Deliverable 7.8: Report on demonstration and implementation of monitoring, maintenance, and automation/digitalization techniques for improving safety during the storage and handling of cemented waste packages

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Abstract

In the framework of Work Package 7 (WP7) of PREDIS, the work of task 7.6 “Demonstration and implementation of monitoring, maintenance and automation/digitalization techniques” is to demonstrate that the technologies, methods, and models developed in Tasks 3 to 5 can be used in a real storage with nuclear waste. This report outlines the work conducted during the PREDIS project to evaluate the technologies developed under Task 3 (Sub-task 7.6.1). It also details the demonstration tests carried out at UJV and NNL to verify and validate the application of these technologies in a real storage environment (Sub-task 7.6.2).

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Acronyms

EU	End User
HLW	High Level Waste
ILW	Intermediate Level Waste
LLW	Low Level Waste
NDE	Non Destructive Evaluation
NDT	Non Destructive Testing
OPC	Ordinary Portland Cement
RFID	Radio Frequency Identification
SoTA	State of The Art
VLLW	Very Low Level Waste
WAC	Waste Acceptance Criteria
WP	Work Package

1 Introduction

Accurately predicting the behavior of nuclear waste especially in a waste package, is a challenging task. Some deterioration is to be expected. However, techniques which offer some early indications of degradation or change would greatly increase the regulators' confidence in the safe storing of waste packages. Such techniques may, in the future, become routine depending on the ease of use, suitability of the information provided and package ageing.

The aim of task **7.6 "Demonstration and implementation of monitoring, maintenance and automation/digitalization techniques"** is to demonstrate that the technologies, methods, and models developed in Tasks 2 to 5 can be used in a real storage with nuclear waste. This leads us to evaluate (test and verify) the performance of the selected technologies by the deployment of an instrumented package at an end-user's real storage facility or, if not possible, at a similar environment.

Task 6 represents 48 months of work, and it is composed of three subtasks, the first one being ***7.6.1: Evaluation of technologies and developed systems from an end-user perspective.***

Work on this subtask has been ongoing since September 2020 (month 3 of the project launch), and it will be finished by the end of the project (month 48), under the lead of Orano.

This subtask continuously gathers and analyses results and outputs from Tasks 2 to 5, and uses this information to choose:

- The waste package prototype for performing large-scale trials,
- The most relevant and promising NDT (Non-Destructive Test) and sensing techniques developed and tested within Tasks 3 to 5,
- The location of the demonstration test,

The second subtask is ***7.6.2: Demonstrating systems and methods***. Work on this subtask has begun at month 31 and lasted until the end of the project under the lead of NNL.

This subtask includes the following actions:

- Implementation of the experimental set-up defined in Sub-task 6.1
- Selection of all technologies to be validated based on their availability, TRL level, and the safety case requirements needed for their implementation. These technologies will include both external and embedded technologies developed in Sub-tasks 3.1 and 3.2 but also the data processing techniques from Task 5, supported by simulation results from Task 4.
- Performing a series of full-scale trials in a realistic testing environment.

The third and the final subtask is ***7.6.3: Definition of potential mitigation actions and design improvements***, which started in month 24 and will end in month 48 under the lead of NNL.
This third subtask consists of the following actions:

- The elaboration of a proposal of improved designs that eliminate any weak points identified during the project
- The conceptual design for the use of the project results in automatized store concepts

This deliverable is developed as part of subtask 7.6.1, regarding the work to be done to prepare the demonstration trial and subtask 7.6.2 presenting the work performed during the demonstration test. It will also give some insight on task 7.6.3 by proposing improvements for the selected technologies.

2 Technologies evaluation from an end-user perspective

The comparison of the technologies and systems developed from an end-user perspective (task 7.6.1), has been carried out considering several parameters relevant for end-users such as their availability, their technical performances, TRL level and the safety requirements needed for their implementation.

Each technology studied in the frame of the PREDIS project has been assessed through a table containing these parameters. For each technology, the table has been filled by technology developers of task 7.3 and by WP7 end-users (Orano, UJV and SOGIN).

2.1 Presentation of technologies

There are eight technologies that are developed in task 7.3 of PREDIS. The technologies and their developers are presented in Table 1 below.

Table 1: Technologies and their developers.

Technology	Developer	Description
RFID embedded sensors	BAM, VTT	This technology consists of an electronic measurement system embedded in the matrix of cemented packages. The sensing system is made of a chain of small units, called SensorNodes which measures pressure, humidity and temperature. The supply of power to the battery-less sensors and the data acquired by such sensors go through the metallic waste drum by wireless technology to ensure long-term operation while keeping the integrity of the container [3].
Sensorized RF identification box for radiation monitoring	Università di Pisa	This technology consists of a network of radiation sensing nodes which performed periodically passive gamma-ray and thermal neutron counting in a defined integration period. The data are transferred to gateways through a wireless communication technology based on LoRa [7]
Muon tomography	INFN	This technology detects the muons coming from cosmic rays. They are highly penetrating particles that can cross large amounts of matter without being absorbed [3]. It allows the investigation of the internal composition of the cemented drums.
SiLiF neutron monitor	INFN	These technologies are based on the detection of gamma and neutron through the use of Scintillation Fibers (SciFi) and silicon detectors coupled to ^{6}LiF converters (SiLiF) respectively. An electronic board was developed for modularity, re-configurability, battery operation, WiFi connection for data transfer and remote control [3].
SciFi gamma monitor	INFN	

Technology	Developer	Description
Acoustic Emission (AE) wireless	Magics	Acoustic Emission is a non-destructive monitoring technique which uses highly sensitive piezoelectric sensors to record the elastic stress waves emitted within the cemented matrix [3]
Air-coupled ultrasonic inspection	NNL, BAM	This technology provides a non-contact, non-destructive inspection which consists of air-coupled ultrasonic transducer. The ultrasonic inspection can be combined with optical/laser scanner [7]

2.2 Methods

The table of comparison, which has been used for technologies evaluation, is based on Orano´s methodology to compare the technologies, concepts and design options during the engineering design process. It is a quantitative assessment which will be used for the selection of technologies, concepts and design options.

Four main criteria are taken into account in the table:

- Technical performance
- Safety/security
- Cost and planning (including procurement, fabrication, exploitation and dismantling)
- Operability (including exploitation, availability, maintenance)

Each main criterion is subdivided into different sub criteria which have been defined regarding the technologies, concepts or design options to be assessed. The definition of the sub criteria is the most important part of the work as they should not be redundant. The number of sub criteria per main criterion can vary.

The weights of the main criteria are equal, but the weights of the sub criteria vary according to their importance for end-users.

The assessment of the sub criteria has been usually done using an excel file resulting in the global assessment.

For R&D it is possible to add information about the maturity and the risks but it is not included in the global assessment.

The criteria and sub criteria used for technologies evaluation have been shared with WP7 end-users and WP7 contributors (task 7.3 to 7.5) during monthly meetings and workshops.

This evaluation needs to be performed throughout the technology development, therefore the first intermediate version, which was performed in 2022 (intermediate version), has been revised in 2024 (final version) in order to include all the newer developments achieved during this last year.

The full table can be found in Appendix A.

2.3 Technology comparison criteria

The comparison table contains:

- A technical section focusing on the technologies' performance in terms of technical efficiency, cost-effectiveness, safety and security, as well as ease of operation for end-users (including operability and required maintenance). Technical performances of the technology provide among others the possibility to use the technology for old packages already produced by the end-users, the measurement uncertainties and the easiness to have information on the ageing indicator.

- Costs required for procurement, manufacturing, operating of the system and additional development cost are assessed.
- Safety/security for operators depends on how the technology has to be implemented and how data retrieval is performed.
- Operability for the end user facility takes into account among others the easiness of calibration of the technology, the impact on the interim storage facility or on the conditioning process and the operator qualification.
- A part dedicated to end-users to assess the impact of the technology on their interim storage facility (in term of additional safety studies required for the technology implementation), the impact on long-term behaviour of the package and on decommissioning.

Other additional data on the technology maturity (TRL) and scalability have been asked from the technology developers. These TRL information are important in order to understand the scoring of each technology (cost of R&D expected, difficulty to assess some parameters due to lower information available), but are not used for the evaluation of the technologies.

The criteria are explained in more detail below.

The technologies were scored according to the mentioned criteria. The scores ranged from 1 to 5, with 5 being the best-case scenario and 1 being the worst.

2.3.1 Technical performances

This criterion is composed of two sub-categories: universality level and measurement level:

University level: This criterion assesses how well the technology can be used on different types of packages as well as its adaptability to both old and new packages. For a high score of 5, it must be possible to use the technology on different types of packages, old and new.

Measurement level: The measurement level informs about the type of measurements expected from the technology (quantitative or qualitative). It also assesses the measurements' precision and accuracy as well as the duration of the measurement. For a high score, the technology must provide a quantitative measurement with little uncertainty in a short period of time.

2.3.2 Costs

This category includes the cost of installation, of manufacturing, of operation, of maintenance, and of development (i.e., to reach a TRL of 9). To achieve a high score, the technology must have low costs.

2.3.3 Safety/security for operators

The operator risks associated with measurement retrieval is assessed. If the measurement can be done remotely, the technology receives a high score. However, if the measurement requires contact with a radioactive source, it receives a low score.

Additionally, the security level against hacking is evaluated. Technologies that encrypt data and retrieve it locally are given a high score due to the reduced risk of hacking. In contrast, if the data is transmitted wirelessly without encryption (for instance, via a public cloud), the technology receives a low score.

2.3.4 Operation

This criterion is made of two subcategories: operability and maintainability/availability:

Operability: The ease of measurement is assessed here. If the measurement can be performed continuously with easy technology calibration and without the need of intervention from an operator, the technology receives a higher score. In addition, its impact on the interim storage facility is also assessed, i.e., if its implementation in the storage facility is complicated (need of a large dedicated area or of a radioactive source) or if it has an impact on the existing conditioning process (for instance for embedded technologies), it receives a lower score.

Maintainability/availability: The maintenance needs of the technology are evaluated in this part. The longer the technology lifetime and the lower its maintenance frequency, the higher its score. In addition, if the procurement of spare parts is possible for at least 10 years, the technology receives a high score.

2.3.5 Induced wastes

The amount and level of induced waste generated has also initially been considered for the evaluation (type and amount of waste produced) but has finally not been taken into account because the waste management is mainly dependent on the waste package class (VLLW, LLW or ILW) on which the technology is implemented and also on the country policies regarding induced wastes.

2.3.6 Technical maturity

The TRL of the technology as well as the envisioned TRL at the end of the project has been gathered. This information is not used for technology scoring but it is relevant for end-users and also enables to assess the amount of uncertainties associated with each criteria assessment (the lower the TRL, the higher the uncertainties).

2.3.7 Scalability

Finally, the possibility to use the technology in other areas (non-cemented radioactive packages, other nuclear areas or non-radioactive areas) is investigated. It is not used in technology evaluation.

2.4 EU scoring of the technologies

In the second part of the Table of Comparison, the EUs were asked to agree about the scoring of each technology regarding the impact on interim storage facilities that cannot be directly assessed by technology developers.

The first criteria assessed whether the storage requires additional safety studies for the implementation of the technology. For the technology to receive a high score, no new risk needing additional safety studies has to be identified (such as drop risk or impact on package handling in the interim storage unit).

Next, the possible impact of the technology on the behavior of the package is evaluated using the number of additional studies required. Additional studies may be needed to justify that the package is not modified by the technology implementation and that the WAC are not affected, for example for new materials embedded in the package or if some corrosives materials are placed in contact to the container.

The compatibility of the technology with the End Users' needs is also evaluated. The EU needs are identified at § 2.5.1.1. If the technology meets at least 3 criteria, it receives the highest score of 5. If it provides information on another parameter, an automatic score of 2 is given.

The impact of decommissioning is also evaluated. If the technology requires no decommissioning, requires a conventional decommissioning, or if the radioactive waste can be managed through the existing storage facilities, then the technology receives a high score of 5. Otherwise, if the technology requires lots of decommissioning operations with several waste sorting actions, then it receives the lowest score of 3.

Finally, the compatibility of the frequency and duration of the measurement with the storage constraints is evaluated (the technology being considered at its final level of development (TRL 9)). If the measurements do not have an impact on the storage, then it is given a high score.

To assess the technologies' overall ability to respond to the EU needs, a coefficient is applied on each criterion and a final score for each technology is obtained.

2.5 Results

2.5.1 Intermediate scoring (end of 2022)

2.5.1.1 Compatibility with end-users' needs

A first part focuses on gathering information on the data collected by the technology in order to compare it to end-users needs.

The aim of this part is to gather information about the data/parameters that can be followed by the technology and the type of packages for which it can be implemented. This information is important in order to regroup several technologies together and also to be able to identify technologies that fit the key degradation phenomena and were stated and defined by end-users in § 3.2.12

The interoperability of the technologies is also a key factor.

Concerning the technologies compatibility with different kinds of cemented packages (for example cylindrical or prismatic forms, metallic container or concrete container), most technologies are compatible with every size, dimension, container material or cemented matrix formulation, with the following exceptions:

- For RFID embedded sensors (BAM / VTT) the long-term compatibility between the matrix and the embedded sensors should be verified by each end-user according to the matrix formulation selected,
- For muon tomography (INFN) the package size is limited by the detector dimension (< 5m),
- Air-coupled ultrasonic inspection (NNL) is designed only for metallic containers and has been tested only with Portland cement contents inside the package.

Concerning interoperability with other technologies, air-coupled inspection has been developed by NNL considering its combination with point cloud laser scans.

The results of the parameters followed by each technology are given in the table below. The parameters stated as "indirect measurement" need a model to access the final information. Information on this model availability is also provided.

Table 2: Parameters followed by the technologies and compatibility with end-user's needs.

	Parameter(s) of the package that is/are followed :	RFID embedded sensors	Sensorized RF identification box for radiation monitoring	Muon Tomography	SiLiF neutron monitor	SciFi gamma monitor	AE wireless	Air coupled ultrasonic inspection
End users need	- crack		Yes, Indirect		Yes, Indirect	Yes, Indirect	Yes, information	Yes, Direct measurement
	- dose rate		Yes, Direct Measurement		Yes, Direct Measurement	Yes, Direct Measurement		
	- contamination				Yes, Direct Measurement	Yes, Direct Measurement		
	- water							
	- gas evolution						Yes, information	
	- Relative humidity	Yes, Direct Measurement						
	- corrosion of the metallic container						Yes, information	Yes, Direct Measurement
Other parameters	- shrinkage	Yes, Indirect		Yes, Indirect				Yes, Direct measurement
	- swelling	Yes, Indirect		Yes, Indirect				Yes, Direct Measurement
	- condensation							
	- temperature	Yes, Direct Measurement						
	- air pollutants							
	- chemical weathering							
	- corrosion of the waste						Yes, information	
	- internal structure and changes (i.e. displacements…)			Yes, Direct measurement	Yes, Indirect	Yes, Indirect		
	Complementary information	*Model is not yet available*	*The dose rate collected by the system can be used to estimate ageing by means of a model (short post processing), not accessible yeet*	*Post treatment is long*	*Can signal an abnormality and provide an indication of a possible crack location*	*Can signal an abnormality and provide an indication of a possible crack location*	*AE sensor will not accurately measure a parameter. It will provide one single value to indicate which drum should be inspected.*	*Data are directly available (no post processing by modele)*

2.5.1.2 Technical part

The table below presents the sub-criteria defined for each criterion with their respective weight.

The detailed scoring results for all the technologies and each sub-criteria are given in Appendix A: Table of comparison. The table below presents the results for each criterion.

Table 3: Scores of the technology for each criterion.

Criterion		Weight of criteria	RFID embedded sensors	Sensorized RF identification box for radiation monitoring	Muon Tomography	SiLiF neutronmonitor	SciFi gammamonitor	AE wireless	US inspection
Technical performances	Universality level	0,4	1,2	2,0	2,0	2,0	2,0	2,0	1,8
	Measurement level	0,6	2,3	2,6	2,1	2,7	2,7	1,7	2,5
Costs		1	4	3,8	3,2	4,4	4,4	3,7	3,4
Safety / Security for operators		1	4,3	5	4,3	5	5	/	5
Oeration	Operability	0,7	2,5	3,0	2,6	3,4	3,4	3,0	2,8
	Maintainability / availability	0,3	1,5	1,5	1,6	1,6	1,6	0,7	1,2
Global scoring		/	3,1	3,4	3,0	3,7	3,7	2,0	3,2

The scoring of global criterion highlight:

- On the criteria university level:
  - RFID embedded sensors technology achieves a lower score because it cannot be installed on already produced packages (or legacy packages) as there need to be sensors embedded in the matrix.
  - The other technologies achieve a similar scoring.
- Concerning measurement level: Muon and AE wireless achieve lower scoring because:
  - Concerning muon tomography, a time-consuming post treatment of data is needed. Moreover, increasing the resolution can be used to improve relevant information thus leading to higher required storage space.
  - AE wireless indicates that a phenomenon is occuring but offers no quantitative information about what is happening (see Table 3). Therefore, the number of uncertainties concerning each parameter is high. Moreover, the temporal resolution of the technology is high which will increase the amount of space for data storage for this technology.
- Costs: Muon tomography and US inspection achieve lower scoring because:
  - Muon tomography: procurement costs are relatively high as well as operating and maintenance costs,
  - Air-coupled US inspection procurement and manufacturing costs are high, and some developments costs are still needed to reach a TRL of 9.
  - Concerning AE wireless high costs are still expected to reach a TRL of 9 due to the technology lower TRL.
- Safety/security for operators: the technologies have similar scoring except AE wireless which could not been scored because the information is missing due to its lower development stage.
- Operability: a lower scoring is given for RFID embedded sensors and Muon tomography:
  - In order to implement RFID embedded sensors, modifications will be needed at the end-users conditioning facility to integrate the embedded sensors in the conditioning process,

  - The long measurement time requires for muon tomography (a few days) has an impact on storage operations.
  - Additionally, for three technologies (RFID embedded sensors, Muon tomography and Air-coupled US inspection) it was stated that the operators cannot be self-reliant on using the technology, and that expert's validation will be needed, which can be done remotely.
- Maintainability: The lifetime of AE wireless technology is yet unknown (due to its lower development stage), thus the scoring of the technology has been lowered. Air coupled US inspection scoring is also a little lower due to uncertainties on the maintenance level frequency and a technology lifetime expected to be under 10 years. Globally, the other technologies achieve similar scoring.

SiLiF neutron monitor and SciFi gamma monitoring achieve the highest scoring in each category.

The assessments of the technologies are very close, only AE wireless has a low global assessment, however it has also a lower TRL compared to the other technologies (see § 2.5.1.4), therefore many parameters are yet unknown which has led to this lower assessment. The new developments of the technology can increase its scoring in a latter phase.

Finally, the technologies can then be ranked in three categories:

- A (global scoring greater than or equal to 3,5): SiLiF neutron monitoring, SciFi gamma monitoring,
- B (global scoring between 3,0 and 3,5): Sensorized RF identification box for radiation monitoring, Muon Tomography, US inspection and RFID embedded sensors,
- C (global scoring under 2,0): AE wireless.

2.5.1.3 End users' additional parameters

The second part of the comparative table evaluates the technologies based on end-users needs and requirements that can only be filled by end-users:

- Need of additional safety studies for the EU storage for the implementation of the technology,
- Possible impact on behaviour of the package (design life), with need of additional studies,
- Compatibility of the measurement with End-Users needs,
- Impact of decommissioning,
- Frequency and duration of measurement compatible with storage constraint.

The assessment of this part of the table has been completed by PREDIS end-users during the workshop of November 2022.

The details of the assessment are given in Appendix C: Assessment of the technology by Predis end-users performed during the workshop of November 2022 for these five criteria.

The results of the end-users' part of the comparison table is given below with the weight associated to each criterion:

Table 4: Results of the end-users' criteria of the comparison table.

No	Criterion	Net weight	RFID embedded sensors	Sensorized RF identification box for radiation monitoring	Muon Tomography	SiLiF neutron monitor	SciFi gamma monitor	AE wireless	Air-coupled ultrasonic inspection
8	**Consequences of implementation of the technology at its final development stage (TRL9)**	*1*							
	8.1 Need of additionnal safety studies for the storage for the implementation of the technology	35%	4	4	3	4	4	5	5
	8.2. Possible impact on behaviour of the package (design life), with need of additional studies	35%	3	5	5	5	5	4	5
	8.3 Compatibility of the measurement with end users needs	9%	3	4	2	5	5	5	4
	8.4 Impact of decommissioning (easiness of decommissioning, management and quantity of induced wastes)	18%	5	5	3	5	5	5	5
	8.5. Frequency and duration of measurement compatible with storage constraint (mouvement of package, duration of storage)	4%	4	5	3	5	5	5	5
Overall assessment EU needs		**100%**	**3,7**	**4,6**	**3,6**	**4,6**	**4,6**	**4,6**	**4,9**

The technologies can be ranked in three categories:

- A (global scoring greater than or equal to 4,5): Sensorized RF identification box for radiation monitoring, SiLiF neutron monitoring, SciFi gamma monitoring, AE wireless, US inspection,
- B (global scoring between 3,5 and 4,5): RFID embedded sensors, Muon Tomography,
- C (global scoring under 3,5): No technology.

2.5.1.4 TRL of the technologies

The TRL of the technologies at the beginning of the PREDIS project is given in the table below along with the TRL expected at the end of the project. The TRL achieved at the end of the project for each technology is also given for comparison.

Table 5: TRL of the technologies at the beginning and at the end of the PREDIS project.

	RFID embedded sensors	Sensorized RF identification box	Muon Tomography	SiLiF neutron monitor	SciFi gamma monitor	AE wireless	Air-coupled ultrasonic inspection
TRL of the technologies at the beginning of the PREDIS project	4	6	5	6	6	3	4
Expected TRL at the end of the PREDIS project (2022)	5	8	7	8	8	4	5
TRL achieved at the end of the PREDIS project (2024)	5	5/6 [5]	6 [5]	8 for the sensors 7 for the electronics [5]	8 for the sensors 7 for the electronics [5]	3 [5]	5 (the non-contact ultrasonic detectors themselves having a TRL of 9 [5])

2.5.1.5 Final results of intermediate scoring

The final results are shown in the table below.

Table 6: Scoring technologies intermediate scoring.

	RFID embedded sensors	Sensorized RF identification box	Muon Tomography	SiLiF neutron monitor	SciFi gamma monitor	AE wireless	Air-coupled ultrasonic inspection
Technological criteria	B	B	B	A	A	C	B
End-users criteria	B	A	B	A	A	A	A

2.5.2 Final scoring (mid 2024)

The evaluation of the technological criteria was reviewed at the beginning of 2024 (after the end of the demo test) in order to take into account any new developments of the technologies achieved during the project.

The modifications stated by the technologies developers are:

- RFID embedded sensors: no modification of the table. The necessity to evaluate the long-term compatibility between the matrix and the embedded sensors remains to be done by each end-user according to the matrix selected.
- Sensorized RF Identification box: the TRL of the technology has been reviewed.
- Muon tomography: no modification
- SiLiF neutron detector and SciFi gamma detector: a lifetime over 30 years has been evaluated for ILW and also HLW. However, a replacement of the system with a spare one, for battery recharge should be performed each year.
- AE wireless: no modification of the table,
- Air-coupled ultrasonic inspection: no modification

These modifications do not lead to any changes of the technology evaluation. Thus, the scoring presented in Table 6 remains unchanged.

3 Demonstration of systems and methods

In this subtask, data from task 2 to 5 of WP7 were gathered in order to choose the most relevant and promising NDT (Non-Destructive Test) and sensing techniques developed and tested within Tasks 3 to 5, taking into account their availability, TRL level (through the information gathered by subtask 7.6.1) and also the safety case requirements needed for their implementation.

Afterwards, a full-scale trial in a realistic testing environment needed to be performed on these technologies, which required to choose:

- The waste package prototype for performing large-scale trials,
- The location of the demonstration test.

3.1 Methodology to define the demonstration test

For the selection of the waste package/mock-up and the location of the demonstration test, the technology as well as the parameters which will be monitored must first be determined.

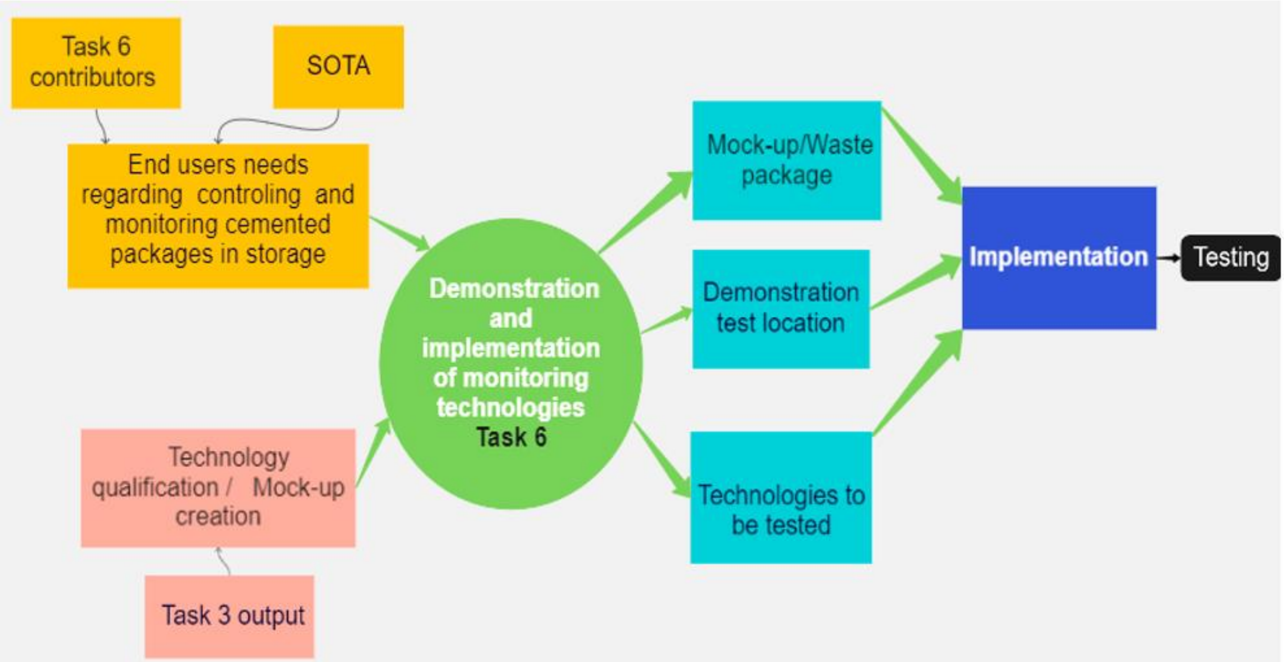


Figure 1: Method for selection of a waste package/mock-up.

As it is seen in the figure above, there are three inputs that are needed for the decision and the implementation of the demonstration trial. These are:

- The EU needs,
- The technologies that will be tested,
- The storage configuration constraints that each technology (and its mock-up) has.

The following sections will give details about the technologies, the mock-ups produced to test them, the End User needs that will be met, and the constraints regarding the mock-ups' storage.

3.2 Input data for the demonstration test

3.2.1 End-users need

The end-users needs regarding controlling and monitoring of cemented waste package have been discussed in the gap analysis and among end-users of PREDIS WP7 (SOGIN, UJV and Orano) in order to identify the parameters on which the demonstration test has to focus.

3.2.1.1 SOTA

The monitoring strategies that are already used by the end-users have been presented in WP7 SOTA [1]. Monitoring can be defined as continuous or periodic observations and measurements of specific parameters/indicators which reveal changes in the conditions of a waste package over time [1].

The following parameters are mostly followed by end-users:

- Metal corrosion, cracks and external contamination of their waste packages (88% of EU).
- Swelling and leakage (75% of EU).
- Lifting feature deformation (63% of EU).
- Presence of chemical reactions (50% of EU).

Although these data are representative of what is yet done by the end users, it might not cover their need of monitoring. Their need of monitoring has been discussed in the gap analysis at the beginning of the project.

3.2.1.2 Gap analysis

The main topics regarding cement waste package degradation that the end-users would like to see detected and monitored as a priority and be considered during the demonstration test have been compiled in the gap analysis report (questioning through on-line feedback survey) [4]. They are given below by order of importance (question 40) [4]:

- **Cracks (83%),**
- **Gas production / overpressure (83%)**
- Loss of thickness (33%)
- Other (33%):
  - ASR and DEF (expansion processes),
  - Leachability, compressive strength, long-term stability,
- Change in dose rate (17%).

Note : The Alkali-Silica-Reaction (ASR) takes place between silica and the Na/K content in concrete pore solution, The ASR product mainly consisting of silica and alkali hydroxide plus some calcium, expands in the presence of moisture and exerts internal pressure, which generates cracks first in the aggregates and later on into the concrete [1]. Expansion processes within the matrix also lead to cracks in the cemented matrix.

3.2.1.3 WP7 contributors' needs

The following parameters have been highlighted by WP7 end users (SOGIN, UJV and Orano):

Table 7: WP7 contributors' needs.

End User 1 (by order of importance)	**End user 2 (by order of importance)**	**End user 3**	**Common needs (by one or two end-users)**
Wasteform internal condition *(gel, gas or void macro/micro "bubbles",* ***wasteform cracks****, shrinkage, corrosion of metallic waste)*	**Crack measurement and evolution**	Limits of individual radionuclides	**Cracks of the matrix (external or internal)**
External cracks	**Gas measurement**	**Dose rate** at drum surface	**Gas emission or evolution**
Swelling	**Corrosion of the metallic container (especially image interpretation)**	**Surface contamination**	**Corrosion of the metallic container (external or internal)**
Gas emissions		Absence of free liquid inside the drum	**Dose rate**
Gas evolution		Rupture of the drum	**Surface contamination**
Leakage of liquid/gel		Leachability	Free liquid / Relative Humidity*
Internal corrosion of the metallic container		Compressive strength	
External corrosion of the metallic container/handling system		Total weight	
Dose rate			
Surface contamination			
Surface condensation			
Package identification			

**None of the technologies of WP7 gives information about the presence of free liquid/leakage, but RFID embedded sensors gives information on the relative humidity inside the cemented matrix. This parameter which is the closest to free liquid / condensation has thus been considered.*

3.2.1.4 Parameters for demonstration test

Considering the end-users needs compiled in the gap analysis report and those of the WP7 contributors, the parameters that should be considered during demonstration test in order to answer end-users need are:

- **Cracks of the matrix (external and internal),**
- **gas emission & evolution,**
- **internal and external corrosion of the metallic container** (= loss of thickness of the container, cracks in the metallic container),
- **dose rate,**
- **surface contamination,**
- **free liquid and Relative humidity**

3.2.2 Technology selection

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

- Embedded RFID,
- SciFi / SiLiF,
- Sensorized RF Identification box,
- Air coupled ultrasonic inspection.

The other technologies were not selected:

- The Muon tomography demonstrator developed by INFN (presented in Figure 2) cannot be shipped to a demonstration site, thus the test should be performed directly at INFN´s location. Therefore, for Muon tomography a dedicated mock-up has been made, which has been shipped to INFN location.
- Acoustic Emission TRL is currently low. In order to increase its TRL prior development is required. That’s why Magics is currently performing a 2-year trial at mock-up scale, following lab scale experiments, with several mock-up containing different kinds of cemented matrix placed in either accelerated or non-accelerated conditions. The data on this test can be found in report D7.3 [3].

