Deliverable 7.9
Economic, Environmental and Safety Impact of the Pre-Disposal Monitoring, Modelling and Decision Framework Technologies for Cemented Waste Packages

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Abstract

In the framework of Work Package 7 (WP7) of PREDIS, this report evaluates the economic, environmental, and safety impacts of the innovative technologies and approaches tested in the context of pre-disposal management (i.e., storage) of cemented packages of radioactive waste. The technologies covered include: SciFi/SiLiF gamma and neutron radiation monitoring, acoustic emission for measuring alkali-silica reactions, non-contact ultrasonic inspection, RFID (radio frequency identification) embedded sensors, sensorised LoRa (long-range radio) wireless sensor network, muon tomography, and digital twin, data platform, and decision framework tools. A "value assessment" approach is adopted to compare these technologies against current practices in terms of key assessment areas relating to operational safety, environmental impact, long-term safety, implementation, technical readiness, and strategic cost impact. The report identifies key findings from project partners on each technology in terms the advantages and challenges associated with implementing the technology during storage of cemented waste packages.

Keywords

Value assessment, PREDIS, monitoring, digital twin, decision framework, cemented waste

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List of Acronyms

AE	Acoustic Emission
ALARP	As Low As Reasonably Practicable
ASR	Alkali-Silica Reaction
BAM	Bundesanstalt für Materialforschung und -prüfung (Federal Institute for Materials Research and Testing in Germany)
DAQs	Data Acquisition Systems
DT	Digital Twin
EC	European Commission
FAIR	Findable, Accessible, Interoperable, Reusable
GSL	Galson Sciences Limited
INFN	Istituto Nazionale di Fisica Nucleare (National Institute for Nuclear Physics; Italy)
IoT	Internet of Things
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LoRa	Long-range Radio
Mu-Tom	Muon Tomography
MQTT	Message Queuing Telemetry Transport
NNL	National Nuclear Laboratory; UK
PPE	Personal Protective Equipment
PREDIS	Pre-Disposal Management of Radioactive Waste
PSI	Paul Scherrer Institute; Switzerland
PUWER	Provision and Use of Work Equipment Regulations
PY	Person-Years
R&D	Research and Development
RFID	Radio Frequency Identification
SciFi	Scintillating optical Fibre
SiLiF	Silicon Lithium Fluoride
THERAMIN	Thermal treatment for radioactive waste minimisation and hazard reduction
TRL	Technology Readiness Level
UJV	Ústav Jaderného Výzkumu (Institute of Nuclear Research in Řež, Czech Republic)
UNIPI	University of Pisa; Italy
VTT	Technical Research Centre of Finland
WAC	Waste Acceptance Criteria
WP	Work Package
WSN	Wireless Sensor Network

1 Introduction

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

- Develop solutions for the future treatment and conditioning of wastes for which no adequate or industrially mature solutions are currently available, including metallic material, liquid organic waste, and solid organic waste.
- Test and evaluate innovations in cemented waste handling and pre-disposal storage.
- Improve existing solutions to improve safer, reduce costs, and increase effectiveness.
- Analyse material and packaging requirements and associated Waste Acceptance Criteria (WAC) for pre-disposal and disposal activities.

The project is structured around seven Work Packages (WPs). Work Package 7 (WP7) is dedicated to innovations in cemented radioactive waste handling, monitoring, and pre-disposal storage. The focus of R&D activities in WP7 is on:

- Compiling information on the state of the art in packaging, storage, and monitoring of cemented wastes (Task T7.2).
- Developing innovative integrity testing and monitoring techniques for cemented waste packages (T7.3).
- Developing a digital twin (DT) of a cemented waste package based on a combination of monitoring results and modelling techniques to predict changes over time (T7.4).
- Developing data platforms and decision frameworks for handling monitoring data (T7.5).
- Evaluating the technologies and developed systems from an end-user perspective, including value assessment and demonstration trials (T7.6).
- Dissemination and synthesis of WP7 outcomes (T7.7).

1.1 Aims and Objectives

This deliverable (D7.9) analyses the economic, environmental, and safety impacts of the technologies developed and tested in WP7 and forms an output of both T7.6 and T7.7. The analysis, conducted through a 'value assessment', brings together research and experimental results documented in previous deliverables (D7.3 [2], D7.5 [3]), and D7.7 [4] and compares the performance of the technologies against current management practices to identify their strengths and weaknesses in terms of economic, environmental, and safety impacts.

The overarching objective of this deliverable is to provide technology developers and end-users with an objective assessment of the performance of novel technologies tested in WP7 across the full waste management lifecycle to support their industrial application and end-user decision making.

1.2 Scope, Interfaces and Exclusions

WP7 of PREDIS focuses on pre-disposal management of cemented waste. Based on a compilation of the state of the art in packaging, storage and monitoring of cemented waste reported in D7.1 at the beginning of the PREDIS project [5], the properties of a reference waste package were defined for use in the remainder of the WP7 programme [6]. This reference package forms the starting point for the value assessments reported here.

The scope of the value assessment includes all technologies being tested by PREDIS Partners in WP7, which are:

- Scintillating optical Fibre (SciFi) gamma radiation monitoring and Silicon Lithium Fluoride (SiLiF) neutron radiation monitoring.
- Sensorised long-range radio (LoRa) wireless sensor network for identification and integrity assessment of radioactive waste drums.
- Acoustic Emission (AE) for measuring Alkali Silica Reactions (ASR).
- Non-contact ultrasonic scanning.
- Embedded Radio-Frequency Identification (RFID) sensors.
- Muon tomography (Mu-Tom).
- DT and data platform and decision framework tools for predictive modelling, data handling and data visualisation.

A detailed description of these techniques is provided in the relevant deliverables (D7.3, D7.5 and D7.7 [2, 3, 4]) and is not repeated herein, although a summary of each technology is provided to support its evaluation.

Dedicated value assessment activities, including workshops with research partners and end-users, were undertaken in preparation for this deliverable [7]. The results of these activities are reported herein.

The value assessment work undertaken draws partly on the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analyses undertaken under WP2 and summarised in Milestone MS16 and Deliverable D2.9. It is also informed by results from research and experimental activities undertaken in WP7 and summarised in D7.3, D7.5, and D7.7 [2, 3, 4].

1.3 Report Structure

This remainder of this report is structured as follows:

- Section 2 presents the approach and methodology for evaluating the economic, environmental, and safety impacts of technologies developed in WP7 of PREDIS.
- Section 3 summarises the evaluation of the monitoring techniques developed in WP7.
- Section 4 summarises the evaluation of the DT, data platform, and decision framework tools developed in WP7.
- Section 5 presents the conclusions of the report.
- Section 6 lists the references used in this report.
- Appendix A presents the raw output tables from the value assessment workshops.

2 Approach to Evaluation of Economic, Environmental and Safety Impacts

2.1 Value Assessment Methodology

The evaluation of economic, environmental, and safety impacts of the technologies developed in WP7 of PREDIS was undertaken using an approach termed 'value assessment'. Value assessment is a type of multi-criteria cost-benefit analysis that provides a methodology for assessing and comparing alternative waste management options. In this context, 'value' refers to realisable benefits in safety, financial, and environmental outcomes resulting from the implementation of a chosen option at a specified time. This includes benefits and challenges across all stages of the waste management lifecycle. However, it should be recognised that value can vary among stakeholders, with different individuals and organisations assigning varying degrees of importance to different criteria. Therefore, the approach to value assessment in WP7 adopted a multi-criteria methodology that draws upon the methodology developed for the overall PREDIS project [8], which itself was based on the value assessment process employed in the European Commission (EC) THERAMIN (Thermal treatment for radioactive waste minimisation and hazard reduction) project [9].

When conducting a value assessment, it is important to follow a structured approach that defines the scope of the assessment before it is undertaken. The value assessment process is outlined in

Figure 2.1. The initial stage in this process involves choosing the specific waste(s) and technologies to be assessed. As noted in Section 1.2, a specific waste package has been developed for use as a reference throughout WP7 and for the demonstration tests [6]. Its key properties are as follows:

- 200-litre cylindrical drum made of austenitic stainless steel, with a diameter of 60 cm and height of 90 cm.
- Single skin construction.
- Waste type comprises Magnox (a magnesium-aluminium alloy) or magnesium metal pieces, encapsulated within a specific grout formulation with a concrete layer between the wasteform and the lid.

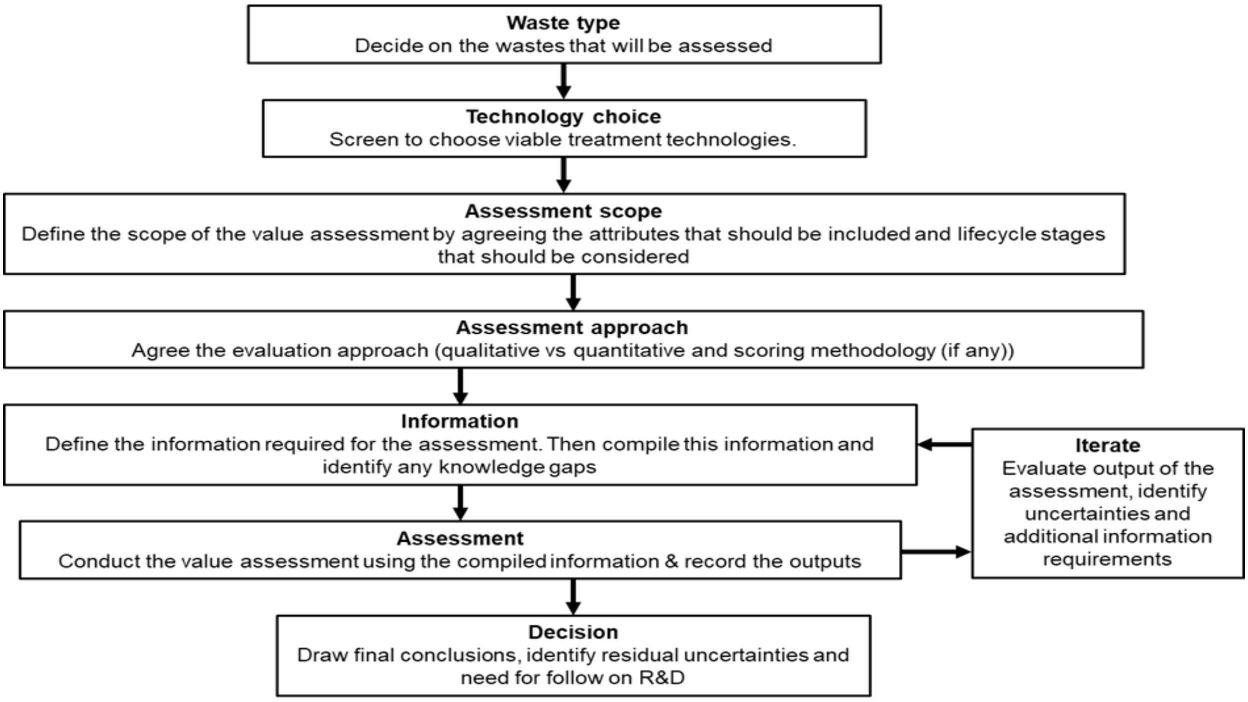

Figure 2.1: Flowchart for the value assessment process (from reference [9]).

2.2 Technology and Baseline Selection

The value assessment compares each technology against a baseline option – this baseline typically represents the current reference approach or standard practice that the technology aims to replace or enhance. This comparative approach enables the criteria of the new technology to be judged as better or worse than, or broadly similar to, the baseline. All technologies being investigated in WP7 are within the scope of the value assessment. The technologies and the corresponding baseline options are summarised in Table 2.1.

The storage facility assumptions within the baselines align with those adopted for the LCA conducted in WP2 of PREDIS. The LCA assumed a standard interim store for cemented waste packages with a lifetime of 100 years and a capacity for 10,000 m^3 of waste. Assuming 200-litre waste drums, the facility can accommodate a total of 50,000 drums [10].

Table 2.1: WP7 technologies and associated baseline for value assessment.

Technology	Technology developer(s)	Baseline
SciFi (gamma) radiation monitoring	National Institute for Nuclear Physics (INFN), Italy	Visual inspection and manual dose rate measurement
SiLiF (neutron) radiation monitoring	INFN, Italy	Visual inspection
Sensorised LoRa wireless sensor network for identification and integrity assessment of radioactive waste drums	University of Pisa (UNIPI), Italy	Visual inspection and manual dose rate measurement
Acoustic Emission for measuring ASR	Magics, Belgium	Visual inspection
Non-contact ultrasonic scanning	National Nuclear Laboratory (NNL), UK	
Embedded RFID Sensors	Federal Institute for Materials Research and Testing (BAM), Germany Technical Research Centre of Finland (VTT), Finland	
Muon tomography	INFN, Italy	X-ray imaging

Technology	Technology developer(s)	Baseline
DT, data platform and decision framework tools for predictive modelling, data handling, and data visualisation	Paul Scherrer Institute (PSI), Switzerland VTT, Finland Institute for Energy Technology (IFE), Norway	Combination of paper records and limited digital archiving of data, but no DT or decision framework used. The baseline also assumes visual package inspection as the monitoring technology. However, the assessment only focuses on the DT, data platform, and decision framework aspects rather than any potential monitoring technologies that might operate concurrently.

2.3 Assessment Scope Definition

The value assessment is based around a set of assessment areas (also called attributes) that are sub-divided into assessment criteria (or data categories). The full list of these is shown in Table 2.2. These assessment areas and criteria are based on those used in the EC THERAMIN project [9]. They have been refined based on lessons learnt from value assessment activities undertaken under PREDIS WP4, 5 and 6, and tailored to suit the context of PREDIS WP7. Owing to the differences between monitoring and modelling technologies, Table 2.2 features two assessment criteria columns, one applicable to monitoring technologies and the other to the DT, data platform, and decision framework tools in WP7. Detailed guidance on the different aspects that should be considered under each assessment area has been developed and is documented separately [11].

Another major consideration when establishing the scope of the assessment is definition of the lifecycle stages over which the assessment is being conducted. These lifecycle stages relate both to the lifespan of the technologies and management of the waste. Lifecycle stages for the technologies in WP7 are outlined in Table 2.3. It is worth noting that not all lifecycle stages may be relevant in every assessment, and it is left up to the assessors to eliminate those that are deemed irrelevant for the assessment.

Table 2.2: Summary of assessment areas and criteria for value assessment of PREDIS WP7 technologies and tools.

Assessment Area	Assessment criteria for monitoring technologies	Assessment criteria for DT, data platform and decision framework tools
Operational and Transport Safety	Technology and equipment manufacture, commissioning and decommissioning	Construction and decommissioning of the tools
	Package or store modification requirements for technology implementation (conventional and radiological safety implications)	Package or store modification requirements for tool implementation (conventional and radiological safety implications)
	Post-monitoring requirements (conventional and radiological safety issues)	

Assessment Area	Assessment criteria for monitoring technologies	Assessment criteria for DT, data platform and decision framework tools
	Storage/monitoring operational safety issues	
	Transport safety issues	
Environmental Impact	Material environmental impacts	
	Process energy requirements	
	Secondary and maintenance waste generated	
Impact on disposability/ long-term safety	Ability to meet waste acceptance criteria	
	Disposability of secondary waste	
Implementation and timescales	Design, construction, implementation and operating timescale	
	Ease of achieving required data collection by the technology during storage	Ease of achieving required performance by the tools during storage
	Potential to monitor a wide range of packages (flexibility) including legacy packages in different storage configurations	Potential to handle a wide range of monitoring data from different technologies in different storage configurations
	Impact on national and site waste management strategies	
	Decommissioning timescale	
Technical Readiness	Maturity of the technology, which can be broadly defined by whether it is a prototype still undergoing active research, deployed at the pilot scale, or deployed at the full industrial scale. Alternatively, the Technology Readiness Level (TRL) scale of 1-9 could be used.	
Strategic Cost Impact	Costs of construction, operation and decommissioning, including secondary waste management and including material costs (but excluding disposal costs)	
	Impact on disposal costs (package & secondary wastes / maintenance wastes destined for disposal)	

Table 2.3: Assessment lifecycle stages for WP7 technologies and tools.

