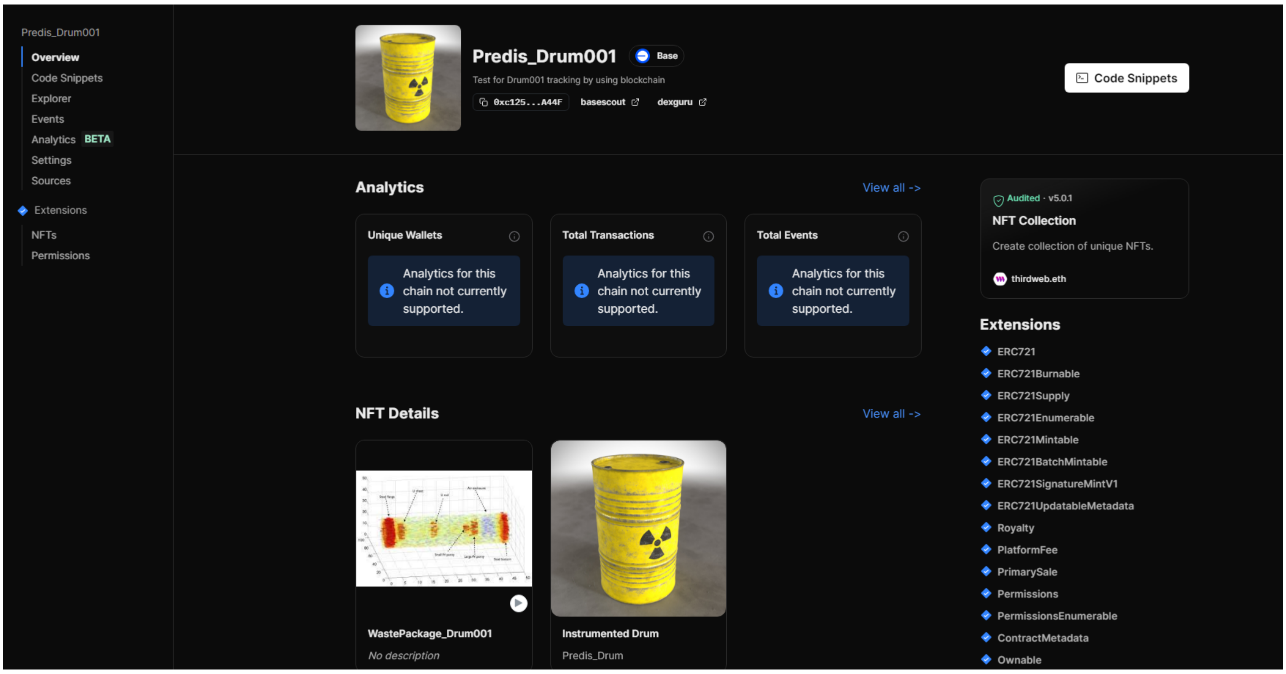
5.3.5 Conclusions and Future Opportunities

A conceptual model for data handling and storage has been developed, and a practical implementation a data management framework has been performed. The demonstration test at UJV confirmed that monitoring data from sensors can be automatically uploaded to the Microsoft Azure cloud platform, and it can be visualised on the decision platform. To ensure traceability, the associated metadata can also be stored and connected with the monitoring data. A web-based decision platform with multiple dashboards has been developed to present information from different perspectives customised to different users. The functionality of the decision platform has been proven in the UJV demonstration test. Predictive numerical models of the DT can be integrated into the platform to further support decision-making.

As information technology (IT) and software solutions can become obsolete within a relatively short period (less than ten years), it is crucial to develop strategies and solutions for long-term data management to ensure continuous and flawless handling of data for radioactive waste storage. Two activities seem particularly interesting for managing data over an extended period (more than ten years):

- Create a Non-Fungible Token (NFT) for each drum produced and realise it on Web3 to establish an autonomous and certified digital life for the drums. This approach, illustrated in Figure 5-3, involves a process that can be implemented using a guessing approach on thirdweb.com, although the NFT is created on a customer server within a Django framework.
- Employing ML based on visual AI to recognise the properties of the drums. This method, as depicted in Figure 5-4, utilises a combination of YOLOv8, Streamlit, Django, and TensorFlow, allowing for sophisticated property recognition and management and can potentially reduce the data storage requirements.

Both technologies present promising and viable long-term data management strategies that can significantly enhance the reliability and efficiency of data handling in radioactive waste storage.



Predis_Drum001

Test for Drum001 tracking by using blockchain

0xc125...A44F

Analytics

Unique Wallets: Analytics for this chain not currently supported.

Total Transactions: Analytics for this chain not currently supported.

Total Events: Analytics for this chain not currently supported.