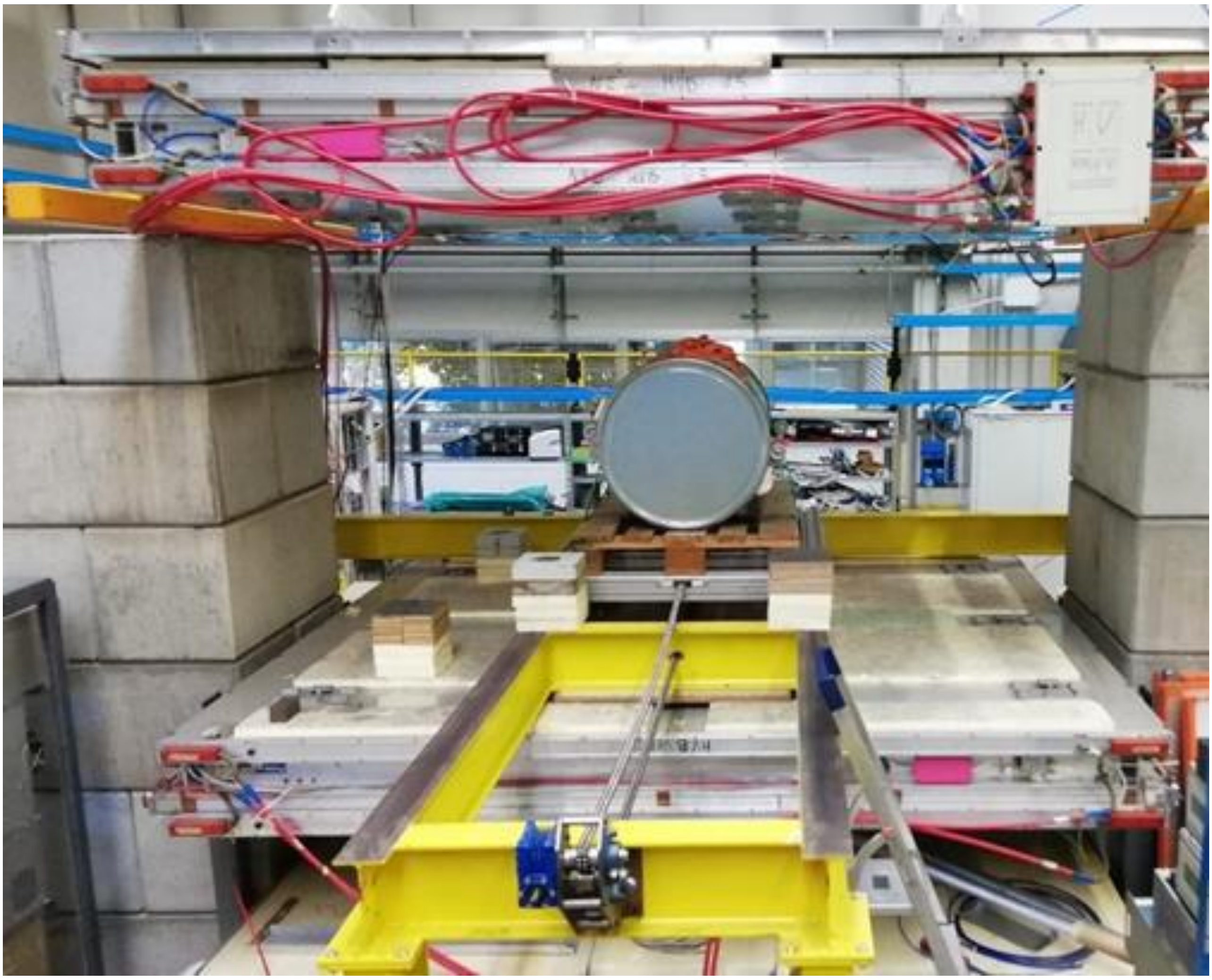


Figure 2: Picture of the Muon tomography demonstrator at INFN with the mock-up produced by UJV [3].

Note: UJV build a dedicated mock-up to test out the Muon Tomography technology developed by INFN in the scope of PREDIS. It is a 200 L single-skinned drum filled with cement. Since this technology is used to identify the internal composition of wastes, pieces of iron, stainless steel, and *lead were also placed in the drum. The metal segments mimic pieces of real waste in a real waste package. An XRD (X-Ray powder Diffraction) was applied by UJV in order to identify the pieces precise location in the mock-up prior to its shipment to Italy at the INFN site, where tests will be performed.*

3.2.3 Selections of mock-ups

3.2.3.1 Reference package

The reference package was defined at the beginning of PREDIS WP7 in task 7.2. The table below provides its details.

Table 8: Reference package [2].

Summary of the reference package details

Number of skins	1 (single-skinned)
Geometry	Cylindrical
Size	200 L (D = 60 cm, H = 90 cm)
Construction material	Austenitic Stainless Steel (300 grade, 1.2 ± 0.2 mm thickness)
Waste type	Magnox metal. Large discrete pieces or small bits evenly distributed throughout the grout matrix. Recommended use: 62 kg of Magnox
Grout formulation	> 3:1 wt/wt BFS: OPC blended mix, 0.35-0.5 w/s, no additives, sand, aggregate, or superplasticizers
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.
Storage environment	Temperature: 0-20 °C, RH < 50%, controlled air change and controlled chloride content (< 100 µgCl.cm^{-2})

3.2.3.2 Mock-up constraints

The End Users were all asked whether it was possible to perform a demonstration trial at their storage sites. None were able to provide access to their sites for the test. Thus, for the tests, mock-ups for each technology were produced. The tests on these mock-ups were performed at the production site in the frame of task 7.3.

The following table presents the options that were evaluated for the demonstration trial and their availability at end-user sites:

Table 9: Different options for the demonstration trial.

	Option 1	Option 2	Option 3	
Type of package	Real nuclear waste package	E.U. old mock-up (NNL, 27-year-old Magnox mock-up)	Task 7.3 mock-ups	
Availability	Not possible*	Possible	Possible	
Test location	Non-active test environment (UJV facility)	Non-active test environment (NNL facility)**	Non-active test environnement (NNL/UJV/…)	
Type of sensor	External sensing technologies	External sensing technologies***	Embedded sensing technologies	External sensing technologies
Radioactivity	Yes	No *(not compatible with technologies from UniPi and INFN which are measuring radiation)*	Yes *(some mock-ups contain sources to simulate radioactivity)*	

** No end-user was able to provide access to their sites or packages for the test.*
*** The magnox mock-up cannot be moved from NNL thus the test on this mock-up has to be performed directly at NNL site.*
**** This mock-up has been produced 27 years ago, and could not be used to test embedded technologies. Moreover, it is inactive and thus is not compatible with SciFi / SiliF from INFN and sensorized RF Identification box from UniPi.*

3.2.3.2.1 Mock-ups for the demonstration test

The three technologies selected have several constraints that must be taken into account for the demonstration test:

- RFID sensor contains sensors that are embedded inside the cemented matrix. For this technology a dedicated mock-up needs to be produced.
- SciFi/SiLiF from INFN and Sensorized RF Identification Box from UniPi are radioactivity measurements. Therefore, they need a mock-up with a certain amount of radioactivity.

3.2.3.2.2 Mock-up 1: NNL Old Mock-up

At Sellafield, the waste packages are stored in buildings known as Interim Storage Facilities (ISF). Waste packages are stacked and accessed via an overhead crane with each stacking having varying levels of access.

Accurately predicting the behavior of waste and a waste package is an obvious challenge. Some deterioration is to be expected. However, techniques which offer some early indications of degradation or change would greatly increase regulatory confidence. Such techniques may, in the future, become routine depending on the ease of use, suitability of the information provided and package ageing.

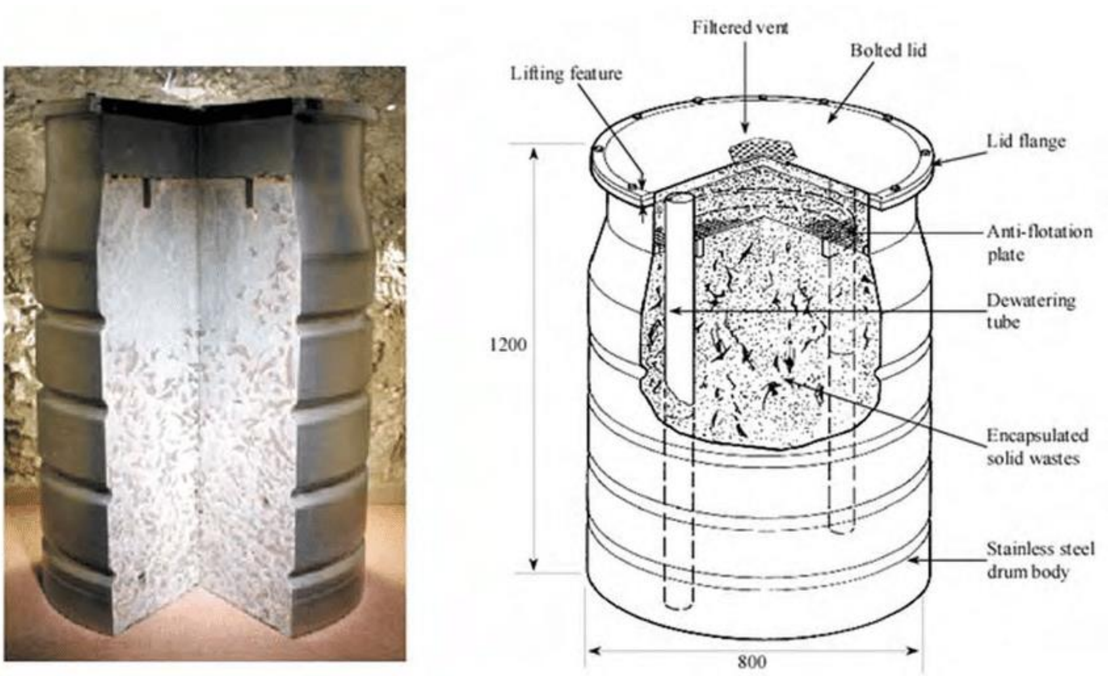


Figure 3 : Magnox package encapsulating a mixed cement matrix.

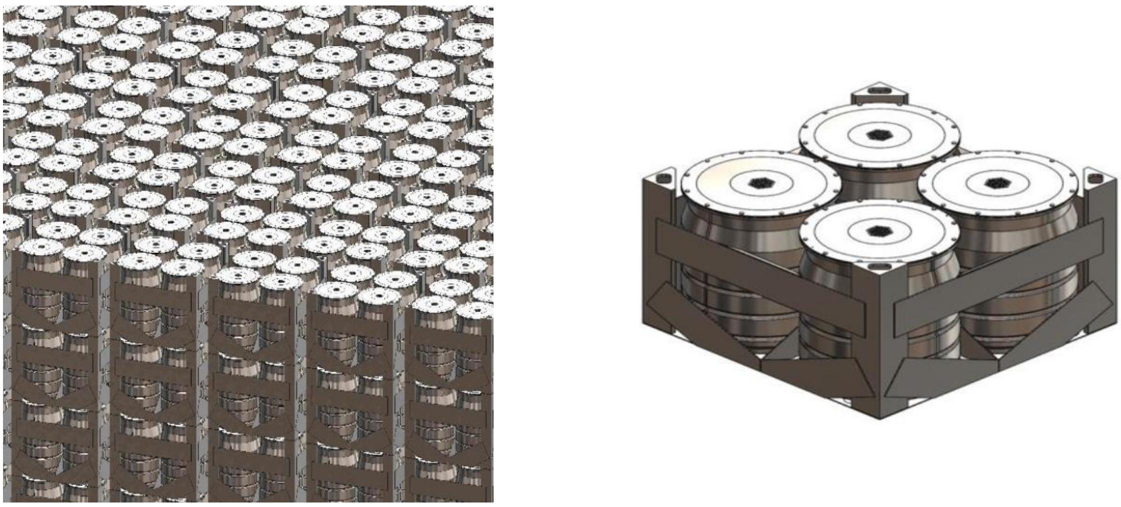


Figure 4: Magnox package stacking at Sellafield storage.

NNL's old mock-up available for use for PREDIS is a > 25-year-old inactive Magnox package from the Magnox Encapsulation Plant (MEP) at Sellafield, UK. It was designed to allow a storage of 50 years above ground followed by 50 years below ground prior to closure of a Geological Disposal Facility (GDF) [5]. However, the decisions regarding GDF are anticipated to be made by future generations, resulting in the possibility of a several-hundred-year storage prior to closure. This extension in the timescale was not accounted for in the design of the packages, which may lead to a performance failure. For this reason, the long-term safe storage of the Magnox packages must be verified.

In terms of the types of tests to be performed on the Magnox mock-ups, only NDT's are permitted by NNL. This means that the package will not be cut open or damaged during monitoring. Moreover, the mock-up cannot be moved outside the NNL location so that the selected technologies had to be brought to the mock-up.

Figure 5: NNL Magnox mock-up.

The table below presents some characteristics of the Magnox mock-up. The mock-up is a vented 500 L drum filled with a grout of BFS:OPC (>75 % BFS) as well as around 150-300 kg of Magnox (total weight of 1000 kg).

Table 10: Magnox mock-up specification.

Specification	Magnox mock-up
Dimensions	Cylindrical; 500 L (800 mm D x 1200 mm H)
External container	Single skin; Stainless steel 316, 3 mm
Parameter followed?	Cracks, swelling, shrinkage, corrosion of the metallic container
Mock-up producer	NNL

The reference package was based on the old Magnox mock-up, being most similar to it.

This mock-up is not compatible with:

- RFID sensor technology which requires embedded sensors within the mock-up. Since the Magnox mock-up was produced more than 25 years ago, subsequent sensor installation was not possible. A dedicated mock-up will be needed to test this technology.
- SciFi/SiLiF from INFN, Sensorized RF identification box from UniPi which perform radioactivity measurements: This old mock-up does not emit any radioactivity. As no end-user was able to give access to their sites and radioactive packages for the demonstration test, a dedicated mock-up was needed to test these technologies.

This mock-up has been selected to test Air-coupled ultrasonic inspection developed by NNL.

Specific mock-ups were produced for:

- RFID embedded technology,
- SciFi / SiliF,
- Sensorized RF identification box,

3.2.3.2.3 RFID sensor non-active mock-ups

The characteristics of the non-active mock-up are shown in the table below.

Table 11: Specifications of non-active mock-ups.

	Non-active mock-ups
Technology	**RFID embedded sensor**
Dimensions	200 L drum (~600 mm D x 876 mm H)
External container	Single skin
Parameter followed	Humidity, temperature, pressure
Mock-up producer	BAM / VTT

The RFID sensors envisioned for PREDIS were tested and demonstrated using 200 l, single skinned drum containing Portland cement and reactive materials (recycled concrete as aggregate, provided by SCK-CEN and Belgoprocess) to perform the measurements. The material was chosen as it was expected to show ASR, leading to internal expansion during the experimental phase. The mock-up, seen below, was produced by BAM.

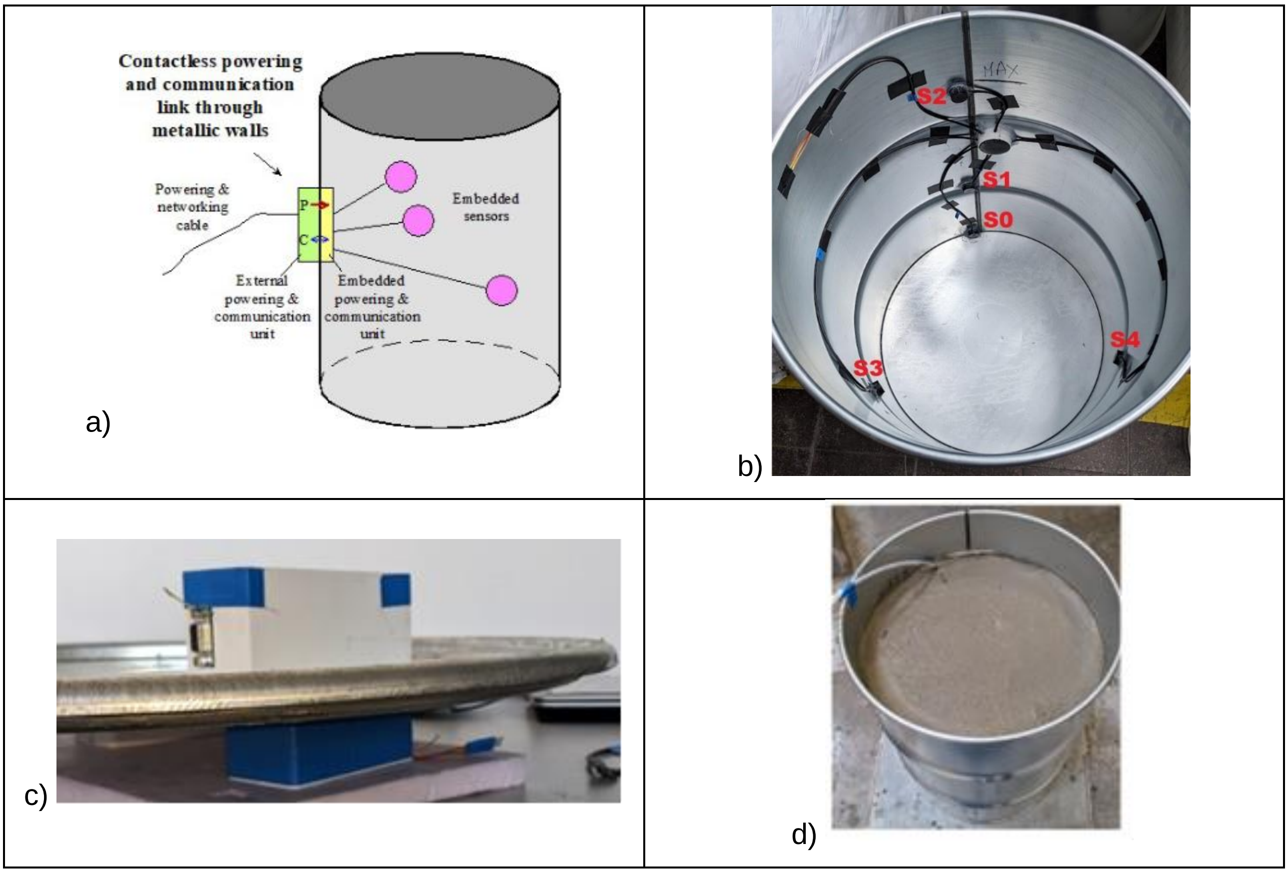


Figure 6: RFID mock-up: a) Sketch; b) Sensor node setup in drum; c) Communication units inside and outside on the lid; d) concreting of the drum.

The sensors were designed to record the following parameters: humidity, temperature, and pressure.

As it can be seen in the figure above, the sensors are mounted at the skin of the drum. A required improvement would be to robustly mount sensors also in the center of the matrix. At the inside of the lid of the package, the powering and communication unit provided by VTT is found. It communicates wirelessly through the steel with a second unit (as well provided by VTT) on the outside, which is then connected to a power supply with a wire. The data is transmitted back using Wi-Fi.

During the process of creating the RFID mock-up, BAM poured cement into the 200 l drum and connected the RFID technology inside the drum before closing the lid and waited for the concrete to harden. After a few hours, the communication system showed some short time failures. After some adjustments in the control software, the issue was fixed, and the technology was working well again. There was no investigation concerning this issue during the fabrication of the mock-up.

3.2.3.2.4 Active mock-ups

In addition to non-active mock-ups, SciFi/SiLIF and Sensorized RFID require the measurement of radioactivity. Therefore, they need a dedicated mock-up that includes a radioactive source. These technologies, as well as sketches of the respective mock-ups, are shown below. Since both technologies can be installed on the same mock-up and have the same mock-up specifications only one single active mock-up was produced. The technologies were installed at the same mock-up during the demonstration test.

Table 12: Specifications of active mock-ups.

	Active mock-ups	
Technology	**SciFi + SciLif**	**Sensorized RF Identification box**
Developer	**INFN**	**UniPi**
Matrix	Portland cement	Portland cement
Dimensions	200 L drum (~600 mm D x 876 mm H)	
External container	Single skin	
Phenomena expected	Cracks (through wedges)	Cracks (through wedges)
Parameter followed	Dose rate	Dose rate
Mock-up producer	UJV	UJV
Additional	Hole in the matrix for insertion of ^{137}Cs and neutron sources	

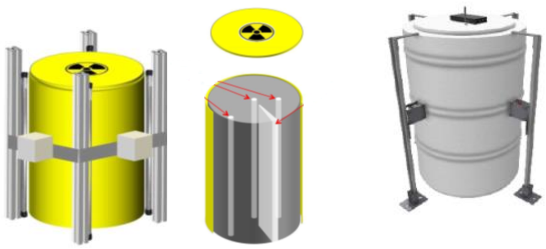


Figure 7: 3D Representation of the active mock-ups.

Finally, some technologies cannot be tested at the selected mock-up. For example, the Muon Tomography requires moving the package to the Muon Tomography device for testing. Because of that, it could not be tested on such a mock-up as shown above.

3.2.3.2.5 Conclusion on mock-ups

To conclude, three types of mock-ups were utilized to realistically test the selected technologies, addressing various constraints and requirements.

NNL successfully tested its air-coupled ultrasonic inspection device using an old Magnox mock-up, which is a representative of the waste packages stored at its Sellafield facility in the UK. This mock-up, over 25 years old, provided a realistic simulation of the long-term storage conditions and potential degradation challenges faced in the actual environment.

Additionally, two other mock-ups were specifically created to test the RFID embedded technology, the Sensorized RF Identification Box, and the SciFi/SiLiF technologies. The RFID mock-up, produced by BAM/VTT, involved a 200L drum with embedded sensors to monitor humidity, temperature, and pressure. This setup allowed the assessment of the sensor's performance in measuring these critical parameters within a cement matrix.

The active mock-ups for the Sensorized RF Identification Box and SciFi/SiLiF technologies included radioactive sources, enabling the measurement of dose rates and the detection of cracks. These mock-ups were essential for evaluating the technologies in conditions that closely mimic the radioactive environment in which they would operate.

Overall, the use of these three distinct mock-ups ensured a comprehensive and realistic testing environment, enabling accurate assessments of each technology's capabilities and performance in simulating real-world conditions.

4 Storage configuration

4.1 Foreword

The demonstration task should be held in a realistic testing environment. Since there was no possibility to perform the test in a radioactive facility, the conditions of a representative storage area of an end-user site have first been defined and were compared with the conditions available at several partners' platforms (NNL, UJV and Orano).

Also, in order to integrate the technology in a realistic storage configuration, the following constraints have been fixed and discussed with technology developers:

- Technology availability: the technologies remain accessible during the whole demonstration test, but the mock-ups are placed behind other cemented packages in order to have cemented packages around each mock-up (integration in a storage). These cemented packages must be moved to access the actual mock-ups.
- Data transfer:
    - accessibility of the data remotely through a "data collecting area" and also in a platform that can be readable from outside to have continuous access to the data.
    - the data collecting area representing a command room is separated for the storage unit (several meters of concrete shielding away).
- Failure protocol: Technology developers must provide spare parts and failure & replacement procedures before the demonstration test to allow operators any reparation procedure during the demonstration test period if needed.

Furthermore, the technology constraints for the demonstration test (in terms of stacking, power and Wi-Fi supply, etc.) have also been considered and taken into account.

4.2 Definition of a representative storage area

A demonstration should be carried out in a realistic environment, representing a storage for cemented packages.

To clearly understand how an interim storage looks like, End Users were asked about the waste package main design characteristics and handling systems as well as about the arrangement of the packages, the needs of shielding walls, the presence of maintenance areas, the ventilation systems, etc. in WP7 SOTA.

Differences exist between end-users' storage facilities, however the following characteristics are shared among the majority of them [1]:

- Storage facility:
    - 80% of the packages are stored in areas with forced ventilation and/or air conditioning systems [1].
    - Many storage areas are accessible by the operators during the operations [1].

  - Presence of package maintenance areas in the storage facilities is declared in only about 30% of the cases [1]. 30% of end-users say they perform monitoring at specific storage positions and 20% in a dedicated area or hot cell [1].
  - The package handling system is mostly semi-automated 65% (the system functions by the combined activities of man and machine) or remotely operated 58% (the system is operated by a person from a distance) [1].
- Storing methods:
  - Almost all packages are stackable, in some cases up to 8 levels and about 70% of the packages are stored in a stack [1].
  - Packages can be in trays with up to four packages per tray in the case of package stacking. Racks or stillages have not been reported [1],
- Package description:
  - Containers for homogeneous cemented waste are mostly metallic and cylindrical whereas heterogeneous cementation is mostly done with prismatic containers made of concrete [1],
  - Cylindrical geometries have been identified more universally. 30% of prismatic geometry entries were associated with the U.K. Thus, prismatic packaging has not been considered for the reference package [2].
  - The most common dimensions for the cylindrical packages among European countries are 90 cm in height and 60 cm in diameter [2]
  - The cement matrix used for homogeneous waste packages is for the most part ordinary Portland cement.
  - Packages consist mostly of LLW.

Note: Stacking can be either vertical or on the package side.

The result of this first analysis is that the representative storage facility is a closed area with forced ventilation and/or air conditioning systems without a dedicated area for package maintenance. The packages are stacked and handled semi-automatically. The most common dimension is a cylindrical package of 90cm height and 60cm diameter within a metallic container.

Other additional information such as the density of package at ground floor level, the local environmental noise (for AE technology), the tools with which the semi-automated handling is performed, the filling method of the storage in case of stacking is necessary to define the reference storage.

These data have been and the results have been compared.

These data have been gathered from WP7 end-users SOGIN, UJV and Orano and were compared with the information compiled through the SOTA report to verify that they are in agreement with the other end-users' storage characteristics.

The outputs of this comparison are:

- UJV storage has many similarities with the reference storage as described in the SOTA. It consists of a closed facility with air filtration and ventilation system where cylindrical packages with metallic containers are stacked on up to 4 levels.
- WP7 end-users have a maintenance area in the storage (mainly with size above 100 m2) but NDE testing is mostly performed at the package spot in the storage location,
- Ground floor packing density is between 0,8 and 0,4 packages/m2. For the reference package, the value is 0,4 package/m2,
- Local industrial noises have to be taken into account for technologies using sound wave,
- Handling of the package in the storage is done with a crane and a lift truck. The handling crane can be controlled either remotely or locally.
- In case of stacking, the first row is completely filled before starting to fill the level above and the highest level of stacking is 4.

As underlined in report [2] differences exist in package dimensions among different end-users. For example, packages reported by EU1 and EU2 have a higher size than the reference package. Many technologies of task 7.3 can be adapted to higher package dimensions (ex: RFID embedded sensors) if the extension is not too high (for example muon tomography requires already a large installation).

Stacking has been reported in the SOTA but not the use of racks or stillage. However, the use of trays has been mentioned by end-users with 4 drums in one tray.

As some technologies developed in task 7.3 need the use of trays or racks (see § 4.4), both configurations are considered. Stacking in the reference storage can be done with or without trays.

The presence of packages maintenance areas within the storage facilities of end-users has been declared in only about 30% of the cases. However, WP7 end-users reported that they mostly carry out NDE testing at the package spot in the storage.

This means that two possibilities of NDE testing need to be considered: either the testing takes place in a dedicated area in the storage or directly at the package spot with no further handling.

The result of this first analysis is that the representative storage facility is a closed area with forced ventilation and/or air conditioning systems with or without a dedicated area for package inspection. Packages are stacked with or without trays and are handled semi-automatically with handling crane and lift truck. The density of packages at ground level is around 0,4 packages/m2. The most common dimension is a cylindrical package of 90cm height and 60cm diameter with a metallic container.

4.3 Test location selection

The environment for the demonstration test could be:

- a real storage available at an end-user´s facility
- a non-active environment similar to a storage facility.
- A non-contaminated low active environment at an end-user site.

After discussion with end-users of WP7 it was clear that no real storage was available for performing the test. However, owners of non-active environments have been identified (NNL, Orano). A non-contaminated site was selected at UJV. The conditions of the selected representative storage environment have been used to define the environment that should be represented in these test locations.

Three partners' platforms have been assessed:

- NNL platform,
- UJV storehouse,
- Orano canister manufacturer.

Table 13: Compatibility of test environments with reference storage configuration

Parameter	**Reference storage**	**NNL platform**	**UJV storehouse**	**Orano canister manufacturer**
Package density at ground floor	0,4 package/m^2	4 mock-ups in a stillage	According to specification	
Type of storage	Closed storage	X	X	X
Operator access	Yes	X	X	X
NDE area	Available area or at package spot	X	X	X
Package handling	Handling crane and lift truck	Lift truck only	X	X

Parameter	Reference storage	NNL platform	UJV storehouse	Orano canister manufacturer
Stacking	Yes, 4 levels	No*	Yes but two levels only (height limitation)	X
Ways of stacking	With or without trays	With stillage	X	Without trays for reference package With trays for bigger packages
Reference package	Cylindrical, most common Ø60cmxH90cm	Bigger	X	X or bigger
Classification of waste	LLW	Not relevant		
Matrix in package	Portland cement	BFS/OPC	X	X or reinforced concrete for bigger packages
Pollutants	Air filtration & ventilation system	X	X	No

**Not compatible with budget*

UJV storehouse one has been selected for the demonstration test. It is in agreement with the reference storage configuration. And although only two levels of staking were possible, a dedicated data collecting area separated from the storage area (2 levels above) was available.

Note: Air coupled ultrasonic inspection demonstration test was performed directly at NNL's location.

4.4 Developer's constraints and need for demonstration test

Additionally, each technology's developers were asked for information regarding:

- Stacking compatibility,
- Power supply,
- Data reporting method,
- Test duration,
- Insertion of a radioactive source
- Accessibility to the mock-up during measurement.

The developers' answers regarding the storage configuration are given in Appendix B. The compiled requirements of all the technologies are discussed in this section.

The first information, stacking compatibility, is used to ensure whether direct stacking or indirect stacking can be used for the mock-up of each technology. In direct stacking, the waste packages can be stacked directly on top of each other in a pyramidal configuration without the use of baskets or stillage. In indirect stacking, stacking is not possible without the use of stillages. For some technologies it was stated during the demonstration test discussions that they require some stillages surrounding the mock-up, either because they require some space around the mock-up for the technology implementation or for wire connection. Also the presence of the power supply on the exterior of the package can hinder stacking in both wired and battery-powered cases.

The information gathered was also important to have the power supply and data transfer equipment needed by each technology in the demonstration area. Indeed, some technologies require wire connections and others realize data transfer using Wi-Fi or another wireless technology.

Some developers specified that they require the same Wi-Fi in both the storage unit and the data collecting area.

Since all technologies are compatible with indirect stacking (a few were not compatible with direct stacking), this has been chosen for the demonstration trial. The stillages for the demonstration test have been set up taking into account the minimum spacing between packages required for the technologies' implementation.

4.5 Storage configuration results

The storage configuration installed in the UJV storehouse is presented in the following figures.

- The active mock-up with SciFi, SiLiF (INFN) and Sensorized Identification box (UniPi) is shown in green,
- The inactive mock-up containing RFID embedded sensors (BAM / VTT) is shown in blue.

Although the mock-ups remained accessible during the demonstration test, they have been placed behind a row of inactive cemented packages (in grey in the displays) in order to be representative of a storage unit having other packages around each mock-up. The room's wall being on the remaining side. The inactive cemented packages could be moved if needed to access the mock-ups during the demonstration test.

Figure 8: Photography of the demonstration test configuration at UJV.