Lifecycle stages	
Monitoring technologies	**DT, data platform and decision framework tools**
Equipment and technology design and manufacture	Tools design and equipment manufacture
Integration of the technology in the waste package / storage facility and commissioning	Integration and commissioning of the tools with the storage system
Monitoring operations (including maintenance)	Monitoring / data analysis (including maintenance)
Removal of the technology after storage	Data archiving
Disposal of the package / technology materials	Disposal of the tools

2.4 Assessment Approach

The value assessment in WP7 was conducted in a collaborative manner, with each technology developer tasked with producing a draft assessment of their technology for discussion and feedback during workshops with other WP7 partners and end-users. Briefing materials were distributed ahead of the workshops to explain the assessment process and provide detailed guidance and instructions on how to conduct the assessment [11].

To ensure consistency across the various assessments conducted in WP7, a template table was included in the briefing material, where strengths and weaknesses of each technology compared to the baseline were identified and recorded for each criterion within each assessment area. The assessment used qualitative statements for the comparisons. However, an overall rating was assigned for each criterion as follows: -2 (much worse than baseline), -1 (worse), 0 (neutral), 1 (better), 2 (much better). The assessment did not aim to compare the WP7 technologies against each other.

The draft assessments were subsequently presented by the technology developers and updated with participants' feedback following the value assessment workshops held on the 15th and 21st of March 2024. The presentation from each technology developer at the workshop covered a summary description of the assessed technology, a reminder of the assessment scope, selected baseline, and methodology employed, as well as discussion of the narratives for each assessment area and its relevant criteria, providing a summary of strengths and weaknesses compared to the baseline.

The finalised assessments form part of this report D7.9 (Appendix A includes the detailed assessment tables).

3 Evaluation of Monitoring Technologies

This section presents a summary of the value assessment outcomes for each monitoring technology in separate subsections. Each subsection provides a brief description of the technology and discusses the advantages and challenges identified in the value assessment compared to its baseline. The discussion is organised around the assessment areas outlined in Table 2.2. Ratings (-2, -1, 0, 1, 2) for individual criteria within assessment areas are provided in a summary figure at the beginning of each subsection, as defined in Section 2.4,. More detailed assessments of each criterion within each assessment area are provided in Appendix A. No overall ratings are derived; an interested organisation or end-user might find it useful to customise the ratings by applying weighting factors that reflect national priorities.

The “assessment panel” in the discussions below refers primarily to the technology developers who conducted the initial value assessment. However, feedback from workshop participants is also incorporated into the discussions.

3.1 SciFi/SiLiF Radiation Monitoring

SiLiF neutron counters and SciFi gamma ray counters are designed as compact flux detection devices, suitable for external installation around a waste drum (Figure 3.1). They are being optimised and assessed in WP7 of PREDIS by INFN. The SiLiF neutron counter contains a semiconductor detector in the form of a silicon diode with a neutron converter layer of ^{6}LiF on each side. The SciFi gamma ray counter contains a scintillating fibre with a silicon photomultiplier at each end, all contained within an aluminium tube. Variations in neutron and gamma counts measured at the external surface of a waste package are expected to reflect variations in the internal structure of the waste package. The proposed monitoring method involves using a set of four SciFi and SiLiF sensors attached to the cemented drum for continuous monitoring throughout the predisposal phase. Before and after its full characterisation, each drum would be monitored for any possible anomalies that may arise while awaiting disposal.

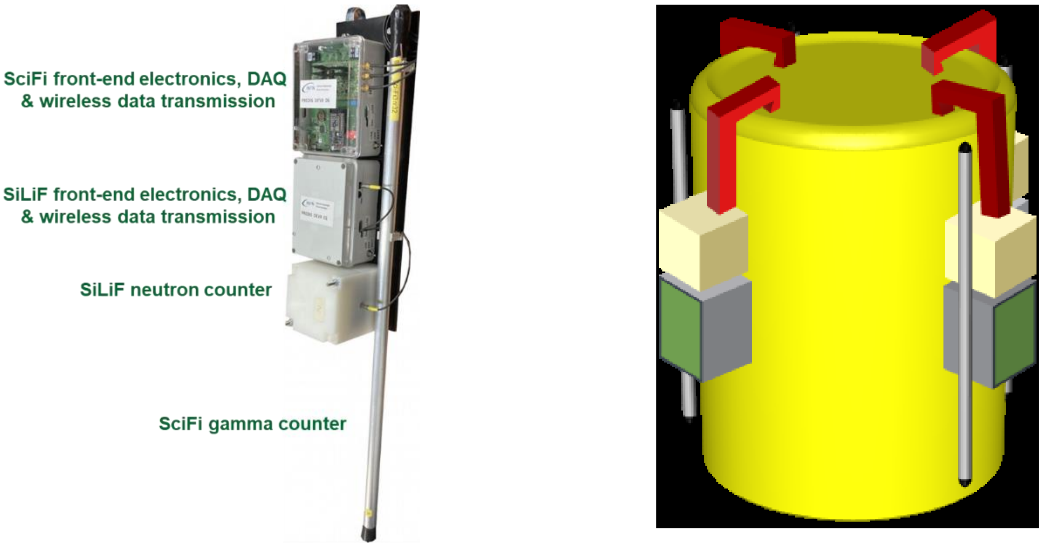

Figure 3.1: Left – Complete monitoring unit consisting of one SiLiF detector and one SciFi detector with the related electronics. Right – A possible arrangement of four radiation monitoring units on a cemented drum during its predisposal phase [2].

A summary of the value assessment ratings for the SciFi/SiLiF technology assigned to the different assessment criteria in comparison to the baseline (visual inspection and manual dose rate measurement) is presented in Figure 3.2.

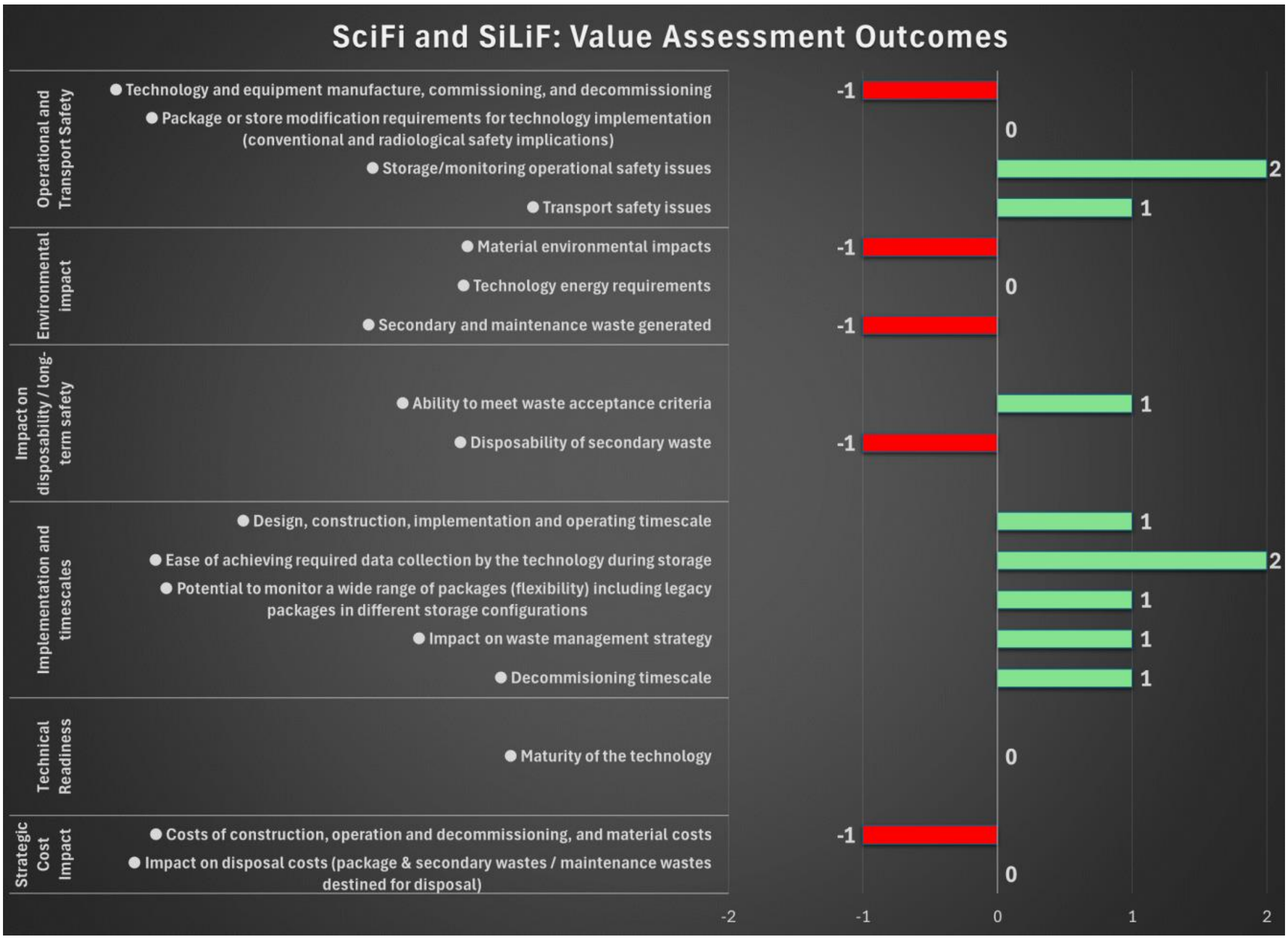

Figure 3.2: Chart of strengths and weaknesses of SciFi/SiLiF technology compared with the baseline (visual inspection and manual dose rate measurement). The ratings are defined as: -2 (much worse than baseline), -1 (worse), 0 (neutral), 1 (better), 2 (much better).

3.1.1 Operational and Transport Safety

The main weakness of this monitoring technology in terms of operation safety is that it relies on a range of scintillation detectors and network equipment, which need to be installed in contact with the waste drum within the store, respectively. Equipment manufacture increases industrial hazards, while equipment installation and commissioning, possibly in an active environment, increase the risks to operators. These considerations are mitigated by the relative simplicity and reusability of the monitoring equipment. It is designed to be placed (hung) on each waste package, which could be achieved remotely, thus reducing the negative impact of installation and commissioning activities.

This monitoring approach has the disadvantage of “front-loading” risks to safety; however, it results in a significant reduction in both conventional and radiological hazards during the storage and post-storage periods. This technology reduces operator exposure to ionising radiation, as data transmission occurs remotely and automatically without operator intervention. In addition, the need for waste package movement for inspection is reduced (or totally removed, depending on other monitoring and site-specific arrangements). Maintenance operations are limited to yearly battery recharge, which can be achieved by remotely swapping the monitoring modules (by hanging a new set of detectors and batteries on the waste package). Early detection of waste package degradation is also likely to result in lesser doses during remediation operations.

*Overall, the assessment panel concluded that, based on the evidence assembled, operational and transport safety was **slightly better** for the SciFi/SiLiF technology than in the baseline scenario. The risk increase during equipment manufacture, installation, and commissioning needs to be balanced with the risk reduction achieved using this remote monitoring method. Quantifying this difference was not possible and requires detailed assessment; however, the value assessment panel concluded that an overall reduction in risks was the likely outcome.*

3.1.2 Environmental Impact

The environmental impact of materials used in the manufacture of monitoring and networking equipment relates to the sensor unit that includes electronics and data transmission equipment with a volume of approximately 4 litres. The local area WiFi network requires at least one router and one server. However, most of this equipment is reusable and constructed from common electronic components such as plastic, aluminium, and coaxial wires. Exotic materials are limited to a small amount of isotopically enriched ^{6}LiF salt used in the scintillators.

The maintenance waste generated mainly includes rechargeable batteries, with each sensor unit producing approximately 0.5 litres of waste. These batteries have an expected lifespan of around 10 years, needing one recharge annually. Replacing batteries every 10 years negatively impacts the technology's environmental footprint.

The energy needed for sensor and network operations is approximately 0.1 kWh per year. The overall environmental impact of the technology's energy requirements is country-dependent and is evaluated separately in the LCA model.

*Overall, the value assessment concludes that the environmental impact of the SciFi/SiLiF system is **slightly worse** than under the baseline. Material requirements and equipment disposal are the main contributors to the technology's impact on the environment. This impact was quantified using LCA; incorporation of the technology in 5% of the waste packages in a store was calculated to potentially increase the store's overall environmental impact (expressed in kg.CO_2 eq.)*

3.1.3 Impact on Disposability/Long-term Safety

Installation of the monitoring equipment is non-destructive and does not rely on waste packages being modified. Therefore, waste package disposability is not negatively impacted by implementing this monitoring method.

Its strength resides in its ability to identify deep cement cracks as narrow as 1 mm wide, even with an intact steel container. The ability to identify such changes in the wasteform's physical integrity during storage is likely to strengthen disposability arguments made by waste producers. It might also enable early remediation, resulting in compliant packages. Continuous or periodic (depending on the store operating procedures) radiological monitoring may provide additional information useful in preparing for waste package disposal. Even though this technology is reusable, if disposed of with the package, it can continue providing data as long as the batteries allow. With one measurement per month, monitoring could continue for approximately 13 years.

Waste management routes already exist for secondary waste issues.

*Overall, disposability and long-term safety are **improved** by using the SciFi/SiLiF system instead of visual inspection and manual monitoring. The ability to detect wasteform failures during storage, and/or prior to disposal is likely to make package remediation easier and can prevent store or disposal system-wide consequences upon waste package failure.*

3.1.4 Implementation and Timescales

The assessment panel concluded that technological enhancements and continuous improvements can be pursued throughout the storage period. However, additional tests and validation are not needed for its implementation, allowing for swift integration. No modifications to the existing storage infrastructure are needed, ensuring operational continuity. Extended commissioning periods are avoided, and IT advantages are leveraged with redundancies in servers and routers for reliability.

Sensor unit replacements incur only a brief downtime, and no extra software is required, reducing the risk of errors. The quantitative measurements offer accuracy, with flexibility in measurement and sensitivity to variations inside the package (e.g., cement cracks or inner displacements). This can also enhance security by signalling any anomalies within the packages which could result from, for example, tampering. In terms of potential future prospects this technology could be used for legacy waste monitoring through streamlined measurements without additional conditioning operations.

*Implementation of the SciFi/SiLiF technology is **better** than that of the baseline approach. It builds on its backward compatibility with existing IT systems and is compatible with various waste packages because package modifications are not needed.*

3.1.5 Technical Readiness

The radiation sensors have undergone extensive testing over the past 12 years in various projects spanning a range of activity levels and different storage configurations. Therefore, the TRL of this technology is relatively high. A TRL of 8 is estimated for the sensors and 7 for the electronics. Although the technology has not yet undergone formal certification, the potential for scalability and industrial application is quite promising as there a reasonably wide range of suppliers for the technology components.

*Although further work is still needed to ensure the maturity of the technology for industrial application, this is not considered to be far off. Therefore, the technical readiness of this technology is considered to be **similar** to the baseline.*

3.1.6 Strategic Cost Impact

Assessing the cost of the monitoring system's manufacture is scale-dependent and ranges from ~€1 k (pilot scale) to ~€500 (mass production) per monitoring unit. The increase in equipment cost (for its manufacture and disposal) compared with the baseline is mitigated by savings in terms of handling equipment and in the number of man-hours required for visual inspection. The cost incurred by energy consumption is negligible. The technology developer reported that the technology had been designed with simplicity in mind, thus removing the need for specialist operators.

The cost of disposing of the monitoring equipment was not quantified (LCC modelling in WP2 will provide costing data upon completion). However, upon waste package disposal, there is an opportunity for the monitoring technology to remain in place and to replace partially or fully some of the disposal facility's monitoring equipment (if applicable). This opportunity was not discussed further under WP7 as it is country and facility dependent.