Audited · v5.0.1

NFT Collection

Create collection of unique NFTs.

thirdweb.eth

Extensions

- ERC721
- ERC721Burnable
- ERC721Supply
- ERC721Enumerable
- ERC721Mintable
- ERC721BatchMintable
- ERC721SignatureMintV1
- ERC721UpdatableMetadata
- Royalty
- PlatformFee
- PrimarySale
- Permissions
- PermissionsEnumerable
- ContractMetadata
- Ownable

NFT Details

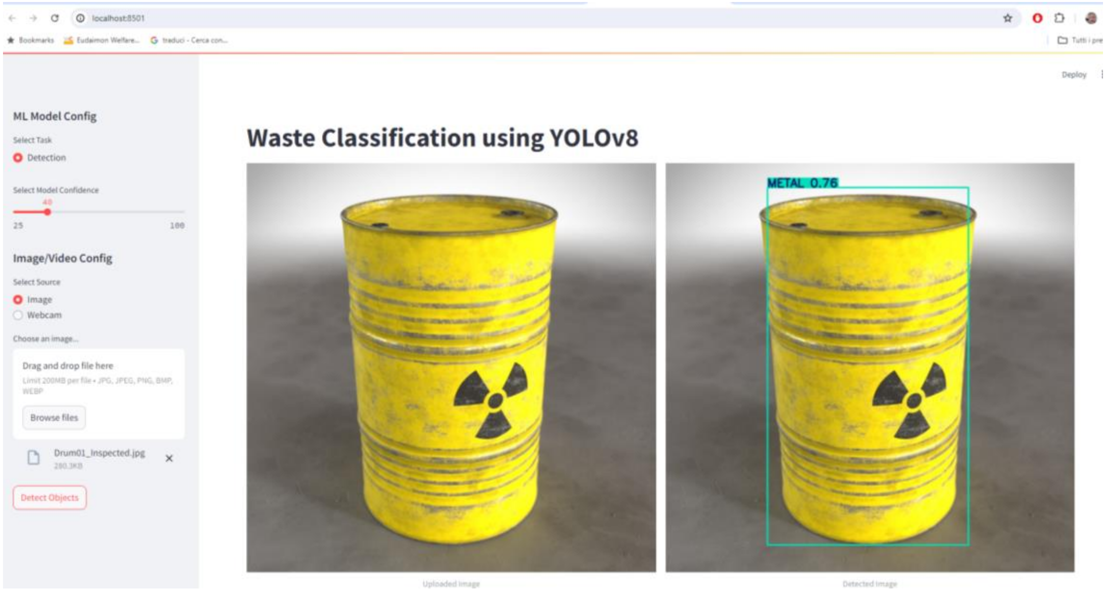
WastePackage_Drum001

No description

Instrumented Drum

Predis_Drum

Figure 5-3: NFT example.



ML Model Config

Select Task
● Detection

Select Model Confidence
40
25 100

Image/Video Config

Select Source
● Image
○ Webcam

Choose an image...

Drum01_Inspected.jpg
280.3KB

Waste Classification using YOLOv8

Figure 5-4: AI recognises the drum as metallic (input on the left, output on the right).

6 Task 7.6: Demonstration and Implementation of Monitoring, Maintenance, and Automation/Digitalisation Techniques

6.1 Objectives

The objectives of Task 7.6 of WP7 were to demonstrate that the technologies, methods, and models developed and identified in Tasks 7.2 to 7.5 are viable for use in a radioactive waste storage environment, and test and verify the performance of the selected technologies, developed prototypes, and models by the deployment of an instrumented package at an end-user facility, possibly within a store environment.

Task 7.6 was subdivided into three sub-tasks: evaluation of technologies and developed systems from an end-user perspective (T7.6.1); demonstrating systems and method (T7.6.2); and definition of potential mitigation actions and design improvements (T7.6.3).

6.2 Approach and Deliverables

The approach followed to undertake Task 7.6 and achieve its objectives of evaluating and testing the technologies developed within WP7 in a real storage environment involved close cooperation of several organisations including Orano (France), SOGIN (Italy), NNL (UK), VTT (Finland), UJV (Czech Republic), UNIPI (Italy), BAM (Germany), and IFE (Norway). In a first step, the technologies were evaluated and scored using a multi-criteria approach involving the EUG to understand the attributes of each technology. The criteria assessed included technical performance, costs, safety / security for operators, operations, induced wastes, technical maturity, and scalability. Following this, the technologies and parameters to be monitored in the demonstration tests, as well as the waste package/mock-up and test location, were selected on the basis of the technology comparisons and feedback from the EUG.