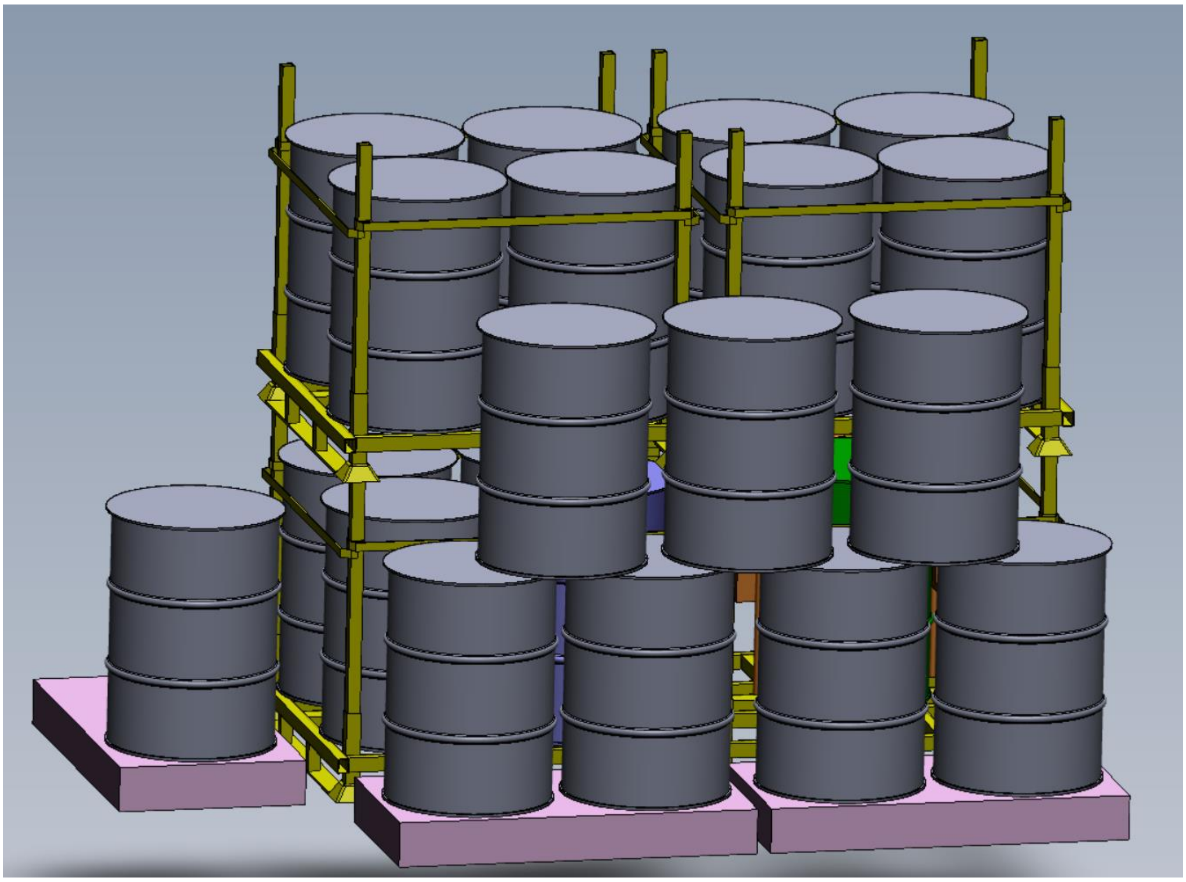


Figure 9: Demonstration test configuration front view.

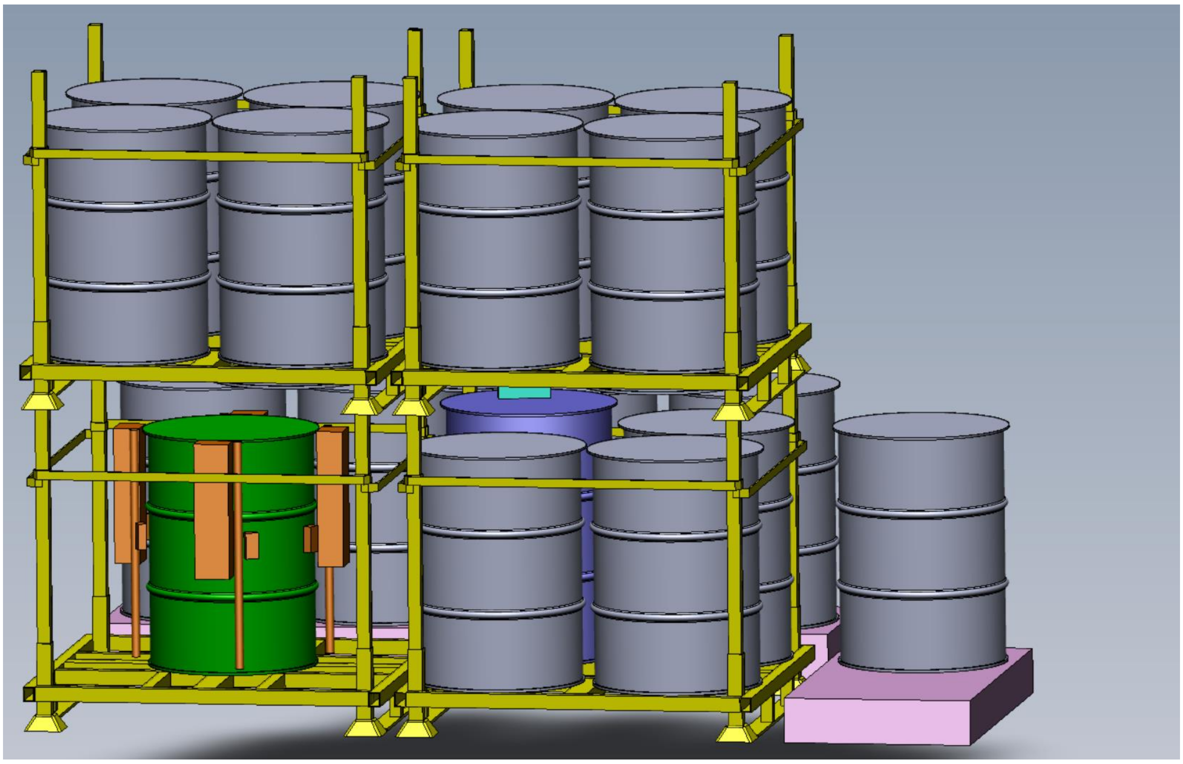


Figure 10: Demonstration test configuration back view.

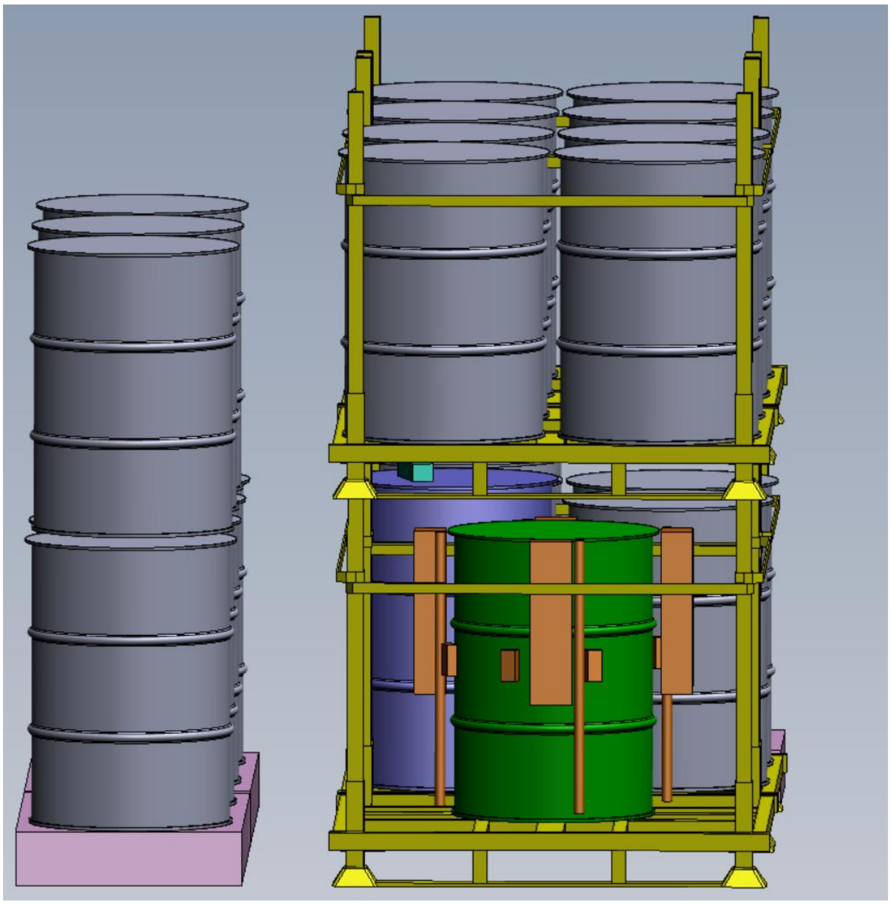


Figure 11: Demonstration test configuration side view.

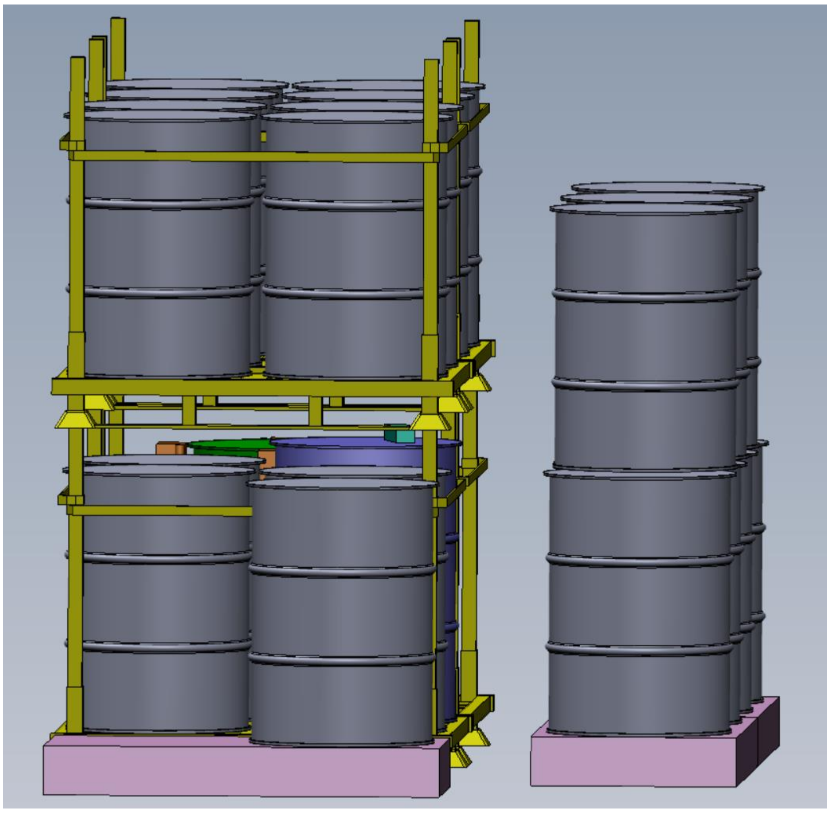


Figure 12: Demonstration test configuration second side view.

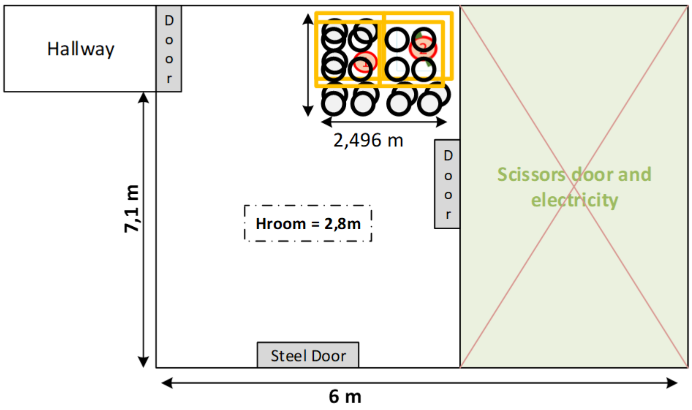


Figure 13: 2D view of the storage area at UJV.

As the goal of the demonstration test was to assess the technologies in a representative environment the following were then asked to technologies developers:

- Be able to access the data remotely through the "data collecting area" located at another level in the UJV building,
- Store the data not only on local computers in the data collecting area / in the technology but also integrate them in a platform that can be read from outside to have continuous access to the data during the 3 months period and to be able to integrate them in the dedicated dashboard developed in task 5.3 (see § 6),
- Provide spare parts and replacement / failure procedures to UJV in order for UJV operators, if needed, to be able to perform any repair needed during the 3 months' period.

The decision about the demonstration test duration was taken:

- a duration of three months was fixed in order to be able to identify a modification, which is caused by the start of the ASR in the mock-up with the RFID embedded sensors,
- a significant duration, in line with the PREDIS timeline, is necessary to evaluate the possibility of performing medium or long-term monitoring of a package.

5 Results of demonstration test methodology

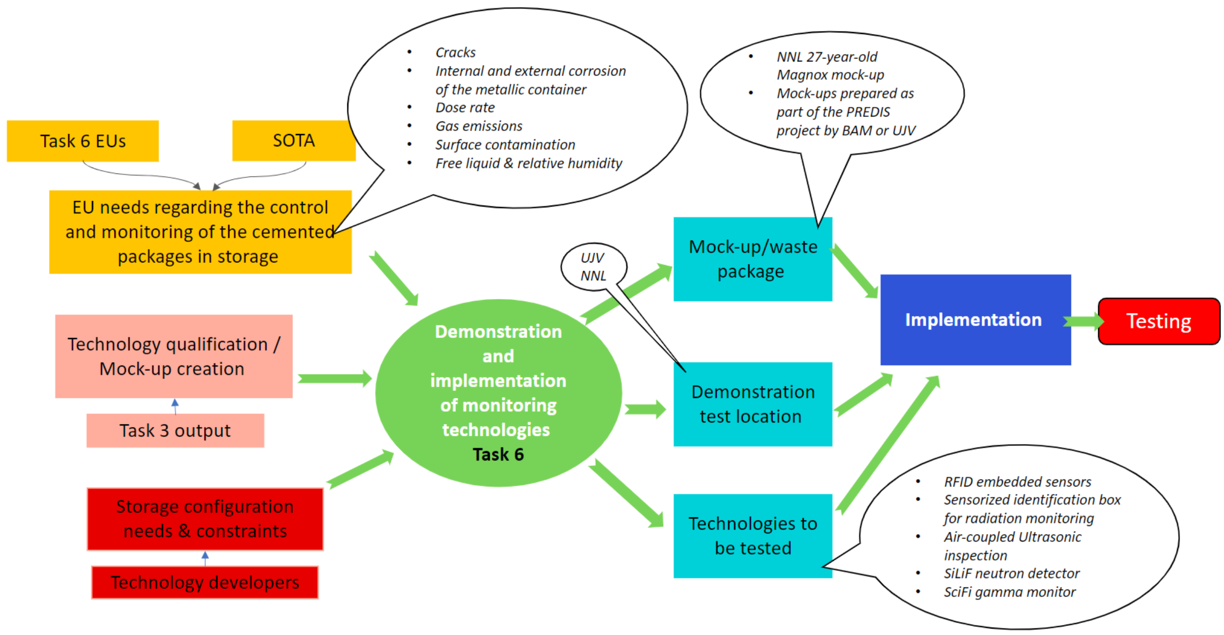


Figure 14: Selection of a waste package/mock-up conclusion.

6 Integration of a dashboard

Based on specifications from Orano and the technology developers (INFN, UniPi, and BAM/VTT) whose technology was tested at UJV, in Task 5.3 of WP7 a dedicated dashboard for the demonstration test was developed. This dashboard enables to the access to the technology on a dedicated platform, providing end-users with compiled information and valuable insights into the technology's results. This is a pre-requisite for informed decision-making.

The aim of the WP7 PREDIS demonstration dashboard was to link the demonstration test to task 5 by displaying the demonstration results in the task 5.3 framework. The content of the dashboard from the demonstration test was based on the work done by Tom-Robert Robert Bryntesen & Reka Szoke (task 5 of WP7) that was presented at Mechelen in May 2023. Because the demonstration test at UJV provides only data from a site / storage unit and does not include data from model prediction and digital twins, only four displays (named worksheets) were integrated:

- A home worksheet with links to the others worksheet (see
- Figure 15),
- A worksheet dedicated to BAM / VTT embedded RFID technology results on mock-up 1.2 (see **Error! Reference source not found.**16),
- A worksheet dedicated to technology results on mock-up 2 Sensorized RF identification Box from UniPi (see Figure 17),
- A worksheet dedicated to technology results on mock-up 2 SciFi/SiLiF from INFN (see **Error! Reference source not found.**18).

The specification describing the dashboard content is given in Appendix D § 8.1.

Note: the dashboard was made for the technologies tested during the demonstration test at UJV and not for the test at NNL location. A dashboard was also made by task 5.3 for AE technology.

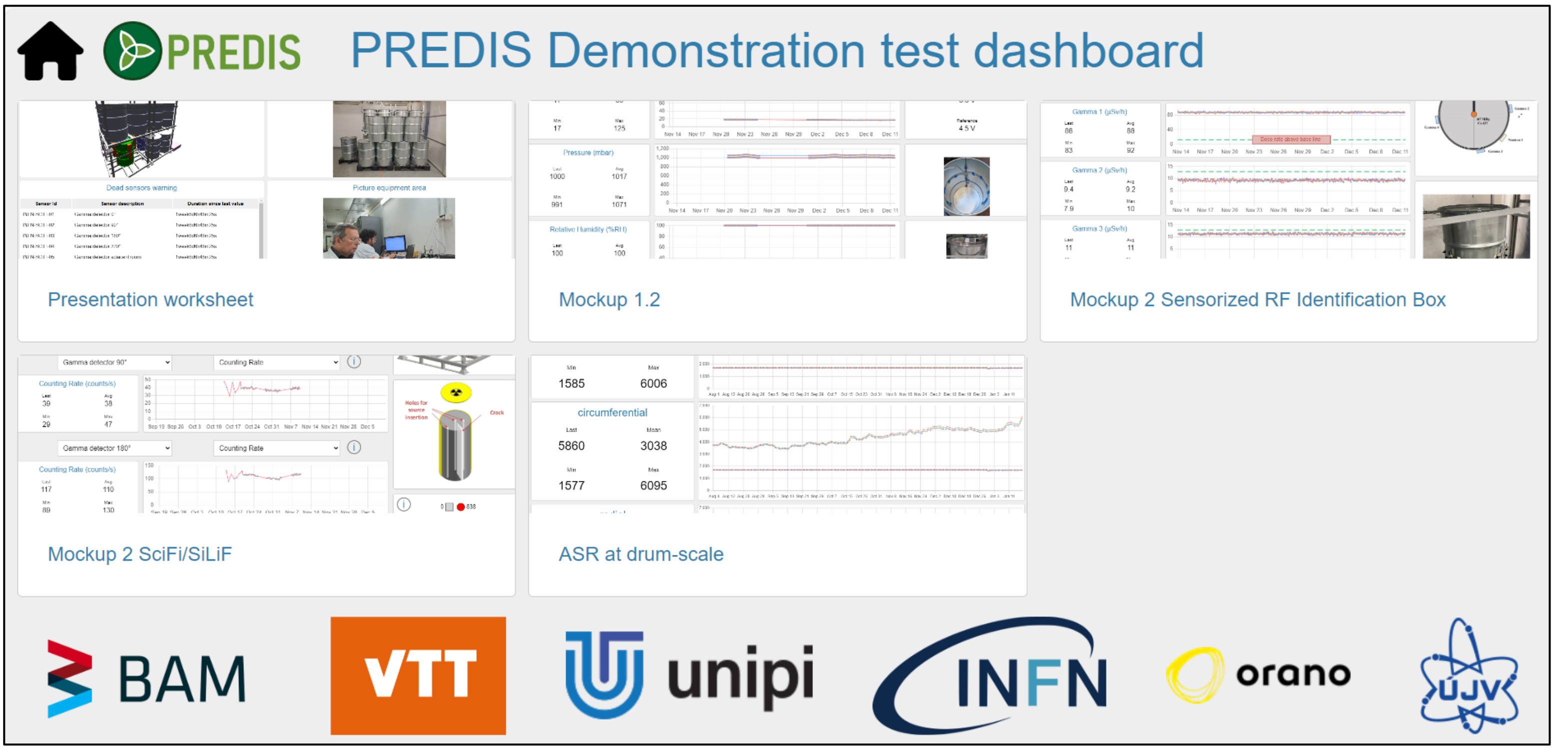


Figure 15: Demonstration dashboard – home worksheet

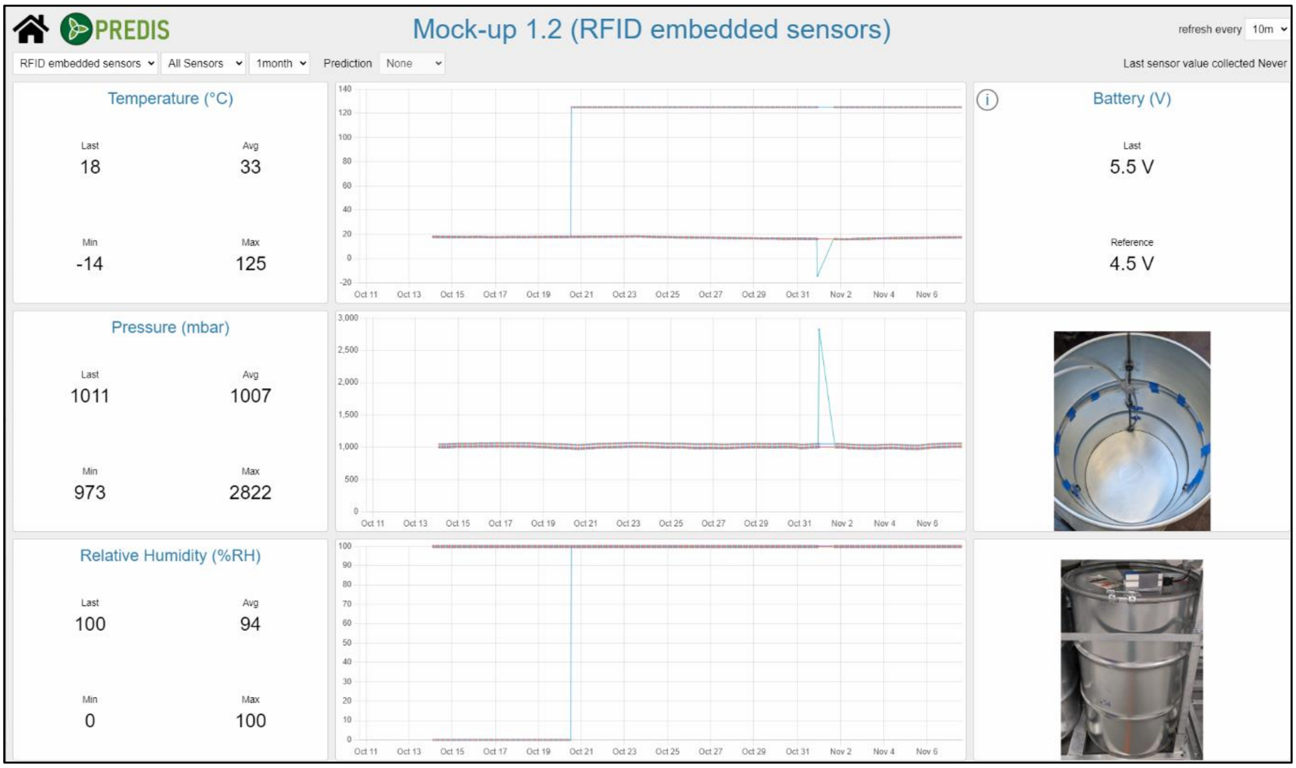


Figure 16: Demonstration dashboard - BAM / VTT Embedded RFID technology worksheet.

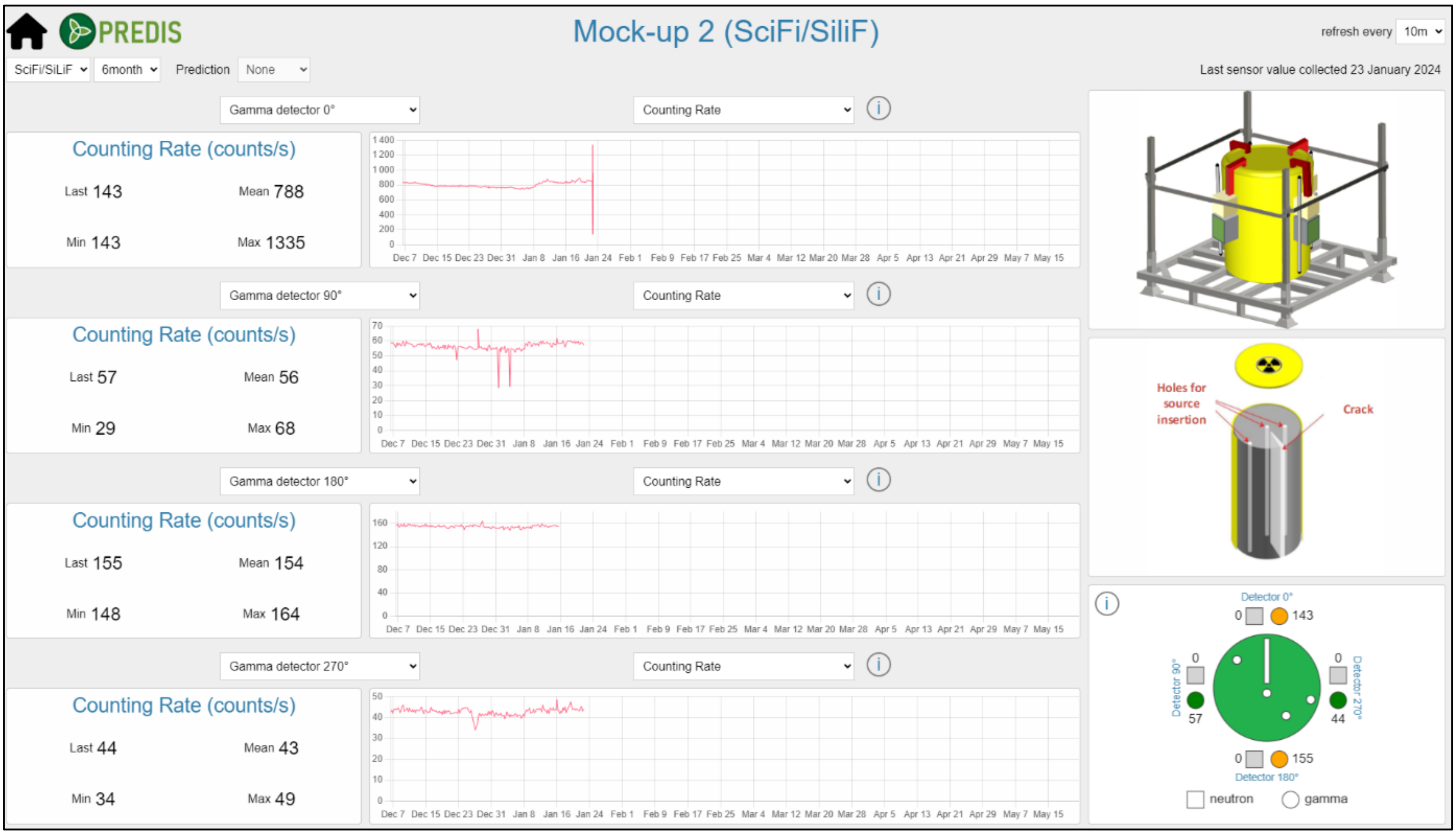


Figure 17: Demonstration dashboard – SciFi/SiLiF (INFN) worksheet.

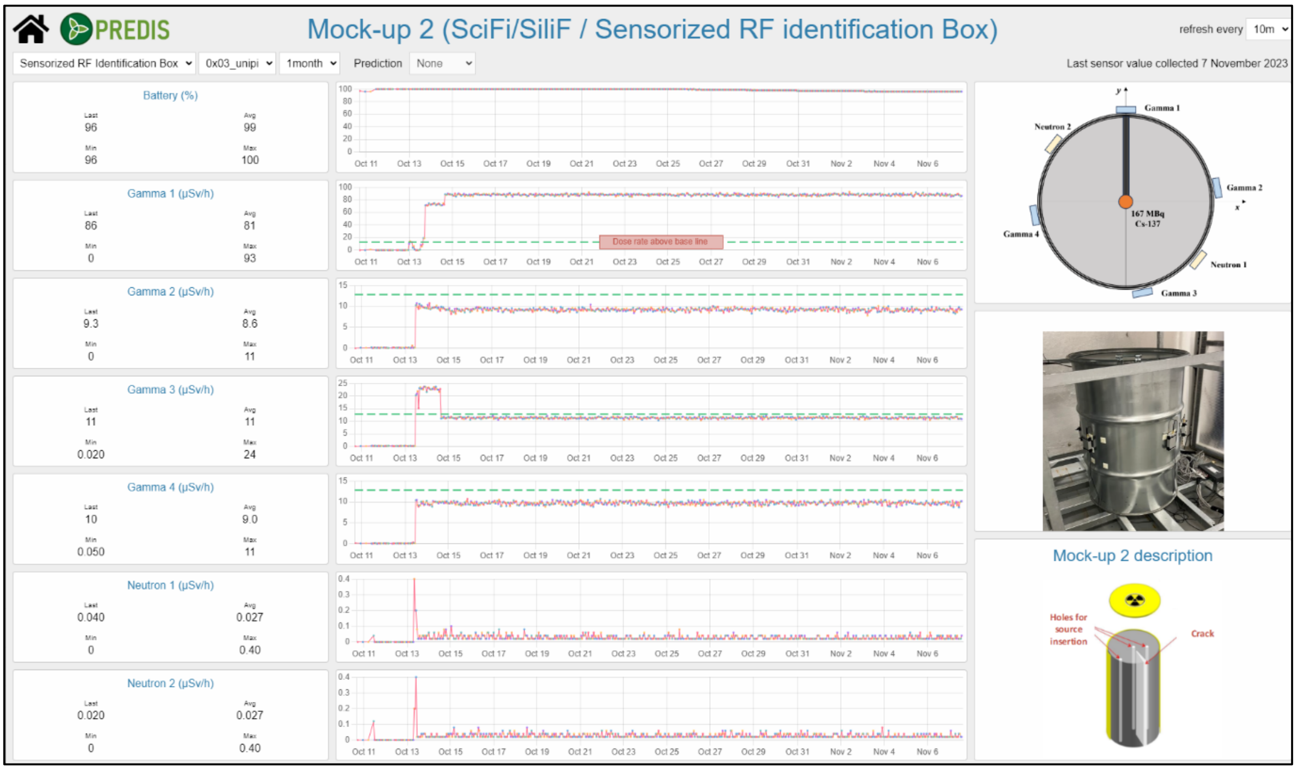


Figure 18: Demonstration dashboard – Sensorized Identification box (UniPi) worksheet.

The dashboard can include several warning signals to provide end-users with useful information / warnings whenever an event occurs in the storage area. For the demonstration test UniPi worked in task 5.3 in order to include such alarms in the demonstration test dashboard for the RF sensorized Identification box.

Every possible event that can occur during monitoring operations and might lead to signal modification was assessed (battery level, sensors failure, detaching or failing, gateway failing, dose rate increase). For each event a dedicated alarm with specific procedure for the operators was proposed.

The specification describing the dashboard alarms for the sensorized identification box written by UniPi is given in Appendix C (§ 8.1).

A specific deliverable D7.7 [4] in Task 7.5 provides an overall view of the dashboard development.

7 Demonstration test results

7.1 RFID embedded technology

The instrumented RFID mockup drum was transported from BAM to UJV on Oct 11th, 2023. It was installed in the demonstration site one day later (Figure 19). Data collection started some days later after issues with the internet connection had been solved (the system itself worked the entire time).