*Overall, the value assessment panel agreed that monitoring using the SciFi/SiLiF technology is **slightly more expensive** than visual inspection. This conclusion needs to be put into perspective, since the baseline is very close to a "do nothing" approach. Therefore, the financial cost of implementing this novel monitoring approach needs to be considered against the resulting improvements in operational and long-term safety. Such arguments are at the core of the As Low As Reasonably Practicable (ALARP) approach and remain the responsibility of each waste management or producing organisation.*

3.2 Acoustic Emissions for Measuring ASR

AE technology is a non-destructive monitoring technique used to assess the integrity of waste drums being developed by Magics (Belgium). Example processes that might induce disturbances in a waste drum include ASR in cemented packages which lead to formation of a gel-like substance that swells and causes stress development and potential cracking of the concrete. AE uses highly sensitive piezoelectric sensors (Figure 3.3) at the surface of a package. When a crack occurs, the elastic stress wave propagates through the material which could be recorded by an AE sensor. To detect such AE events, processing is needed on the continuous waveform. Given the detected events, a cumulative event count can be generated as a function of time. Further details are provided in reference [2].

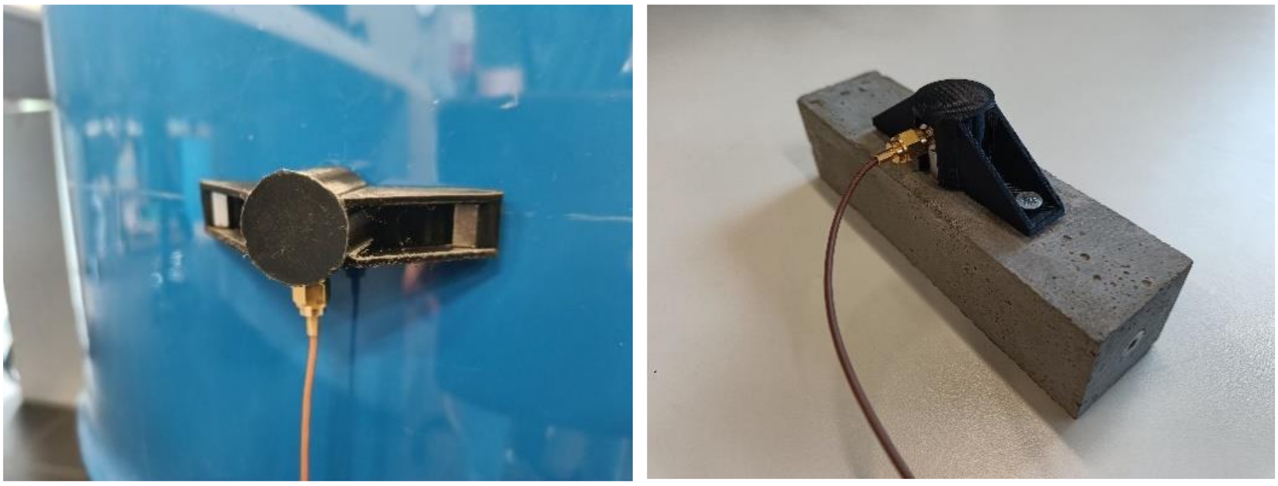

Figure 3.3: AE sensor attached to a waste drum (left) and placed on top of a concrete sample for testing (right) [2].

A summary of the value assessment ratings for AE technology assigned to the different assessment criteria in comparison to the baseline (visual inspection) is presented in Figure 3.4.

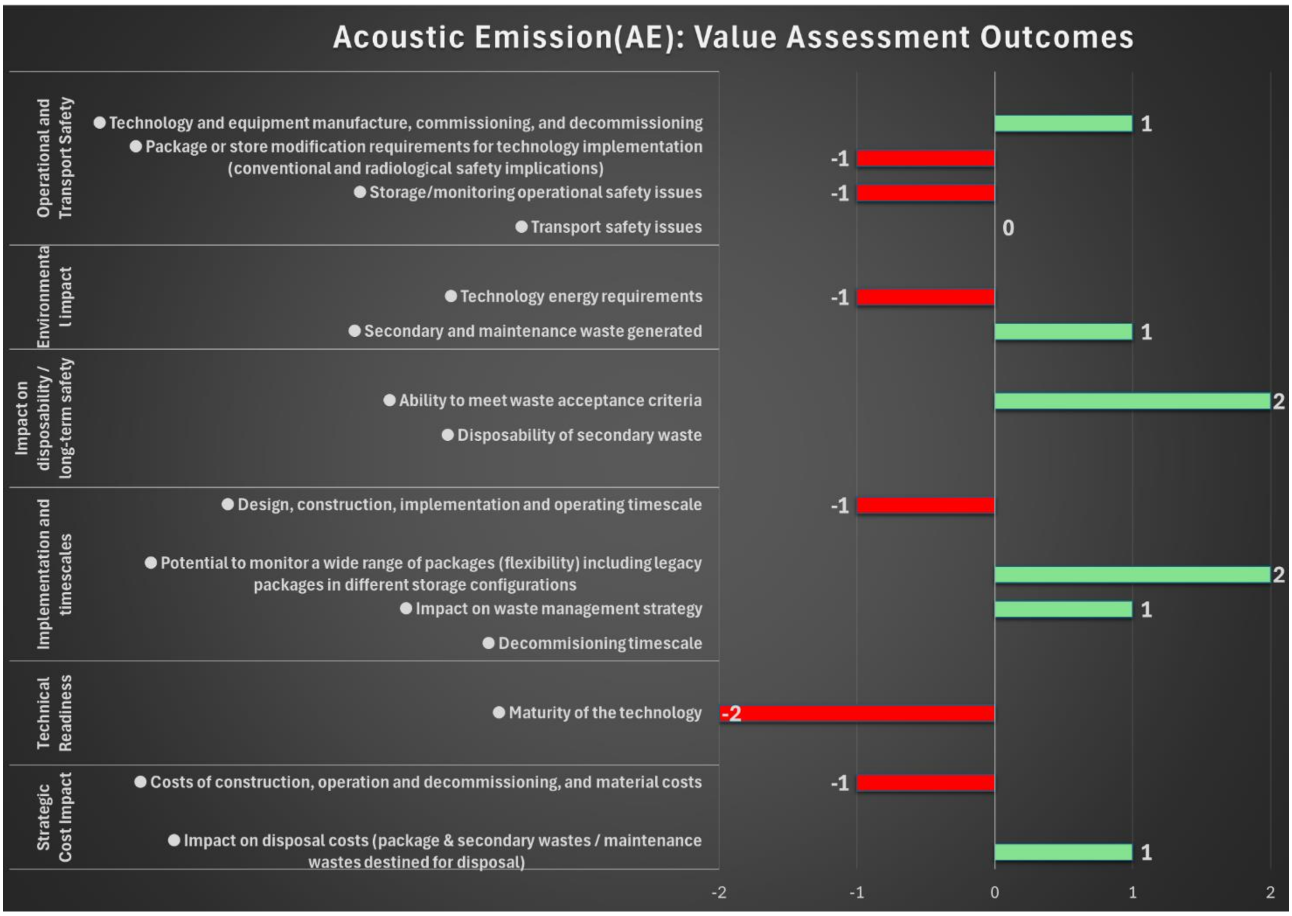

Figure 3.4: Chart of strengths and weaknesses of AE technology for measuring ASR compared with the baseline (visual inspection). The ratings are defined as: -2 (much worse than baseline), -1 (worse), 0 (neutral), 1 (better), 2 (much better).

3.2.1 Operational and Transport Safety

The main advantage of AE technology relates to its ability to facilitate a more streamlined and efficient inspection process. The technology is designed for continuous monitoring, which significantly reduces the need for visual inspections and thereby lessens labour and associated safety risks. Furthermore, data collection is automated, eliminating the need for operators to be present near waste packages to collect data using hand-held monitors, thus reducing exposure to radiological and conventional hazards.

Weaknesses relate mostly to the initial manual installation phase, which is not required under baseline assumptions. This phase comes with radiological and conventional safety risks. Additionally, infrastructural changes are necessary to accommodate the technology, giving rise to standard construction hazards. Practical constraints also arise from the need to disconnect physical sensors from their cabling if drum movement is necessary, which adds complexity and potential safety issues during operation. It is noted, however, that drum movements are not required as the measurements are continuous. There is an element of uncertainty regarding the sensors' susceptibility to radiation, which could pose a risk if not properly understood and mitigated.

*Overall, the assessment panel concluded that operational and transport safety was **slightly worse** when using the AE technology than under baseline assumptions. While AE technology brings advancements in operational safety through automation and continuous monitoring, the initial setup and potential infrastructural modifications introduce elements of risk. The requirement for manual handling during certain procedures could offset some of the safety benefits provided by the automated aspects of the technology.*

3.2.2 Environmental Impact

The environmental impact of the AE technology is closely tied to that of its components' material, and to its energy usage throughout its lifecycle. The AE sensors are small, approximately 1 cm^3 in size, and are attached to waste packages using a non-structural adhesive method (glued). These sensors connect to a data acquisition client via coaxial cables, which then relay information to a server for aggregation. The materials used in the construction of the sensors, data acquisition units, and servers include metals, plastics, and epoxy. One significant strength of this technology is that the sensors can be reused, potentially reducing waste and the need for new materials over time.

However, the AE technology requires cabling for each drum monitored, which could increase the volume of materials used, and hence the environmental footprint, depending on the number of drums that need to be monitored. Additionally, while the sensors themselves are passive, the data acquisition units require 30W per 4 sensors, and the server requires 1kW per 4 data acquisition units, indicating an ongoing energy demand during operation.

*Overall, the environmental impact of AE technology is **slightly worse** than that of the baseline. This is mitigated by the ability to reuse sensors, thus reducing material waste and resource consumption over time but this benefit is somewhat offset by the need for cabling and energy consumption during operations.*

3.2.3 Impact on Disposability / Long-term Safety

AE monitoring is a non-destructive technology and relies on placing the AE sensor outside the package. Therefore, waste package disposability is not negatively impacted by implementing this monitoring method. Waste management routes already exist for secondary waste issues.

*Overall, the impact of AE technology on disposability / long-term safety is **not considered to be an issue**. the ability to detect wasteform cracking or package swelling during storage, and/or prior to disposal is likely to make package remediation easier and can prevent store or disposal system-wide consequences upon waste package failure.*

3.2.4 Implementation and Timescales

The AE technology is highly sensitive to changes in the content of the drums, is flexible, and can potentially be applied to a wide range of package types, including legacy packages. It does not rely on prior knowledge of the waste package and might be applicable to heterogeneous wasteforms (although this has not been demonstrated to-date).

On the downside, the current reliance on wired cabling restricts the flexibility of installation, necessitating facility-specific feasibility assessments and envisioning a final wired product. The need for additional software to compare data between drums introduces another layer of complexity. There is also a risk of software obsolescence if the company that developed it stops trading. Moreover, the current setup has limited allowance for additional spacing and there is a need to filter out vibrations that are picked up by the sensors. These may pose operational challenges.

In terms of impact on waste management strategy, this technology could refine inspection processes by replacing random visual checks with targeted monitoring, thus directly influencing waste management systems. However, manual disconnection of sensors during drum movement is currently a limitation that could be addressed with a wireless solution. Decommissioning aspects remain uncertain due to a lack of experience.

*The AE technology is expected to have a **positive** impact on waste management strategies and is versatile enough to be implemented without significant delay to existing or planned waste management programmes. However, some areas require refinement and further testing (such as decommissioning and operational challenges associated with wired setups), but the assessment panel concluded that these aspects are partly counterbalanced by the ability of the AE approach to facilitate targeted inspections.*

3.2.5 Technical Readiness

The AE technology is in the prototype stage and has a TRL of 3. It has been deployed on the laboratory and drum scales in simulated conditions, but not in actual nuclear environments. Formal certification processes and regulatory requirements have yet to be addressed. Therefore, the technology requires further development, testing under realistic conditions, and engineering improvements to enhance its usability, safety, and practicality to increase the TRL.

*Further work is still needed to ensure the maturity of the AE technology for industrial application. Therefore, the technical readiness of this technology is considered to be **lower** than the baseline.*

3.2.6 Strategic Cost Impact

The economic assessment of the AE technology system relates to the costs of construction, operation and decommissioning, and material and setup costs. Each sensor is priced at €1000 and when coupled with data acquisition systems (DAQs) and servers, a configuration with 16 sensors incurs a cost of €20,000. The energy consumption is also a factor, with 1.5 kWh required per 16 sensors. Labour costs may be optimised in the future through automation, but currently, expert involvement is necessary, and periodic calibration testing adds to the operational expenses.

The impact on disposal costs (package and secondary wastes / maintenance wastes destined for disposal) is judged to be minimal, hence leading the panel to rate this cost impact as roughly neutral.

*The assessment panel concluded that, based on the evidence assembled, the strategic cost impact of the AE wireless technology is **neutral** compared to the baseline.*

3.3 Non-contact Ultrasonic Scanning

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

Air-coupled ultrasonic transduction offers a non-contact, non-destructive, and non-invasive means of inspection. To perform the required measurements using this technology, a longitudinal ultrasonic wave is emitted by the transmitter at a specific angle normal to the drum's circumference to create a Lamb wave in the drum's shell (Figure 3.5). This Lamb wave then travels around the drum circumference, emitting longitudinal waves along its path, which can be used to detect the time of flight of the Lamb wave around the drum. The pattern and angle of the Lamb waves detected by the transducer indicate the presence of defects across the circumferential direction of the package.

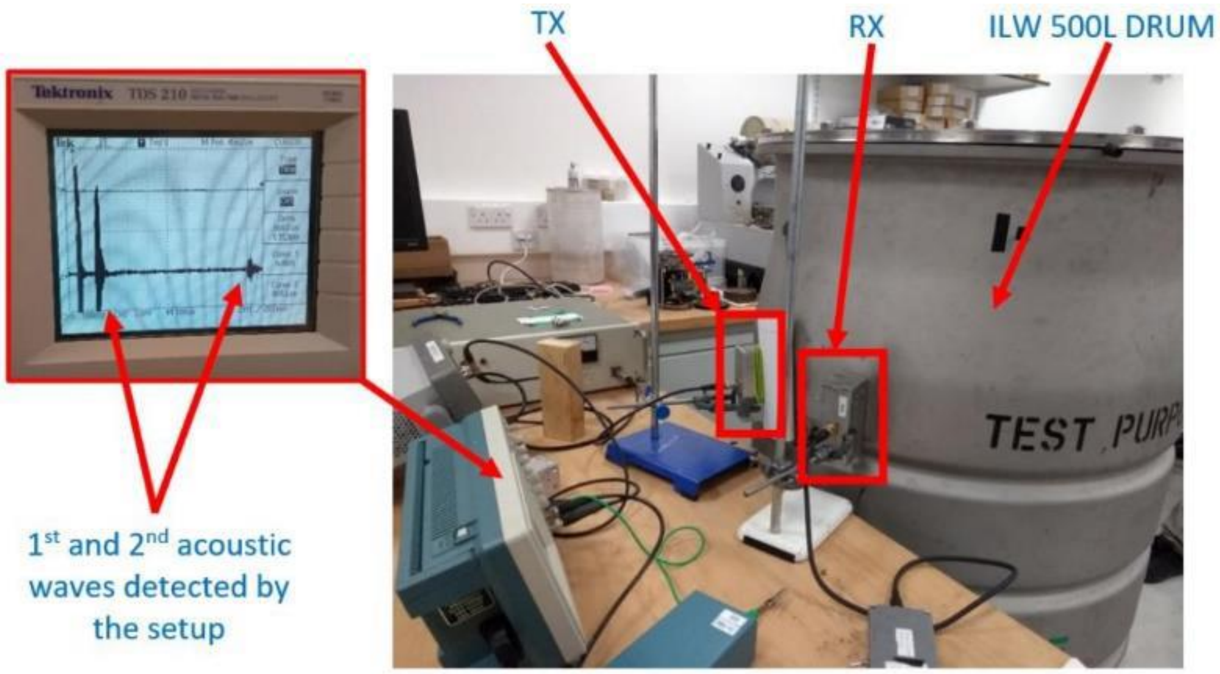

Figure 3.5: Air coupled transmitter (TX) and receiver (RX) setup generating and receiving a wave on / through the surface of an empty 500 L drum sample and an oscilloscope view of the acoustic waves detected by the receiver during the successful wave generation/detection [2].

A summary of the value assessment ratings for the non-contact ultrasonic technology assigned to the different assessment criteria in comparison to the baseline (visual inspection) is presented in Figure 3.6.