The EUG feedback was an important input to ensure that the monitored parameters and data collected from the tests align with the EUG needs. This feedback also helped inform decisions on the types of packages, technologies, and degradation phenomena to be studied. In selecting the technologies, their interoperability and compatibility with different cemented package types were evaluated, concluding that most technologies would be compatible with different package sizes, dimensions, container materials, and cement matrix formulations, with the following exceptions:

- For RFID embedded sensors (BAM/VTT), the long-term compatibility of the embedded sensors with the cement matrix should be verified for each end-user according to the matrix formulation selected.
- For Mu-Tom (INFN), the package size is limited by the detector dimensions (<5m).
- Air-coupled ultrasonic inspection (NNL) is designed only for metallic containers and has been tested only with Portland cement contents inside the package. This technology has also been considered in combination with point cloud laser scans.

Figure 6-1 illustrates the three main inputs that were considered for the decision and implementation of the demonstration tests. These inputs are: EUG needs, technologies to be tested, and the storage configuration constraints for each technology (and its mock-up). Once these factors had been determined, the location and types of tests for the demonstration trials were identified.

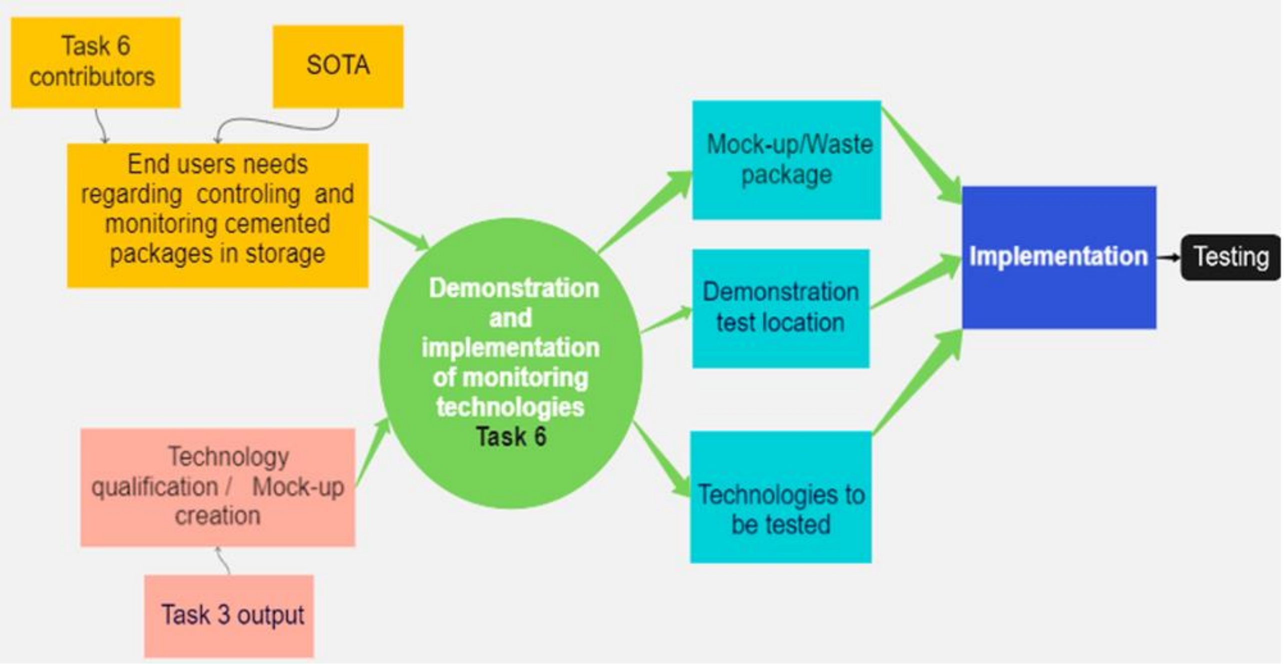


Figure 6-1: Method for selection of a waste package/mock-up [23].

Five technologies were selected for the demonstration test, based on their availability and TRL:

- RFID embedded sensors.
- SciFi/SiLiF.
- Sensorised Lora Wireless Sensor Network.
- Air-coupled ultrasonic inspection.
- Mu-Tom.

The air-coupled ultrasonic inspection technique was tested at NNL using an old 500 L inactive Magnox mock-up drum. Mu-Tom was tested using a dedicated mock-up assembled at UJV and shipped to INFN facilities for assessment. The other selected technologies (RFID embedded sensors, SciFi/SiLiF, Sensorised LoRa Wireless Sensor Network) were tested in a storage configuration at UJV (Czech Republic) using a set of mock-ups. The reference package for the tests was defined within Task 7.2 (Section 2.3.3). The commissioning of the UJV mock-up facility was completed in October 2023. Preliminary data collection tests were conducted locally at UJV to ensure seamless integration and data transmission to the Azure platform. Remote troubleshooting procedures were established for any potential issues during the three-month testing period, which concluded in January 2024. The storage configuration adopted is shown in Figure 6-2. This approach used indirect stacking of waste packages which was identified to be suitable with all technologies tested in WP7.

Deliverable D7.8 [23] provides comprehensive information on the demonstration tests performed and their results, including more details on the methodologies followed to select the technologies, monitoring parameters, and storage configuration. A summary of the outcomes and future improvements are given in Section 6.3.