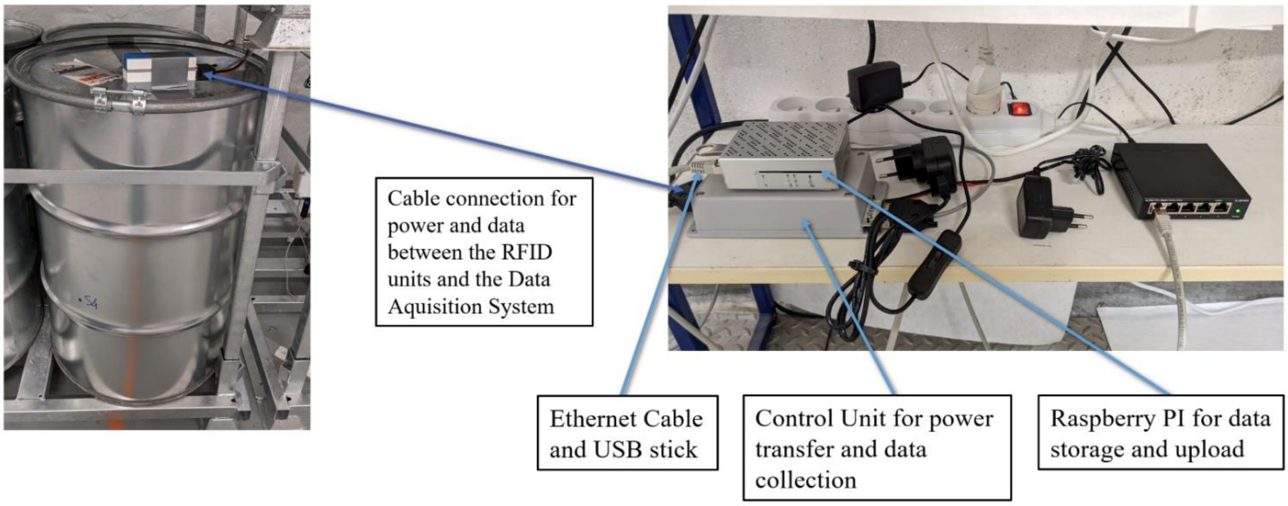


Figure 19: RFID mockup in the demonstration test facility (left). Power supply, external communication unit and WiFi have been placed in the room next to it.

Since then, data have been collected continuously for three months. Date have been directly uploaded almost in real time to the MS Azure database provided by VTT. PREDIS WP7 partners had direct access to this data (*Figure 20*), which can also be displayed in a dashboard such as the one provided by IFE (both task 7.5).

There have been sporadic missing uploads due to issues with the internet connection and the box responsible for the upload. It has to be taken into account that outgoing data via internet connection are unusual in nuclear facilities. In addition, the facilities are several stories beneath the surface. Developing and implementing a more robust connection would be needed in a commercial project. The sensors and the wireless communication/power units on the mock-ups lid worked all the time.

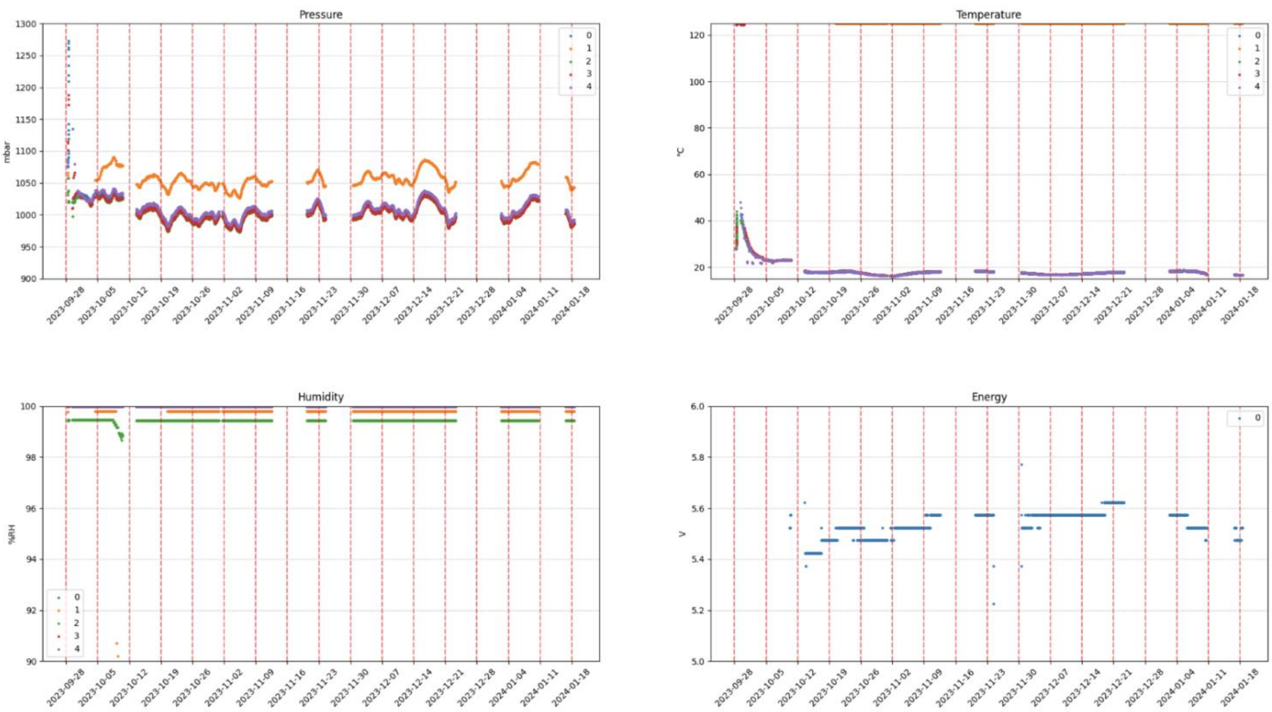


Figure 20: Data recorded from the RFID mock-up during demonstration.

The measurements from the SensorNode1 are likely not reliable since the temperature is saturated at the maximum value and the pressure has an offset compared to the others. A possible explanation are issues with the sensor node electronics or its connection to the communication unit on the lid, probably caused during concreting. Due to the installation of multiple sensors, these faults can be identified easily. Future versions of the nodes will be more robust.

The humidity measure values are stuck at 100% over the monitoring period. Measurements in the next months (after end of PREDIS) will give more information to explain this behaviour. The voltage of the interim storage in the Embedded RFID unit is stable around the default value showing that the communication through the metal lid remained stable. That means the embedded unit remained well fixed to the lid and the distance to the External Unit remained the same.

The temperature values showed a peak around 40°C at the beginning of measurements due to the hydration of the cement - an important input for the validation of simulations or for a digital twin. The pressure values have been around the atmospheric values all the time – there were no anomalies indicating swelling or other types of deterioration.

The main conclusions from the demonstration test (from the viewpoint of the developers) are:

- It is possible to mount sensors inside a waste package which can provide data for months and potentially for years or decades. This is supported as well by the work at SCK-CEN.
- Currently temperature, humidity (with some limitations) and atmospheric pressure can be measured. The system is extendable with other sensing technologies such as corrosion monitoring.
- It is possible to power the internal sensors, take the readings and transfer data without batteries and without wires penetrating the skin of the package.
- The data can be directly transferred to databases and dashboards.
- The system relies on a stable and secure internet connection.
- To raise the TRL, sensor nodes, powering, communication units and the control software have to be more robust. In the next step they need to be certified according to electric and communication standards.

7.2 SciFi / SiLiF

For the demonstration test at UJV, INFN installed five detection systems: four of them were hung on the mockup drum at different angles (0°, 90°, 180° and 270°) with respect to the internal crack direction (Figure 1B and C) and the fifth was placed in an adjacent room (about 6 m away) to do ambient background measurements. Each system consisted of one SciFi sensor, one SiLiF sensor and the related read-out electronic boards (Figure 1A). Due to its hook-shaped mechanical fixing, the system can be installed, positioned, displaced and removed quickly and easily. The sensors were initially connected via wires for their preliminary setup and tuning. Then the wires were disconnected and the drums, filled with concrete, were placed all around in order to verify the signal transmission capability through such a heavy shielding.

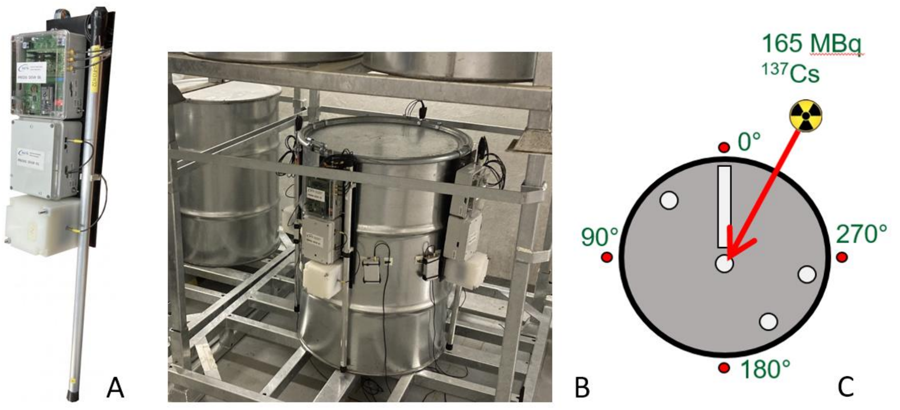


Figure 21. A) Single monitoring system. B) Arrangement on the drum. C) Position of detectors.

The systems were powered with long-life rechargeable battery packs and connected via a WiFi subnetwork to a router allowing a remote access to each electronic board and to a local PC/Server (fig. 2). The data were redundantly stored on the electronic boards (micro-SD card), on the PC/Server (hard disk) and were automatically transferred to the Azure cloud. After a first phase of testing and optimization of the electronics parameters (sensor bias voltages, thresholds, measure time interval and duration, etc.), the systems were programmed to automatically perform four runs a day (every six hours) lasting 60s each, but also the capability to wake-up the systems on demand, via a Bluetooth Low Energy signal, was successfully tested.

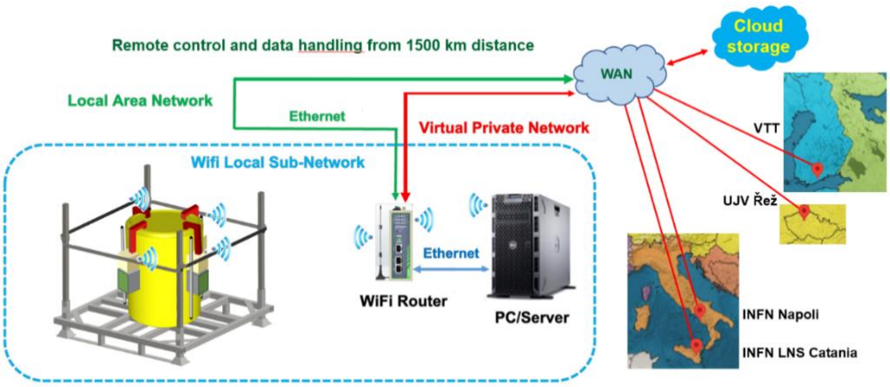


Figure 22. The SciFi and SiLiF readout architecture scheme for the remote control and data transfer.

The gamma rays emitted by a 165 MBq ^{137}Cs source placed in a quasi-central hole of the mockup were measured by the SciFi detectors and proved the stability, sensibility and accuracy of the system, usable for monitoring radioactive waste drums in mid-term storage sites. The different counting rates measured for the different detectors (Figure 3A) showed the capability to reveal an anisotropy in the gamma emission from the drum, which could possibly indicate a concrete crack. This was in very good agreement with FLUKA simulation results and independent measurements performed with a calibrated handheld detector by UJV technicians. Before concluding the demonstration, we acquired data at several angular positions by displacing the 0° sensor around the drum, thus discovering that its nominal position (and the other three) was shifted by about 4° from the initially assumed one, as clearly shown in Figure 3B.

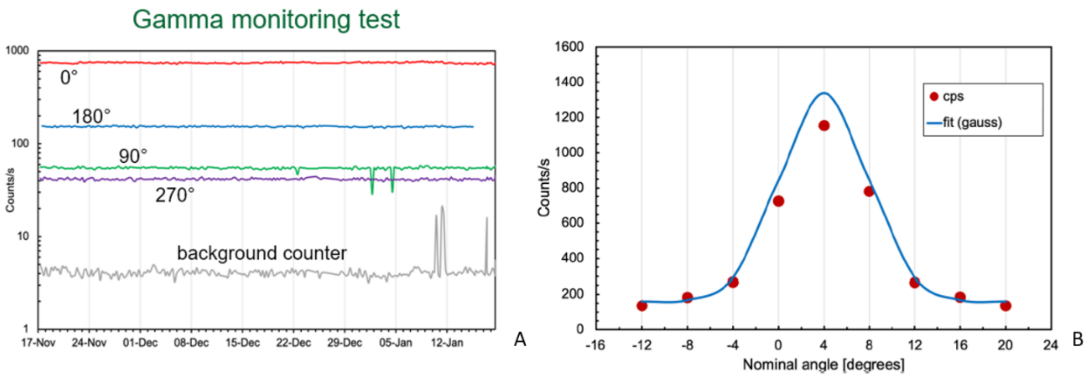


Figure 23. A) Counting rate for the five detectors. B) Angular displacement from the nominal 0°.

The data acquired from SiLiF detectors were unfortunately not significant because of the missing neutron source and the consequent impossibility to calibrate the discriminator thresholds. However, at the end of the demonstration test, we got a PuBe neutron source from UJV and we performed a 1 hour measurement of the neutron energy spectrum with and without the source, reported in fig. 4. The measurements assessed the quality of the detection system and its capability to disentangle neutrons from the common neutron and gamma background.

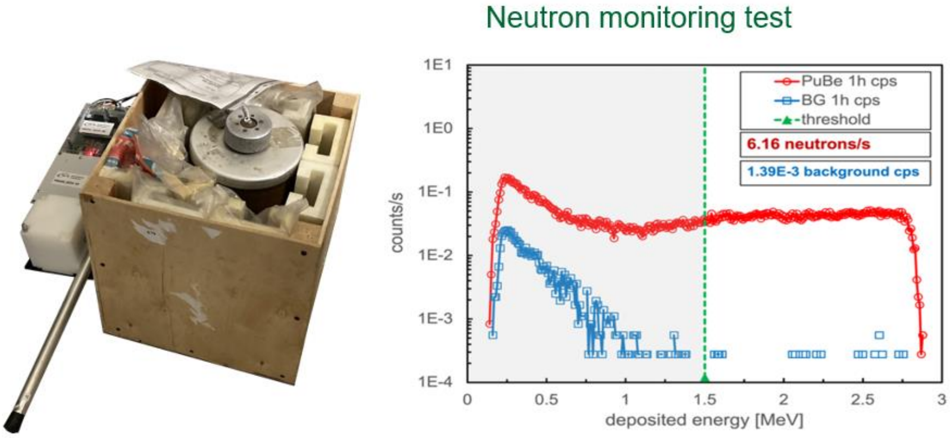


Figure 24. Neutron detection test performed with PuBe source compared with background (no source).

8 Sensorized RF identification box

UniPi developed an innovative device and approach utilizing passive gamma and neutron counting coupled with LoRa technology for the identification and monitoring of radiological levels in conditioned radioactive waste drums (RWDs). This technique aims at monitoring both the radiation intensity emission of the waste packages and the potential changes in their internal structure.

During the demo test, a LoRa node, with four gamma detectors numbered 1 through 4, and two thermal neutron detectors, numbered 1 and 2, was attached to the active mock-up. The gateway, linking to a Wi-Fi network, was in a data equipment area (DEA) two floors up from the storage location. All detectors were calibrated and used to measure the ambient equivalent dose rate on the surface of the drum (µSv/h). Wireless communication between the storage and the DEA was achieved without repeaters thanks to the penetrating nature of LoRa technology. Data capture was programmed every hour resulting in an average current consumption of tens of µA. The arrangement of the detectors around the drum is shown in Figure 25, where the expected theoretical Monte Carlo computed ambient dose equivalent rate at the gamma measuring points is also depicted.

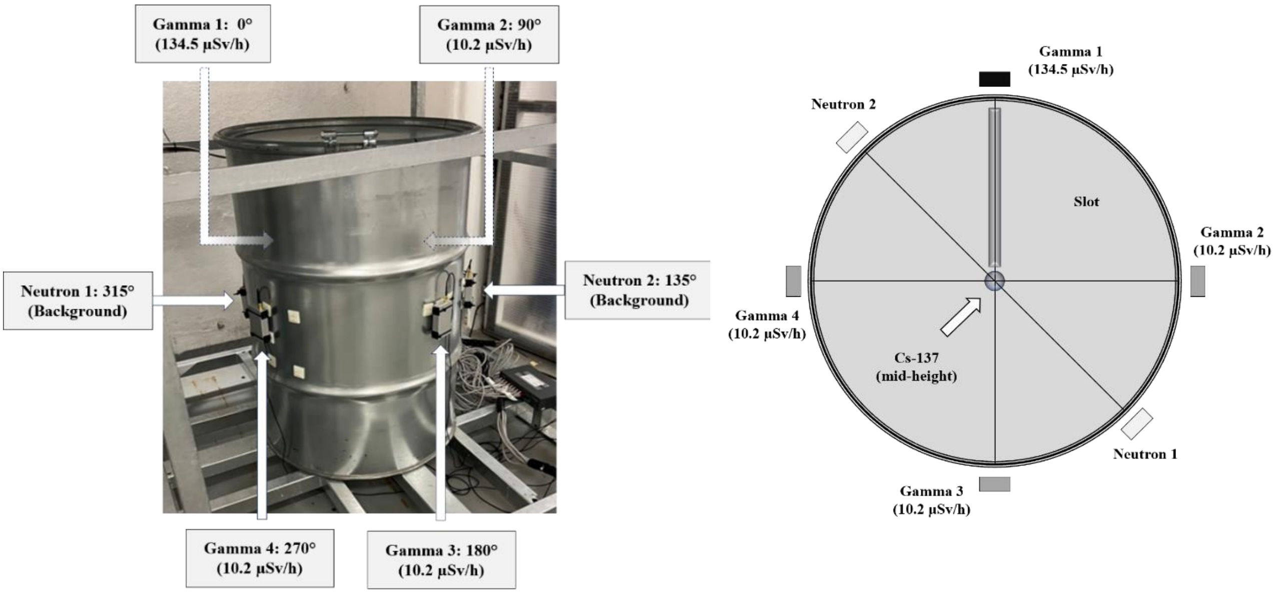


Figure 25: Demo test LoRa setup and expected ambient equivalent dose rates.

The objectives of the test were to verify the accuracy of radiation intensity measurements, assess the effectiveness of wireless data transmission in environments lacking internet connectivity, and assess the battery's longevity. Additionally, the test aimed to evaluate the system's ability to detect signs of structural integrity loss, indicated by increased radiation fluency, using the lateral slot as a defect. The results of the test are shown in Figure 26.

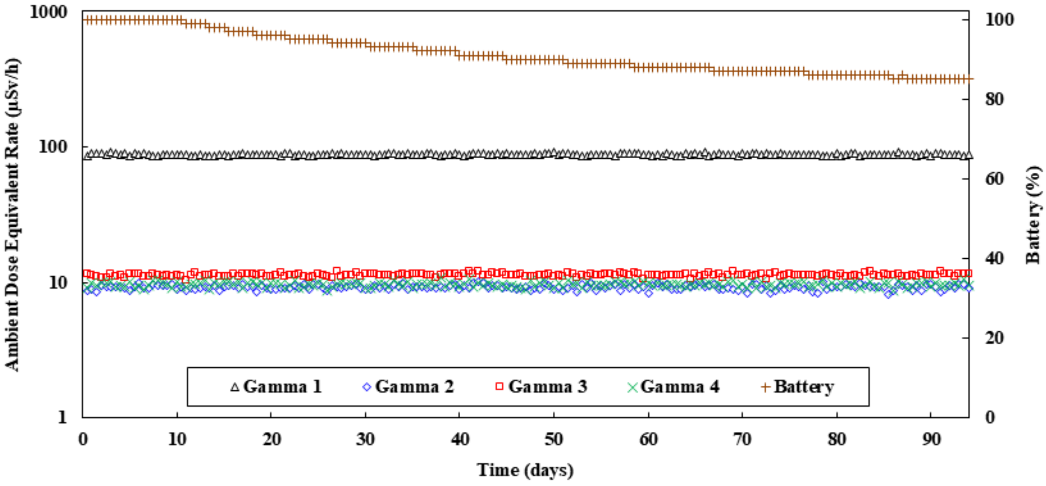


Figure 26: Ambient equivalent dose rates from gamma detectors and battery percentage over the 3 months of the demo test

Three months in operation, the system experienced a 15% reduction in battery life, however, by reducing the frequency of measurements from the original hourly schedule, the system's battery life could be substantially prolonged, also decreasing power usage.

The system's communication strength remained strong, as indicated by an RSSI (Received Signal Strength Indicator) value exceeding 190 dBm (max 255 dBm) with the gateway situated in the DEA, demonstrating the system's aptitude for long-term radiation monitoring of waste drums, even without internet access and through heavily attenuating concrete structures.

The ambient dose equivalent rates measured closely corresponded to the anticipated values, with the Gamma 1 detector observing a notably elevated dose rate that successfully identified the slot's presence through increased radiation fluence. These dose rate values were further validated by ÚJV technicians using calibrated handheld detectors, confirming the system's accuracy.

Overall, the detector aligned with the slot has demonstrated its capacity to accurately detect its presence, as illustrated previously.

9 Air-coupled ultrasonic inspection

The aim of this monitoring technology is to detect discontinuities in the skin of drums, which can provide screening for defects such as cracks, dents, or corrosion cavities.

To evaluate the potential use of this technology for 500L drum inspections, NNL procured a set of ultrasonic transducers for testing within the NNL Workington Laboratory Rig Hall. A transducer was positioned towards a mock package, maintaining a distance of a few millimeters, and the transmitted wave was detected by a receiver. This detection proved that the transducers were successfully sending and receiving a wave across the skin of the container. It was noted at this stage that the transducers were very sensitive to air flow within the room. This was mitigated by closing all doors and shielding the transducers from each other.

To prove the benefits of automation and to test the repeatability of the inspection, the transducer transmitter and receiver were mounted on a Kinova 6 degree-of-freedom robot arm and programmed to repeat the transducer positions in defined positions at various points along the height of the can. At each point, the transducer receiver display indicated that a wave had been successfully detected.

The small package did not have any ridges or deformities, nor did it have any barriers that may affect access. This is not an accurate representation of the typical drum-in-stillage configuration, so the experiment was repeated once again with a 500L drum housed within a mock stillage.

Figure 27: 500L drum being inspected by transducer mounted on industrial 6 axis robot.

The transducer transmitter was mounted on a KUKA KR120 robot arm and programmed to repeat positioning of a transducer at a single point on the drum. The receiver was fixed to the other side of the drum at the same height. Upon repetition of this measurement, the transducer receiver display indicated the same results, proving the repeatability of the inspection method.

Finally, the inspection system was deployed on a dented 500L drum to prove that a signal could be deployed and received even when the drum skin was damaged. A signal was successfully received, and the results saved for future analysis.

Overall, the results of the tests proved that non-contact ultrasonic inspection is a viable potential method for detection of discontinuities within 500L drums.

10 Proposed improvements

This chapter corresponds with subtask 7.6.3 “definition of potential mitigations actions and design improvements”, it describes improvements and further developments that could be done for each technology in order to better suit end-users’ needs.

The reference package for WP7 has been defined as cemented waste in a cylindrical metallic container made of stainless steel [2]. Thus, the developments in WP7 for every technology focus on this type of package. However, report [1] stated that other typologies of waste packages exist among end-users for example containers made of concrete, reinforced concrete or of carbon steel that can be either cylindrical or prismatic.

The exchanges with technology developers (in subtask 7.6.1) led to the conclusion that:

- RFID embedded sensors (BAM / VTT) could be used with every size, dimension or container material but the long-term compatibility between the matrix and the embedded sensors remains to be investigated for each matrix selected by the respective end user,
- Sensorized RF identification box (UniPi), SciFi (INFN), SiLiF (INFN), AE wireless (Magics) and Muon tomography (INFN) can be used with every size, dimension or container material. Muon tomography being only limited by the detector dimensions (<5m),

- Air-coupled ultrasonic inspection (NNL) is designed only for metallic containers (either with cylindrical profile or prismatic with rounded edges profile and not sharp corners).

10.1 SciFi / SiLiF for gamma and neutron monitoring (INFN)

This technology of neutron and gamma monitoring, achieves a high TRL at the end of the PREDIS project: TRL of 8 for the sensors and of 7 for the electronics.

Indeed, in addition to the demonstration test, INFN already performed an active test on non-cemented waste packages within the MICADO project in 2022.

During the demonstration test at UJV, some possible improvements of the electronics have been found:

- A temperature sensor was noisy and needed to be fixed,
- Some components on the electronic board could be improved. Indeed, one electronic board stalled at the very end of the demonstration test, due to a faulty contact that halved the charge available.

Also, the minimal size of crack in the cemented matrix that can be detected by the technology is yet defined by simulation. The development of more sophisticated mock-ups with thinner cracks sizes would be needed to validate the results obtained by these simulations. The simulation showed that cracks as narrow as 1mm wide can be theoretically detected with the technology [5].

Finally, from an implementation point of view, the system remains large (especially the SiLiF cubic sensors) and would be more easily installed if its size was reduced.

The assessment of the technology indicates that it can remain attached to the package at its interim storage location, enabling remote data transfer and requiring only one annual maintenance operation for battery recharging. However, the technology is currently mounted on the container lid, which, while allowing for quick and easy installation, could interfere with container handling. To avoid the risk of the technology falling off, it may need to be removed before the container is handled. Therefore, depending on the constraints of the end-user site, alternative installation solutions may need to be developed.

10.2 Sensorized RF Identification box for radiation monitoring (UniPi)

The sensorized RF identification box was tested on a mock-up (featuring a 2.5 cm lateral gap and a middle opening which housed a Cs-137 source of 167 MBq secured within a steel container) at UJV site for three months during the demonstration test. The system maintained a robust communication and the ambient dose equivalent rates observed corresponded well to the predicted values.

However, in a real package scenario, a crack would likely be thinner than the one simulated in the mock-up and several cracks may be present at various location in the cemented matrix. Therefore, more testing with conditions that enables multiple and thinner cracks in the mock-up matrix would be of interest. Yet, as can been seen during the AE testing (see § 10.5), this mock-up production can be challenging.

Moreover, one asset of this technology is its ability to monitor several packages simultaneously through several instrumented packages. Since the test at UJV was performed on a unique mock-up, a test with several systems installed on several mock-ups would thus enable to assess this feature:

- Assess the performance of the network for example within an area with strong structural attenuation (for the radio signals through concrete),
- Assess the needs of repeaters for the signal,
- Assess the impact of a background level that is modified over time for example through packages movement (impact on recalibration according to the test duration).

Additionally, the demonstration test was performed using a ^{137}Cs source for a three-month period (thus with no significant radioactive decay due to ^{137}Cs half-life of 30 years). In a real package, multiple gamma emitters with different half-lives are likely to be present. Therefore, sensors capable of detecting various gamma energy levels would be beneficial to account for each radionuclide's decay, allowing for more accurate alarm integration in the dashboard. Developments are currently being done by UniPi on this topic [3].

Also report [5] stated that challenges still exist in measuring complex and heterogeneous packages which may require advanced spectral analysis, not available on the platform.

Regarding the system installation, wire connections were used between the sensors and the LoRa node during the demonstration test. To achieve a fully wireless technology and simplify installation and maintenance, this dependency on wired connections could be eliminated. A research into standalone units with LoRa transceivers is currently underway at UniPi to address this issue. [3]

Finally, the impact of long-term exposition to irradiation of sensors and Lora node (which are the closer to the package) and their material ageing remains to be evaluated in order to validate the measurement reliability and longevity in various radioactive environments (VLLW, LLW and ILW). Further data are expected, as the platform's durability is yet under evaluation by UniPi through radiation hardness tests [3].

10.3 RFID embedded sensors (BAM & VTT)

The embedded technology developed by BAM and VTT is innovative as it proposes to embed sensors directly in the matrix of the cemented package in order to measure the cemented matrix parameters evolution (humidity, temperature and pressure) with power supply transmitted to the battery less sensor through the metallic container.

The incorporation of the sensors in the package was challenging during the real size mock-up production. Indeed report [5] underlines that the procedure for the prototype construction complexity demands technical expertise, requiring experienced individuals. Thus, developments remain necessary in order to be able to perform this operation in a full-size active conditioning process.

The first phase of monitoring is also a challenge because the fresh and moist concrete impacts the cable capacitance and alters the signal. Changes in the technology cable should be considered to choose a cable material or a cable type with less moisture absorbance and low capacitance. The cross-talk between the clock and data signals observed in the laboratory tests could be eliminated by replacing the multicore cable by two coaxial cables.

Finally, as the sensors and cables are embedded in the matrix, they will remain in the package when it is sent to disposal. Therefore, they must comply with WAC and avoid causing any unwanted degradation phenomena, such as generating corrosive or explosive gases under radiation aging. For instance, the current sensors are encased in a mix of PVC and Teflon. While Teflon performs well in high-temperature and basic pH environments, its resistance to irradiation is low. PVC, on the other hand, may release HCl(g) under irradiation aging, potentially causing pitting corrosion of the metallic container if located nearby. Additionally, once embedded in the package, no maintenance is possible for the sensors and cables after the cement is poured. Thus, further developments are needed according to each end-user condition to assess:

- The compatibility of the embedded equipment with the end-user disposal constraints and WAC,
- The long-term resistance of the embedded materials used under the end-users cemented matrix conditions and radiation environment (VLLW, LLW, ILW),
- The reliability of the measurements during the sensors ageing process according to interim storage duration.

Finally, the compatibility of the embedded sensors and cables with each end-users WAC criteria must be checked before the technology is chosen. According to the results, modification of sensor or cable materials can be needed.

Note: In report [5] *it is considered that, because the compatibility of the embedded sensors with the WAC criteria is not acquired yet, operations to remove the sensors may be needed (cutting of the metallic package) associated with new conditioning of the cemented wastes. The removal of the embedded sensors from the package seems unsuitable from an end-user perspective. It will cause important operations and will require new conditioning, meaning a new package qualification for disposal. Therefore, it would be more suitable to validate compatibility of the embedded sensors with WAC for each conditioning and end-users beforehand and the dedicated developments / R&D stages will be needed to obtain this compatibility for each end-user application.*

10.4 Air-coupled ultrasonic inspection (NNL)

Air-coupled ultrasonic inspection developed by NNL aims to detect swelling in the drums and provide screening for discontinuity defects such as cracks or corrosion cavities [5].

This technology needs skilled workers to position the measurement tools correctly, which adds some complexity to the use of the technology. Moreover, interpretation of measurement requires an expert knowledge [5].

Air-coupled transducers eliminate the need for contact or fluid media, but the technology still requires proximity to the package for measurement, and data collection must be done at close range to the detector.

Although laboratory tests have shown that that the Air coupled US technology could measure the circumference and detect discontinuity & crack as well as pressure build up inside the drums with restricted minimal access to them, the ultrasonic circumferential measurements and the discontinuity/defect detection process still need to be validated using real full scale filled drums [3].

Concerning optical scanning, the sensors shall be able to operate within a few millimetres away from their target, which reduces the scanning area, forcing the scanner to acquire more images to be able to cover the package surface and thus leading to longer scanning durations and the need to be able to access a larger area of the package [3]. Additionally, it prevents the monitoring of the package bottom surface without direct access to it.

Finally, if the technology is to be used while packages are still stacked, more development is needed to consider how to deploy the system [5].

10.5 Acoustic Emission wireless (MAGICS)

The applicability of Acoustic Emission has been shown in lab-scale experiments.

During the one-year test performed on AE wireless, 4 mock-ups drums with cemented mixtures generating ASR reaction were produced. They contain embedded strain and temperature sensors to correlate the expansion of these embedded sensors with the data from the Acoustic Emission sensors (one located on the metallic container outside and one on top of the concrete) [3].

However, the selected mixtures did unexpectedly not generate ASR reaction. The test couldn't deliver proper results resulting in a need to keep monitoring until the reaction happens.

Therefore, the TRL AE wireless remains low at the end of the PREDIS project and many developments are still needed:

- The applicability of AE to heterogeneous waste forms monitoring has not been demonstrated to-date [5],

- There remains uncertainty regarding the sensors' susceptibility to radiation [5],
- Also, although the technology is aimed to be wireless the sensors still need cabling yet, which have to be disconnected if drum movement is necessary for storage constraints [5] and whose susceptibility to radiation also needs to be addressed,
- Operational developments are needed to filter out vibrations coming from the interim storage that are picked up by the sensors [5],
- Expert involvement is currently necessary due to the low TRL of the technology,

10.6 Muon tomography (INFN)

The Muon Tomography (Mu-Tom) technique enables investigation of the internal composition of cemented drums in a non-destructive manner using naturally occurring cosmic ray muons.