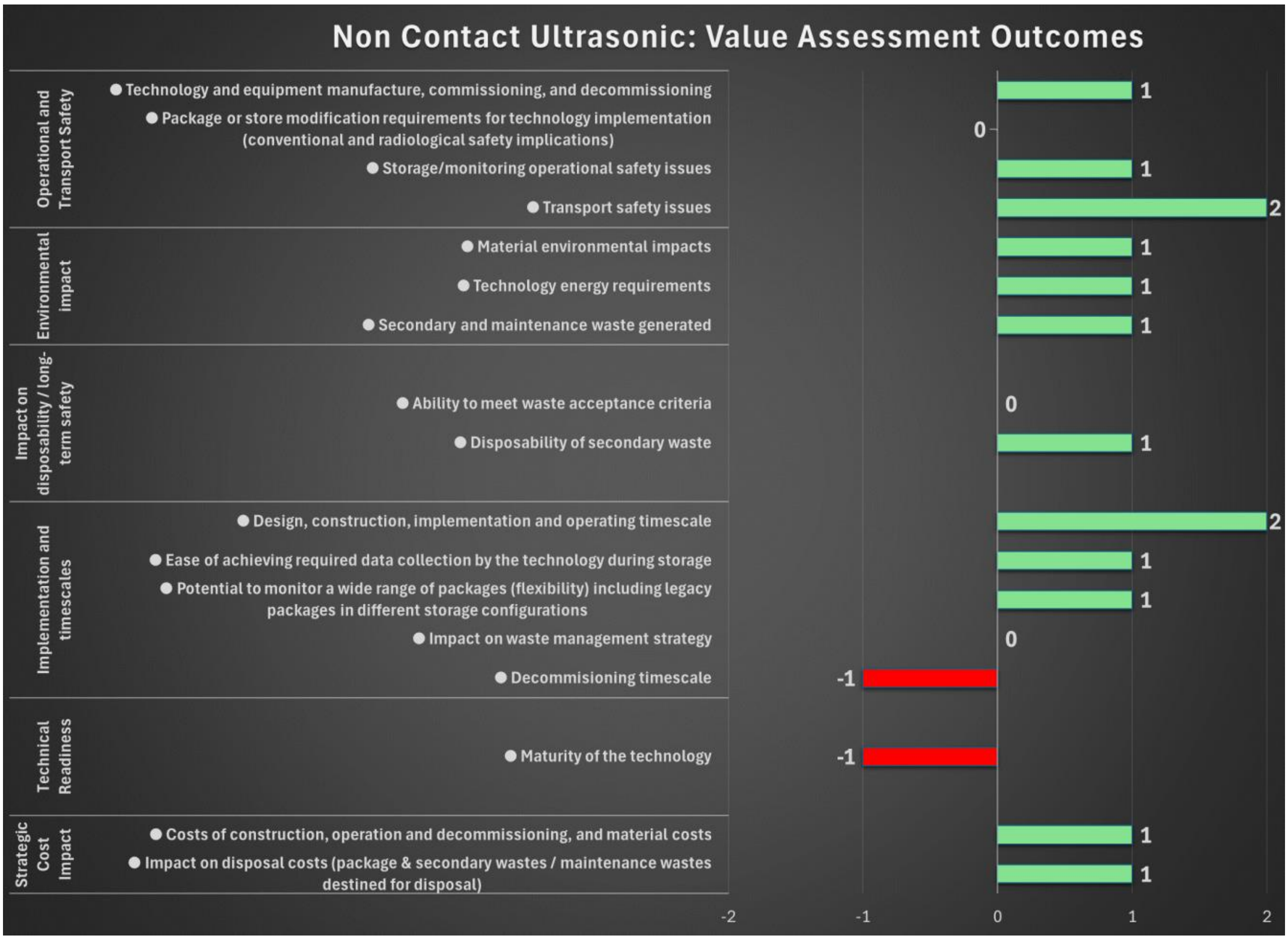

Figure 3.6: Chart of strengths and weaknesses of non-contact ultrasonic technology compared with the baseline (visual inspection). The ratings are defined as: -2 (much worse than baseline), -1 (worse), 0 (neutral), 1 (better), 2 (much better).

3.3.1 Operational and Transport Safety

As with the baseline technology, this monitoring approach does not alter the design of the waste packages or require any extra equipment inside the waste package. Unlike visual inspection, this technology can also detect subsurface defects present on the surface of the cylindrical package without changing how packages are handled. The technology can also identify defects on the package which are visually obscured, and so are not available for visual inspection. All that is required is that the transducers can access a point on the package at approximately the same height as the defect.

The technology offers another advantage that it can be used alongside existing inspection processes or near-stacked packages. However, it needs skilled workers to position the measurement tools correctly at each measurement point along the height of the package which adds some complexity to its deployment in the store.

Minor adjustments are to be expected in the storage area due to the integration of the technology and any associated deployment method into the inspection cell. If the technology is to be used while packages are still stacked, more development is needed to consider how to deploy the system (e.g., using stacker cranes). However, development of an automated or semi-automated deployment method may reduce the effort required by skilled workers. The technology does not raise any additional conventional or radiological safety concerns. However, the technology requires the installation of high-voltage transducers within the store, which will add a hazard. Data collection requires additional safety consideration since the signal needs to be captured at close range to the detector. The proposed technology is confined to operations within a store/store inspection bay, thus the packages can be safely sent for disposal with no post-storage processing requirements. The safety considerations for licensed packages during transportation are also unaffected by this technology.

*Overall, the assessment panel concluded that operational and transport safety was **better** when using the air-coupled ultrasonic technology than under baseline assumptions. It can be seamlessly integrated into existing facilities without the need for package modifications and does not impact the safety of the packages. The complexity increases during equipment installation, and commissioning needs to be balanced with the risk reduction achieved using this remote monitoring method. Quantifying this difference was not possible and requires detailed assessment; however, the value assessment panel concluded that an overall reduction in risks was the likely outcome.*

3.3.2 Environmental Impact

The environmental impact of this technology can be considered low. The technology is compact and connects directly to the existing power source in the store, reducing the need for additional infrastructure. However, the exact energy consumption remains unknown. Further, it can be easily replaced or repaired, reducing its impact on generating secondary waste. The system includes materials like electronics, metals, and plastics, with disposal assumed at the end of its 2- to 3-year lifespan. Any deployment method developed, including the one demonstrated with robotic manipulators, may add to the end disposal requirements.

Overall, this technology shows efficiency and effectiveness over the baseline technology with low environmental consequences, though careful consideration must be given to deployment techniques to quantify their long-term impact.

Air-coupled transducers eliminate the need for contact or fluid media, which reduces waste generation when compared against other similar technologies. Long-term waste generation could be reduced even further through selective radiation hardening of sensitive components which minimises the need for their maintenance or replacement. Additionally, interchangeable equipment allows for targeted maintenance without replacing the entire system, minimising waste. Nonetheless, a specific maintenance strategy is required for both the device and its deployment method, which adds to baseline activities.

*Overall, the environmental impact of air-coupled ultrasonic technology is **more favourable** than the impact induced by the baseline. Its ability to reuse sensors is an environmentally favourable aspect that could reduce material waste and resource consumption over time, but it does need a specific maintenance strategy, which needs to be assessed with its impact.*

3.3.3 Impact on Disposability/Long-term Safety

This technology meets the waste acceptance criteria without affecting them. It supports the assessment of package integrity for store operations, not by influencing the contents of the package itself but rather documenting its structural integrity to ensure its safe storage throughout the interim period.

There are no anticipated secondary wastes associated with the technology apart from operator personal protective equipment (PPE) used during maintenance.

*Overall, the value assessment panel concluded that this technology is **slightly better** in terms of disposability and long-term safety when using air-coupled ultrasonic technology compared to baseline assumptions. It aligns with the waste acceptance criteria, but the secondary waste can come from the operator's maintenance of the store or technology which needs consideration.*

3.3.4 Implementation and Timescales

The advantage of this technology over other technologies lies in its adaptability, which is due to it being a commercially available system that can be adjusted based on the deployment requirements. Any deployment method developed will need to be accurate enough to ensure correct positioning of ultrasonic transducers and receivers. Licencing is not expected to pose a challenge, as the system conforms to safety standards and does not require regulatory approval. It would need to undergo a standard Provision and Use of Work Equipment Regulations (PUWER) assessment before deployment, alongside other relevant design and safety assessments specific to the location in which the technology will be deployed.

Deployment methodology could limit the assessment of the waste package. Data collection is not continuous, requiring effort to deploy the technology to stacked packages or bring packages to an inspection area. Nonetheless, this technology includes additional modules for deployment (such as robotic arms or stacker crane systems) adding complexity to the commercially available system and increasing technology development timescales. While operating timescales for obtaining information are short in commercial software, interpretation requires expert knowledge, potentially slowing down the development process. Development may be required optimise preparation of the data for operator evaluation, reducing effort and skill required by the operator.

The duration of measurement is brief, with results visible within seconds due to seamless data processing. It measures parameters (with quantitative accuracy and minimal error) necessary for waste package management to determine the structural integrity during storage, including features that can signal localised corrosion, general corrosion, wall thickness differences and dents. The technology is standalone and compatible with legacy and new waste. It can potentially monitor a wide range of packages, including legacy waste, with no need for new conditioning processes due to its ease of installation.

Although this technology is effective across a wide array of conditions, its effectiveness may be limited when the contents of the drum have swelled enough to make contact with the drum. This is due to potential dispersion of the lamb wave away from the drum skin and into the drum contents, weakening the signal. Further development of the solution will confirm its effectiveness in these conditions.

Once commissioned, this technology is expected to be available as and when required, taking more accurate and repeatable measurements than the baseline. Should a deployment method be developed, then the technology could yield even greater benefits.

*The air-coupled ultrasonic technology has a **lower** impact on implementation and timescale aspects than the baseline approach. While there are areas that require refinement and further testing (such as decommissioning and integration into the existing system), the assessment panel concluded that these aspects are partly balanced by the ability of the air-coupled ultrasonic approach to facilitate targeted inspections, its interoperability, and its adaptability to various waste types.*

3.3.5 Technical Readiness

The PREDIS scope is to progress the combination of non-contact ultrasonic to TRL 5. While the non-contact ultrasonic detectors themselves are at TRL9, indicating a high level of maturity, further trials are needed to confirm their readiness for deployment in a nuclear environment. Development of a deployment method will also limit the TRL of the complete solution. The combination of ultrasonic measurements with stereo imaging techniques shows promise, but it is still undergoing active research, which indicates its continuous growth.

*Technical readiness of this technology is considered **lower** than the baseline. It requires further development, testing under realistic conditions, and engineering improvements to enhance its usability, safety, and practicality.*

3.3.6 Strategic Cost Impact

This technology offers cost-saving benefits across multidisciplinary nuclear sectors. Commercially available non-contact ultrasonic sensors require minimal development before deployment. However, the main costs associated with further R&D is linked to the selected deployment method for the technology. This includes any hardware required to position the devices and the necessary software required to assess and translate the signal captured by the transducer system, such that it can then be easily interpreted by operators. Installation costs for ultrasonic methods are low, and energy consumption during operation is minimal. Decommissioning costs are also low as the technology involves a single system with no secondary waste generation, and there is a potential for reusability of this technology.

*The assessment panel concluded that, based on the evidence assembled, the strategic cost impact of the non-contact ultrasonic technology is **slightly lower** than the cost under the baseline assumption.*

3.4 RFID Embedded Sensors

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

The sensing system is made of a chain of small units, called SensorNodes (Figure 3.7). Each SensorNode includes two off-the-shelf sensors, with one for relative humidity and temperature and one for pressure and temperature. A SensorNode is designed to have a unique identifier to be connected to other units while being uniquely discoverable by a standard communication protocol. In this way, a distributed matrix of measurement points is created. Further details are provided in reference [2].

Figure 3.7: A SensorNode of the sensing system developed by BAM [2].

A summary of the value assessment ratings for RFID embedded sensors assigned to the different assessment criteria in comparison to the baseline (visual inspection) is presented in Figure 3.8.

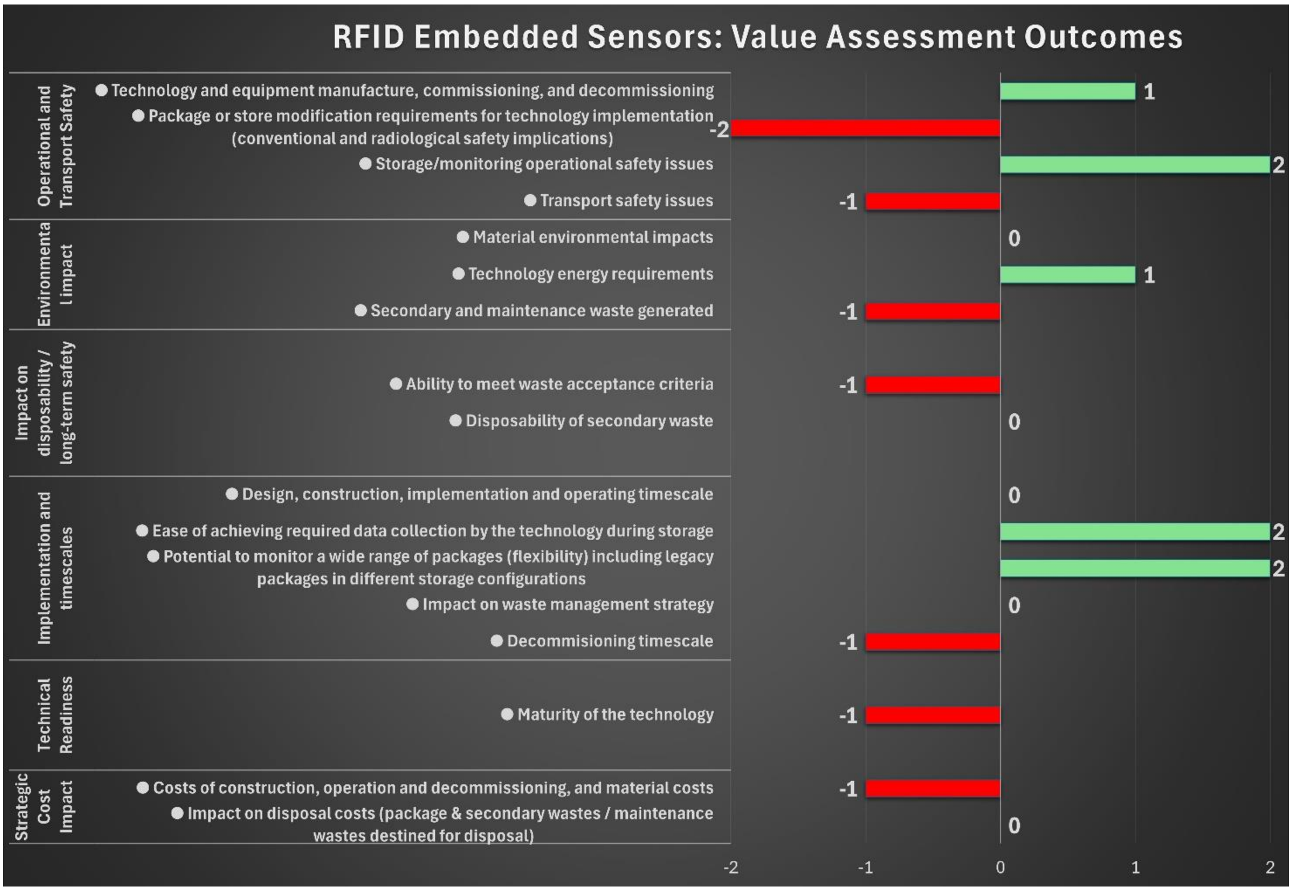

Figure 3.8: Chart of strengths and weaknesses of RFID embedded sensor, compared with the baseline (visual inspection). The ratings are defined as: -2 (much worse than baseline), -1 (worse), 0 (neutral), 1 (better), 2 (much better).

3.4.1 Operational and Transport Safety

RFID embedded sensors improve safety and regulatory compliance during both storage and transport. With remote data collection, it reduces operator exposure to hazards and enables early detection of potential issues, facilitating proactive risk management. Additionally, it assures regulatory compliance and improves emergency response readiness during transport.