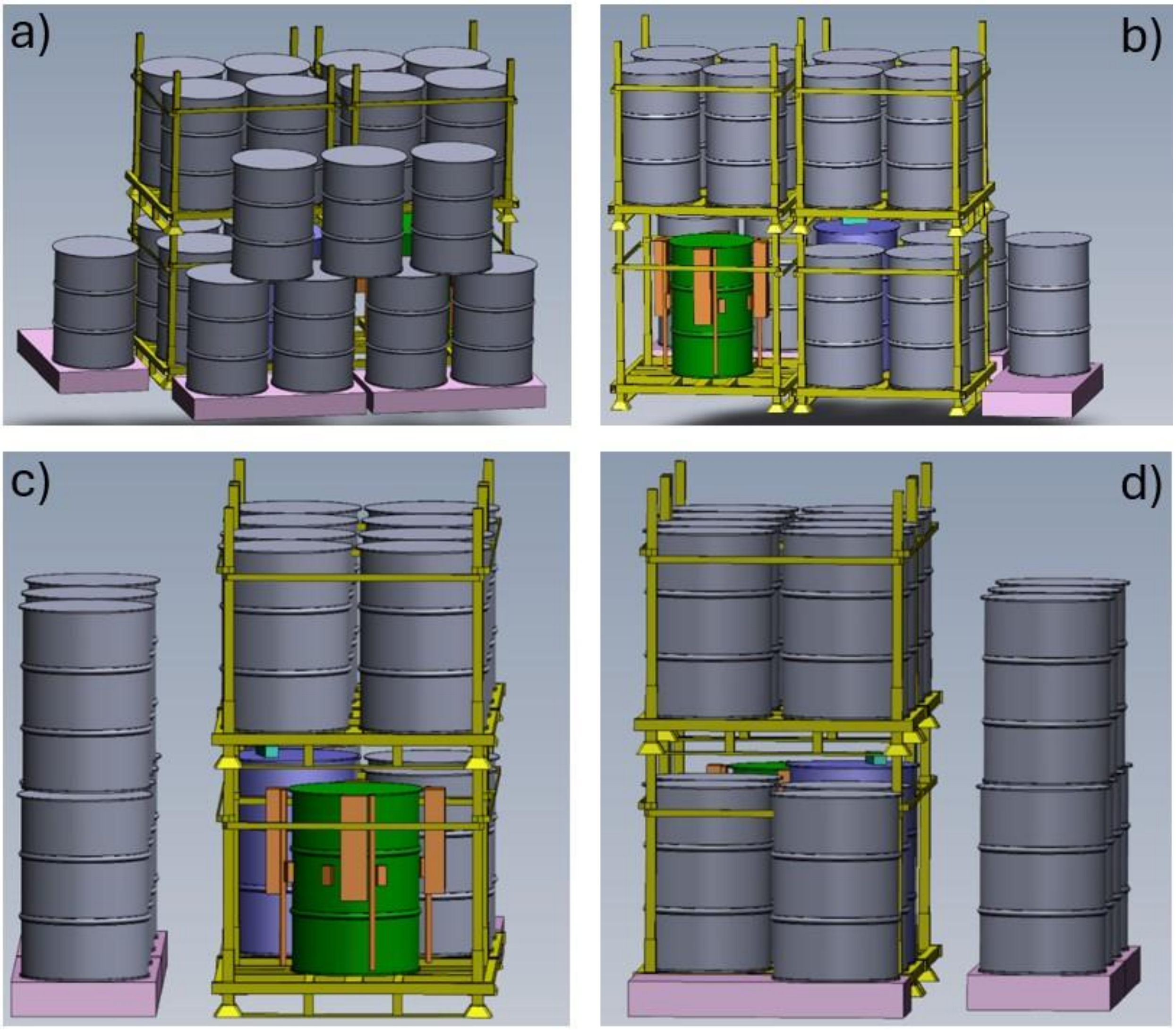


Figure 6-2: Demonstration test configuration at UJV: a: front view; b: back view; c: side view; d: second side view.

6.3 Outcomes

The main outcome of Task 7.6 is the successful demonstration of the technologies, methods, and models developed in Tasks 7.2 to 7.5 in a realistic storage environment at UJV (Czech Republic) and other locations (NNL, INFN) using mock-ups to validate the real-world functionality of these technologies and advance their TRLs. Preliminary data collection ensured seamless integration and data transmission. The tests confirmed the effectiveness of these technologies and helped develop monitoring tools for end-users.

The technologies assessed in the demonstration test conducted at UJV included RFID embedded sensors, Sensorised LoRa Wireless Sensor Network, and SciFi/SiLiF. Over a three-month period, these technologies were assessed for their performance in monitoring waste package conditions, yielding valuable insights into their strengths and weaknesses.