Two of muon major difficulties for end-users are the required size of the installation and the long acquisition times, which will impact storage processes.

The technology enables to detect and measure the metallic content inside cemented drums. However, end-users show interest in the monitoring of cracks. Unfortunately, the muon tomography cannot identify unless the cracks or voids are significantly large. Further studies are needed on this topic.

Muon tomography shows flexibility as it can be used for packages with different shapes (cylindrical and cubical), sizes (provide the installation is big enough) and containers (steel or concrete).

Finally, the technology has not yet achieved full industrial scalability, and software and computing optimisations are still needed [5]. Optimisations that lower the measurement acquisition time or minimise the need for expert supervision and results validation or interpretation would be beneficial for end-users and could be a way to upgrade the technology.

10.7 General improvements

During the demonstration test, UniPi and task 7.5 implemented several warning signals on the Dashboard related to the measurements performed by the Sensorized RF identification box on the mock-up. These signals, triggered by events such as an increase in dose rate, abnormal dose rate values, sensor disconnection, or data loss, served as alarms to alert the Dashboard user of any detected issues with the package. This development, highly relevant for technologies with a high TRL, adds value by enabling end-users to better understand and utilize the information provided by the technology.

This system is not only beneficial for the technology itself, but it also helps end-users to better understand and deal with issues occurring with their waste. The same process could be applied to technologies with higher TRL levels (SciFi, SiLiF, and Muon Tomography).

The next step for all technologies is to finalize the tests conducted during the demonstration by extending them to a representative environment, specifically within an industrial setting that includes multiple active cemented packages and package movement. This will allow for the assessment of their impact on calibration procedures (such as modifications in dose rates around the packages) and the integration of the new data monitoring into the dedicated dashboard.

11 References

[1] Deliverable 7.1 – State of the art in packaging, storage and monitoring of cemented wastes
[2] Deliverable 7.2.2 – Reference package and factors affecting package evolution and degradation
[3] Deliverable 7.3 – Innovative Integrity Testing and Monitoring Techniques – 2024-02-19 version 1.2 Final

[4] Deliverable 2.6 – Gap analysis
[5] Deliverable 7.9 – Economic, environmental and safety impact
[6] Deliverable 7.7 – Report on innovative Report on innovative data handling & decision framework technologies

Technical Publications

[7] Corrosion and Expansion of Grouted Magnox – J. Cronin and N. Collier – December 2012
[8] Milestone MS52 – M7.3 – Month 24 – internal report - Prototypes ready for virtual tests (lab environment, test of data exchange)

Appendices

Appendix A: Table of comparison

No	End-users need	RFID embedded sensors	Sensorized RF identification box for radiation monitoring	Muon Tomography	SiLiF neutron monitor	SciFi gamma monitor	AE wireless	Air-coupled ultrasonic inspection	Comment
		Parameter(s)	Parameter(s)	Parameter(s)	Parameter(s)	Parameter(s)	Parameter(s)	Parameter(s)	
A	Parameter(s) of the package that is/are followed :								No scoring here. These data will enable grouping technologies.
	- crack	No	Yes	No	Yes	Yes	Yes	yes	
	- swelling	Yes	No	Yes	No	No	No	yes	
	- shrinkage	Yes	No	Yes	No	No	No	yes	
	- water	No	No	No	No	No	No	no	
	- condensation	No	No	No	No	No	No	no	
	- gas evolution	No	No	No	No	No	Yes, indirectly	no	
	- temperature	Yes	No	No	No	No	No	no	
	- surface humidity	Yes	No	No	No	No	No	no	
	- air pollutants	No	No	No	No	No	No	no	
	- chemical weathering	No	No	No	No	No	No	no	
	- corrosion of the metallic container	No	No	No	No	No	Yes	Yes	
	- corrosion of the waste	No	No	No	No	No	Yes	no	
	- dose rate	No	Yes	No	Yes	Yes	No	no	
	- contamination	No	No	No	Yes	Yes	No	no	
	- internal structure and changes (i.e. displacements...)			Yes	Yes	Yes			
B	Description of the geometry of package for which the technology is designed	Any	cylindrical and prismatic packaging system of any size (best performance if sensorized box is positioned close to a potential leackage, e.g. close to the lid or bottom of the package), any material	any shape, any material, size limited by detector dimension (e.g. <5m)	Drum and box, any size, any material	Drum and box, any size (best performance <1m high), any material	Any	Any metalic container with cylindrical profile or prismatic with rounded edges profile and not sharp cornerns.	No scoring here. This data will enable grouping technologies.
C	Description of the cementation matrix aimed by the technology (portland cement, reinforced concrete, metallic container...)	Any (with some limitations)	any matrix	any matrix	any matrix	any matrix	Any	tested with portland cement contents	No scoring here. This data will enable grouping technologies.
D	Technology interoperability	No direct interoperability, complementary to other systems	Yes, with gamma and neutron counting	Yes, gamma and neutron detectors	Yes, with passive gamma counting	Yes, with passive neutron counting	Acoustic Emission sensor is so far used as a sensor and not embedded into a final solution. Hence, infrastructure and HW is not defined yet.	ideally to be combined with pointcloud laser scans	No scoring here. Specify here if the technology can be combined with others technologies and which ones.

No	Criterion	Net weight	Scoring	Scoring	Scoring	Scoring	Scoring	Scoring	Scoring	Scoring (5 : best score / 1: lowest score)
	Technical performances	*1*								
	1.1 Universality level	*0,4*	1,2	2,0	2,0	2,0	2,0	2,0	1,8	
	1.1.1 Universality level of the technology (all the packages, all the surface of the packages, samples packages, samples materials…)	20%	5	5	5	5	5	5	4	Scoring: 5 - the technology can be used on all packges and enables their complete control (all the surface and inside) 4 - the technology can be used w ith every packages but w ithout a complete control (all the surface and inside) 3 - the technology cannot be used w ith every package geometry or is only adaptated for sample packages (complete control, all the surface and inside) 2 - the technology is only adaptated for samples packages w ithout a complete control (sample package = one package only si follow ed in an entire interim storage) 1 - the technology is only adaptated for sample materials
	1.1.2. Easiness to adapt the technology to old packages in addition to new ones (ex: sensor has to be inside the package)	20%	1	5	5	5	5	5	5	Scoring: 5 - the technology can be used on former/existing packages, 4 - the technology ca be used on former/existing packages if they comply w ith a few criteria, 3- the technology can be used on former/existing packages but they have to comply w ith several criteria (geometry, ...), 1 - the technology can only be used on new packages w hich are produced via the embedded technology
	1.2 Measurement level	*0,6*	2,3	2,6	2,1	2,7	2,7	1,7	2,5	
	1.2.1 Measurement level : qualitative or quantitative	20%	5	5	4	5	5	5	5	Scoring: 5 - quantitative 1 - qualitative/accuracy
1	1.2.2.1 Measurement uncertainties : Global	10%	4	5	4	5	5	0	3	Scoring: levels in percentage (the percentages shall be discussed in accordance w ith the experience feedback on technologies and the parameter that is measured): measurement duration < 8h 5 - <±10%, 4 - <±30%, 3 - <±70%, 2 - <±100%, 1 - >±100%
	1.2.2.2 Measurement uncertainties : parameter 2			-	position +- 1 cm	-	-	NA	-	Scoring: levels in percentage (the percentages shall be discussed in accordance w ith the experience feedback on technologies and the parameter that is measured): measurement duration < 8h 5 - <±10%, 4 - <±30%, 3 - <±70%, 2 - <±100%, 1 - >±100%
	1.2.2.3 Measurement uncertainties : parameter 3			-	density +-30%	-	-	TBD	-	Scoring: levels in percentage (the percentages shall be discussed in accordance w ith the experience feedback on technologies and the parameter that is measured): measurement duration < 8h 5 - <±10%, 4 - <±30%, 3 - <±70%, 2 - <±100%, 1 - >±100%
	1.2.2 Measurement uncertainties : duration	5%	1	5	5	5	5	5	3	Scoring: 5 - If uncertainties is low er w ith increase of measurement duration 1 - no impact of measurement duration
	1.2.3 Easiness to have information on the ageing indicator Example : gas evolution gives information on the presence of cracks but does not indicate directly its location or its size, surface humidity indicates presence of water but nots its quantity,… --> detection --> localization	7%	3	3	1	3	3	5	5	Scoring: 5 - Data (on the ageing indicator) are given directly (ex : cracks), 3 - Requires a specific model to estimate the ageing and/or combinaison w ith another technology. Duration of post-processing is short 1 - Requires a specific model to estimate the ageing (for example a qualification) and/or combinaison w ith another technology. Duration of post-processing is high.
	1.2.4 Reliability of data transfer	5%	5	5	5	5	5		5	Scoring: taking into account cemented package (size 200L drum) and one 1m concrete w all in the facility 5 - No loss of data during data transfer from the sensor/technology to the "computing unit" (through the cemented package, the w alls of the facility ...) 3 - Loss of data during the transfer that can lead to a lost in accuracy (increase of uncertainties) 1 - Loss of data during the transfer that can lead to unusable measurement
	1.2.5 Temporal resolution How quick a change is significant for the waste package and how quick a change is even possible. In the long term, this affects the required storage space for the data and possible maintenance procedures for the sensors in the future.	5%	5	4	5	5	5	1	5	Scoring: 1. value needs to be monitored for every second or less, 2. value needs to be monitored every minute, 3. value needs to be monitored every hour, 4. value needs to be monitored each day, 5. value needs to be monitored each w eek or more.
	1.2.6 Scan data The inspection procedure should determine the required resolution to find possible defects or other targets. The main question here might be is there an advantage to increase the resolution to get more information	7%	2	3	1	3	3	1	2	Scoring: 1. increasing resolution increases relevant information 5. no know n benefit of increasing resolution.

2	**Costs**	*1*	**4**	**3,8**	**3,2**	**4,4**	**4,4**	**3,7**	**3,4**	
	2.1 Procurements costs (Cost of instrumentation)	22%	4	3	3	4	4	3	3	Scoring: (order of magnitude has to be discussed according to the technologies) ; considering 100 packages 5 - <10k€ 4 - <100k€ 3 - <500k€ 2 - <1M€ 1 - >1M€
	2.2 Manufacturing costs (technology and adaptation for the end-user need) taking into account acceptance tests/delivery checks	22%	4	4	4	4	4	3	3	Scoring: (order of magnitude has to be discussed according to the technologies) 5 - <10k€ 4 - <100k€ 3 - <500k€ 2 - <1M€ 1 - >1M€
	2.3 Operating costs and maintenance + retention of data (normalized by the duration and the number of packages)	44%	4	4	3	5	5	5	4	Scoring: (order of magnitude has to be discussed according to the technologies) 5 - <100€/year/package 4 - <1k€/year/package 3 - <5k€/year/package 2 - <10k€/year/package 1 - >10k€/year/package
	2.4 Development cost (to reach a TRL of 9)	11%	4	4	3	4	4	1	3	Scoring: (order of magnitude has to be discussed according to the technologies) 5 - <10k€ 4 - <100k€ 3 - <500k€ 2 - <1M€ 1 - >1M€
3	**Safety/Security for operators**	*1*	**4,3**	**5**	**4,3**	**5**	**5**	**0**	**5**	
	3.1 Measurement implementation (operator safety)	70%	4	5	4	5	5		5	Scoring: 5 - minor risk ==> remote measurement outside storage 4 - Small risk ==> remote measurement 3 - major risk==> contact measurement 1 - High risk ==> contact measurement w ith a radoactive source
	3.2 Data retrieval	30%	5	5	5	5	5		5	Scoring: 5 - minor risk ==> transfert is crypted and measurement is performed localy 1 - High risk ==> transfert w ireless non crypted (public cloud)

4	**Operation**	*1*								
	4.1 Operability	*0,7*	2,5	3,0	2,6	3,4	3,4	3,0	2,8	
	4.1.1 Possibility to make continuous measurement (monitoring)	13%	5	5	5	5	5	5	4	Scoring: 5 - possible 1 - not possible
	4.1.2 Duration of the measurement (acquisition time)	3%	5	4	1	5	5	1	4	Scoring: 5 - a few minutes, 4 - around one hour 3 - a few hours 2 - around one day 1 - a few days
	4.1.3 Need of followed up during measurement ? Need of an operator	3%	3	5	5	5	5	5	3	Scoring: 5 - no one is needed, 3- an operator is needed periodically 1 - an operator is needed continously
	4.1.4 Easiness of radioactive source management	4%	5	5	5	5	5	5	5	Scoring: 5 - No radioactive source, 1 - A radioactive source with challenging management (managed by an expert with a specific equipment, short lifetime)
	4.1.4.1 Easiness of technology calibration : parameter 1	13%	5	4	3	5	5	5	5	Scoring: 5 - the technology requires a short calibration. It must not be renewed for each package, 4 - the technology requires a time consuming calibration. It must not be renewed for each package 3- the technology requires a calibration that must be renewed for each package measurement but it is not time-consuming 1 - The technology requires a calibration that is time-consuming and must be renewed for each package measurement
	4.1.4.2 Easiness of technology calibration : parameter 2			-	-	-	-	-	4	Scoring: 5 - the technology requires a short calibration. It must not be renewed for each package, 4 - the technology requires a time consuming calibration. It must not be renewed for each package 3- the technology requires a calibration that must be renewed for each package measurement but it is not time-consuming 1 - The technology requires a calibration that is time-consuming and must be renewed for each package measurement
	4.1.4.3 Easiness of technology calibration : parameter 3			-	-	-	-	-	4	Example of scoring: 5 - the technology requires a short calibration. It must not be renewed for each package, 4 - the technology requires a time consuming calibration. It must not be renewed for each package 3- the technology requires a calibration that must be renewed for each package measurement but it is not time-consuming 1 - The technology requires a calibration that is time-consuming and must be renewed for each package measurement
	4.1.5 Impact on the interim storage facility	13%	3	3	3	5	5	3	3	Scoring: 5 - technology can be used remotely (outside storage area) and does not require a large area, 4 - technology can be used remotly (outside storage area) but requires a large area, 3 - technology has to remain in the interim storage. but does not require a large area (the packages can remain at their place in the interim storage), 2- technology has to remain in the interim storage. It requires a large specific area in the interim storage
	4.1.6 Impact on the conditioning process or on the package for new packages (ex : sensor embedded in the package)	13%	1	5	5	5	5	5	5	Scoring: 5 - No impact or not applicable, 1 - Change in the conditioning process
	4.1.7 Operator qualification	6%	3	5	3	5	5	5	3	Scoring: 5 - no qualification needed (ex: the operator will have a light training to use a software), 3 - no qualification needed for the operator (ex : light training to use a software) and an expert is needed (remotely) for validation 1 - An expert with a certification is needed (ex: external operator coming from approved/recognised organisation)
	4.2 Maintainability / availability	*0,3*	1,5	1,5	1,6	1,6	1,6	0,7	1,2	
	4.2.1 Technology lifetime (sensors and data handling)	13%	4	4	5	5	5	TBD	3	Scoring: (order of magnitude has to be discussed according to the technologies) 5 - (> 30 years) 4 - (< 30 years) 3 - (< 10 years) 2 - (<3 years) 1 - (< 1year)
	4.2.2. Components procurement durability and number of suppliers (example of muon)	13%	5	5	5	5	5	4	5	Scoring: (order of magnitude has to be discussed according to the technologies) 5 - components procurement is possible for at least 10 years, lots of suppliers 1 - < 2 years, few suppliers
	4.2.3 Maintenance level	6%	5	5	5	5	5	3	3	Scoring: 5 - few maintenance (remplacement of small parts, periodic control...), 3 - unknown, 1 - maintenance duration is high and very frequent

Appendix B: Storage configuration table

			Comment	RFID embedded sensors	Sensorized RF identification box for radiation monitoring	SiLiF neutron monitor	SciFi gamma monitor	AE wireless	Air-coupled ultrasonic inspection
Stacking	Direct	Is the technology compatible with direct stacking?	Yes/No, **if yes fill the sheet "1 - Direct stacking"**	No	No	Yes	Yes	Yes	yes
		Minimum space needed between the adjacent packages in the same row (horizontal direction) ?	On each side : x = *(see figure A in sheet "1- Direct stacking")*		N/A	15-20 cm	15-20 cm	3 cm	23 cm
	Indirect	Is the technology compatible with indirect stacking?	Yes/No, **if yes fill the sheet "2 - Indirect stacking"**	Yes	Yes	Yes	Yes	Yes	yes
		Minimum space needed between the packages (with stillages/ trays ...) (vertical and horizontal directions) ?	If yes, specify wich one(s) is/are compatible	Stillage	A,B,C are compatible	both	both	Stillages, trays	no direct contact between adjacent package inside the stillage
			If yes, specify wich one is preferable		C is preferable for 3 reasons: easy access for radioactive source insertion/removal, installation/management of the devices, improved radio communication from the devices to the radio receiver installed away from the drums.	Stillage	Stillage	Stillages	vertical contact will not effect readings
		Minimum space needed between the packages (with stillages/ trays ...) (vertical and horizontal directions) ?	Above/below : y = *(see figure A' in sheet "2- Indirect stacking")*	15cm	20 cm	0cm	0cm	0	no direct contact between adjacent package inside the stillage
			On each side : x = *(see figure A' in sheet "2- Indirect stacking")*	15cm	20 cm	15-20 cm	15-20 cm	3 cm	vertical contact will not effect readings
Power		Need of power supply?	Yes/No	Yes	NOT for the unit installed on the drum. Power is needed for the radio receiver which can be installed away from the drums.	No for detectors/Yes for Server and Router (see NOTE 1)	No for detectors/Yes for Server and Router (see NOTE 1)	No	yes
		Electric wire (electric outlet) ? Or battery ?	Precise	Electric wire	Battery, already embedded in the prototype. You do not need to provide it since several years of battery lifetime are expected.	1 power outlet	1 power outlet	No	wire
		How many connections?	Precise	1	No external connections are needed for the unit installed on the drum. 220V are needed for the radio receiver which is installed away from the drums.	1	1	/	2
Data reporting		WiFi needed?	Yes/No	Yes	Wi-Fi is not necessary. However, if present, will allow to directly upload data to the Azure platform. Otherwise, data will be stored on a SD card.	No, it is included in our electronics	No, it is included in our electronics	No	no
		Wire connection ?	Yes/No, if yes, precise how many	No	No wire connection for data collection/reporting are needed.	Yes (one for Router) (see NOTE 2)	Yes (one for Router) (see NOTE 2)	Yes, 1 coax wire per sensor	yes one multicore cable
Duration		Duration of the test?	Precise (min,hrs, ...)	5min	Measurements are periodic. Each measurement period can go from 1 h to 1 day, depending on the radioactive activity of the sources inside the drums. Several measurements may be needed, depending on the goal. If the radioactive activity is very low, more time is needed to achieve a good counting statistic.	1 week	1 week	Continuous, 300 kHz	minutes but can extend to hours depending on resolution
Insertion of a source in the mock-up		Is it compatible with stacking (direct/indirect)?	Explain		Insertion of one or more radioactive sources is compatible with indirect stacking: sources are inserted in drills of the concrete which fills the drums. However, it may be preferable to access easily to the top of the drum in order to insert or remove the sources if needed.	Yes: there is no equipments on top of the drum	Yes: there is no equipments on top of the drum		
		Is a stillage required?	Yes/No		Stillage may be NOT required, since we plant to install our devices directly on the externa surfaces of the drum.	No, but it is preferred	No, but it is preferred		
Can you identify other specification(s) ?				if the drum is steady in the stillage (cannot rotate/move), the x distance can be reduced to 5cm	Not at this time			Mounted to the side of the barrel. Coax cable running towards a datacollection unit outside the barrel.	requires an acurate deployment tool that can fit between the stacks

Appendix C: Assessment of the technology by PREDIS end-users performed during the workshop of November 2022

he assessment of this part of the table has been completed by PREDIS end-users during the workshop of November 2022.

The detail of the assessment is given below for these five criteria.

1) Need of additional safety studies for the EU storage for the implementation of the technology

Detail of scoring:

- 5 – high score – need for less additional studies/maintains occurrence of the risk
- 4, 3, 2 – intermediate scoring
- 1 – lowest score – need for more additional studies /increases occurrence of the risk

Results:

- RFID (BAM): scoring 4 because the detector will need to be at a short distance from the RFID sensor (limited range). Detector will need to be deployed within the store or inspection area at short distance from the waste containers. Detector also needed short distance for power supply
- RF sensorized box (UniPi): scoring of 4 because a box is positioned on top of the package which has an impact on handling of the package. Additional safety study will be required to assess if damage to a waste container can be sustained by a dropped load.
- Muon (INFN): scoring of 3, this is a promising non-contact new technology with foreseen deployment in a store inspection bay/dedicated area (with movement of package) and with new materials in the storage
- SiLiF / SciFi (INFN): scoring of 4 because the technology will need to be positioned close to the package (inside the stillages for examples). The stillages of the storage used for handling are impacted or if direct stacking is used in the storage then a dedicated area is needed with sensors and each package has to be transported to this area,
- AE (Magics): Scoring 5, No need to have special structure to maintain the sensors identified yet, no new risk identified at this stage from a safety study perspective and very little impact on a store safety case. This may change if the technology requires long residency time.
- US (NNL): scoring 5, No new risk identified with this technology

2) Possible impact on behavior of the package (design life), with need of additional studies

Detail of scoring:

- 5 – highest score - minor impact/ no impact
- 4,3,2 – intermediate score - small impact
- 1 – lowest score - high impact

Results:

- RFID (BAM): scoring 3, because it has been identified that several studies/tests will be necessary to justify that the technology has no impact on the package (matrix or container): compatibility of the embedded sensor materials with the cement matrix and with radiation (degradation of the matrix, radiolysis) or corrosion of the container
- RF sensorized box (UniPi): scoring 5, No new potential impact identified with this technology (box is not in contact with the package/container)
- Muon (INFN): scoring 5, No new potential impact identified with this technology (technology is not in contact with the package/container)
- SiLiF / SciFi (INFN): scoring 5, No new potential impact identified with this technology (technology is not in contact with the package/container)
- AE (Magics): scoring 4, scoring lower than ultrasonic technique as the sensors are in contact with the container of the package and it has to be justified that it has no impact on the container corrosion behavior.
- US (NNL): scoring 5, No new potential impact identified with this technology

3). Compatibility of the measurement with End-Users needs

Detail of scoring:

- 5 – yes, responds to at least 3 criteria
- 4 – yes, responds to 2 criteria
- 3 – yes, responds to 1 criterion
- 2 - some other parameters
- 1 – no parameters

Scoring in agreement with the end-users' parameters (presented in § 5.4) and the feedback from technology developers on their technology (presented in § 6.2.3.1.1).

Note: For this evaluation all the technologies are considered at their last development stage (TRL9).

Results:

- RFID (BAM): score 3 one EU parameter (relative humidity)
- RF sensorized box (UniPi): score 4, two end users' parameters (cracks and dose rate)
- Muon (INFN): score 2, some other parameters
- SiLiF / SciFi (INFN): score 5, three end users' parameters (cracks, dose rate and contamination)
- AE (Magics): score 5, three end-users' parameters (cracks, gas evolution, corrosion of the metallic container),
- US (NNL): score 4, two end-users' parameters (cracks and corrosion of the metallic container)

4). Impact of decommissioning

Detail of scoring:

- 5 - No decommissioning / not applicable or conventional decommissioning, the radioactive waste can be managed via the existing storage facilities
- 3 - lots of decommissioning operations with lots of waste sorting operations

Results:

- RFID (BAM): scoring 5, the major part of the technology is embedded in the package thus no decommissioning is needed for it. The power supply box on the side of the package will have to be decommissioned.
- RF sensorized box (UniPi): scoring 5, because the sensors are not in contact with the container, they can be reused several times
- Muon (INFN): scoring 3 for the muon unit a high amount of material will enter the storage unit and will need to be decommissioned (lots of decommissioning operations with waste sorting operations) if it cannot be reused
- SiLiF / SciFi (INFN): scoring 5, because the sensors are not in contact with the container, they can be reused several times
- AE (Magics): scoring 5, it is considered that the sensor can be reused.
- US (NNL): scoring 5, because the US sensor are not in contact with the container (air coupling) they can be reused several times

5) Frequency and duration of measurement compatible with storage constraint

Detail of scoring:

- 5 - minor impact
- 4,3,2 - medium impact
- 1 - high impact

Results:

- RFID (BAM): scoring 4, the technology is embedded in the package and the measurement frequency or duration has no impact in the storage. BAM explains that in the time scope of PREDIS, the RFID system will not be ready to be operated fully remoted. The most reasonable scenario in PREDIS still requires an operator to go periodically into the storage (not in contact with the package) to get the measures. The fully remoted scenario is a feasible improvement that would require some further development after PREDIS. The technology is considered at this last development level with distance transmission of the information to the control room.

- RF sensorized box (UniPi): scoring 5, No impact of measurement has been identified with this technology
- Muon (INFN): scoring 3, movement of the package is needed for the measurement, and it will stay in this specific area for a duration of several hours to several days (information of acquisition time provided by INFN in criteria 4.1.2 of comparison table: scoring of 1 – “a few days”)
- SiLiF / SciFi (INFN): scoring 5, No impact of measurement has been identified with this technology
- AE (Magics): scoring 5, No impact of measurement has been identified with this technology
- US (NNL): scoring 5, No impact of measurement has been identified with this technology

Appendix D: Specification for the dashboard alarms on Sensorized LR identification box (UniPi)

This appendix describes the alarms that have been identified for Sensorized RF identification box by UniPi and how they were implemented in the dashboard of the demonstration test.

Battery

Battery value < 20% triggers an alarm. The alarm stays triggered, and it is reset if the battery >= 20% or manually through a reset button.

Dynamic Threshold

For a given count rate (CR) or dose rate (DR), the minimum significant change (at a 99.7% confidence level) can be calculated based on the measuring window duration (ΔT). This change denoted as ΔCR or ΔDR, is important for detecting issues like matrix integrity loss or the formation of cracks over time. It can be approximated as $\Delta CR \approx 3 \times (CR / \Delta T)^{1/2}$ for large count values, where ΔT is the integration window.

For gamma detectors, ΔT is 12.5/60 hours (12.5 minutes), while for neutron detectors it is 1/60 hours (1 minute).

Assuming the same calibration factor K of 300 CPH/µSv/h (5 CPM/µSv/h) (verified) for all gamma detectors, the formula for DR is $\Delta DR \approx 3 \times (DR / (K \times \Delta T))^{1/2}$. For neutron detectors, K is different and equal to 4200 CPH/ µSv/h (70 CPM/µSv/h).

An alarm should be configured to trigger for each detector when the absolute value of the dose rate change (|ΔDR| exceeds $6 \times (DR / (K \times \Delta T))^{1/2}$. Factor 6 accounts for the double-sided distribution of DR. A different and more complex approach may be based on the implementation of edge detection algorithms, but at this time this solution should suffice.

For example, let's assume a measured DR of 110 µSv/h, and a previous reading of 100 µSv/h, with ΔT being 12.5/60 hours. ΔDR is therefore 10 µSv/h. Since $6 \times (DR / (K \times \Delta T))^{1/2}$ equals 7.59 µSv/h in this case, an alarm would be triggered. These calculations assume that the counts follow a Poisson distribution, making the formulas suitable for this statistical model.

Percentage Change

If a significant change in dose rate occurs, as per the dynamic threshold criteria, the dashboard will calculate and display the corresponding percentage change for the relevant detector. This information will be prominently highlighted, possibly within a designated label, for easy identification.

Additionally, the system should be configured to trigger an alarm in the event of an increase in dose rate—distinct from a drop. This alarm specifically alerts the end-user to the detection of an elevated dose rate, ensuring prompt awareness and response to potential increases in radiation levels.

Detaching of Single Detector Failing (sudden variation, potentially to zero)

Each detector should be equipped with an alarm system to signal potential detachment or failure. While determining a precise threshold for the time derivative is challenging, we can set reference values for triggering alarms. Specifically, an alarm will activate if there's a significant drop in the signal — exceeding 50% of its previous value and meeting the 99.7% confidence level, as established earlier. This alarm may require manual reset.

Additionally, the alarm system is designed to indicate detector failure. A detector is considered non-functional if it registers a significant drop as per our defined criteria, coupled with a current detector reading (currentDR) of zero. This ensures that the alarm does not trigger for mere background noise reductions, but only in cases of substantial drops leading to zero readings.

To streamline the system, a unified alarm will cover both detachment and failure scenarios. Upon activation, a brief popup will inform the user of the potential cause, whether it be detachment or failure, facilitating immediate and appropriate action. This simplification balances the need for detailed alerts with user-friendly operation.

All detectors failing (drops to zero) – Front-end failing

If a scenario arises where all detectors simultaneously register a reading of 0, accompanied by a significant drop in readings for each (as determined by the significant drop checks returning true for every detector), then a distinct alarm, labelled 'Front-End Failing', should be activated. This specific alarm suggests a potential system-wide issue, such as a failure in the front-end data acquisition or processing system. To ensure thorough resolution of the underlying problem, this alarm can only be reset manually by the user, after confirming that all necessary repairs or checks have been satisfactorily completed.

No data after the scheduled period – Lora transceiver failing/Gateway failing/ No Internet at the gateway level

If a period of 1 hour and 10 minutes' elapses without receiving any new data from the detectors, an alarm should be automatically triggered. This alarm will not only indicate a possible lapse in data transmission but also suggest potential causes for this interruption, such as a malfunction in the LoRa transceiver, a failure at the gateway, or a lack of internet connectivity at the gateway level. The alarm will be manually reset, signaling the resolution of the transmission issue.

Popup page for the detailing of the failing

Based on the layout of the dashboard and the feasibility of implementing interactive features, we can consider adding pop-up notifications that are activated by specific alarm conditions. For instance, if there's a sudden drop in the detector's reading (currentDR) but it hasn't dropped to zero, a pop-up could appear stating "Potential Detaching of Detector X". Conversely, if the currentDR drops to zero alongside a detected drop, the pop-up should indicate "Potential Failure of Detector X". This targeted alert system would provide immediate, context-specific information, enhancing the user's ability to promptly identify and address potential issues with the detectors.

FUNCTIONALITIES

1. Name: Dynamic Threshold
   1.1. Goal: set a threshold which is updated dynamically (increase or drop) based on the measured Dose Rate (DR)
   1.2. Trigger Condition: $|\Delta DR| > 3 \times (DR \times \Delta T^{-1})^{1/2}$. ΔDR = DR_Current – DR_Previous (μSv/h). ΔT = 12.5 (minutes) for Gamma detectors, and 1 minute for Neutron detectors.
   1.3. Effect: threshold is updated to DR_Current if triggered.
   1.4. Comment: each detector needs its own dynamic threshold.
2. Name: Percentage change
   2.1. Goal: highlight the % change when the threshold is updated (which reflects a significate change in the DR)
   2.2. Trigger Condition: dynamic threshold update.
   2.3. Effect: the % change should be shown in a label.
   2.4. Comment: each detector needs its own label for % change.