However, the construction and decommissioning of these sensors require specialised resources and expertise, which can increase costs. Decommissioning also poses contamination risks and challenges during sensor removal. Modifying or removing the technology from concrete-filled drums is invasive and complex, made more difficult by the package design and technology accessibility. This process may also require strict radiation shielding and decontamination procedures, further increasing complexity and time. While the sensors improve safety, the introduction of new materials, such as polymers, could lead to gas release or container corrosion, altering waste hazard risk. Improper handling of packages, despite the technology's benefits, could still result in accidents if not mitigated by specific training procedures.

*Overall, the impact of RFID embedded sensors on operational and transport safety is assessed as **neutral** when compared to the baseline visual inspection approach. Whilst the sensors provide benefits, such as data and early detection, implementation challenges offset these advantages. These challenges include increased complexity and costs due to the need for specialised resources and expertise in construction and decommissioning. Contamination risks and structural vulnerabilities also present safety concerns. Introducing new materials may pose issues, emphasising the need for rigorous handling and specific training to manage risks.*

3.4.2 Environmental Impact

The environmental impact of RFID embedded sensors is influenced by various factors. The choice of materials is significant; selecting environmentally friendly options can reduce potential harm. Sustainable manufacturing practices are critical, as producing sensors may generate waste and emissions. Proper disposal is also essential at the end of the sensors' life cycle to minimise pollution and resource depletion.

The sensors themselves have a limited direct environmental impact, but their entire life cycle must be considered. The energy consumption of the technology is low; one measurement cycle for each node requires about 0.4mAs (20mW x 60ms). No additional waste is produced during its use. However, extracting sensors from concrete can be challenging and energy-intensive, and sensors are likely to be damaged during the process, preventing their recovery. A life cycle analysis is necessary to identify options for minimising environmental harm. Additionally, modifications to the sensor arrangement may require cable changes but do not consume additional materials.

*The environmental impact of RFID embedded sensors is assessed as **neutral** when compared to the baseline approach. The limited direct impact of the sensors and the potential for sustainable practices in their manufacturing and disposal presents a positive outlook.*

3.4.3 Impact on Disposability / Long-term Safety

The incorporation of RFID embedded sensors into waste packaging offers enhanced monitoring capabilities. However, it also introduces potential challenges that regulators and waste management organisations must address to ensure that the waste continues to meet acceptance criteria and can be safely disposed of in accordance with applicable regulations.

A key concern is ensuring that sensors do not negatively impact the long-term integrity of the waste package or the disposal facility. Embedded sensors should not compromise the structural integrity of the concrete or contribute to corrosion, and they must be chemically compatible with the waste and packaging materials to prevent reactions or degradation over time. The placement and type of sensors are important factors, as they could influence the radiation shielding properties of the waste package, requiring additional evaluation to ensure compliance with radiation protection standards.

*The assessment panel stated the **need** to conduct additional evaluations regarding the impact of the embedded sensors on the long-term safety of waste packages. Without these assessments, the impact of RFID embedded sensors on disposability / long term safety could be **higher** than the baseline. Further work could mitigate this impact, potentially reducing to a level similar to the baseline approach.*

3.4.4 Implementation and Timescales

One key strength of the RFID embedded sensors is that no modifications to the existing storage infrastructure are necessary, and sensor housing can be securely embedded without major structural changes. Proper design ensures the technology's reliability during the interim storage period. The sensors provide crucial data, including pressure monitoring within concrete drums, which aids in assessing structural integrity and potential leakage. This continuous monitoring enhances safety and offers real-time insights. Furthermore, the technology is flexible and can be adapted to different configurations.

The type of waste and the environmental conditions can affect sensor lifespan requiring more effort in case of malfunctioning of the sensors. Obtaining operational licensing can also be complex due to stringent safety and environmental regulations, which vary across jurisdictions. The implementation of this technology may impact the available storage area, and the use of embedded sensors may affect waste disposal strategies by limiting options or requiring additional steps for package disposal.

*Implementation of the RFID embedded sensors and its impact on timescales was considered to be **better** than that of the baseline approach. The technology can be seamlessly integrated into existing infrastructure without any modifications, ensuring a smooth adoption process. Its flexibility in design allows for customisation to meet the challenges of interim storage, and the sensors' reliability is assured through continuous monitoring and data collection. Furthermore, the sensors' ability to provide crucial data on pressure and storage environment offers enhanced safety and efficiency.*

3.4.5 Technical Readiness

Currently, the technology is at the pilot scale, having been developed and tested within PREDIS. While this indicates a certain level of maturity, particularly regarding the sensors and equipment, full-scale implementation in a storage facility would require further refinement and optimisation. This includes addressing compatibility issues with waste conditioning and disposal criteria, as well as optimising the impact on the storage area.

One of the challenges lies in the limited number of suppliers for this technology, which can affect its maturity and reliability. However, the sensors themselves are mature, indicating that the core functionality is established and ready for integration.

*Technical readiness of RFID embedded sensors is considered to be **lower** than the baseline. With further development, the sensors should overcome current limitations that relate to the restricted market.*

3.4.6 Strategic Cost Impact

At the laboratory level, the RFID embedded sensors approach exhibits promising cost efficiency. Negligible material costs and relatively low personal expenses for prototype construction make it an economically viable option for initial testing and development. However, the procedure's complexity demands technical expertise, requiring experienced individuals, which can result in higher labour costs.

Upon transitioning to a full-scale implementation, the costs associated with this technology increase significantly. The setup process is labour-intensive, and the need for skilled personnel to ensure proper sensor embedding drives up expenses. With each additional waste package monitored, the costs escalate, emphasising the strategic challenge of determining the optimal monitoring coverage in a repository to balance reliability and financial constraints.

The assessment panel concluded that the strategic cost impact of the RFID embedded sensors is ***slightly worse*** *than under baseline assumption. While the approach offers promising cost efficiency in the initial experimental stages, the strategic cost impact becomes less favourable when scaling up the technology. The surge in costs is mainly associated with setup, maintenance, and skilled labour requirements.*

3.5 Sensorised LoRa Wireless Sensor Network

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

The proposed Wireless Sensor Network (WSN) consists of three integrated levels as presented in Figure 3.9. The first layer comprises LoRa Nodes responsible for package identification and radiation data collection from within the waste package, facilitating monitoring of the waste drums' structural condition. The second layer, LoRa Gateways, manages the LoRa traffic and forwards the data to local storage or cloud-based applications, employing a Message Queuing Telemetry Transport (MQTT) broker. These gateways also synchronise all nodes using acknowledgment radio payloads to prevent data transmission collisions. Finally, the third layer is a Cloud-based platform, implemented through an Azure IoT Central application, facilitating remote access and data processing.

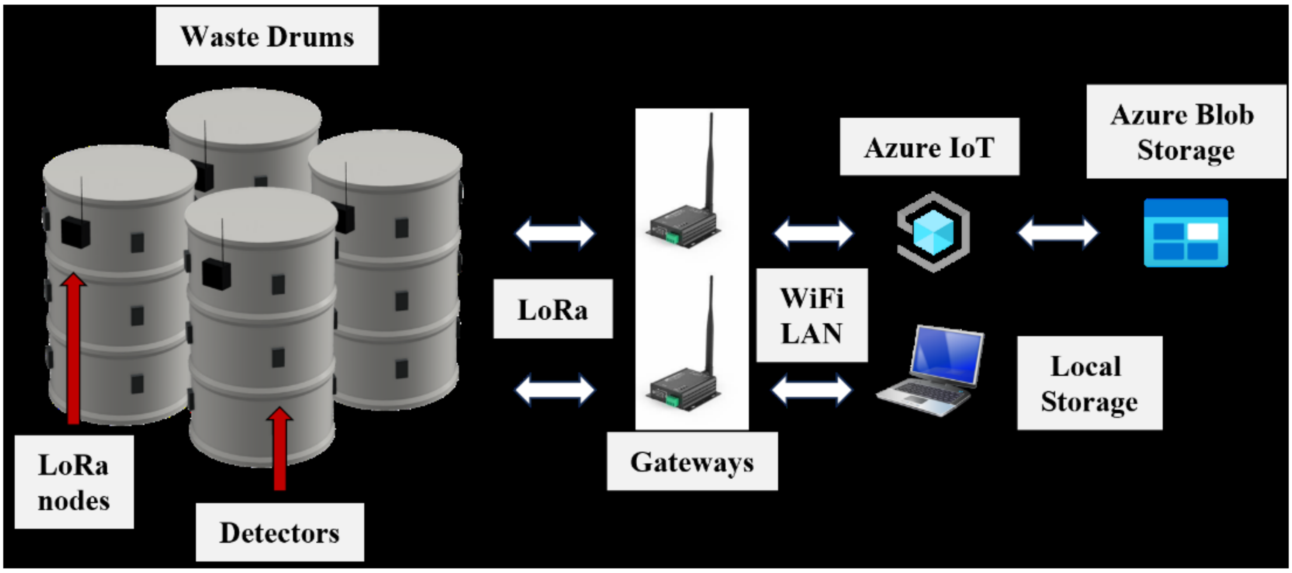

Figure 3.9: Radiation monitoring framework for radioactive waste drums [2].

A summary of the value assessment ratings for Sensorised LoRa wireless sensor network technology assigned to the different assessment criteria in comparison to the baseline (visual inspection) is presented in Figure 3.10.

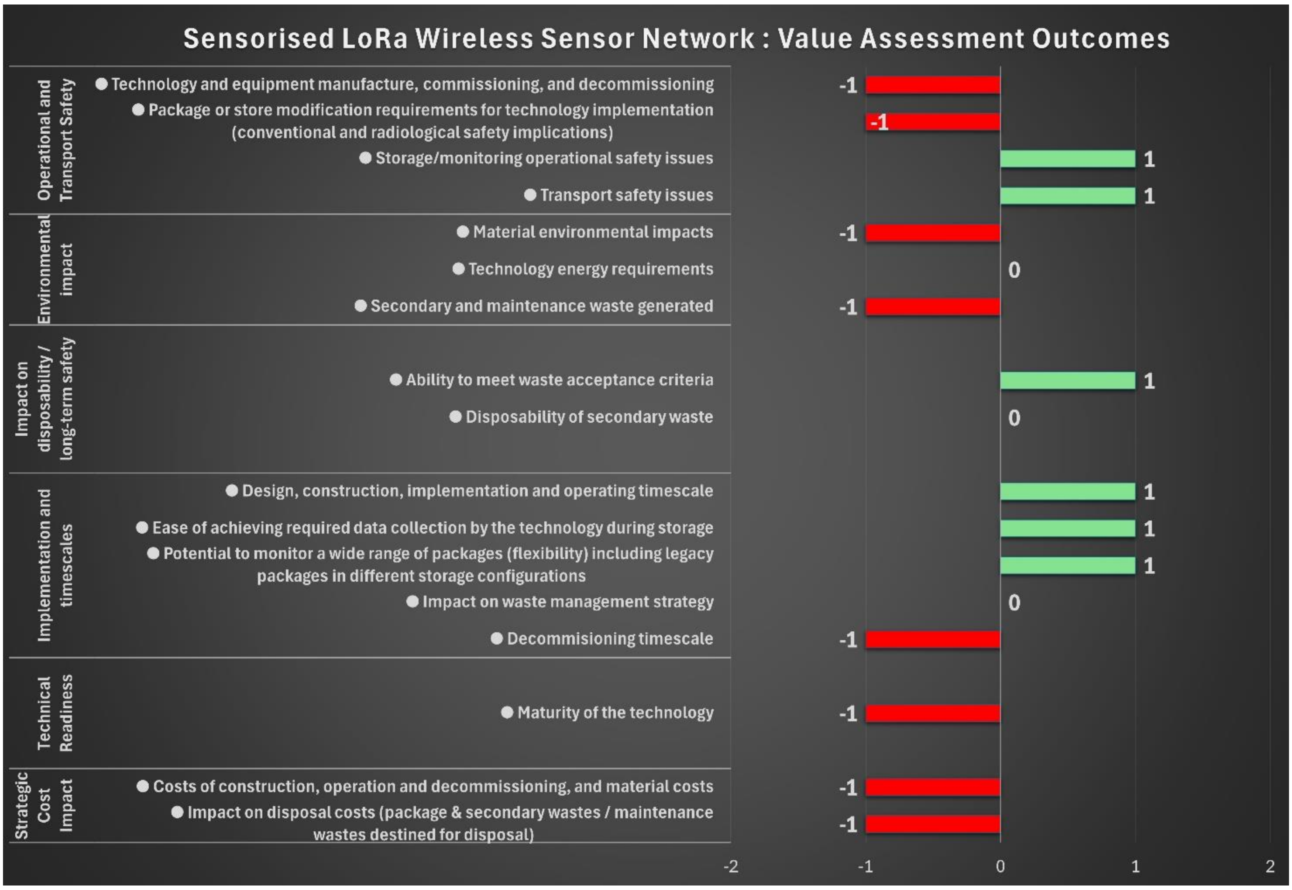

Figure 3.10: Chart of strengths and weaknesses of Sensorised LoRa wireless sensor network technology compared with the baseline (visual inspection and manual dose rate measurement). The ratings are defined as: -2 (much worse than baseline), -1 (worse), 0 (neutral), 1 (better), 2 (much better).

3.5.1 Operation and Transport safety

The technology presents a notable reduction in complexity and hazard exposure throughout its lifecycle due to its simplified construction processes and modular sensor deployment. During commissioning or decommissioning period, this technology mitigates risks associated with both radiological and non-radiological hazards. Its long-term, maintenance-free operations are coupled with remote calibration, and they enhance safety by minimising worker interaction within the contaminated areas. Furthermore, safety is enhanced during post-monitoring steps, as the sensors are detachable and non-invasive, which simplifies disposal processes. Challenges arise due to the need for technical expertise in wireless technology for installation, which may delay its deployment in facilities.

Despite these challenges, the technology offers several strengths, such as reducing worker exposure to radiation through remote monitoring capabilities. Due to their compact and lightweight nature, these sensors minimise transport-related accident chances, although challenges remain in the initial transport and occasional movement during installation or maintenance.

*Overall, the assessment panel concluded that, based on the evidence assembled, operational and transport safety were **similar** between the sensorised LoRa wireless sensor network technology and the baseline assumptions. Challenges include the need for expertise for data management, and complexities in decommissioning. The requirement for initial manual handling during certain procedures could offset some of the safety benefits provided by the automated aspects of the technology.*

3.5.2 Environmental Impact

The simplified construction process of this technology and the focus on using reusable components effectively minimise waste generation and enhance sustainability. In terms of energy efficiency, the technology shows technological enhancements and operational efficiency with its low consumption across its lifecycle. Yet, challenges such as initial setup energy consumption need to be addressed. Nevertheless, the potential for renewable energy utilisation highlights its environmental advantages, despite its current reliance on non-renewable sources.

Secondary and maintenance waste generated has challenges (e.g., battery disposal) and processing recyclable waste from decommissioning remains a necessity. Additionally, specialised treatment for various wasteforms generated during maintenance would require specific treatment process to be considered which ensures minimal contamination levels in secondary waste.

*Overall, the environmental impact of this technology is **slightly worse** than the impact induced by the baseline. Its ability to adapt sustainable materials and methodology is an environmentally favourable aspect that could reduce material waste and consumption over time, but this benefit is somewhat offset by the need for battery disposal and energy consumption during initial operation.*

3.5.3 Impact on Disposability/long-term Safety

This technology improves waste package management, ensuring safety through better handling without inspections, thus minimising secondary waste generation. However, potential modifications for sensor attachment may impact package handling and integrity, raising concerns about integrity and corrosion resistance. Disposal of non-permanent sensors poses challenges in managing secondary waste and may affect package chemistry and durability. Ensuring sensor accuracy and reliability for critical safety decisions remains a concern, potentially impacting waste acceptance criteria compliance.

This technology excels in the disposability of secondary waste by minimising its generation through durable design and minimal maintenance. Despite various advantages, certain components may require specific treatment, adding complexity and potentially increasing the waste management process.