The RFID embedded sensors proved effective in measuring the evolution of the cemented matrix parameters (humidity, temperature and pressure) with power supply transmitted wirelessly to the battery-less sensor through the walls of the metallic container. However, several challenges and potential areas for improvement were identified when implementing this technology including the need for highly-experienced personnel to ensure appropriate incorporation of the sensors inside the package, the absorption of moisture from fresh concrete by sensor components during early-stage monitoring, and the requirement of technology compliance with disposal WAC for the waste packages since the sensors are embedded within the matrix and will remain in the package for disposal.

The Sensorised LoRa Wireless Sensor Network utilised passive gamma and neutron counting along with LoRa technology for radiological monitoring of the test drums at UJV. The system maintained robust communication and the ambient dose equivalent rates observed corresponded well to the predicted values. Future work that would benefit further improvement of this technology includes testing of several packages in a real environment simultaneously and using sensors capable of detecting various gamma energy levels to account for different radionuclides in the waste. The impact of long-term exposure of the sensors and LoRa node to irradiation and their material ageing would also need to be evaluated to confirm the reliability and longevity in different radioactive environments.

The SciFi/SiLiF technology also measured neutron and gamma radiation from the tested packages. Key improvements identified during the tests relate to components of the electronic board. The need to factor in potential package handling when installing the technology was also highlighted. The sensors are attached to the package and, owing to equipment size, the sensors may need to be removed prior to package movement within a storage facility. Therefore, alternative technology installation solutions may need to be developed based on the storage facility constraints.

Another key outcome of the demonstration tests in Task 6.7 was the creation of a dedicated dashboard that integrated and displayed the results from the various technologies. This user-friendly interface provided continuous remote access to the collected data through four distinct worksheets, each focusing on different technologies and their results, which facilitated comprehensive analysis and comparison.

Overall, the demonstration tests were a success and highlighted the need for advancements in a number of areas to ensure the practical usability of the technologies. The next step for all technologies is to complete the tests conducted during the demonstration in a representative environment at an industrial setting (e.g., containing several active cemented packages with package movement), incorporating the insights gained from the demonstration tests. This progression is crucial for demonstrating the viability and robustness of these technologies in radioactive waste storage and for improving waste management practices.

7 Task 7.7: Dissemination and Reporting

7.1 Objectives

The objectives of task 7.7 of WP7 were to disseminate the work carried out and produce a project summary report documenting the outcomes of WP7 (this report). The dissemination activities included participation at scientific conferences and technical workshops to raise awareness of the achievements, preparation of specific dissemination materials for distribution, engaging in dialogue with the EUG, and preparation of open access publication and finalising project results for publication.

7.2 Approach and Deliverables

The partners in WP7 of the PREDIS project disseminated their work and results through various means, including oral and poster presentations at scientific and technical conferences and workshops, journal publications, and webinars. A spreadsheet log was maintained to record all dissemination activities conducted in the WP7. Through these dissemination activities, the WP7 partners engaged with diverse audiences and reached an international community, contributing to the advancement of knowledge and practices in cemented waste management, particularly regarding innovative pre-disposal treatments and digital tools for the monitoring of radioactive waste.

To involve the EUG and gather their feedback, a value assessment of the WP7 technologies across the full waste management lifecycle was carried out. The value assessment aimed to analyse the economic, environmental, and safety impacts of the technologies developed and tested within WP7, with the participation of the EUG.

WP7 included two main deliverables: D7.9 which documents the value assessment work [24] and D7.10 summarising the overall WP7 outcomes (this report).

7.3 Outcomes

7.3.1 Dissemination activities

Figure 7-1 provides a summary of the dissemination activities by WP7 partners over the duration of the PREDIS project, including the number of each type of activity and location of the conferences and meetings where presentations were delivered. These presentations covered a range of topics related to WP7, including digital tools for waste management, innovative pre-disposal treatments, and management of cemented wastes.

At the end of the project, a total of 28 dissemination activities were recorded. These included:

- 14 oral presentations at several conferences including the international conference on nuclear decommissioning (ICOND)[1], DigiDecom 2022[2], EURADWASTE 2022[3], international Conference on Nuclear Engineering (ICONE30)[4], international conference on environmental remediation and radioactive waste management (ICEM 2023)[5], and the 67th IAEA general conference[6].
- Nine articles and journal publications [11,12,14,15,16,20,21,25,26], including several which are publicly available.

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[1] https://www.icond.de/welcome.html
[2] https://decommissioning.com/en/events/digidecom-2022/
[3] https://www.sfen.org/evenement/fisa-2022-euradwaste-22/
[4] https://www.icone30.org/
[5] https://event.asme.org/ICEM
[6] https://www.iaea.org/about/governance/general-conference/gc67/gc-at-glance

- Five poster presentations at the IAEA international conference on radioactive waste management[7], EURADWASTE 2022[3], IGD-TP symposium 2022[8], Waste Management 2023 (WM2023)[9], and ICEM 2023[5].
- One webinar on the DT tools [27].