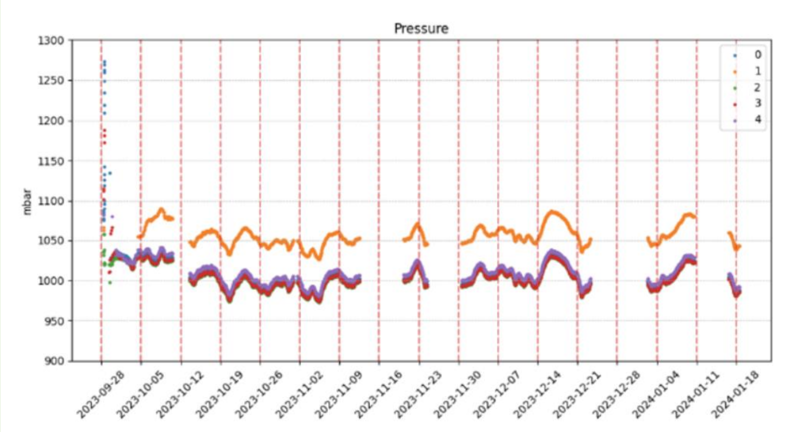
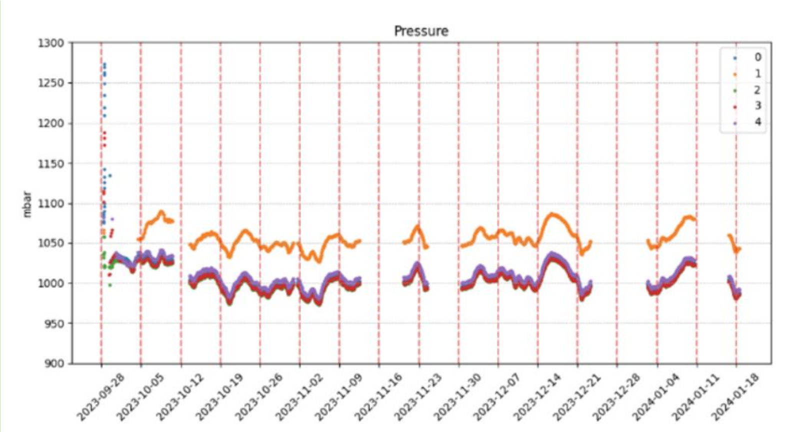
ALARMS

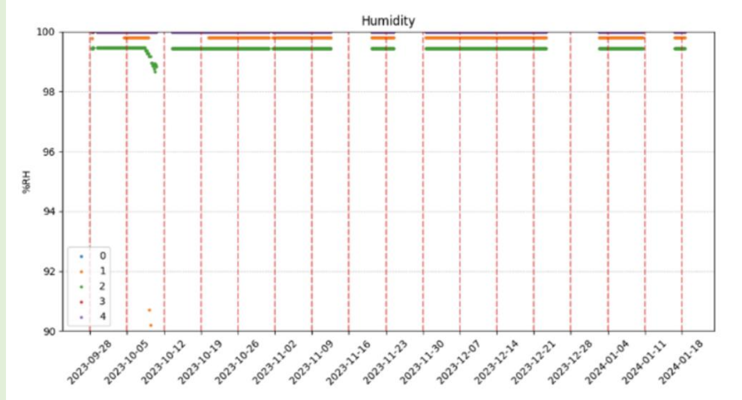
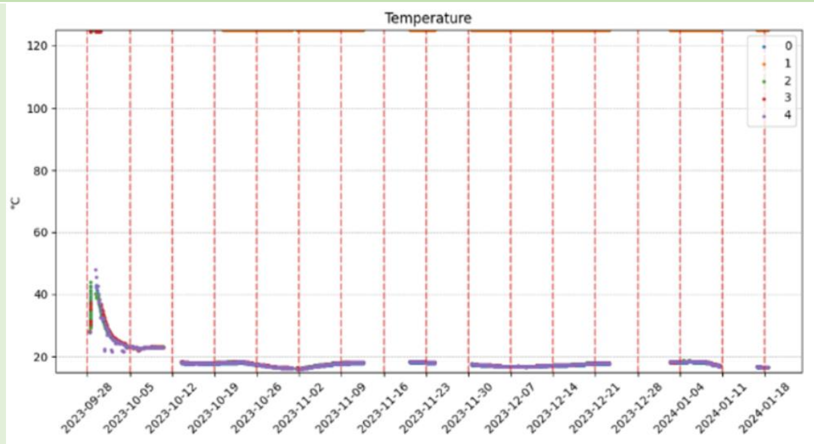
1. Name: Battery
   1.1. Trigger Condition: battery value < 20%
   1.2. Reset Condition: battery value >= 20% or when the user push a "stop button"
   1.3. Pop-up: "Battery Level is LOW" + button "STOP the alarm" + "Please change the battery"
   1.4. Comment: a single alarm is need for the whole LoRa node.
2. Name: Battery2
   2.1. Trigger Condition: battery value < 10%
   2.2. Reset Condition: battery value >= 10%
   2.3. Pop-up: "Battery Level is LOW" + "Please change the battery"
   2.4. Comment: a single alarm is need for the whole LoRa node. This one won't stop until the battery is charging (battery level >= 10%)
3. Name: Signal Increase
   3.1. Trigger Condition: dynamic threshold triggered with positive increase.
   3.2. Reset Condition: manual (or after a new value is received)
   3.3. Pop-up: "Significate Signal Increase ("+ ΔDR +") Signal on detector X" + "1) Validate the signal increase/decrease with DD contact measurement. 2) If value confirmed: check integrity of container or degradation through another adapted NDT"
   3.4. Comment: each detector needs its own alarm.
4. Name: Detector Detaching or Failing
   4.1. Trigger Condition: significate drop of the previous_DR by more than 50% (detach). If significate drop of the previous_DR by more than 50% and current_DR = 0, then detach or failure. If $|\Delta DR| > 3 \times (DR \times \Delta T^{-1})^{1/2}$ AND current_DR < 0.5 × previous_DR, then it triggers. If current_DR = 0, a modified pup-up appears.
   4.2. Reset Condition: manual.
   4.3. Pop-up: if detach "Possible Detector Detaching" and if current_DR = 0 "Possible Detector Detaching or Failing" + "Please check the instrumentation on the drum"
   4.4. Comment: each detector needs its own alarm.
5. Name: front end failing
   5.1. Trigger Condition: all detector failing alarms have been triggered.
   5.2. Reset Condition: manual.
   5.3. Pop-up: "All detectors failed, possible front-end failing" + "Please check the instrumentation on the drum"
   5.4. Comment: one alarm for the whole LoRa node.
6. Name: no data after period from last transmission (problem of LoRa, Gateway Failure, No WiFi)
   6.1. Trigger Condition: 1:10 hours have passed from previous transmission.
   6.2. Reset Condition: new transmission is received or manual stop;
   6.3. Pop-up: "No data received after scheduled time, check WiFi, Gateway or LoRa"
   6.4. Comment: one alarm for the whole LoRa node.

Appendix E: Results of the demonstration test – demo form

RFID embedded technology (BAM / VTT)

Technical Results

Parameter followed	Comment	Answer
Cemented matrix shrinkage? ***if your tech cannot measure this parameter, please cross it out***	Detected : Yes/no	No
	Where is the phenomenon detected? (in the bottom, in the lid, in the lateral surface, at what height from the bottom, x/y/z position…) please add a figure/sketch	/
	How much shrinkage? (%, mm or mm³, Pa)	/
	Accuracy of measurement (± %, mm or mm³, Pa)	1 kPa
	Is calibration of the detector required before each scan? If yes, please describe how	No
	Is calibration of the detector required before each scan?	/
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	1/hour for each SensorNode
	Please provide a graph showing the variation over the duration of the PREDIS demo test	
	Additional Information and comments	The pressure values are in the range of the atmospheric pressure variations.*
Cemented matrix swelling? ***if your tech cannot measure this parameter, please cross it out***	Detected : Yes/no	No
	Where is the phenomenon detected? (in the bottom of the mock-up, in the lid, in the lateral surface, at what height from the bottom, x/y/z position…)	/
	How was swelling detected (e.g. measured change in waste package circumference or change in pressure)?	/
	How much? (%, mm or mm³, Pa)	/
	Accuracy of measurement (± mm or mm³, Pa)	1 kPa
	Is calibration of the detector required before each scan? If yes, please describe how	/
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	1/hour for each SensorNode
	Please provide a graph showing the variation over the duration of the trial	
	Additional Information and comments	The pressure values are in the range of the atmospheric pressure variations.*

Relative humidity in the cemented matrix? ***if your tech cannot measure this parameter, please cross it out***	Detected: Yes/no	Yes
	Value detected (% RH)	100%
	Location of the measurement	Figure below: S0 at 1.5cm, S1, S3, S4 at 37cm, S2 at 67cm 
	Accuracy of measurement (± % RH)	2%
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	1/hour for each SensorNode
	Please provide a graph showing the variation over the duration of the trial (%RH/h)	
	Has the measurement been validated through another detector or in a controlled environment?	No
	Is calibration of the detector required before each scan? If yes please precise how	Yes, in climatic chamber at different reference humidity values.
	Additional Information and comments	Expected value below 80%.
Temperature? ***if your tech cannot measure this parameter, please cross it out***	Detected: Yes/no	Yes
	Value detected (°C)	Around 18°C average
	Location of the measurement	Figure above: S0 at 1.5cm, S1, S3, S4 at 37cm, S2 at 67cm
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	1/hour for each SensorNode
	Accuracy of measurement (± °C)	0.5°C
	Is calibration of the detector required before each scan? If yes please precise how	Yes, in climatic chamber at different reference temperature values.
	Please provide a graph showing the variation over the duration of the trial	
	Additional Information and comments	

* There are two fixed values of negative pressures (different during day and night) in the UJV building due to air ventilation system.

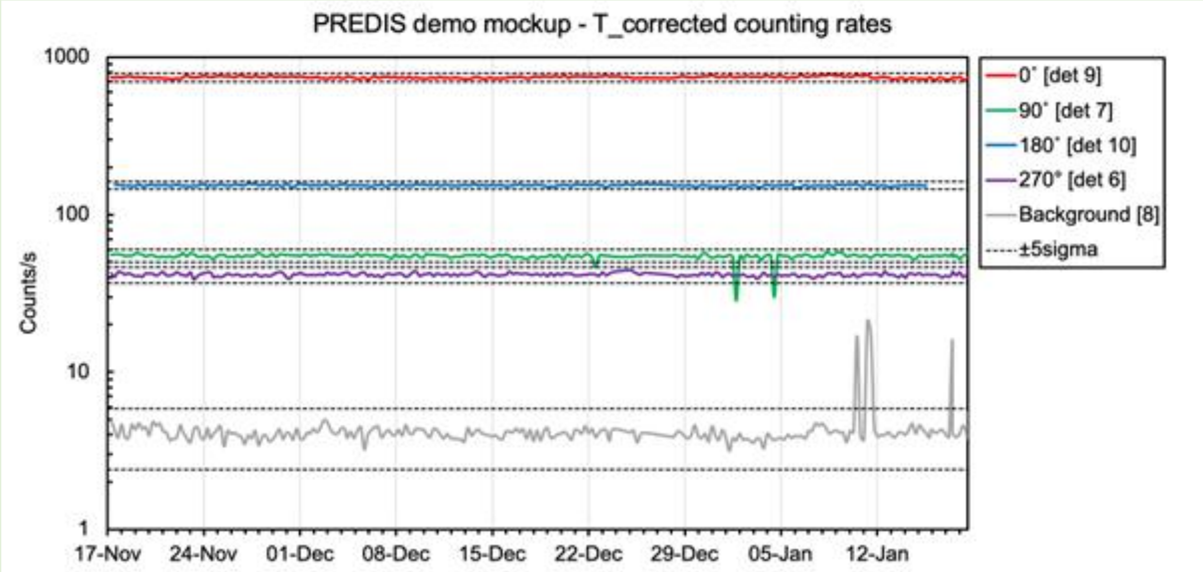
Lesson learned

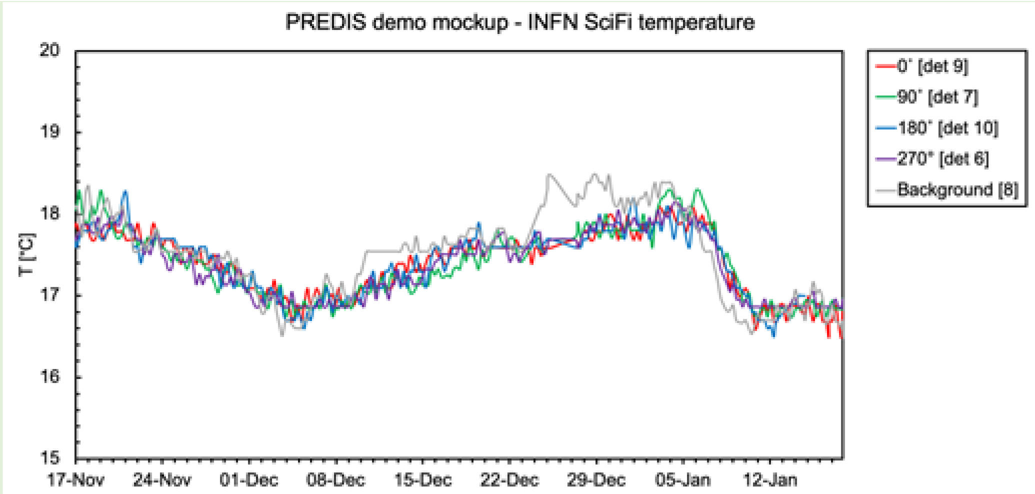
Questions	Answer
What knowledge/validation on the technology did we hope to gain from the demonstration test and was this achieved?	Reliability of data transfer through the drum (achieved) and consistency of the measurements (achieved in part).
What was learned regarding the technology during the demonstration test?	Embedded monitoring and through-metal communication is feasible. Further developments focused on the overall robustness of the system are required to deploy safely the system in harsh environments. That means upgrades both on the Hardware side (fastenings of the Transponder/Reader Units and communication between sensors) and on software developments in error management and detection.
How could we improve the demonstration for the next steps (increase the TRL)?	Software upgrades, improve communication reliability between sensors and Transmitter Unit
Can results from the technology be validated against known environmental parameters (e.g. temperature and humidity) or other measurement devices?	No environmental measurements have been recorded by external devices
Can the results given by the technology be influenced by external parameters? (ex: environmental conditions, T, HR, noise, dose rate,…)	No
Is the calibration sufficient to get rid of these external impacts? If yes for how long? Is it compatible with long term measurement?	Calibrations not required to mitigate external impacts, only to improve accuracy
What went well during the demonstration test?	Communication through the lid remained stable, sensors still work, data have been stored, problems clarified and fixed
Can the process be automated?	The measurement process is already automatized
Were there any technical issues encountered during the demo test (e.g. non exhaustive: malfunction of some parts of the system (detectors, electronic boards) in the mock-up area or in the data equipment area (Router, PC), failing of uploading data to azure platform, wifi failure, power supply/battery failure, loss of data?)	- Missing sensors data with fresh concrete - Unexpected reboot of the system - 3 Missing uploads - Data from SensorNode1 are not reliable - Humidity is stuck to 100%
Did they result in an interruption of the test?	Yes
Please describe the problem(s)	- Communication with sensors was unreliable with fresh concrete because of the moisture absorbed by the cable, which increased the cable capacitance and slowed down the time response of the pulses, so the DAQ couldn't decode the signal correctly. It could be solved by choosing a cable with less moisture absorbance and low capacitance. - Unexpected reboot reset to default the network configurations and so the upload on Azure failed - 3 software errors caused the interruption of the data upload on Azure - SensorNode1 may be damaged since it is measuring max temperature and pressure is not compliant with the other sensors. No plans to investigate it at moment. - Humidity stuck to 100% may be clarified by further monitoring
How long did the problem(s) last?	about 4 days, depending on when the error was detected
How were they mitigated?	Fixed restarting the software dedicated to the data storage
How long did it take to mitigate?	Once detected, 1 minute
How were the results affected?	Missing data
Additional Information and comments	Measurement data can be considered consistent and qualitative since the sensors have been calibrated and the manufacture ensures long term stability in measurements. A plausibility check (max difference between two consecutive measurements) determines if the measurement is reliable. For example, SensorNode 1 is not considered reliable since it detected a step to 125°C in one time interval.

SciFi & SiLiF (INFN)

Technical Results

Parameter followed	Comment	Answer
Cracks in metallic canister?	Detected: Yes/no	probably
	Minimum size detectable by the technology (mm) (info from your qualification test on lab-scale or bigger scale)	
	Minimum size detected during the PREDIS demonstration test (mm)	the test was not finalized at detecting cracks
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	4 measurements/day
	Accuracy of measurement (± mm)	
	Is calibration of the detector required before each scan? If yes please describe	only once at the very beginning
	Can you estimate the evolution of cracks from when the cracks are first detected during the trial, if yes please indicate it (mm/s)	probably
	What is the maximum area of coverage for the detector (% of metallic surface area)	4 detectors 80cm tall around the drum at 90° from each other; coverage was ≈100% with peaks and valleys in efficiency
	What is the maximum thickness of material the technique can measure cracks through?	it depends on the drum radioactivity content
	In what material can the cracks be detected ? metals (aluminium/steel (ferritic/austenitic)? ceramic/etc.?	in principle any material
	Are there any geometric restrictions to the technique when deployed (e.g. corner/ welds / fixtures)?	no
	Are they any waste or container characteristics that may impede crack detection?	don't know
	Additional Information and comments	
Cracks in the cemented matrix?	Yes/no	probably
	Minimum size detected during the demonstration test (mm)	-
	Minimum size detectable by the technology (mm)	At least 1mm
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	4 measurements/day
	Accuracy of measurement (± mm)	10mm
	Is calibration of the detector required before each scan? If yes, please describe how	threshold setting only once at the very beginning
	Evolution of cracks from when the cracks are first detected during the trial (mm/s)	don't know
	What is the maximum area of coverage for the detector (% of outer surface area)	4 detectors 80cm tall around the drum at 90° from each other; coverage was ≈100% with peaks and valleys in efficiency
	What is the maximum thickness of matrix material the technique can measure cracks through?	it depends on the drum radioactivity content; order of magnitude ≈10cm
	What is the maximum thickness of container metallic material the technique can measure cracks through?	it depends on the drum radioactivity content; order of magnitude ≈1-2cm
	Are there any geometric restrictions to the technique when deployed (e.g. corner/ welds / fixtures)?	no
	Are they any waste or container characteristics that may impede crack detection?	don't know
	Additional Information and comments	
Dose rate?	Yes/no	yes
	Value detected (Gy/h, µSv/h, Bq/s)	cps, µSv/h
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	4 measurements/day
	Accuracy of measurement (±Gy/h, µSv/h, Bq/s)	≈2%
	Is calibration of the detector required before each scan? If yes, please describe how	threshold setting only once at the very beginning
	Was the measured dose rate consistent with the expected actual dose rate?	yes

	How was the measurement validated? Modelisation?	FLUKA simulation
	What is the measured location of detector from source (mm)?	10mm from the drum
	Dose detected from a single container or from a batch of containers? (note that only one mock-up with source at UJV)	32.0, 2.4, 6.6, 1.8 µSv/h in four positions on the drum; 0.2 µSv/h background (4m away)
	Please provide a graph showing the variation over the duration of the trial	
	Additional Information and comments	
Contamination?	Detected: Yes/no	no
	What was the amount detected? (Bq/s, Gy/h, µSv/h)	0.2 µSv/h (background)
	Location of the measurement	 background measured 4m away to the right
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	4 measurements/day
	Is calibration of the detector required before each scan? If yes please precise how	threshold setting only once at the very beginning
	Additional Information and comments	
Temperature?	Detected: Yes/no	Yes*
	Value detected (°C)	16-18 °C
	Location of the measurement	4 points on the drum at 90° from each other, and one at 4m away
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	4 measurements/day
	Accuracy of measurement (± °C)	0.5 C°
	Is calibration of the detector required before each scan? If yes please describe how	only at the very beginning, against a thermometer

	Please provide a graph showing the variation over the duration of the trial	
	Additional Information and comments	
Internal structure and changes? (i.e., displacement, etc.)	Yes/no	Yes
	Please describe the changes detected and the methodology.	We measured the asymmetries inherent to the drum (different dose rates in the 4 sensors positions)
	Is calibration of the detector required before each scan? If yes please describe how	threshold setting only once at the very beginning
	Additional Information and comments	

* *The temperature measurement is not performed inside the drum but at the package outer side or in the room*

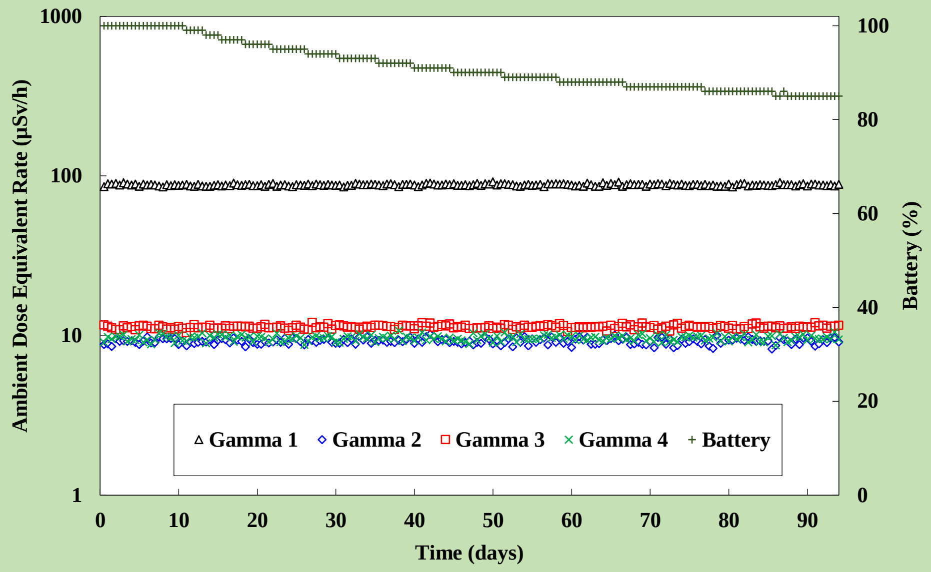
Lesson learned

Questions	Answer
What knowledge/validation on the technology did we hope to gain from the demonstration test and was this achieved?	Successful operation during 3 months Successfully detected the different dose rates out of the internally asymmetric cemented mockup Validation of the measurements by an additional background sensor
What was learned regarding the technology during the demonstration test?	Slight improvements to the electronics will be beneficial
How could we improve the demonstration for the next steps (increase the TRL) ?	Using two mock-ups with more specific (better tuned) geometrical features
Can results from the technology be validated against known environmental paraments (e.g. temperature and humidity) or other measurement devices?	This was partially done (w.r.t. temperature) Can be done w.r.t. other devices
Can the results given by the technology be influenced by external parameters? (ex: environmental conditions, T, HR, noise, dose rate,…)	Possibly, by extreme conditions
Is the calibration sufficient to get rid of these external impacts? If yes for how long? Is it compatible with long term measurement?	Variations of a few degrees over the three months demo have been successfully taken care by a compensation algorithm
What went well during the demonstration test?	Everything went smoothly
Can the process be automated?	It was automated
Were there any technical issues encountered during the demo test (e.g. non exhaustive: malfunction of some parts of the system (detectors, electronic boards) in the mock-up area or in the data equipment area (Router, PC), failing of uploading data to azur platform, wifi failure, power supply/battery failure, loss of data?)	Yes
Did they result in an interruption of the test?	no
Please describe the problem(s)	one electronic board stalled at the very end of the test
How long did the problem(s) last?	a couple of days
How were they mitigated?	redundancy: there were four sensors installed
How long did it take to mitigate?	zero, because of the redundancy
How were the results affected?	we lost a few days of data from one position around the drum
Additional Information and comments	

Sensorized RF identification box (UniPi)

Technical Results

Parameter followed	Comment	Answer
Cracks in the cemented matrix?	Detected: Yes/no	Yes, but only if the cracks can generate a sensible degradation of the attenuation of the concrete matrix.
	Minimum size detected during the demonstration test (mm)	25 mm × 300 mm (W x L)
	Minimum size detectable by the technology (mm)	Hard to assess. During the demo, the slot acted as a very large, simulated crack. in real-world scenarios, cracks would likely be subtler in both size and spread. The coverage of the detectors active area is limited, but if the loss of containment is gradual and extended to the whole package, we can expect to measure a reduced attenuation promptly.
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	24 measurements per day. Each measurement includes 6 detectors (4 gammas and 2 neutrons). Gamma detectors operative 12.5 minutes per measurement, neutron detectors operative for 1 minute per measurement.
	Accuracy of measurement (± mm)	See answer to: Minimum size detectable by the technology (mm)
	Is calibration of the detector required before each scan? If yes, please describe how	no
	Evolution of cracks from when the cracks are first detected during the trial (mm/s)	See answer to: Minimum size detectable by the technology (mm)
	What is the maximum area of coverage for the detector (% of outer surface area)	1-2% (fixed detectors), but detectors can be moved to increase the %
	What is the maximum thickness of matrix material the technique can measure cracks through?	Hard to assess, depends on material, activity of the sources, crack size
	What is the maximum thickness of container metallic material the technique can measure cracks through?	Hard to assess, depends on material, activity of the sources, crack size
	Are there any geometric restrictions to the technique when deployed (e.g. corner/ welds / fixtures)?	At least 1 cm is needed outside the surface of the drum for detectors placement
	Are they any waste or container characteristics that may impede crack detection?	Container with only low energy gamma ray sources and no neutrons
	Additional Information and comments	
Dose rate?	Yes/no	Yes
	Value detected (Gy/h, µSv/h, Bq/s)	Ambient dose equivalent rate in µSv/h
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	24 measurements per day. Each measurement includes 6 detectors (4 gammas and 2 neutrons). Gamma detectors operative 12.5 minutes per measurement, neutron detectors operative for 1 minute per measurement.
	Accuracy of measurement (±Gy/h, µSv/h, Bq/s)	In terms of accuracy (deviation of the measured value from the real value), the dose rate values measured by the gamma detectors were within 10-20 % of the simulated ones. Keep in mind the geometry of the setup was not as expected (source off-center), which caused an extra error in the simulated values. In terms of precision (error), the standard deviation (assuming a Poisson distribution of the counts) is $STD_{DR} \approx (DR / (\Delta T * K))^{1/2}$, where DR is the actual dose rate, ΔT is the integration window for the detectors, K is the calibration factor. Example, with a DR of 88 µSv/h, the error is 1.2 µSv/h
	Is calibration of the detector required before each scan? If yes, please describe how	No
	Was the measured dose rate consistent with the expected actual dose rate?	yes
	How was the measurement validated? Modelisation?	Montecarlo modelling and handheld detectors from UJV.
	What is the measured location of detector from source (mm)?	250-300 mm
	Dose detected from a single container or from a batch of containers? (note that only one mock-up with source at UJV)	single

	Please provide a graph showing the variation over the duration of the trial	 *Data collected for more than 90 days: the gamma detector placed in front of the slot can easily identify an increased dose rate compared to the other 3*
	Additional Information and comments	

Lesson learned

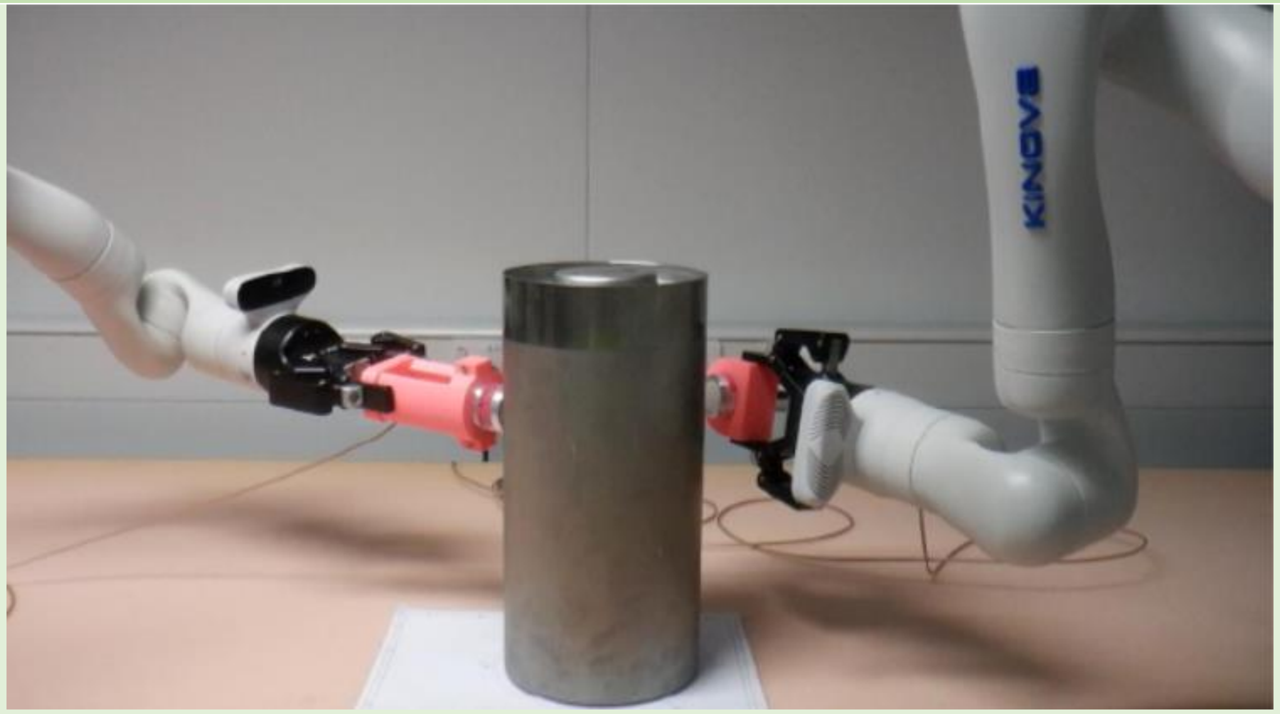
Questions	Comment	Answer
What knowledge/validation on the technology did we hope to gain from the demonstration test and was this achieved?	Radiation detectors accuracy, wireless data transmission in no-internet zones, battery durability, and ability to detect structural degradation through increased radiation fluency, with an emphasis on statistical analysis for long-term integrity assessment.	Yes, the validation of the technology was achieved. Gamma radiation detectors accurately reflected dose rates obtained from simulations and compared to handheld detectors from UJV. LoRa data transmission between the package in the storage room and the DEA remained strong (RSSI > 190 dBm). Battery charge decrease by 15% over 3 months, but it can be reduced easily by a factor 10 by limiting the frequency of measurements (for example going from 24 measurements per day to just 1 or 2). The detector placed on the slot/crack registered a dose rate almost 10 times higher than the other detectors, identifying its presence. No degradation over time was observed for the other detectors due to the limited duration of the test, however alarms were implemented to assess any significant increase over time.
What was learned regarding the technology during the demonstration test?	Reliability in performing scheduled operations, strong communication capabilities, easy installation, insensitivity to noise and environmental changes.	The technology did not fail once during the 3 months' demo test, and all measurements were collected and forwarded to Azure and IFE dashboard. No repeaters were needed between the storage and the DEA. No unexpected events were observed (detectors failing, noise pick-up). The installation was straightforward, requiring just a couple hours, and sensitivity to environmental parameters was not observed (for example fluctuation of the signal due to temperature changes).
How could we improve the demonstration for the next steps (increase the TRL) ?	Use of several systems on different packages of a real storage site. Modelling the relationship between the increase of dose rates and loss of containment of the packages.	It would be interesting to install many systems on several different packages in a real storage site to assess the performance of the network (several units, not only one) within an area with strong structural attenuation (for the radio signals through concrete). Assess the needs of repeaters. Moreover, testing the system with different sources, and in conditions that allow to test the loss of containment of the package would further validate the technique.
Can results from the technology be validated against known environmental paraments (e.g. temperature and humidity) or other measurement devices?	Other calibrated radiation detectors, and/or different NDTs.	Yes, these results can be validated against reference calibrated radiation detectors to assess the goodness of the measurements. Moreover, it would be interesting to use different NDTs to investigate the relationship between radiation and other measurements (example: internal pressure changes).
Can the results given by the technology be influenced by external parameters? (ex: environmental conditions, T, HR, noise, dose rate,…)	/	No sensitivity to noise, EMI, environmental changes was observed. However, the installation of the system on a package within a facility filled with drum will change the background radiation levels. For example, if a package with a large activity is moved closer to the drum under investigation, this must be taken into account since it will generate a higher dose rate value recorded by the detectors.
Is the calibration sufficient to get rid of these external impacts? If yes for how long? Is it compatible with long term measurement?	/	Calibration is enough in a static configuration (no packages with very large activities are moved around). If packages are shuffled, a few measurements must be taken to recalibrate the system. Thanks to the large battery life, it is compatible with long-term measurements.
What went well during the demonstration test?	/	