*Overall, the value assessment panel concluded that this technology is **slightly better** in terms of disposability and long-term safety when using Sensorised LoRa wireless sensor network technology compared to baseline assumptions. It meets the compliance with regulations and monitors package integrity. While excelling in secondary waste disposability through durable design and recyclable components. Challenges remain with potential modifications for sensor attachment and ensuring sensor accuracy for critical safety decisions.*

3.5.4 Implementation and Timescales

This monitoring technology can be quickly deployed and scaled up, thanks to its use of off-the-shelf components and LoRa technology. Commissioning processes are streamlined with shorter inactive and active periods, and the sensor's durability ensures long-term operational efficiency with minimal maintenance needs. Concerns include the technology's lifetime due to continuous radiation exposure and battery shelf-life impact.

In achieving the required data collection during storage, through automated, long-term monitoring of gamma and neutron dose rates, the technology ensures quantitative analysis of structural changes. Its scalability and modular design allow seamless integration across various storage areas, enhancing flexibility. Yet, challenges exist in managing complex data and addressing measurement limitations (e.g., limited package coverage). Its compact detectors allow for remote monitoring, supporting non-destructive analysis and customisable integration times. However, challenges exist in measuring complex and heterogeneous packages which may require advanced spectral analysis, not available on the platform.

In terms of the waste management strategy, the technology minimises the need for operators. It requires them only for installation and eliminates the necessity to move packages for monitoring. Challenges emerge concerning space limitations for sensor attachment and antenna placement, disposal complexities, and potential sensor detachment during package movements. Lastly, decommissioning timescales are slightly worse due to contamination risks and necessary equipment detachment, despite infrastructure components not needing disposal.

*This technology induces a **lower** impact on implementation and timescale aspects than the baseline approach. While there are areas that require refinement and further testing (such as decommissioning and operational challenges associated with detector setup), the assessment panel concluded that these aspects are partly counterbalanced by the ability of this technological approach to reduce radiological risks and its adaptability to various waste types.*

3.5.5 Technical Readiness

This technology is at an estimated TRL of 5/6, demonstrating promising maturity, having undergone pilot-scale deployment with successful lab tests. Its ease of installation, reliability, and validated model contributed to its readiness, with the high availability of integrated circuits ensuring consistent performance. Additionally, it has been implemented at the industrial level as LoRaWAN, with feasibility studies and publications supporting its implementation in industrial facilities. Despite these strengths, the technology is still in the refinement stage, with further testing needed to assess its reliability in real storage facilities.

Certain weaknesses need to be addressed for the technology to be used industrially. Although deployed at the pilot scale, it lacks real-world deployment in storage facilities with many packages.

Managing a large number of units poses challenges such as data collision and interface implementation. Reliability needs to be assessed in real networks and storage facilities, particularly concerning package movement.

*Technical readiness of this technology is considered **lower** than the baseline. It requires further development, testing under realistic conditions, and engineering improvements to enhance its usability, safety, and practicality.*

3.5.6 Strategic Cost Impact

Each unit, inclusive of hardware and software, is priced at approximately €2000, with an estimated lifespan of 5 to 10 years. Industrial-scale development costs around €100,000 in R&D, less than the €35,000 per unit for detectors like the Inspector for Gammas and Neutrons. Operational cost (physical installation) is less than €1000 per unit and IT systems for data management and network infrastructure exceeds €50,000. Maintenance expenses could go up to €6000. However, Energy costs remain low, at less than 5 kW for the entire network infrastructure, primarily for servers and databases, along with battery expenses.

The baseline solution predicts lower construction costs per unit, requiring only a few handheld detectors, while commercial detectors, albeit pricier, offer more features without requiring additional R&D. Through operations, the baseline solution is more cost-effective, as it doesn't require installation on packages or complex network implementation, and its simpler data management software reduces expenses. However, weaknesses arise regarding secondary radioactive wastes, which may become contaminated, increasing disposal costs. The risk of activation or contamination for secondary waste is higher than the baseline, necessitating extra steps and expenses for detachment, assessment, and decontamination during disposal.

*Overall, the value assessment panel agreed that monitoring using this technology is **more expensive** than visual inspection. This conclusion needs to be put into perspective, since the baseline is very close to a “do nothing” approach. Therefore, the financial cost of implementing this novel monitoring approach needs to be considered against the resulting improvements in operational and long-term safety. Such arguments are at the core of the ALARP approach and remain the responsibility of each waste management or producing organisation.*

3.6 Muon Tomography

The Muon Tomography (Mu-Tom) technique is an interesting and promising method for investigating the internal composition of cemented drums in a non-destructive manner. It is being tested in PREDIS by INFN. This technique uses muons produced by cosmic rays, which are highly penetrating particles capable of traversing matter without being absorbed. The interaction of muons with matter through Multiple Coulomb Scattering affects their trajectories. The distribution of the diffusion angles depends on the density, the atomic number and the thickness of the materials being traversed. By analysing the scattering angles, Mu-Tom allows exploration of the inner contents of radioactive waste drums without the need for destructive intervention. The system consists of two muon detectors placed about 3 m apart from each other (Figure 3.11). The technique is capable of producing 3D images and scanning the object at different horizontal layers using a 3D reconstruction algorithm (although the current apparatus is not optimised for the vertical coordinate). Further details are provided in reference [2].

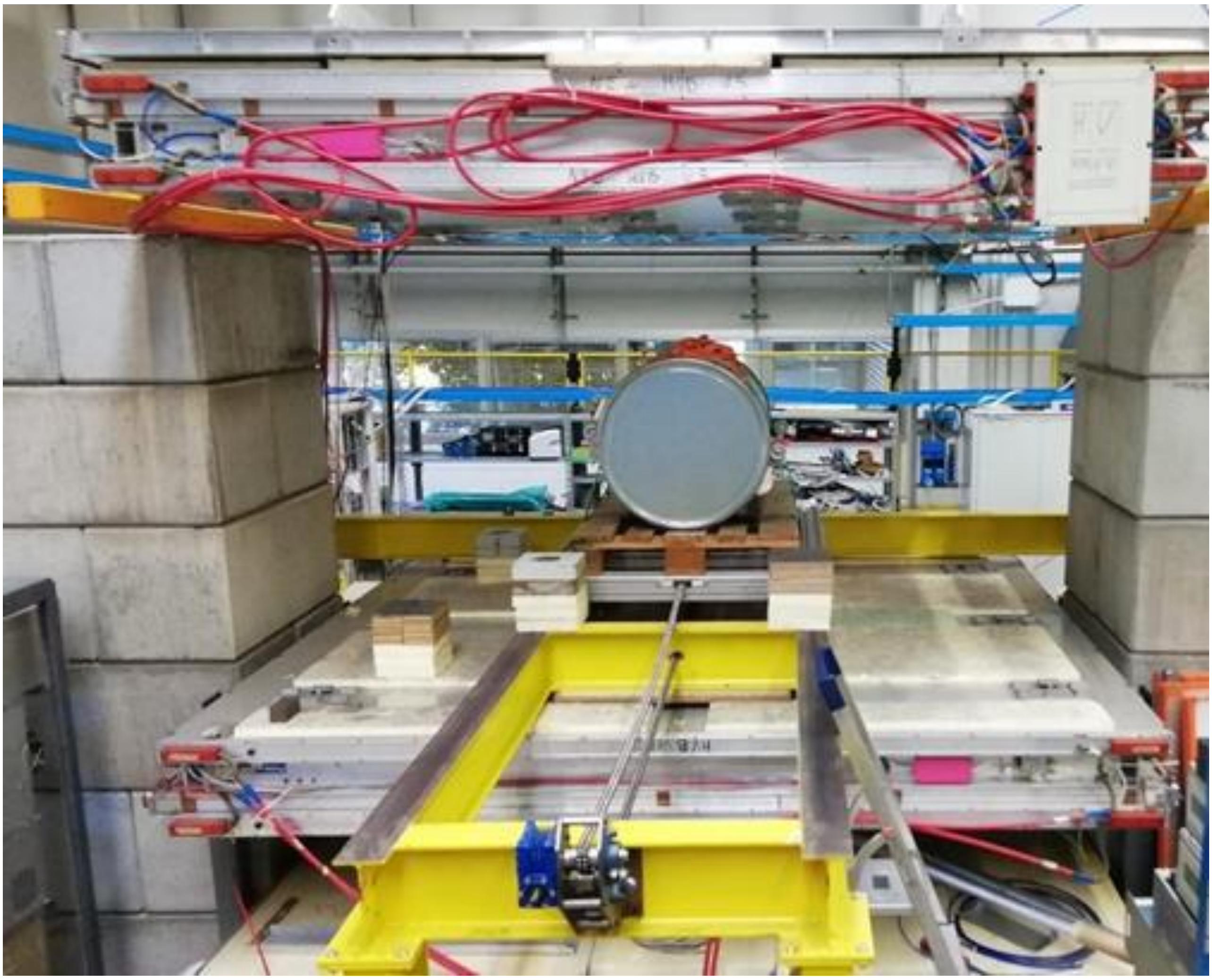

Figure 3.11: A picture of the mock-up produced by UJV installed in the INFN Padova Mu-Tom demonstrator. The two muon detectors are above and below the waste drum.

A summary of the value assessment ratings for Mu-Tom assigned to the different assessment criteria in comparison to the baseline (X-ray imaging) is presented in Figure 3.12.

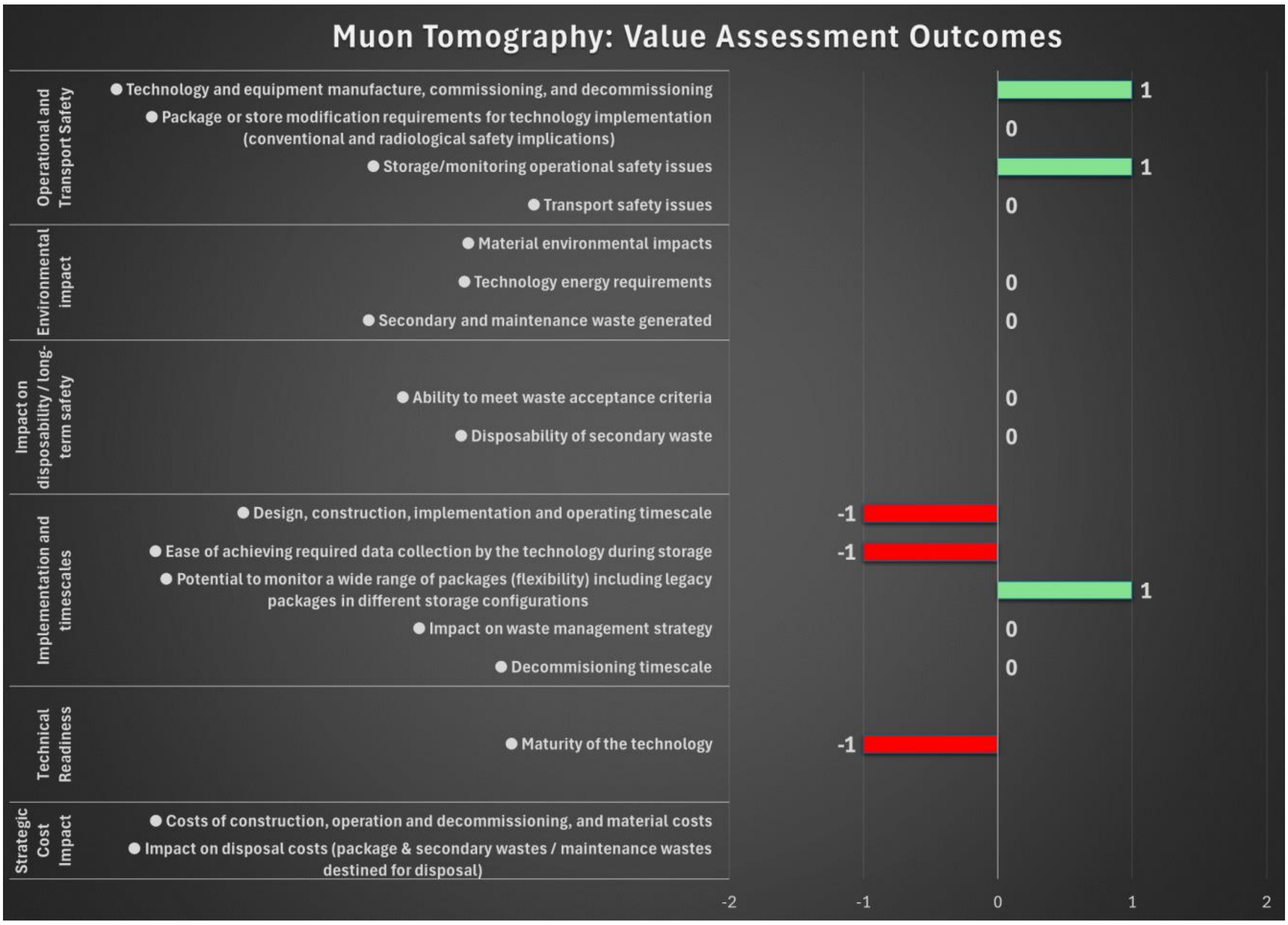

Figure 3.12: Chart of strengths and weaknesses of Mu-Tom, compared with the baseline (X-ray imaging). The ratings are defined as: -2 (much worse than baseline), -1 (worse), 0 (neutral), 1 (better), 2 (much better).

3.6.1 Operational and Transport Safety

One of the primary advantages of Mu-Tom lies in its radiation safety. Unlike X-ray imaging (baseline), Mu-Tom does not require any radiation safety protocols or concerns about radiation doses for workers. This is because Mu-Tom utilises naturally occurring cosmic ray muons, which do not emit harmful radiation like X-rays. As a result, Muon-Tom simplifies decommissioning processes and direct disposal options, making it a safer and more straightforward choice in terms of radiation hazard management.

Furthermore, the muon detectors can be operated and controlled remotely, eliminating the need for operators to be physically close to the detectors and avoiding any potential radiological hazards, which enhances operational safety during storage and monitoring.

Mu-Tom and X-ray imaging have comparable levels of complexity in their construction processes, likely requiring similar equipment such as cranes. They also share similarities in terms of package modification requirements, as the waste drums need to be transported between storage and the detector for both methods, presenting identical hazards.

*The assessment panel concluded that operational and transport safety is **slightly better** when using the Mu-Tom technology than with the baseline. Although construction complexities and package modification requirements are similar to X-ray imaging, the strength of Mu-Tom lies in eliminating radiation hazards for workers during operations and decommissioning, thanks primarily to its reliance on naturally occurring muons.*

3.6.2 Environmental impact

The construction of muon detectors primarily utilises aluminium, stainless steel, and minimal plastics for cabling and high voltage insulation. The gas mixture of Ar and CO_2 is derived from the atmosphere, and standard electronic components are used without batteries. This simplicity of materials and their reusability potential mean that muon detectors can be recycled, reducing environmental waste. On the other hand, the material impact of the baseline X-ray imaging technology is difficult to evaluate and remains undetermined at the time of the assessment.

In terms of energy requirements for Mu-Tom, electric power consumption is estimated at 1 kW for detector operation and data acquisition, and 0.5-1.0 kW for data storage and analysis. While there is no specific data for the baseline method, it is presumed to have similar energy needs. Importantly, neither system generates waste during their operational cycles.

*The environmental impact of the Mu-Tom approach is assessed as **neutral** when compared to the baseline approach. The recyclability and reusability of its constituent materials, along with its energy requirements, suggest a well-understood and manageable environmental impact. The lack of waste generation during operations is also a positive feature shared by both technologies. A more detailed analysis of the baseline X-ray imaging method would enable a more definitive conclusion regarding the environmental advantages of each approach.*

3.6.3 Impact on Disposability / Long-term Safety

Both Mu-Tom and the baseline technology can detect and measure the metallic content inside cemented drums. However, neither method can identify cracks or voids unless they are significantly large; further studies are required in this regard.

Both Mu-Tom and the baseline method exhibit limited secondary waste production. The potential waste generated primarily consists of replaceable electronic components, such as failed electronics boards, which can be treated as standard electronics waste. Additionally, computers, monitors, and data storage devices may need to be replaced due to obsolescence.