The WP7 dissemination activities reached a diverse audience, including industry professionals, researchers, and the public. These activities were communicated internationally across Europe and beyond (Figure 7-1). This widespread reach is consistent with the aim of engaging with global audiences to increase the impact of the project.

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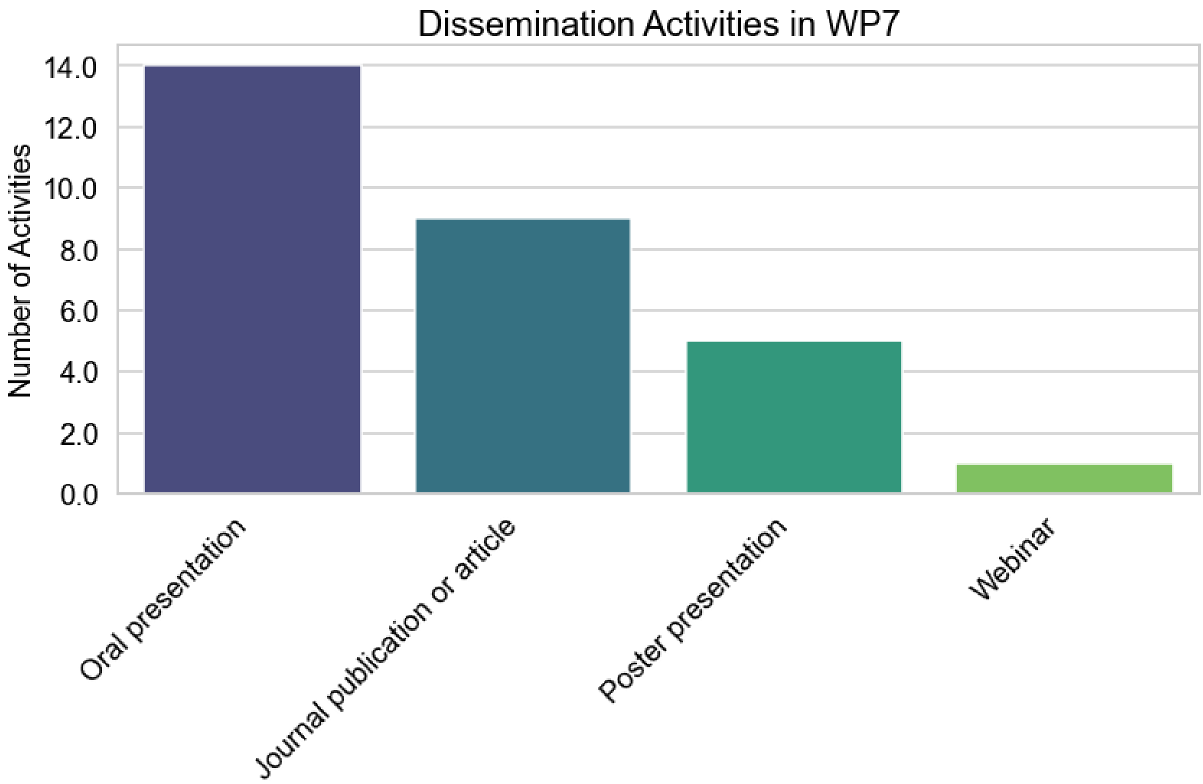
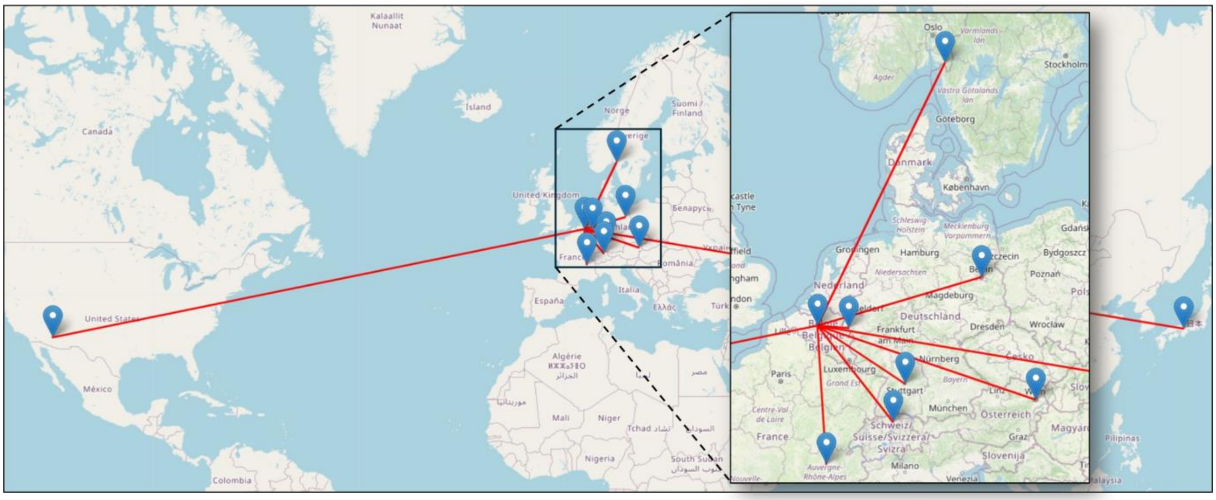
[7] https://www.iaea.org/events/international-conference-on-radioactive-waste-management-2021
[8] https://igdtp.eu/event/igd-tp-symposium/
[9] https://www.wmsym.org/wm2023-conference/