Can the process be automated?	Yes	The process is already completely automated. After installation, which is straightforward, a first sample measurement is performed to calibrate the system (for example to determine the baseline radiation levels), then the operators do not need to interact with the package anymore. Everything is scheduled with a real time clock installed on the LoRa node, and data are transmitted wirelessly to gateways which can be positioned outside the storage site. Data from gateways is downloaded locally if not internet is available, of automatically forwarded to Azure IoT central (and potentially to other dashboards).
Were there any technical issues encountered during the demo test (*e.g. non exhaustive: malfunction of some parts of the system (detectors, electronic boards) in the mock-up area or in the data equipment area (Router, PC), failing of uploading data to azur platform, wifi failure, power supply/battery failure, loss of data?)*	No	
Did they result in an interruption of the test?	No	
Please describe the problem(s)	/	
How long did the problem(s) last?	/	
How were they mitigated?	/	
How long did it take to mitigate?	/	
How were the results affected?	/	
Additional Information and comments		

Air-coupled ultrasonic inspection (NNL)

Technical Results

Parameter followed	Comment	Answer
Cracks in metallic canister?	Detected: Yes/no	Yes
	Minimum size detectable by the technology (mm) (info from your qualification test on lab-scale or bigger scale)	Cracks under 50mm long with thickness less than 0.5mm can be detected. More research is required to establish the minimum crack size that can be detected by the technology
	Minimum size detected during the PREDIS demonstration test (mm)	2mm
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	1 measurement per 3 minutes (approximation) i.e., 20 measurements per hour. This technology can be developed further to provide a higher reading count per hour
	Accuracy of measurement (± mm)	2mm
	Is calibration of the detector required before each scan? If yes please describe	General calibration required No per-scan calibration needed
	Can you estimate the evolution of cracks from when the cracks are first detected during the trial, if yes please indicate it (mm/s)	No
	What is the maximum area of coverage for the detector (% of metallic surface area)	100%. Future work may elaborate to include the bottom surface on which the drum is resting
	What is the maximum thickness of material the technique can measure cracks through?	Approximately 6mm using the available sensors, the true maximum thickness possible with the technology is to be confirmed
	In what material can the cracks be detected ? metals (aluminium/steel (ferritic/austenitic)? ceramic/etc.?	Non-brittle or porous metals (e.g., steel, stainless steel, aluminium, copper, non- porous alloys)
	Are there any geometric restrictions to the technique when deployed (e.g. corner/ welds / fixtures)?	Sharp corners can reflect the ultrasonic waves and complicate the readings, consequently cylindrical surfaces are easier to scan
	Are they any waste or container characteristics that may impede crack detection?	Yes, Increase in internal pressure due to cement containment expansion can push against the drum shell and dampen the waves propagation which can inhibit their detection
	Additional Information and comments	None
Corrosion of the metallic canister ?	Detected: Yes/No	Yes
	Loss of thickness (µm)	To be confirmed using further experiment where samples with varying thickness and/or induced controlled corrosion to be used to simulate real life corrosion/erosion.
	Accuracy of measurement (± µm, µm/h)	0.5mm
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	N/A

	Please provide a graph showing the variation over the duration of the trial	N/A
	Type of corrosion phenomena detected (uniform corrosion, crevice corrosion, pitting …)	Uniform corrosion and pitting
	Is calibration of the detector required before each scan? If yes please describe	General calibration required. No per-scan calibration needed
	What is the maximum thickness of material (metallic container)? (during Predis demonstration test and/or during qualification tests)	5mm estimated
	Does a trained operator need to perform and interpret the test results?	Yes
	Does the automated approach enable a better detector positioning than a trained operator?	Yes
	Additional Information and comments	N/A
Cemented matrix shrinkage?	Detected : Yes/no	To be confirmed
	Where is the phenomenon detected? (in the bottom, in the lid, in the lateral surface, at what height from the bottom, x/y/z position…) please add a figure/sketch	On the side walls of the drums (packages)
	How much shrinkage? (%, mm or mm³, Pa)	The results can indicate contact or no contact between the cement and the drum's shell
	Accuracy of measurement (± %, mm or mm³, Pa)	N/A
	Is calibration of the detector required before each scan? If yes, please describe how	No
	Is calibration of the detector required before each scan?	No
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	3 per minute estimated, with room for improvement
	Please provide a graph showing the variation over the duration of the PREDIS demo test	 *A pair of 7-axis Kinova robot arms deploying of air-coupled ultrasonic transducer to induce and detect an ultrasonic Lamb wave along circumference of an empty nuclear SNM package*
	Additional Information and comments	Non
Cemented matrix swelling?	Detected : Yes/no	Yes
	Where is the phenomenon detected? (in the bottom of the mock-up, in the lid, in the lateral surface, at what height from the bottom, x/y/z position…)	The side walls of the 500L ILW drum
	How was swelling detected (e.g. measured change in waste package circumference or change in pressure)?	Both circumference change and pressure buildup
	How much? (%, mm or mm³, Pa)	Can measure up to 1.3bar above atmospheric pressure
	Accuracy of measurement (± mm or mm³, Pa)	To be confirmed
	Is calibration of the detector required before each scan? If yes, please describe how	General calibration required No per-scan calibration needed
	What was the number of parameterized measurement in time? (x measurements per hour or day or …)	Approx. per 3 per minutes with room for improvement
	Please provide a graph showing the variation over the duration of the trial	To be confirmed
	Additional Information and comments	N/A

Lesson learned

Questions	Answer
What knowledge/validation on the technology did we hope to gain from the demonstration test and was this achieved?	The validation test aimed to prove the robotic arms ability align the air-coupled transducers accurately to create a detectable Lamb wave.
What was learned regarding the technology during the demonstration test?	Further development is required to adjust the transducers remotely with an automated test rig that can align the transducer to the correct angle with the package surface
How could we improve the demonstration for the next steps (increase the TRL) ?	Develop a test rig with closed loop feedback that aligns the transducers to the optimum orientation of the package which would provide a high-quality signal
Can results from the technology be validated against known environmental paraments (e.g. temperature and humidity) or other measurement devices?	Potentially this can be proven using atmospheric control rooms.
Can the results given by the technology be influenced by external parameters? (ex: environmental conditions, T, HR, noise, dose rate,…)	Yes, the technology is sensitive to airflow from vents, and Electro-Magnetic Interference (EMI).
Is the calibration sufficient to get rid of these external impacts? **If yes for how long?** **Is it compatible with long term measurement?**	Yes, provided enough time is given to filter the signal and remove the background noise created by the wind/EMI
What went well during the demonstration test?	The transducers output was powerful enough to induce the lamb waves despite minor misalignments in the Lamb waves induction and detection angles. The transducers' resonance frequency response peak curve was shallower than expected which allowed NNL to experiment with frequency sweeping for nominal thickness measurement
Can the process be automated?	Yes. A robotic arm can be used to deploy the sensors to automate the scanning process and a dedicated alignment tool can align the sensor to the different drums' shells.
Were there any technical issues encountered during the demo test (*e.g. non exhaustive: malfunction of some parts of the system (detectors, electronic boards) in the mock-up area or in the data equipment area (Router, PC), failing of uploading data to azur platform, wifi failure, power supply/battery failure, loss of data?)*	Yes. The standard time sample of the ultrasonic acquisition equipment is limited to 2ms. This is adequate for the small 150mm diameter SNM (Special Nuclear Material) packages but not sufficient for the 800mm diameter 500L ILW (Intermediate Level Waste) drums.
Did they result in an interruption of the test?	Yes
Please describe the problem(s)	A longer acquisition sample is required for the larger 500L drums due to the relative long waiting time requirement for the ultrasonic wave to travel around the drum circumference multiple times
How long did the problem(s) last?	4-6 weeks.
How were they mitigated?	Updated the acquisition software to increase the sample time span to accommodate our experiment. This update also included increase of the maximum averaging value, which helps remove background noise from the signal
How long did it take to mitigate?	4-6 weeks
How were the results affected?	The test was only performed on the small SNM packages and currently awaiting to be repeated on the larger ILW package
Additional Information and comments	N/A

Appendix F: Specification describing the dashboard's content

Introduction

The dashboard developed by task 5.3 (Decision framework) of WP7 of PREDIS has been presented at PREDIS May 2023. workshop in Mechelen in It is a part of the decision platform developed by task 5.

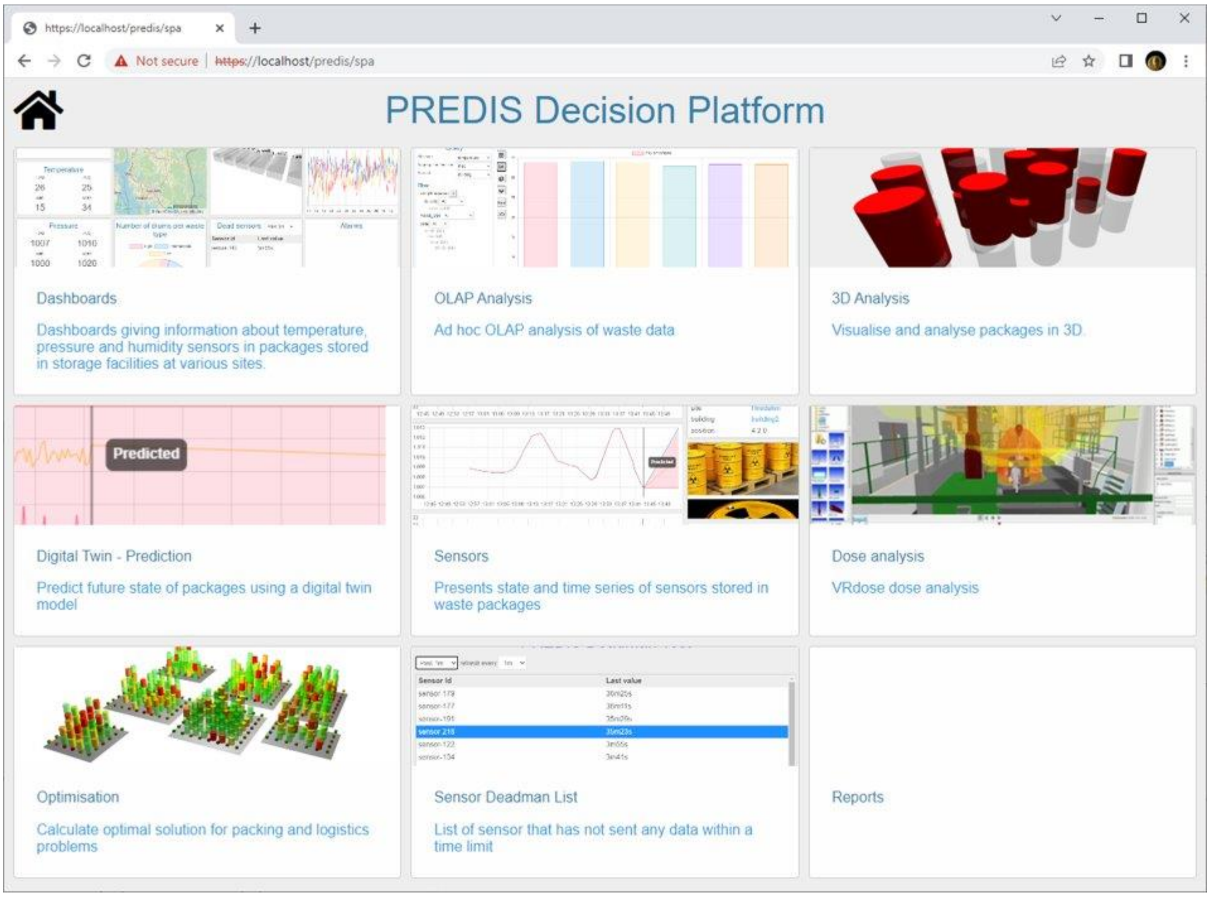


Figure 1: Global display of decision platform developed by Predis task 7.5.3 [Mechelen Predis Whole consortium workshop May 2023, Tom-Robert Bryntesen & Reka Szoke].

The aim of the WP7 PREDIS demonstration dashboard is to link the demonstration test to task 5 by displaying the demonstration in task 5.3 framework. Thus, the content of the dashboard for the demonstration test is based on the work developed by Tom-Robert Robert Bryntesen & Reka Szoke (task 5 of WP7) and presented at Mechelen in May 2023. Because the demonstration test at UJV is only one site / storage unit and does not include data from model prediction and digital twin, only four displays (named worksheets) are considered:

- A home worksheet with links to the others worksheet named “home worksheet” in the following paragraphs,
- A presentation worksheet with general presentation of the demonstration test configuration named “demo presentation worksheet” in the following paragraphs,
- A worksheet dedicated to technology results on mock-up 1.2, named “Technology results worksheet mock-up 1.2” in the following paragraphs,
- A worksheet dedicated to technology results on mock-up 2 Sensorized RF identification Box from UniPi, named “Technology results worksheet mock-up 1.2 – Sensorized RF Identification box” in the following paragraphs.
- A worksheet dedicated to technology results on mock-up 2 SciFi/SiLiF from INFN, named “Technology results worksheet mock-up 1.2 – SciFi / SiLiF” in the following paragraphs.

The content of the dashboard has been discussed between technology developers of RFID embedded sensors (BAM /VTT), SciFi/SiLiF (INFN), Sensorized RF identification box (UniPi) and developers of task 7.5.

Home worksheet

The content of the presentation worksheet is based on the work developed by Tom-Robert Bryntesen and Reka Szoke presented at Mechelen (sheet Kjeller – building1).

The home worksheet is the worksheet that is logged when the dashboard is loaded, it contains links to the other worksheets.

Only these three worksheets are active. The other features are not developed they can either not be shown or remain idled and greyish if it is possible (as displayed in Figure for the digital twin).

In the top left side, the PREDIS logo is featured and also on the bottom the logos of the company working on the demonstration test dashboard (BAM, VTT, UniPi, INFN, Orano, UJV and IFE).

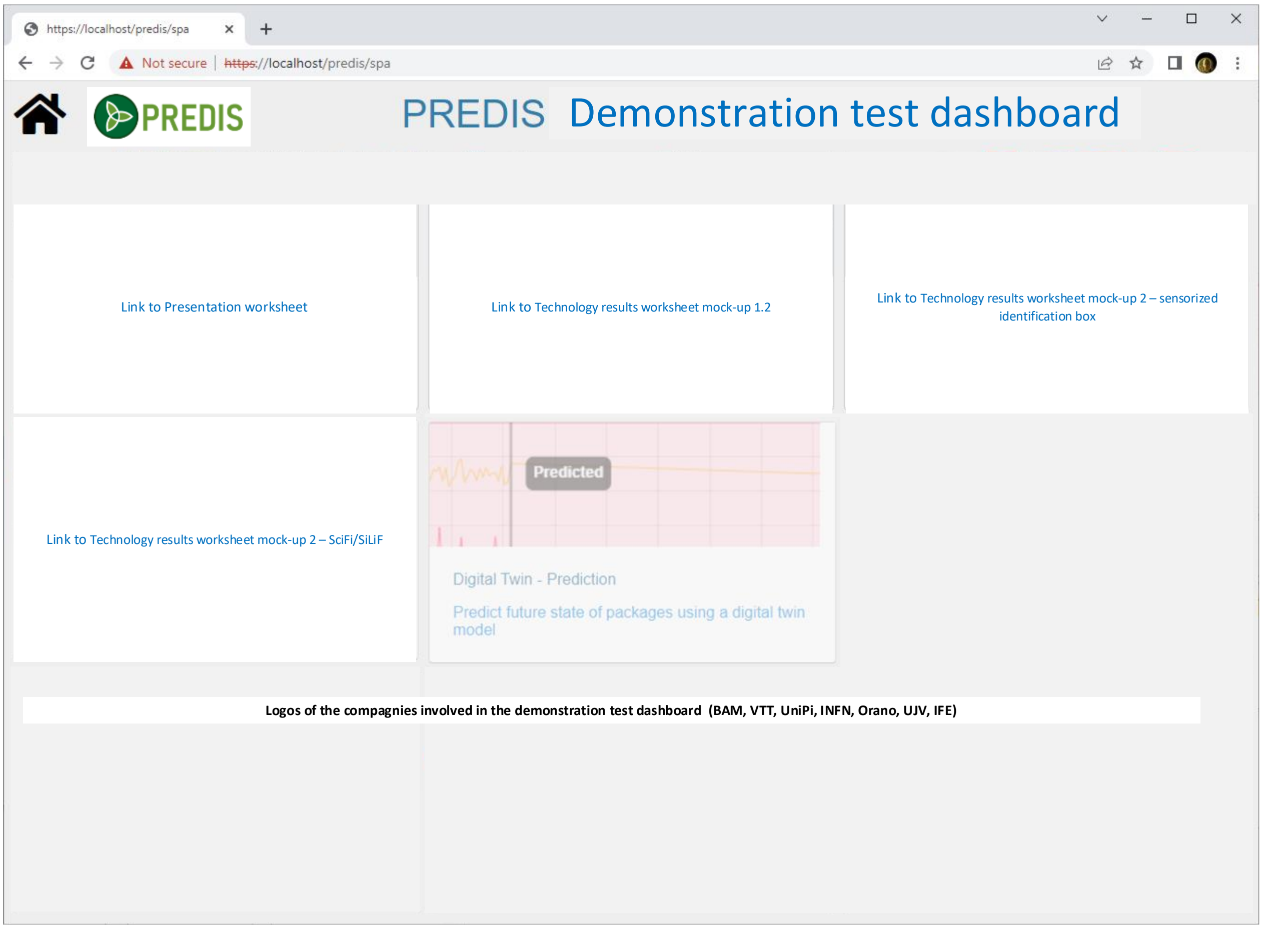


Figure 2: Proposition of layout of the "Home worksheet.

Demo Presentation worksheet

The content of the presentation worksheet is based on the work developed by Tom-Robert Bryntesen and Reka Szoke presented at Mechelen (sheet Kjeller – building1).

The presentation worksheet is accessible through the home worksheet.

It contains information of the demonstration test configuration as if it were an interim storage facility. Because the demonstrations test at UJV contains only one unit many features will remain idled but will be shown to display final possibilities to enable end-users who will have access to this dashboard to see all the final possibilities.

It contains:

- A title “demonstration test at UJV storehouse 241”,
- A button featuring a “home” which redirects to the “home worksheet”
- A presentation of the storage configuration for the demonstration test, through a 3D sketch where the cemented drums are differentiated from the 2 mock-ups through a color code,
- A picture of the demonstration test (non 3D):
    - The picture will be provided by UJV after installation of the demonstration test,
- A picture of the data equipment area:
    - The picture will be provided by UJV after installation of the demonstration test area.
- An area dedicated to the storage unit parameters (“Storage room temperature”, “Storage room pressure”, and “Storage room humidity”) follow-up:
    - **These cells are just presented as an example of worksheet and no temperature, pressure and humidity will be logged from UJV. Thus, this area will remain idle / “greyish”**,
- Information on the sensor follow-up through information on dead sensors “Dead sensor warning”: a sensor is considered dead or malfunctioning if it does not upload data on Azure for a minimum period of time more than 1 day,
    - Table can contain three columns “sensor Id”, “Sensor description” and “duration since last value” (as shown in Figure), data for “sensor Id” and “Sensor description” are given in Appendix § 0 for each technology.
- A cell named “refresh every” which aim is to define the refresh frequency from the data of the dashboard coming from the azure platform.

Sensor Id	Sensor description	Duration since last value
Ex: RFID – 000&	Ex: Embedded RFID energy storage after measurement	Ex: 1d01h00m00s

Figure 3: Content of the table for dead sensors information to be completed in the appendix.

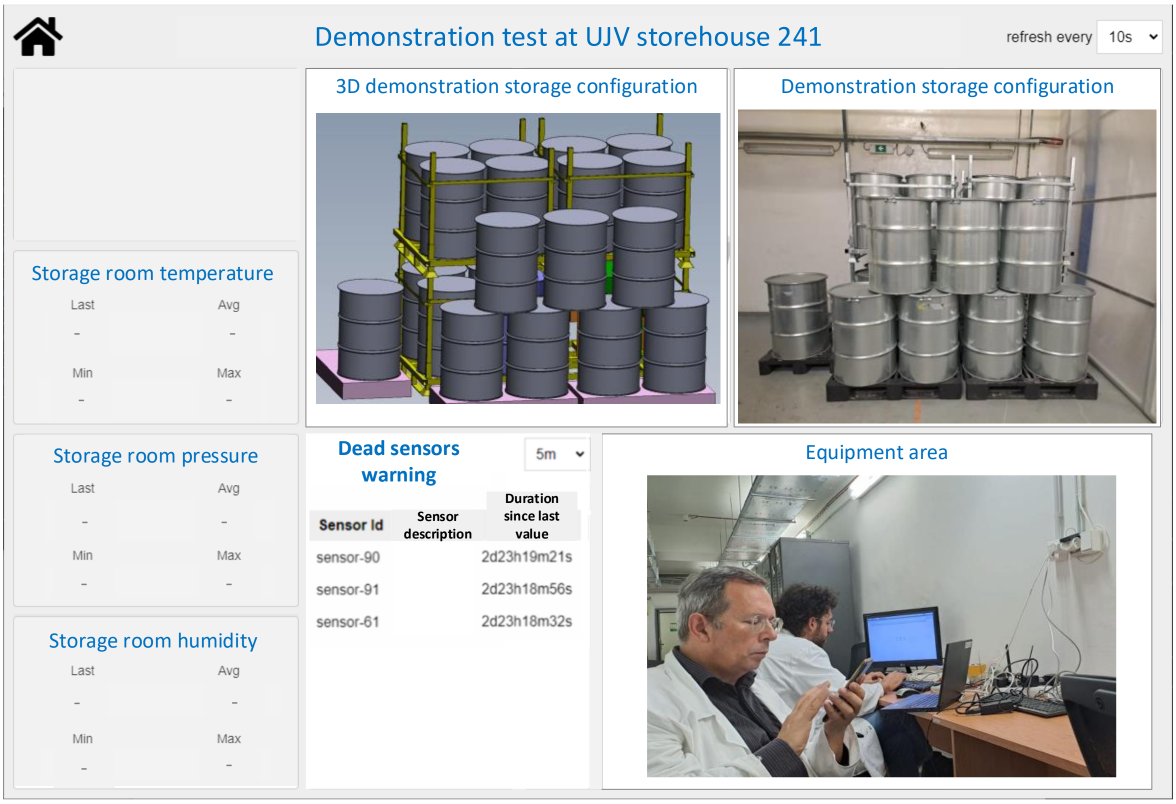


Figure4: Proposition of layout of the Presentation worksheet.

Technology results worksheet mock-up 1.2

The content of the “Technology results worksheet mock-up 1.2” is based on the work developed by Bryntesen and Reka Szoke presented at Mechelen (sheet All sensors).

This worksheet contains the data from the technologies put on mock-up 1.2.

Only one technology is installed on mock-up 1.2, the RFID embedded sensors from BAM / VTT.

Contact: Pasquato, Leone <leone.pasquato@bam.de>

The worksheet contains (see Figure):

a) A title “mock-up 1.2 (RFID embedded sensors)”
b) A button featuring a “home” which redirects to the “home worksheet”
c) The selection of technology: only one choice is possible: “RFID embedded sensors”,
d) The selection of the sensors: either “all sensors”, “RFID- SN-00”, “RFID-SN-01”, “RFID-SN-02”, “RFID-SN-03”, “RFID-SN-04”.
e) The duration of the results plotted from 1day to 6 months,
f) The model used for prediction: the models are not available yet, thus this cell remains “greyish” with no content and no selection possible,
g) The date of the last sensor data collection using format: Day-Month-year (in full text to avoid inversion between day and month, for example: 05 January 2024),
h) A cell named “refresh every” which aim is to define the refresh frequency from the data of the dashboard coming from the azure platform,
i) The results of “RFID embedded sensors” described below.

Results associated to the selection of the technology “RFID embedded sensors” (see Figure):

j) Two pictures (top and lateral views) to show where the SensorNodes are located in mock-up 1.2. The picture will be in format .png,

k) Three plots for the three parameters followed by the RFID unit: temperature, pressure and relative humidity,
    a. Parameter temperature: One plot with 1 to 5 curves: data from the selected sensor or from the 5 sensors for temperature (in °C),
    b. Parameter pressure: One plot with 1 to 5 curves: data from the selected sensor or from the 5 sensors for pressure (in mbar)
    c. Relative humidity: One plot with 1 to 5 curves: data from the selected sensor or from the 5 sensors for relative humidity (in %RH).

l) The last, minimal, maximal and average data of each for temperature, pressure and humidity displayed plot on the left side.

m) An indicator of the battery showing the last received value (in V), the reference value (4,5 V) and the description: "*The capacitor is charged at every measurement cycle to store the energy for the data acquisition routine. The voltage displayed on the dashboard correspond to the end of the measurement and should be around the reference value.*" (The description can be display through an "information" tooltip for example).

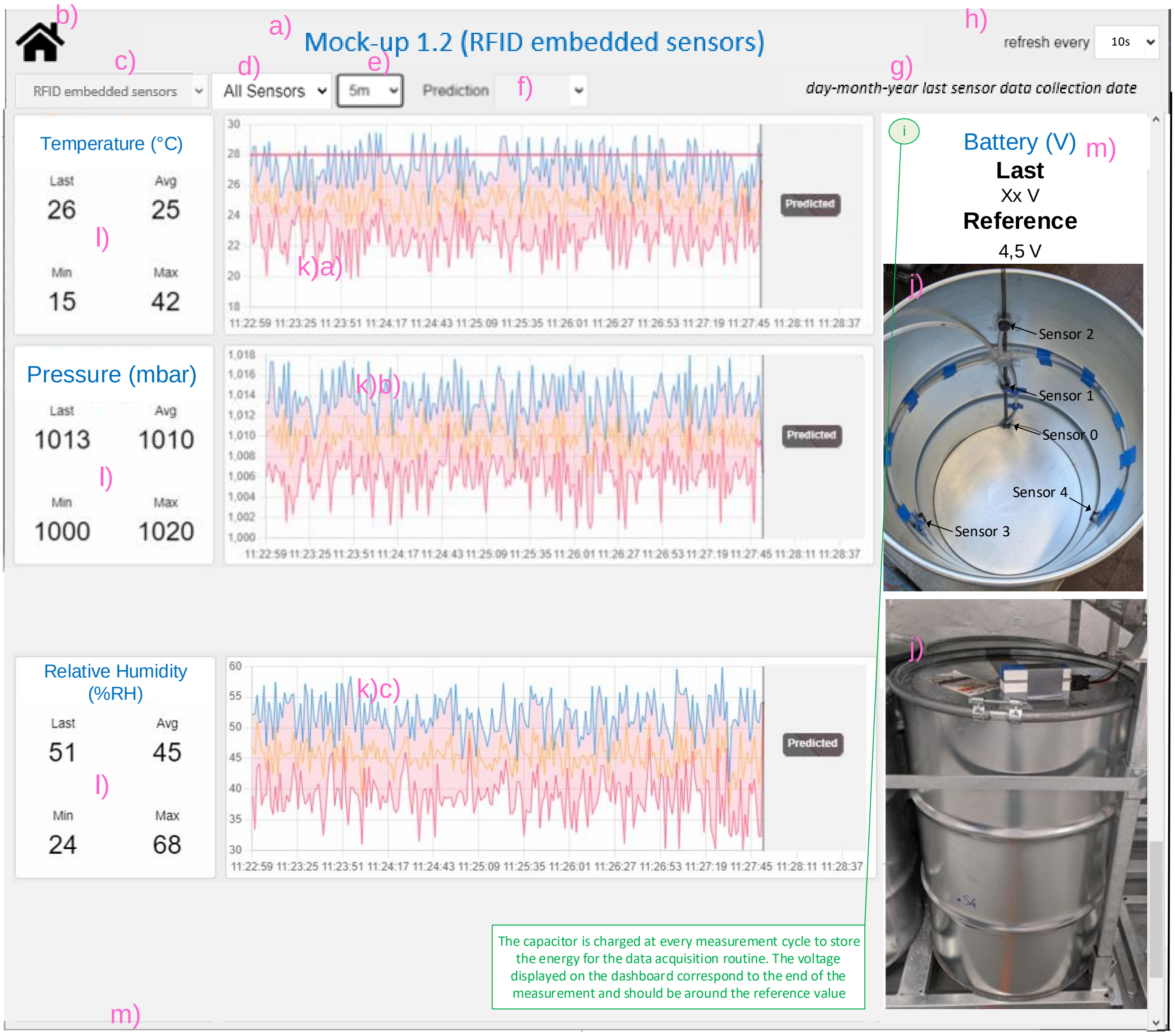


Figure 5: Proposed layout for the results from RFID embedded sensors on mock-up 1.2.

Technology results worksheet mock-up 2 – Sensorized RF Identification Box

The content of the "Technology results worksheet mock-up 2" is based on the work developed by Tom-Robert Bryntesen and Reka Szoke presented at Mechelen (sheet All sensors).

This worksheet contains the data from the technology Sensorized RF Identification box put on mock-up 2.

Contacts: Rosa Lo Frano <rosa.lo.frano@unipi.it>, Andrea Chierici <andrea.chierici@ing.unipi.it>.

The worksheet contains:

a) A title “mock-up 2 (Sensorized RF Identification Box)”,
b) A button featuring a “home” which redirects to the “home worksheet”
c) The selection of technology: displaying only “Sensorized RF Identification Box”,
d) The selection of the sensors: either “all sensors” or “gamma sensors”.
e) The duration of the results plotted from 1 day to 6 months,
f) The model used for prediction: the models are not available yet, thus this cell remains “greyish” with no content and no selection possible,
g) The date of the last sensor data collection using format: Day-Month-year (in full text to avoid inversion between day and month, for example: 05 January 2024)
h) A cell named “refresh every” which aim is to define the refresh frequency from the data of the dashboard coming from the azure platform
i) The results of” Sensorized RF identification box” described below.

Results associated to the selection of the technology “Sensorized RF Identification Box” (see Figure):

j) Two pictures to show where the sensors are located on mock-up 2,
k) A picture to present mock-up 2 (hole drilled with source insertion),
l) A plot showing the battery level in % (channel 9 of the data in the blob storage): displayed only if “all sensors” is selected
m) Four plots for the results:
    a. One plot with 1 curve: the data from gamma detector 1 (channel 1), in dose rate: µSv/h
    b. One plot with 1 curve: the data from gamma detector 2 (channel 2), in dose rate µSv/h,
    c. One plot with 1 curve: the data from gamma detector 3 (channel 3), in dose rate: µSv/h,
    d. One plot with 1 curve: the data from gamma detector 4 (channel 4), in dose rate µSv/h,
    e. One plot with 1 curve: the data from neutron detector 1 (channel 5), in dose rate µSv/h: displayed only if “all sensors” is selected
    f. One plot with 1 curve: the data from neutron detector 2 (channel 6), in dose rate µSv/h : displayed only if “all sensors” is selected
n) The last, minimal, maximal and average data of each displayed plot on the left side.

Mock-up 2 used for the test of "Sensorized RF identification box” contains a large crack that should be identified through measurement of a difference in dose rate for sensors nearby the cracks. Also new cracks appearing in the cemented matrix can be detected through an increase of the dose rate measurement.

An alarm can be displayed if the crack is detected through an increase in dose rate.

- The plots with the data from gamma detector 1, gamma detector 2, gamma detector 3 and gamma detector 4 will also display a baseline, depicted in green in Figure ,
- The baseline value is 12,8 in µSv/h (or 800 in counts).
- The measurements of sensors (gamma detector 1, gamma detector 2, gamma detector 3 and gamma detector 4) are compared to the baseline to ascertain if they are statistically different. If it is the case an alarm indicating increasing activity is triggered.