*The impact of Mu-Tom on disposability / long-term safety is assessed as **neutral** when compared to the baseline approach. Both Mu-Tom and the X-ray imaging baseline have similar capabilities in detecting metallic content, similar limitations in identifying smaller cracks and voids, and limited secondary waste production.*

3.6.4 Implementation and Timescales

Currently, Mu-Tom has not yet reached full industrial scale, which could be a potential drawback in terms of immediate applicability. However, both Muon tomography and the baseline method share similarities in their data collection processes, creating 3D reconstructions of the metallic content within cemented drums through offline data analysis.

One key difference lies in the data acquisition time, with Mu-Tom requiring significantly longer data collection times, which could impact storage procedures. Nevertheless, Mu-Tom exhibits greater flexibility in monitoring various package configurations, accepting different geometries, dimensions, and materials, including mixed compositions. This advantage of Mu-Tom eliminates the need to move the object under inspection and prior knowledge of waste content. Any movement of drums during inspection for both Mu-Tom and the baseline approaches impacts waste management strategies and requires dedicated detector areas.

Implementation of Mu-Tom and its impact on timescales was considered to be ***slightly worse*** *than that of the baseline approach. While it offers flexibility in package monitoring and eliminates the need for object movement, its longer data acquisition time and lack of full industrial scalability may pose challenges. Additionally, like for the baseline approach, it requires qualified personnel and the potential need for cranes during installation and decommissioning.*

3.6.5 Technical Readiness

The current TRL of Mu-Tom is 6 which is lower than the more established X-ray imaging technology of the baseline. Key areas that require improvement include software and computing optimisations.

Technical readiness of Mu-Tom is considered to be ***lower*** *than the baseline. It requires further development, testing under realistic conditions, and software and computing improvements to enhance its usability and practicality.*

3.6.6 Strategic Cost Impact

To reach an industrial level for Mu-Tom, an estimated cost of around €1M is anticipated. However, the evaluation of costs to increase the TRL is acknowledged to be challenging.

In terms of disposal costs, both Mu-Tom and the baseline method have similar maintenance requirements. The potential maintenance waste streams consist of replaceable electronic components, such as failed electronics boards, and obsolete computers, monitors, and data storage devices, all of which can be treated and disposed of as standard electronics waste. This suggests that the impact on disposal costs may be comparable to the baseline.

The assessment panel concluded that the strategic cost impact of the Mu-Tom approach is slightly ***higher*** *than the baseline. The impact on disposal costs is expected to be similar due to the standard nature of electronic waste generated. The need for software and computing optimisations suggests possible additional costs but further detailed analyses would be needed.*

4 Evaluation of Digital Twin, Data Platform, and Decision Framework Tools

Within T7.4 and T7.5 of WP7, a set of digital tools have been developed and tested to support the overarching goal of innovation in the areas of degradation prevention, early detection, and efficient handling of cemented waste. Within T7.4 of WP7, a prototype DT toolkit has been developed to simulate the chemical and physical behaviour of cemented waste packages during interim storage as a function of time [3] (Figure 4.1). It enables simulation of processes such as cement hydration and carbonation through a DT dashboard.

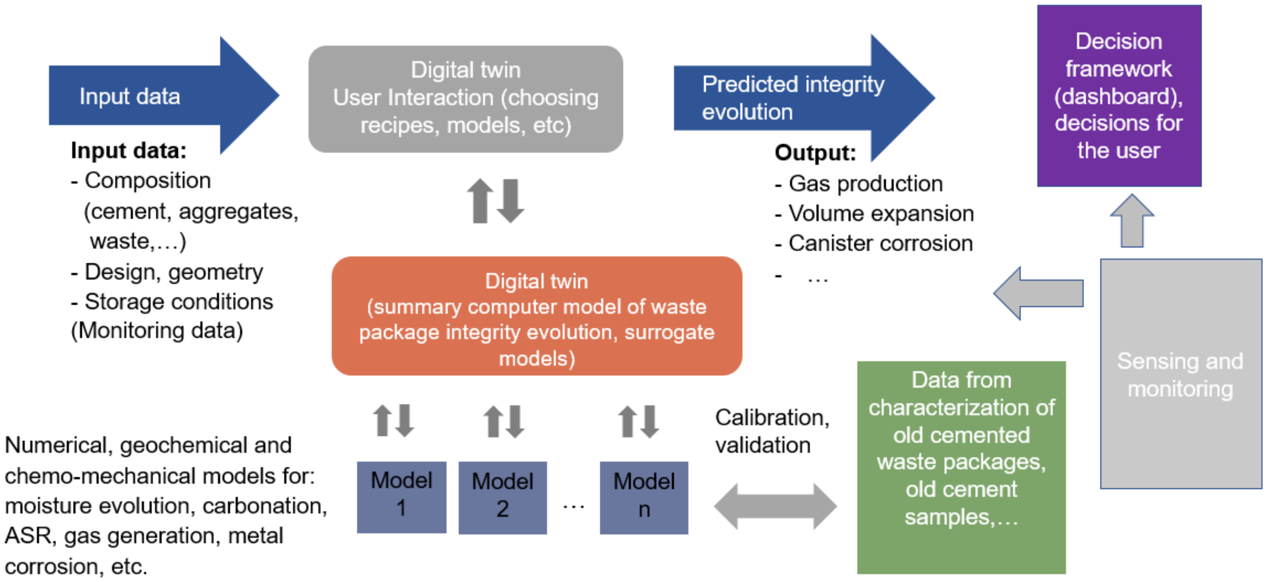

Figure 4.1: A schematic overview of the processes in a digital twin [3].

Within T7.5, a data platform and decision framework, collectively called data management framework, have been developed. The framework provides a means for handling the flow of information from the processes of monitoring and modelling of the waste package. Data from the monitoring technology and DT are collected in the data platform, which acts as a central repository for processing, storing, and transferring data between the different systems. The decision framework then provides visualised information to end users, aiding in the decision-making process. The high-level system architecture of the data management framework is shown in Figure 4.2.

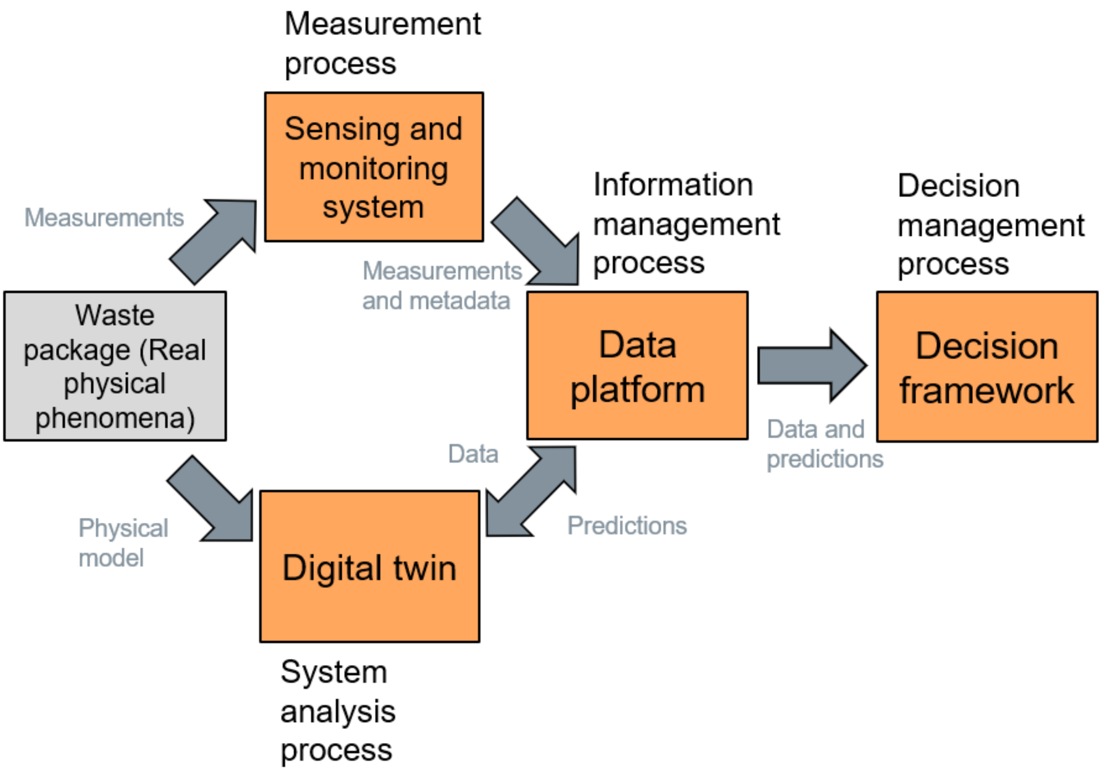

Figure 4.2: Data management framework high-level system architecture [4].

Further details on the DT and data management framework are provided in references [3, 4]

The evaluation of the economic, environmental, and safety impacts of the DT, data platform, and decision framework (backed by remote and automatic waste package monitoring) is discussed in this section. Owing to their similarities, these digital tools are evaluated together. The baseline for comparison involves a combination of paper and limited digital records for data obtained through visual inspection of waste packages. No DT or decision framework are assumed to be used.

A summary of the value assessment ratings for the DT, data platform, and decision framework tools assigned to the different assessment criteria in comparison to the baseline (paper and limited digital records with no DT or decision framework) is presented in Figure 4.3.

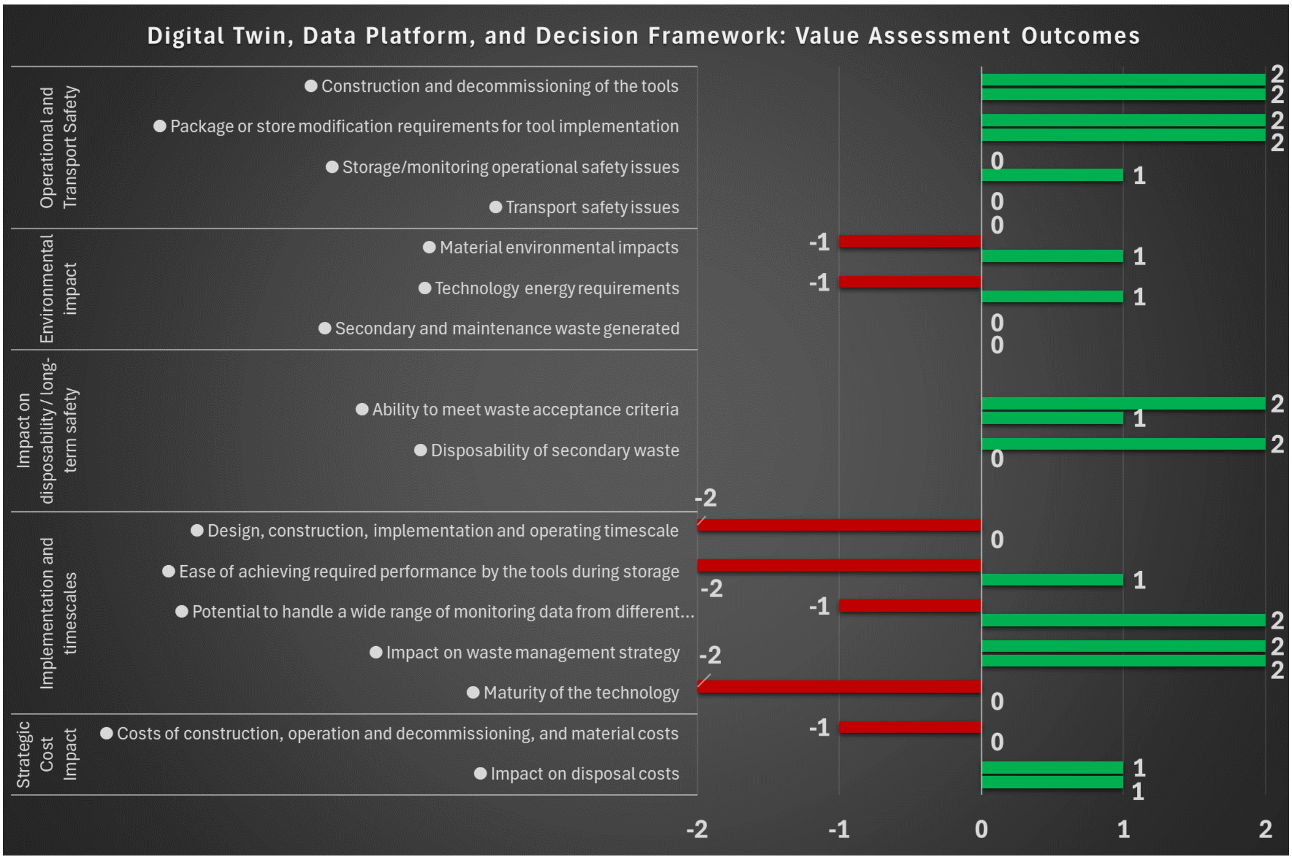

Figure 4.3: Chart of strengths and weaknesses of the DT, data platform and decision framework tools compared with the baseline (combination of paper records and limited digital records of data). For each criterion, the top bar corresponds to the DT assessment and the bottom bar is for the data platform and decision framework assessment. The ratings are defined as: -2 (much worse than baseline), -1 (worse), 0 (neutral), 1 (better), 2 (much better).

4.1 Operational and Transport Safety

The DT, data platform, and decision framework are digital tools which are safe and non-intrusive tools for waste package storage and management, requiring no modifications to the waste packages. This ensures the integrity of the packages is maintained, without introducing unintended consequences or vulnerabilities. The DT offers a virtual replica of the physical package, providing insights into its evolution without any physical intrusion or modification to the package.

Potential risks associated with these digital tools include cybersecurity threats to the IT infrastructure, the presence of bugs, or design flaws that could affect performance. In addition, the use of cloud services may be restricted due to regulatory compliance or cybersecurity concerns. One potential mitigation for these risks is the ability to remove or disable the tools if needed, as they are not necessarily physically located in the storage facility.

*The assessment panel concluded that operational and transport safety is generally **better** when using the DT, data platform and decision framework tools compared to the baseline. With their non-destructive nature and ease of implementation, these digital tools enhance safety during operations and transports. Despite potential cybersecurity concerns, the overall operational advantages outweigh these risks, which can be mitigated with appropriate implementation processes and good practice measures.*

4.2 Environmental Impact

The main environmental impact from the DT, data platform, and decision framework concerns the IT infrastructure required and associated energy consumption. A typical high-performance computer or server is likely to consume approximately 5000 kWh per year. Maintenance and renewal of the tools will also lead to electronic waste.

It is noted that these impacts can be mitigated by utilising virtual and cloud computing, which can provide more efficient resource allocation and reduce energy consumption.

The overall environmental impact of these tools is highly dependent on various other factors, including the efficiency of the IT infrastructure, energy sources, and waste management practices.

The DT, data platform, and decision framework tools present a ***neutral environmental impact*** *profile compared to the baseline. While there may be some waste and energy consumption considerations associated with the IT infrastructure requirements, these impacts can be mitigated through efficient practices and alternative implementations.*

4.3 Impact on Disposability / Long-term Safety

The DT offers a unique advantage by integrating various data sources and providing a virtual representation of the waste packages. This integration enables a more holistic understanding of the waste, including its current state and historical context. By utilising DTs, operators can make more informed decisions regarding disposability and long-term safety, as they have access to a comprehensive virtual model. A weakness of DTs is the challenge of acquiring data for training which is crucial for the reliability of the technology.

One of the key strengths of the data platform and decision framework is the ability to analyse and assess the state of a waste package, including historical data, to enable a better understanding of the waste, allowing for more informed decision-making and improved long-term safety. By utilising historical data, the decision framework can identify trends and patterns, supporting more effective waste management strategies.

The impact of the DT, data platform, and decision framework tools on disposability / long-term safety is ***better*** *than the baseline approach. The ability to analyse waste, including historical data and potential future evolution of the waste, enables better informed decision-making.*

4.4 Implementation and Timescales

While digital technologies can theoretically have an indefinite lifetime, offer flexibility, scalability, and adaptability for further enhancements, they also have associated challenges. Example challenges include difficult data accessibility (e.g., waste owners may wish to withhold data and limit access/usage), relatively large resources to set up, run, and maintain equipment, potential obsolescence of hardware and software, and compliance with the Findable, Accessible, Interoperable, Reusable (FAIR) principles of data management. On the other hand, these digital systems offer efficiency gains in waste management through early detection of failing packages and supporting efficient decision making.