a) Number and type of dissemination activities in WP7.



b) Locations where some of the dissemination activities of WP7 took place; cities highlighted include: Vienna, Aachen, Berlin, Stuttgart, Lyon, Zurich, Halden, Phoenix, and Kyoto.

Figure 7-1: Dissemination activities in WP7 of PREDIS.

7.3.2 Value Assessment of the WP7 Technologies

The economic, environmental, and safety impacts of the innovative technologies and approaches tested in WP7 were evaluated by mean of a “value assessment” approach to compare these technologies against current practices in terms of key assessment areas relating to operational safety, environmental impact, long-term safety, implementation, technical readiness, and strategic cost impact. This process involved close collaboration between technology developers and the EUG through workshops to discuss the outcomes of the value assessment and incorporate EUG feedback into the final value assessment D7.9 report [24].

D7.9 provides further details on the assessment methodology and its application and identifies key findings on each technology in terms the advantages and challenges associated with its implementation during storage of cemented waste packages. The following are key findings from the value assessment:

- **SciFi/SiLiF radiation monitoring**. This monitoring technology offers enhanced safety by reducing operator exposure to radiation and minimising the movement of waste packages compared to the baseline of visual inspection and manual dose rate measurement. However, it increases industrial hazards during equipment setup and has a slightly higher environmental impact than the baseline due to the materials used. Most of the equipment is reusable, and maintenance waste consists mainly of rechargeable batteries that need replacement every 10 years. This technology improves long-term safety and waste package disposability by detecting deep cement cracks, allowing for early remediation.
- **AE for measuring ASR**. This monitoring technology reduces the need for visual inspections, reducing exposure to hazards compared to the baseline of visual inspection. However, it requires manual installation and infrastructural changes, introducing safety risks. The environmental impact of this technology is due to its component materials and energy usage. Reusable sensors and a neutral economic impact are noted, but further development is needed to increase its TRL.
- **Non-contact ultrasonic scanning**. This monitoring technology provides non-invasive, non-destructive inspections without altering package design, and can identify issues such as swelling, cracking, and corrosion. It requires skilled workers for correct positioning and data interpretation. Its environmental impact is low, and it can be integrated with existing processes. However, its TRL is low, indicating the need for further trials.
- **RFID embedded sensors**. This monitoring technology offers improved safety and monitoring during storage and transport and requires specialised expertise for construction and decommissioning. The environmental impact is slightly positive, although long-term impacts need further evaluation. The technology can be seamlessly integrated into existing infrastructure but has high setup and maintenance costs and a low TRL.
- **Sensorised LoRa wireless sensor network**. The advantages of this monitoring technology include simplified construction, modular deployment, remote calibration, and automated data collection, enhancing safety and reducing operational costs. However, it requires technical expertise in wireless technology and has data management and decommissioning challenges. The technology is pilot-ready but requires further testing in real storage facilities.
- **Mu-Tom**. This monitoring technology improves safety by using cosmic ray muons, eliminating the need for radiation safety protocols. It uses recyclable materials, reducing environmental impact compared to the X-ray imaging baseline, but has longer data acquisition times and has not yet achieved full industrial scalability. Industrialisation costs are estimated at €1M, with software and computing optimisations needing further research.
- **DT, data platform, and decision framework tools**. These non-intrusive digital tools maintain package integrity and improve decision-making by aggregating part and real-time monitoring information. Risks include cybersecurity threats and cloud service restrictions, with environmental impacts primarily caused by the IT infrastructure. These tools enable streamlined decision-making, reducing remediation and disposability costs. Further R&D is needed to ensure effective implementation of these tools.

8 Conclusions

Efficient and safe management of radioactive waste is crucial for protecting both present and future generations. Medium to long-term storage necessitates the monitoring of waste packages for potential degradation phenomena. Managing any issues arising before transport to the final disposal repositories is essential. To this end, the PREDIS project conducted a comprehensive four-year (2020-2024) R&D programme, focusing on developing advanced monitoring systems, implementing pre-disposal treatment activities, and managing radioactive waste streams other than nuclear fuel and high-level radioactive waste.