To determine if a measurement is statistically different the following formula is used [Data from UniPi]:

$$Z = \frac{\Delta N}{\sigma_{\Delta N}}$$

with $\Delta N = N_2 - N_1$

$\sigma_{\Delta N} = (\sigma_1^2 + \sigma_2^2)^{1/2}$

$\sigma_1 = (N_1)^{1/2}$ and $\sigma_2 = (N_2)^{1/2}$

N_1 the pulse from the baseline,

N_2 the pulse value collected by a detector,

$N_i = DeD_i \times \zeta \times \Delta t$

Ded_i the dose rate measured by the detector i,

ζ the sensitivity of the detectors (in cpm/µSv/h): the value for each detector is given in the table in Appendix 0,

Δt the measuring window of detector i in hour: the value for each detector is given in the table in Appendix 0.

$|Z| \leq 2$: difference under 95% confidence level, considered not relevant.

$|Z| > 2$: difference significant at the 95% confidence level (equivalent to ±2 standard deviations for a normal distribution).

$|Z| > 3$: difference significant at the 99.7% confidence level (equivalent to ±3 standard deviation for a normal distribution).

Example of calculation of Z between two values [Data from UniPi] considering a baseline of 10.00 µSv/h and a detector measuring 15.00 µSv/h, for a measuring window of 1 hour (60 minutes) and a sensitivity of 5 cpm/µSv/h for each detector

- If the measurement is statistically relevant ($|Z| > 2$) then a warning "Dose rate above baseline" will appear on the plot of the gamma detector, example is given for gamma detector 1 in Figure ,

Note: no alarm is implemented for neutron detector because there will be no neutron source during the test.

Note: The baseline is considered constant during the demonstration test because of the small duration of the test (3 months) compared to the gamma source half-life (30,7 years for ^{137}Cs). However, for a real package, an evolution of the base line in time should be implemented to take into account the modification of the radiological inventory of the cemented waste with time.

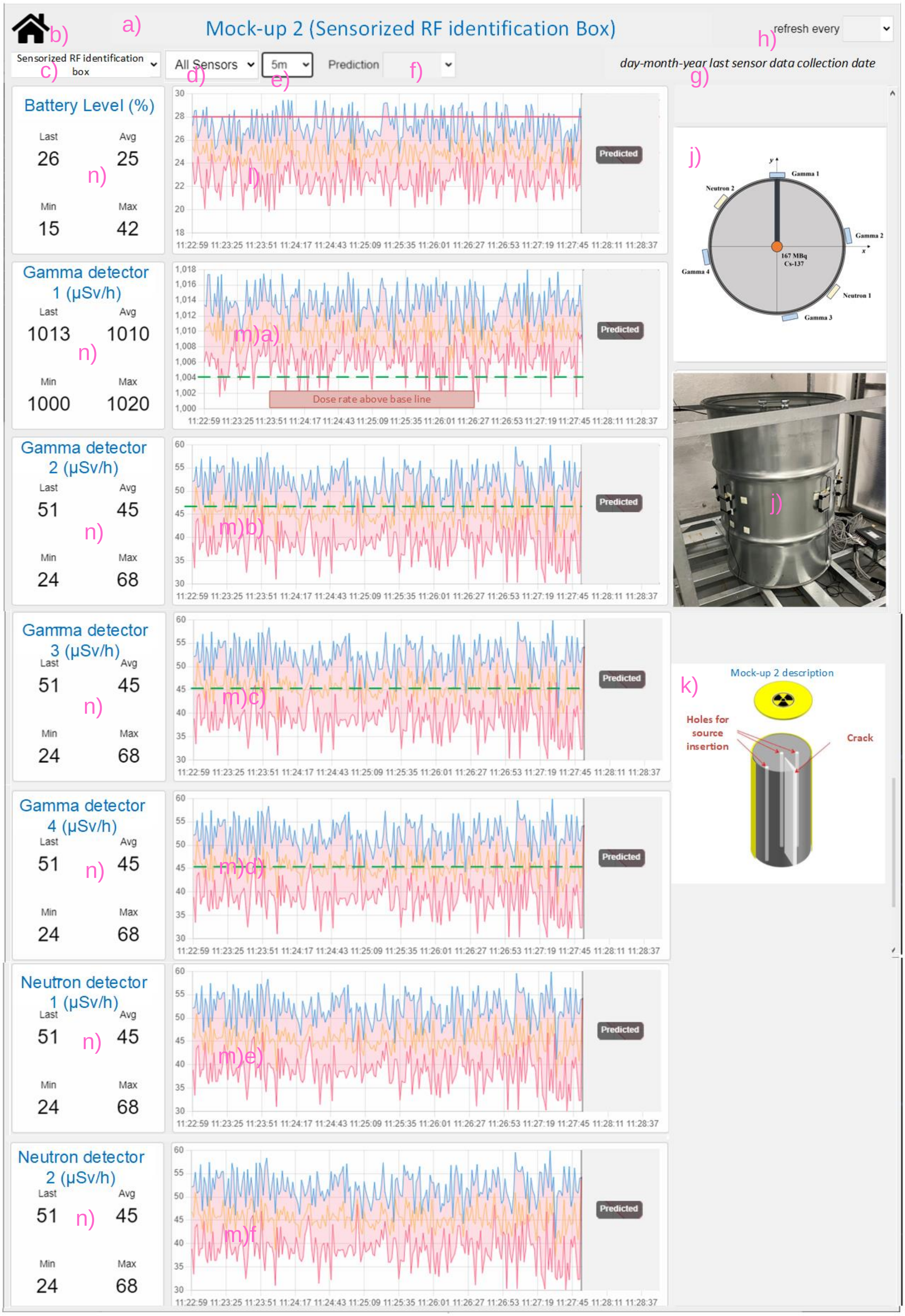


Figure 6: Proposed layout for the results from Sensorized RF identification box on mock-up 2.

Note: no predicted result will be integrated in the display.

Technology results worksheet mock-up 2 – SciFi/SiLiF:

This worksheet contains the data from the technologies SiLiF neutron monitor and SciFi gamma monitor from INFN put on mock-up 2.

Contacts: Mauro Romoli <romoli@na.infn.it>, Paolo Finocchiaro <finocchiaro@lns.infn.it>.

The worksheet contains:

a) A title “mock-up 2 (SciFi / SiLiF)”,
b) A button featuring a “home” which redirects to the “home worksheet”
c) The selection of technology: only “SciFi/SiLiF” can be selected,
d) The duration of the results plotted from 1 day to 6 months,
e) The model used for prediction: the models are not available yet, thus this cell remains “greyish” with no content and no selection possible,
f) The date of the last sensor data collection using format day-Month-year (in full text to avoid inversion between day and month, for example: 05 January 2024)
g) A cell named “refresh every” which aim is to define the refresh frequency from the data of the dashboard coming from the azure platform:
h) The results of or “SciFi/SiLiF “described below.

Results associated to the selection of the technology “SciFi/SiLiF” (see Figure):

j) One pictures to show where the sensors are located on mock-up 2: 4 neutrons detectors (SiLiF, in the box) and 4 gamma detectors (SciFi, in the pipes) on mock-up 2,
k) A picture to present mock-up 2 (hole drilled with source insertion),
l) A picture showing the state of the sensor of SiLiF neutron monitor and SciFi gamma monitor from INFN on mock-up 2 (example from INFN displayed in Figure). This picture contains several information:
    a. the drum is depicted at the center (for example in green),
    b. the neutron detectors are represented as squares positioned at 4 sides of the drum and the gamma detectors as circles nearby.
    c. The color of the square or circle indicated the average counting rate (i.e. the latest measured in counts/s for each of the 4 gamma detectors and in counts/min for each of the 4 neutrons detectors), the scale of the color is given in Table ,
    Note: There is no neutron source during the demonstration test it is expected that the neutrons detectors squares remain in grey (value = 0).
    d. The numbers on the square and circle sides also indicates the average counting rates.
    e. The explanation of color and counts below can be displayed through an “information” tooltip for example: *“The colour indicates the average counting rate, also shown by the numbers. The counting rate is the latest measures, in counts/s for gammas and in counts/min for neutrons”*
m) The last, minimal, maximal and average data of each displayed plot (dedicated sensor and parameter) on the left side.
n) On the central panel, four plots are shown at the same time with the possibility to select for each of them: **one detector and one parameter on the y-axis vs time**.
The list of detector ID is: Gamma detector 0°, Gamma detector 90°, Gamma detector 180°, Gamma detector 270°, Gamma detector adjacent room, Neutron detector 0°, Neutron detector 90°, Neutron detector 180°, Neutron detector 270°.
The list of parameters that could be displayed through these selections is presented in Table
o) Near each parameter selection there is a tooltip. It contains the explanation of the parameter selected by the end-user. Explanation for each parameter is given in Table in appendix.

Note: no predicted result will be integrated in the display.

Table 1: Scale of the color for the picture showing the state of the sensor of SiLiF neutron monitor and SciFi gamma monitor from INFN on mock-up 2.

Type of detector (unit) / Color scale	Gamma detectors (counts/s)	Neutron detectors (counts/min)
Grey	< thr_1	0
Green	thr_1 ≤ Y < thr_2	
Orange	thr_1 ≤ Y < thr_3	
Red	Y ≥ thr_3	

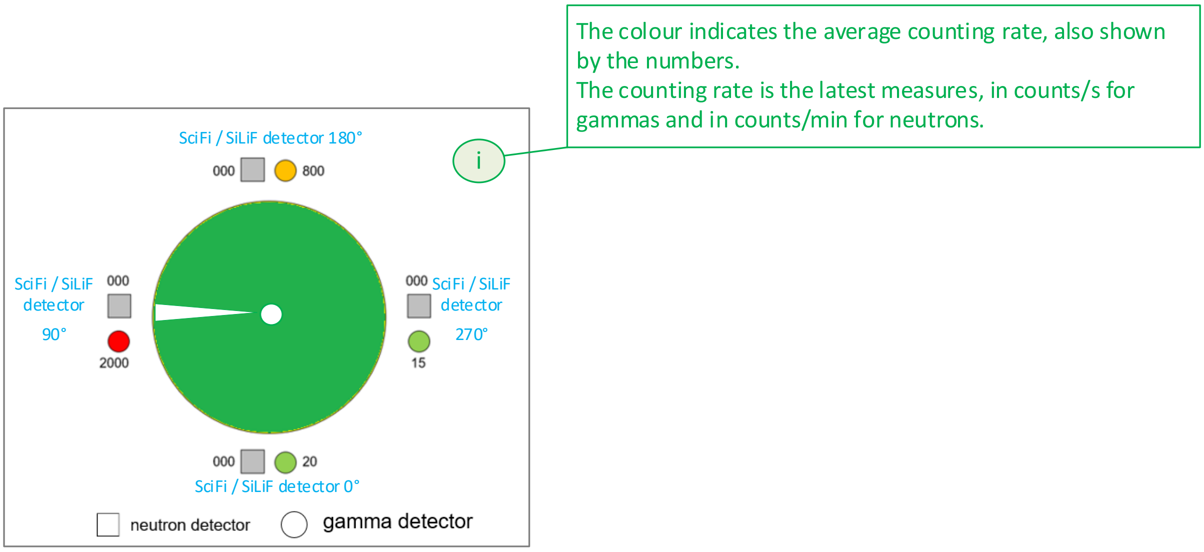


Figure 7: Display of the state of the SiLiF neutron monitor and SciFi gamma monitor from INFN on mock-up 2 worksheet [adapted from INFN, P. Finocchiaro].

Figure 8: Proposed layout for the results from INFN technology on mock-up 2.

Appendices

Appendix 1: Input data in Azur / blob storage for each technology

RFID embedded sensors from BAM / VTT in mock-up 1.2

Contact: Pasquato, Leone <leone.pasquato@bam.de>

Measurement data are uploaded to an InfluxDB server at one sample per day. Once uploaded, the data can be retrieved programmatically by using the influxdb API or by exporting a csv file, manually from the web interface or by CLI.

Due to the InfluxDB nature, there is not a strong schema which refer to. Instead, data are categorized by "measurement" (usually a sensor), "field" (measured quantity), and "tag" (label to group/filter data). For our system, inside a bucket there will be:

Table 1: Descriptions of the four measurement of the BAM/VTT technology.

Measurement	Field (double)	Tags (string)
Energy	voltage	drum_id
SensorNet	temperature	drum_id, sensornode_id, status
SensorNet	humidity	drum_id, sensornode_id, status
SensorNet	pressure	drum_id, sensornode_id, status

Table 2: Descriptions of the four sensors of the BAM/VTT technology.

Sensor Id	Sensor description
RFID-0001	Embedded RFID energy storage after measurement
RFID-SN-00	SensorNode 0
RFID-SN-01	SensorNode 1
RFID-SN-02	SensorNode 2
RFID-SN-03	SensorNode 3
RFID-SN-04	SensorNode 4

Sensorized RF identification box for radiation monitoring from UniPi in mock-up 2:

Contacts: Rosa Lo Frano <rosa.lo.frano@unipi.it>, Andrea Chierici <andrea.chierici@ing.unipi.it>.

DATA LOCATION AND STRUCTURE

Data from UniPi will be stored in a Blob Storage placed inside the **euwdatahandlingstorage01** storage account created by VTT for all partners. There are several containers in it, and one of them is named **unipi**. Inside the **unipi** container, specifically in **unipi / f8c5a3e1-c87a-47db-9a90-658a45e0275d / 18 / 2023** data are organized in folders. Each folder represents a month (for example month 08 corresponds to August). Inside the month folder, data are once again organized according to their upload time, for example **https://euwdatahandlingstorage01.blob.core.windows.net/unipi/f8c5a3e1-c87a-47db-9a90-658a45e0275d/18/2023/08/02/07/42/ljtekwaewe3yg** is the path to a JSON file (ljtekwaewe3yg, the extension of the file is not created by Azure IoT Central) containing data uploaded on August 2, at 7:42 (UTC).

Inside each file, a single row represents a single telemetry upload, in other words, the collection of data that leads to a refresh of the dashboard. Each row is organized in the following way:

```
{
 "applicationId": "f8c5a3e1-c87a-47db-9a90 658a45e0275d",
 "deviceId": "8cb1w0hgla",
 "enqueuedTime": "2023-06-28T11:43:03.164Z",
 "enrichments": {},
 "messageProperties": {},
 "messageSource": "telemetry",
 "schema": "default@v1",
 "telemetry": {
  "channel_1": 456,
  "channel_2": 523,
  "channel_3": 12334,
  "channel_4": 14567,
  "channel_5": -1,
  "channel_6": -1,
  "channel_7": -1,
  "channel_8": -1,
  "channel_9": 4535,
  "lora_node_id": "0x3_unipi",
  "measurement_id": "0x3_unipi_13:40:00-28/06/2023",
  "timestamp": "13:40:00-28/06/2023"
 },
 "templateId": "dtmi:azureiot:devkit:freertos:so7ke9i"
}
```


Only the "telemetry" property is relevant for data storage and visualization.
Specifically, channels 1-6 return 32-bit integers which represent the total nuclear pulses recorded by "gamma detector 1", "gamma detector 2", "gamma detector 3", "gamma detector 4", "neutron detector 1" and "neutron detector 2", respectively. In terms of sensors' IDs, they can be uniquely identified according the table :

Table 2: Descriptions of the nine sensors of the SciFi / SiliF technology.

Channel ID	Sensor ID	Description	Data Description	Unit	Format	Integration window (minutes)	Sensitivity (cpm/µSv/h)
1	Gamma_01_unipi	Gamma-ray detector	Total gamma pulses detected during the measuring window	µSv/h	32-bit integer	60	5
2	Gamma_02_unipi	Gamma-ray detector	Total gamma pulses detected during the measuring window	µSv/h	32-bit integer	60	5
3	Gamma_03_unipi	Gamma-ray detector	Total gamma pulses detected during the measuring window	µSv/h	32-bit integer	60	5
4	Gamma_04_unipi	Gamma-ray detector	Total gamma pulses detected during the measuring window	µSv/h	32-bit integer	60	5
5	Neutron_01_unipi	Thermal neutron detector	Total neutron pulses detected during the measuring window	µSv/h	32-bit integer	15	770
6	Neutron_02_unipi	Thermal neutron detector	Total neutron pulses detected during the measuring window	µSv/h	32-bit integer	15	770
9	Battery_01_unipi	Battery monitor	Voltage of the battery used by the LoRa node	%	32-bit integer	/	/

Channels 7-8 are not used and can be neglected. They return -1.
Channel 9 is the "battery level" expressed as a 32-bit integer (ex: 80%).

Then, there is a unique identifier for the RF box "lora_node_id" (string), a unique identifier for the measurement "measurement_id" (string) which consists in the "lora_node_id" + "_" + "timestamp" and a "timestamp" (string) hh:mm:ss-dd/mt/yyyy.

7 views are required in the dashboard:

- the first 6 as the counts recorded by the detectors,
- 1 as the voltage level in %.

The ID of the LoRa node (ex: 0x03_unipi) and the timestamp of the measurement (ex: 13:40:00-28/06/2023) can also be used. The timestamp of the measurement may differ from the upload time, since the latter may be scheduled to avoid interference with other instrumentation.

Very important: if some data returned on channels 1-4 (the active ones) is -1, then it should not be sent to the dashboard (I hope there is some control that can be implemented).

This can happen for 2 reasons:

1) A reset/resync payload, for example during installation to check radio communication and data upload to Azure.

2) During the first measurement. Since sensors are activated sequentially and based on the scheduled time, a measurement may start from (for example) Gamma_02_unipi instead of Gamma_01_unipi.

DEAD SENSOR DELAY

- Data will be uploaded once per day, therefore if **more than 1 day** is passed from the last upload it means a part of the system may be malfunctioning. This is true for all sensors since their data are uploaded all by the same unit.
- Regarding the potential actions that can be carried out by UJV technicians to solve the problems, we are preparing a troubleshooting guide.

Table 4: Descriptions of the seven sensors of the UniPi technology.

Sensor Id	Sensor description	Duration since last value
Gamma_01_unipi	Gamma detector 1 (channel 1)	Ex: 1d20h05m45s
Gamma_02_unipi	Gamma detector 2 (channel 2)	
Gamma_03_unipi	Gamma detector 3 (channel 3)	
Gamma_04_unipi	Gamma detector 4 (channel 4)	
Neutron_01_unipi	Neutron detector 1 (channel 5)	
Neutron_02_unipi	Neutron detector 2 (channel 6)	
Battery_01_unipi	Battery Monitor (channel 9)	

SiLiF neutron monitor and SciFi gamma monitor from INFN in mock-up 2:

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Nine detectors will be installed on mock-up 2, they are identified in the table below:

Table 5: Descriptions of the nine sensors of the SciFi / SiliF technology.

Sensor Id	Dev# (=ID of the sensor on azure platform)	Position of sensor on the mock-up compared to the "crack"	Description
INFN-SCIFI-01	009	0°	Gamma detector
INFN-SCIFI-02	007	90°	Gamma detector
INFN-SCIFI-03	010	180°	Gamma detector
INFN-SCIFI-04	006	270°	Gamma detector
INFN-SCIFI-05	008	/	Gamma detector in adjacent room
INFN-SILIF-01	002	0°	Neutron detector
INFN-SILIF-02	004	90°	Neutron detector
INFN-SILIF-03	005	180°	Neutron detector
INFN-SILIF-04	006	270°	Neutron detector

Table 6: Data for dead sensors table on presentation worksheet for SciFi/SiLiF technologies.

Sensor Id	Sensor description	Duration since last value
INFN-SCIFI-01	Gamma detector 0°	1d01h00m00s
INFN-SCIFI-02	Gamma detector 90°	
INFN-SCIFI-03	Gamma detector 180°	
INFN-SCIFI-04	Gamma detector 270°	
INFN-SCIFI-05	Gamma detector adjacent room	
INFN-SILIF-01	Neutron detector 0°	
INFN-SILIF-02	Neutron detector 90°	
INFN-SILIF-03	Neutron detector 180°	
INFN-SILIF-04	Neutron detector 270°	

Table 7: Data acquired by each sensor of the SciFi/SILiF technology.

Corresponding content on the Azure files			**End -user view on the dashboard**					
Parameter name on the Azur file	**Unit**	**Example**	**Parameter name for end-user on dashboard**	**Unit**	**Conversion**	**Tooltip content**	**Comment**	**Display order in main dashboard**
Temperature	**a.u.**	**282**	**Temperature on the front-end board**	**°C**	**T[in °C]=0.16*T[in a.u.]-22.5**	**Board temperature**	**/**	**5**
Humidity	*/*	*/*	*/*	*/*	*/*	*/*	*/*	*/*
Set Duration	*ms*	*80300*	*/*	*/*	*/*	*/*	*/*	*/*
Read Duration	**ms**	**80301**	**READ Δt**	**s**	**1 s = 1000 ms**	**READ Acquisition Time**	**/**	**4**
Set HV Bias	*a.u.*	*2000*	*/*	*/*	*/*	*/*	*/*	*/*
Read HV Bias	**a.u.**	**1895**	**READ V_bias**	**V**	**HV [in V]=0.0129*HV[in a.u.]+2.5432**	**READ Detector V_bias**	**/**	**6**
Null	*/*	*0*	*/*	*/*	*/*	*/*	*/*	*/*
Absorbed current	*a.u.*	*8000*	*/*	*/*	*/*	*/*		*/*
Threshold 1	*mV*	*1600*	*/*	*/*	*/*	*/*	*/*	*/*
Threshold 2	*mV*	*1600*	*/*	*/*	*/*	*/*	*/*	*/*
Channel1	*counts*	*80301*	*/*	*/*	*/*	*/*	*/*	*/*
Channel2	*counts*	*80302*	*/*	*/*	*/*	*/*	*/*	*/*
Real coincidences	**counts**	**10000**	**Detected Events**	**counts**	**/**		**/**	**3**
Analyzed coincidences	*counts*	*9800*	*/*	*/*	*/*	*/*	*/*	*/*
/	**/**	**/**	**Counting Rate**	**counts/s**	**« Real Coincidences» / « READ Acquisition Time »**	**Detector Count Rate**	**/**	**1**
/	**/**	**/**	**Average dose rate**	**µSv/h**	**0.043*«Counting Rate»**	**Average dose rate along the sensor**	**/**	**2**

Each sensor will have its own file on the azure platform in csv format. Nine files will be uploaded daily with new data.

A sensor is considered "dead" if no data is fund after the daily uploaded on Azure.

Data stored in the Blob Storage will be in CSV format, more precisely three kinds of file will be uploaded:

- A Standard mode type, containing the number of detected events for each measurement and information about the time stamp, the detector ID, the set-up of the device and the data measured by external sensors (temperature, humidity…). The upload frequency of this kind is about one per day in standard conditions.

```
23-02-13_11-29                            Data e ora
22.7C 44.1%                               Temperatura[°C] e umidità [%]
00010000  00010001                        tempo nominale[mSec] Tempo effettivo di acq [mSec]
01000 00001817  01200  01360              valore impostato HV  -  Valore letto HV  -  Soglia A - Soglia B
00014682 00014524 00010408 00010081       Conteggi A   -  B    - Coincidenze   - Coincidenze Analizzate
```

the ADC1 and ADC2 columns express the energy values measured from each channel of the electronic device and different lines correspond to different detected events.

The number of those items depends on the measurement duration and on the event rate.

These information is useful for spectroscopy purpose and to test the calibration of the electronic thresholds with an upload frequence of about one or two per months.

- A List mode type, containing also the punctual information about each detected event, as a matrix of 2Xenergy items

	A	B
	22-12-07_18-44	
1	ADC1	ADC2
2	0.000000	2560.156250
3	1406.960815	3270.824707
4	2295.452637	3564.280029
5	3601.469727	2058.875732
6	2313.266113	2361.081543
7	2154.819092	2762.668701

- A Summary mode type: containing the summary of X Standard mode type and giving a compared view of an extended set of measuments performed at different times

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	date	time	temperature °C	himidity %	nominal duration	effective duration	set value HV	read value HV	THA	THB	count A	count B	coincidences	analyzed coincidences
0	23-02-27	15:33	27.7	33.0	00002000	00002001	01000	00001811	01000	01000	00000249	00000269	00000204	00000183
1	23-02-27	02:48	21.3	44.3	00060000	00060001	01000	00001817	01000	01000	00000052	00000063	00000037	00000037
2	23-02-25	21:57	22.5	42.2	00060000	00060001	01000	00001815	01000	01000	00000047	00000058	00000031	00000031
3	23-02-27	05:56	20.9	41.9	00060000	00060001	01000	00001812	01000	01000	00000052	00000061	00000038	00000038
4	23-02-24	14:16	24.7	38.1	00060000	00060001	01000	00001818	01000	01000	00000078	00000087	00000057	00000057
5	23-02-27	12:46	26.4	36.0	00060000	00060001	01000	00001815	01000	01000	00007997	00008760	00006674	00006641
6	23-02-27	12:14	24.1	40.2	00060000	00060001	01000	00001818	01000	01000	00000051	00000059	00000038	00000038
7	23-02-27	09:36	21.8	42.8	00060000	00060001	01000	00001814	01000	01000	00000068	00000070	00000050	00000050
8	23-02-25	19:52	22.4	40.7	00060000	00060001	01000	00001815	01000	01000	00000071	00000068	00000048	00000048
9	23-02-26	14:16	21.4	52.2	00060000	00060001	01000	00001814	01000	01000	00000073	00000078	00000055	00000055
10	23-02-25	16:13	23.4	38.9	00060000	00060001	01000	00001819	01000	01000	00000062	00000071	00000042	00000042
11	23-02-24	13:54	25.2	37.2	00060000	00060001	01000	00001819	01000	01000	00000069	00000081	00000047	00000047
12	23-02-26	09:48	22.3	51.6	00060000	00060001	01000	00001817	01000	01000	00000069	00000083	00000052	00000052
13	23-02-25	17:47	22.5	40.5	00060000	00060001	01000	00001815	01000	01000	00000074	00000088	00000058	00000058
14	23-02-27	13:13	27.1	34.4	00060000	00060001	01000	00001814	01000	01000	00007934	00008730	00006612	00006572
15	23-02-26	02:08	22.4	43.8	00060000	00060001	01000	00001815	01000	01000	00000054	00000063	00000039	00000039
16	23-02-26	16:53	21.3	45.0	00060000	00060001	01000	00001815	01000	01000	00000056	00000063	00000040	00000040
17	23-02-24	15:19	23.9	40.5	00060000	00060001	01000	00001818	01000	01000	00000064	00000084	00000050	00000050
18	23-02-24	22:06	22.4	40.2	00060000	00060001	01000	00001817	01000	01000	00000058	00000063	00000039	00000039
19	23-02-26	02:39	22.4	43.6	00060000	00060001	01000	00001815	01000	01000	00000061	00000062	00000041	00000041
20	23-02-26	22:38	22.3	43.0	00060000	00060001	01000	00001814	01000	01000	00000064	00000069	00000046	00000046

These files are generated on the local server and could be aggregated in clusters, each related to a single electronic device.

Appendix 2: View of the dashboard developed by task 5 of WP7 of PREDIS and presented at Mechelen in may 2023

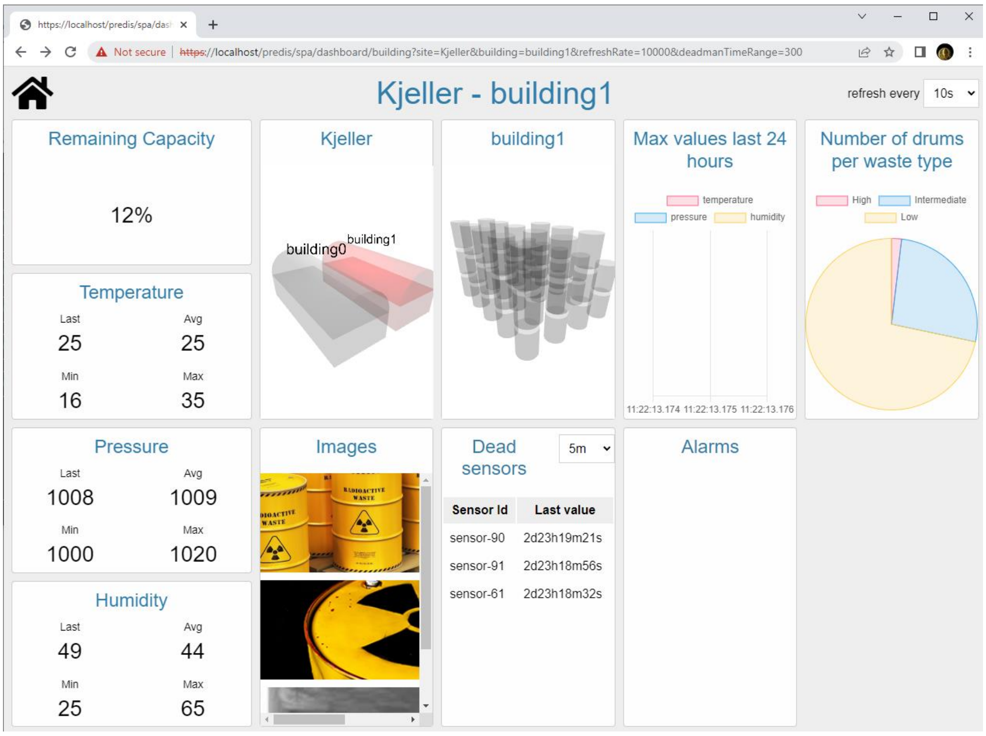

Figure 9: Kjeller- building1 display of decision platform developed by Predis task 7.5.3 [Mechelen Predis Whole consortium workshop May 2023, Tom-Robert Bryntesen & Reka Szoke]

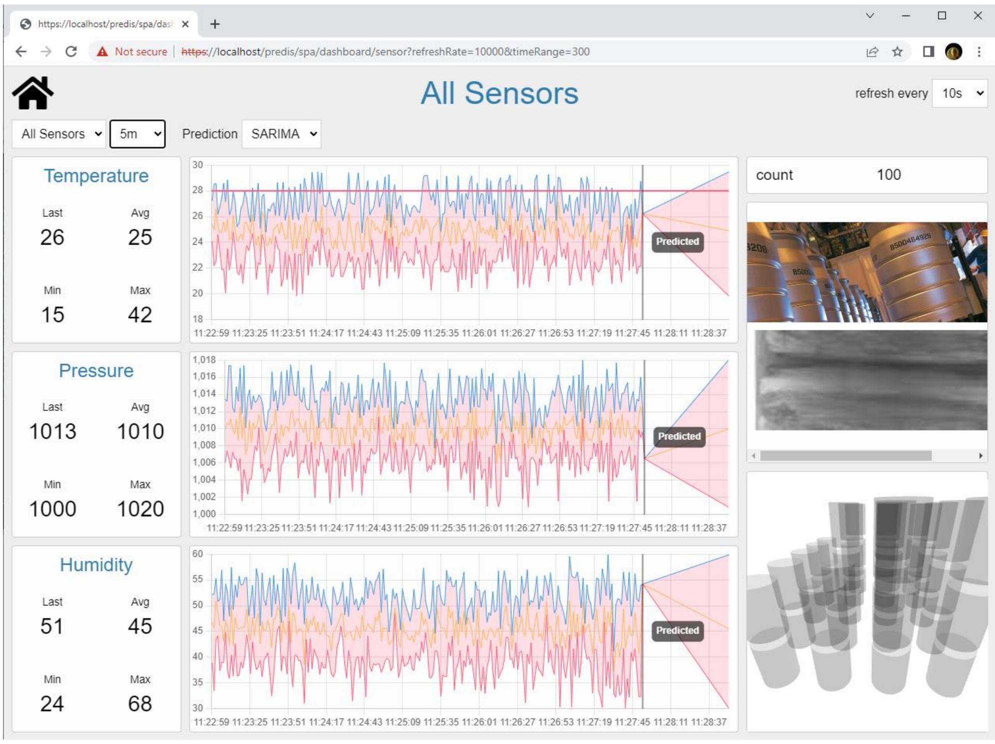

Figure 10: All sensors display of decision platform developed by Predis task 7.5.3 [Mechelen Predis Whole consortium workshop May 2023, Tom-Robert Bryntesen & Reka Szoke]