WP7 specifically targeted innovations in cemented waste handling and storage, aiming to improve storage operations, reduce costs, enhance safety, and provide a better understanding of waste characteristics before final disposal. This report describes the work completed within WP7 of the PREDIS project. The main outcomes of the six technical tasks of WP7 are summarised below. Task 7.1 relates to project management and coordination and is not discussed.

Task 7.2: SoTA in Packaging, Storage, and Monitoring of Cemented Wastes

Task 7.2 aimed to conduct a gap analysis in the early phases of the project and compile a comprehensive SoTA report on the existing methods and procedures for managing cemented waste packages. This task also involved identifying a reference package and degradation mechanisms for use in further activities in WP7 and provided necessary data for LCA/LCC activities in WP2 of PREDIS. The gap analysis aimed to evaluate industry and stakeholder needs to help inform the WP7 scope and plans. The approach to the SoTA report included distributing a questionnaire to collect information on cemented waste management practices across Europe, which highlighted the widespread use of cement grouting for various waste streams and the common use of metallic drums and prismatic concrete containers. Monitoring strategies revealed a reliance on visual inspection and periodic data collection. Key degradation phenomena identified were corrosion, cracking, and ASR. Based on this, a reference package with specific characteristics was recommended for further studies and demonstrations within WP7.

Task 7.3: Innovative Integrity Testing and Monitoring Techniques

The advancements made in Task 7.3 have significantly improved the monitoring and integrity testing of radioactive waste drums. The technologies covered included: SciFi/SiLiF gamma and neutron radiation monitoring, AE for measuring ASR, non-contact ultrasonic inspection, RFID embedded sensors, sensorised LoRa wireless sensor network, and Mu-Tom. The tests and development activities with Task 7.3 demonstrated the potential of these technologies for continuous remote monitoring of a store and revealed the need for further optimisation and processing of data collection to enhance the reliability and accuracy of these monitoring systems. Future work will focus on developing and validating these technologies through extended testing and optimisation in real-world end-user facilities.

Task 7.4: Digital Twin

Task 7.4 successfully achieved its primary objective of developing a proof of concept for certain aspects of DT technology in the pre-disposal management of radioactive waste packages, demonstrating the use of ML algorithms to predict the geochemical and mechanical evolution of waste packages over time. The DT dashboard developed on the geoml platform provides a valuable tool for real-time monitoring and decision support, integrating complex geochemical and mechanical models. Continued development and testing of the surrogate models and Bayesian inference methods are essential to improving the accuracy and efficiency of parameter estimation methods used for the evolution prediction. Experimental results of the characterisation of a LLW cemented waste drum, stored at the BZL facility in Switzerland for 30 years, can be used in the future to obtain more detailed DTs for cementitious waste drums. Additionally, ongoing drum-scale experiments will provide further insights into ASR kinetics and the role of recycled concrete aggregate in waste packages.

Task 7.5: Data Handling, Processing and Fusion

Task 7.5 of WP7 successfully established a framework for secure data management and processing, integral to the efficient management of cemented radioactive waste. The task achieved its key objectives, including the development of a comprehensive data management system, the translation of NDE and monitoring data into engineering parameters, and the integration of multi-method monitoring data for informed decision-making.

Ensuring data integrity and secure storage over the medium to long term required the development of sophisticated models and methods, including the potential use of ontologies and advanced preprocessing techniques. The project outlined areas for enhancing long-term data management in radioactive waste storage. Creating NFTs for each waste drum on Web3 could provide a certified digital life for the drums, ensuring continuous data integrity and traceability. Additionally, using ML based on visual AI for property recognition can streamline data handling and reduce storage requirements.

Task 7.6: Demonstration and Implementation of Monitoring, Maintenance, and Automation/Digitalisation Techniques

The main outcome of Task 7.6 was the successful demonstration the technologies developed in other WP7 tasks within a realistic storage environment at UJV in the Czech Republic and at other locations at NNL and INFN. The tested technologies were evaluated for monitoring waste packages over a three-month period. A dedicated dashboard was also created to integrate and display data from the technologies and provide a visual user interface for interpreting the monitored data. The demonstration highlighted the strengths of the technologies and various areas for improvement. Further testing in a representative industrial setting is necessary to validate the practical usability and effectiveness of these technologies.

Task 7.7: Dissemination and Reporting

The primary focus of Task 7.7 was on disseminating the findings of the project and engaging with stakeholders and the EUG to raise awareness of its achievements. This was accomplished through various means, including participation at scientific conferences and technical workshops, and production of open-access publications. The EUG were also involved and provided feedback on the value assessment task which analysed the economic, environmental, and safety impacts of the technologies developed and tested in WP7. This feedback was incorporated into the analysis. Another objective of Task 7.7 was to develop a comprehensive project summary report, documenting the key outcomes of the work (this report).

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