*The impact of DT, data platform, and decision framework tools on implementation and timescales is assessed to be **neutral** when compared to the baseline approach. While the technologies offer advantages, they do require significant setup and maintenance resources, highlighting the importance of considering trade-offs and challenges in their adoption.*

4.5 Technical Readiness

DTs in the field of radioactive waste management are still an area under development. There is a need to collect a large amount of data to train the DTs, which should be subject of future R&D work.

The tools used by the data platform and decision framework have varying TRLs, ranging from TRL 2 for decision platform prototypes to TRL 3 for a dashboard of a single drum to TRL 9 for cloud computing technologies such as Microsoft Azure.

*Technical readiness of the DTs, data platform, and decision framework tools is considered **lower** than the baseline. These tools require further training and development to enhance their usability and implementation.*

4.6 Strategic Cost Impact

The strategic cost impact of implementing the DT, data platform, and decision framework tools involves various considerations. Running a DT is likely to require at least one person-year (PY) of a scientist and 0.2 PY of an IT specialist. This is a relatively modest resourcing requirement. However, the DT is still in the early phases of development in this field and uncertainties remain regarding its effectiveness and reliability, potentially impacting strategic cost planning.

For the data platform and decision framework, considerable cost is required to increase the TRL. There will be maintenance costs associated with the IT equipment, software licensing, and support provision. These factors highlight the need for comprehensive cost-benefit analyses to inform strategic decision-making and resource allocation.

The main advantage of using these digital tools is enabling more streamlined and efficient decision making regarding management of potentially failing packages. This could reduce the higher remediation and disposability costs that would otherwise be required.

*The assessment panel concluded that strategic cost impact is **slightly lower** when using the DT, data platform, and decision framework tools than with the baseline. Although the tools are still in the early phases of development and there are uncertainties about their performance and reliability, they show promise for long-term cost savings in radioactive waste pre-disposal management.*

5 Conclusions

This report evaluates the economic, environmental, and safety impacts of the technologies and approaches developed and tested in WP7 of PREDIS to monitor, model, and managed data from cemented waste package during storage. The evaluation was based on the value assessment methodology which compared the performance of these technologies with current practices, highlighting their advantages and challenges across various assessment areas. The assessment areas included operational and transport safety, environmental impact, impact on disposability/long-term safety, implementation and timescales, technical readiness, and strategic cost impact.

The following are key findings from the value assessment:

- **SciFi/SiLiF radiation monitoring**. This monitoring technology offers improved safety by reducing operator exposure to radiation and limiting waste package movement compared to the baseline of visual inspection and manual dose rate measurement. While SciFi/SiLiF reduce risks during storage and post-storage, they rely on scintillation detectors and network equipment which increase industrial hazards during equipment manufacture, installation, and commissioning. The environmental impact is slightly higher than the baseline due to the materials used in monitoring and networking equipment, but most of this equipment is reusable and made from common electronic components. The maintenance waste is primarily rechargeable batteries, which need to be replaced every 10 years. The energy requirements are low. This technology also enhances long-term safety and waste package disposability by identifying deep cement cracks, enabling early remediation.

- **Acoustic emissions for measuring ASR**. This monitoring technology streamlines the inspection process by reducing the need for visual inspections and eliminating the presence of operators near waste packages, thereby reducing exposure to hazards compared to the baseline of visual inspection. However, it requires initial manual installation and infrastructural changes, introducing safety risks. The environmental impact of AE technology is tied to its component materials and energy usage. While the sensors are reusable, the need for cabling and energy consumption during operations impact the environment. At a TRL of 3, it requires further development and testing under realistic conditions to enhance usability and practicality. Its economic impact is neutral, with costs primarily related to construction, operation, and energy consumption.

- **Non-contact ultrasonic scanning**. This monitoring technology provides a non-invasive, non-destructive means of inspection that can be used alongside existing processes. It assesses the integrity of waste packages without altering their design and can identify issues such as swelling, cracks, or corrosion cavities in cylindrical packages without modifying handling procedures. The technology is safe and can be used with existing inspection processes but requires skilled workers for correct positioning and data interpretation. Its environmental impact is low due to its compact design and direct connection to existing power sources, reducing the need for extra infrastructure. The system is easily replaceable, and its materials are assumed to be disposed of at the end of its 2 to 3-year lifespan. It is adaptable and can monitor a wide range of packages without new conditioning processes. However, it has a lower technical readiness level, indicating the need for further trials. Overall, it offers advantages such as being non-invasive, adaptable, and interoperable, but challenges include skilled worker requirements and equipment installation.

- **RFID embedded sensors**. This monitoring technology offers benefits such as improved safety and regulatory compliance during storage and transport, and enhanced monitoring capabilities. However, it also presents challenges, including the need for specialised resources and expertise for construction and decommissioning, and the complexity of sensor removal from concrete-filled drums. The environmental impact of the sensors is assessed as slightly positive due to the potential for sustainable practices, while the impact on disposability and long-term safety requires additional evaluation. The technology can be seamlessly integrated into existing infrastructure, and its flexible design allows for customisation.

Technical readiness is lower than the baseline (visual inspection), and the strategic cost impact is slightly worse, with higher costs associated with setup, maintenance, and skilled labour requirements.

- **Sensorised LoRa wireless sensor network**. The advantages of this monitoring technology include simplified construction, modular sensor deployment, reduced hazard exposure, compact design, long-term maintenance-free operation, remote calibration, enhanced safety, and automated data collection of gamma and neutron dose rates. However, it requires technical expertise in wireless technology for installation and has potential challenges with data management and decommissioning. The technology is pilot-ready but requires further testing in real storage facilities. With a unit cost of €2000 and a predicted lifespan of 5-10 years, it offers strategic cost benefits with minimal operational costs.

- **Muon tomography**. This monitoring technology offers significant advantages in operational and transport safety due to its utilisation of naturally occurring cosmic ray muons, eliminating the need for radiation safety protocols. Its construction primarily uses recyclable materials, reducing environmental impact compared to the X-ray imaging baseline. Both methods have comparable levels of complexity in construction and similar disposal costs. However, muon tomography has longer data acquisition times, impacting storage processes. The technology has not yet achieved full industrial scalability. The cost to industrialise muon tomography is estimated at €1 M, with software and computing optimisations needed. Further research is needed to address technical challenges and evaluate the cost implications thoroughly.

- **Digital twin, data platform, and decision framework tools**. These are non-intrusive digital tools with no requirements for package modification, maintaining package integrity. While they offer advantages such as virtual package replicas and improved decision-making, potential risks include cybersecurity threats and cloud service restrictions. Environmental impact primarily concerns IT infrastructure and energy consumption, although use of cloud computing could mitigate this. One of the key strengths of these tools is their ability to aggregate and analyse past and existing waste package data, including historical records and real-time monitoring information. This enables a more comprehensive understanding of the waste, facilitates decision-making, and enhances long-term safety and disposability. Challenges in implementation include data for training the models, resource requirements and compliance with data management principles. Further research and development are needed to address these challenges. Strategic cost impacts involve maintenance and development costs, but the streamlined decision-making enabled by these tools could reduce remediation and disposability costs.

6 References

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Appendix A Value Assessment Tables

This Appendix provides the value assessment tables used as a basis for the discussions in the main report. Each subsection below contains the table completed by the relevant technology developer in WP7. Preceding each table is a summary of key information concerning the assessment such as the assessor details, organisation, and baseline against which the assessment was undertaken.

A.1 SciFi/SiLiF Radiation Monitoring

Name	Paolo Finocchiaro, Mauro Romoli
Organisation	INFN, Italy
Date	11-Mar-24
WP7 Monitoring technology	SciFi (gamma) and SiLiF (neutron) radiation monitoring
Baseline	Visual inspection and manual dose rate measurement

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Operational and Transport Safety	Technology and equipment manufacture, commissioning, and decommissioning	• The technology is quite simple and low-cost. • It has no conventional hazards. • It poses no radiological or chemical hazards during construction or decommissioning. • No need for post-monitoring before disposal • The technology is reusable after package disposal. • The technology is non-invasive; it is simply hung on the package. • No modification to the package is required.	The technology requires the production and installation of equipment, to be compared with the no installation and operator with handheld instruments for measurement in the baseline assumption.	• Equipment and technology design and manufacture • Integration of the technology in the waste package or storage facility and commissioning • Removal of the technology after storage • Disposal of the package or technology materials	-1
	Package or store modification requirements for technology implementation (conventional and radiological safety implications)	• No package modification is required. • Installation is faster than a single baseline monitoring operation. • No conventional hazards • No additional radiological exposure	None	• Integration of the technology in the waste package or storage facility and commissioning • Removal of the technology after storage • Disposal of the package or technology materials	0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Storage/monitoring operational safety issues	• The technology prevents the exposure of operators to radiological doses, thus removing that risk. • The data is automatically transmitted outside without operator intervention. • No operator is needed inside for data collection. • The technology requires no package rearrangement or moving, only a once-per-year replacement for battery recharge. • Each sensor unit is simply hung on the package. • Installation and replacement are few-second operations. • No additional shielding is required. • No additional hazard risks (thermal, chemical, mechanical, radiological, etc.) • Operators are required inside only for the yearly replacement of sensors (battery recharge maintenance), to be compared with periodic in-person measurements.	None	• Integration of the technology in the waste package or storage facility and commissioning • Monitoring operations	2
	Transport safety issues	• No in- or out-of-package transportation is needed. • The technology has to be transported inside only for its installation.	None	• Integration of the technology in the waste package or storage facility and commissioning • Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Environmental impact	Material environmental impacts	• The sensor unit, including electronics and data transmission, is about 4 litres in volume. • A local area WiFi network is required, with at least 1 router and 1 server. • The technology is simple and totally reusable, apart from rechargeable batteries. • The materials in one sensor are normal electronic components, plastics, aluminium, coaxial wires, and 9mg of 6LiF (a salt). • The technology is simple and low-cost. • The only non-standard material is 9 mg/sensor of isotopically enriched 6LiF.	Need for rechargeable battery replacement and disposal (once every 10 years?)	• Equipment and technology design and manufacture • Integration of the technology in the waste package or storage facility and commissioning • Removal of the technology after storage • Disposal of the package or technology materials	-1
		• No package modification is necessary	None		0
	Technology energy requirements	• The energy required for the sensor fabrication is negligible. • No package modification is needed. • Each sensor unit uses less than 0.1 kWh per year from rechargeable batteries. • Additional energy is required to power the router(s) and server(s). • The required (quite low) amount of energy could be provided by solar panels. • There is no impact on the energy requirements from the package properties. • Decommissioning consists of simply removing the sensor unit; no energy is required.	None	• Equipment and technology design and manufacture • Integration of the technology in the waste package or storage facility and commissioning • Removal of the technology after storage	0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Secondary and maintenance waste generated	• The maintenance waste generated is basically only rechargeable batteries. • The volume is ≈0.5 litres per sensor unit. • The battery's lifetime is expected to be ≈10 years (only one recharge per year). • No contamination in the maintenance waste • The maintenance waste (batteries) is handled in standard pre-existing facilities. • No mutual impact on decommissioning between package and technology	This partly duplicates the Environmental Impact point above. Need to dispose of rechargeable batteries once every 10 years?	• Disposal of the package or technology materials	-1
Impact on disposability / long-term safety	Ability to meet waste acceptance criteria	• None of the waste acceptance criteria is affected by the technology, as it is a quick and simple external add-on not requiring any modification to the package or to the stillage. • The technology can provide useful radiological data to end-users. • It checks the radiological stability of the package and can detect radiological anomalies occurring during the monitoring period. • It can spot deep cement cracks down to 1mm wide, even with an intact steel jacket. • It is reusable, but if disposed of with the package, it can provide data as long as the batteries allow. The number of possible measurements with one recharge is about 800. With one measurement per month, the monitoring could go on for ≈13 years.	None	• Integration of the technology in the waste package or storage facility and commissioning • Monitoring operations • Removal of the technology after storage • Disposal of the package or technology materials	1
	Disposability of secondary waste	• The secondary waste basically consists of exhausted rechargeable batteries to be discharged after treatment in standard existing facilities.	This partly duplicates the Environmental Impact point above. Need to dispose of rechargeable batteries once every 10 years?	• Disposal of the package or technology materials	-1

Implementation and timescales	Design, construction, implementation and operating timescale	• The technology is bespoke and could be improved throughout the storage period while still conserving backward compatibility. • No modifications to the storage are needed to implement the technology. • No long periods of inactive or active commissioning are required. • As the technology is an add-on, not affecting the integrity of the packages, a licence to operate should be quite straightforward. • Corrosive waste leaking out of a package could be detected radiologically by the technology. • Damage to the sensor would trigger an anomaly (missing data). • The maintenance strategy would be to replace the sensor unit with another one quickly and easily • The technology is in principle suitable for the interim storage duration; its radiation hardness has been tested and evaluated at ≈100–1000 years with 10 mG/h (which is 100–1000 times higher than expected from packages). Even in such an unfortunate or unrealistic case, the damage would consist of a 10% decrease in detection efficiency. • No significant maintenance downtime is expected, as the system is based on individual autonomous sensor units, which also have internal memory for redundancy, making up for possible network or server downtime. The only downtime in a monitoring position would be a few seconds for the replacement of the sensor unit. • The duration of each measurement is one minute, and it occurs automatically on a predefined schedule. No impact on any constraint of the storage facility is envisaged. • The measurements are reproducible; the operator's handheld sensor is more approximative.	None	• Equipment and technology design and manufacture • Integration of the technology in the waste package or storage facility and commissioning • Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Ease of achieving required data collection by the technology during storage	• The technology makes it possible to count gamma rays and neutrons out of the packages and to check periodically the stability of the counting rates (scalable to the dose rate). • Many sensor units can be installed on packages and/or on stillages with great flexibility in number and position in order to monitor single packages or groups according to end-user needs. • No additional software is required to process the data. • Two to four sensor units can reasonably control a full package; alternative geometrical arrangements can control groups; for instance, five units can control a stillage of four packages, as the technology is modular. • The information is quantitative, with uncertainties bound to the Poisson statistics (counts/s). • The data transfer, according to the demo test results, is highly reliable. • Human mistakes in reporting the measured data into the database are prevented. • Monitoring is done periodically; for the moment, it has been reasonably assumed to be one measurement per day, but the schedule can be easily modified interactively. • The technology is quite sensitive to variations in the package (cement cracks or inner displacements), to rearrangements of the nearby packages, and in particular to tampering, thus representing an additional security tool. • The data provided by the technology can be freely combined with other data from other technologies.	None	• Integration of the technology in the waste package or storage facility and commissioning • Monitoring operations	2

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
		• The sensor unit is slim enough to easily fit in the natural room between packages. • It can also easily fit any kind of stillage. • Not only is the technology and its data collection compatible with the overall storage constraints (package displacements, maintenance, or other activities occurring in the vicinity), but it is sensitive to those activities; if a daily measurement occurs during such operations, the technology signals the anomaly, which is then recorded. This represents an additional security tool against tampering or unauthorised operations in the storage.			1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Potential to monitor a wide range of packages (flexibility) including legacy packages in different storage configurations	• The technology can accept any package geometry. • It can accept any waste content, from VLLW to spent fuel. • It is not bound to the matrix (no matter if it is cemented or of any other type). • It can be used for any type of package. • It is general purpose, not designed for a specific package and/or waste type. • It is compatible with different types of stacking scenarios (direct and indirect stacking, for example). • It does not require previous knowledge of the package content to be used and/or to model the results. • It detects and records radiological information from the package inside, brought out by gamma and neutron radiation. • It is totally flexible to monitor any different package geometry, container, and matrix. • It is compatible with a full range of concurrent activities. • It accepts heterogeneous content in the package (and possibly mixed materials). • It can be fruitfully used in addition to other present and future technologies. • Legacy wastes can be monitored without new conditioning operations.	None	• Integration of the technology in the waste package or storage facility and commissioning • Monitoring operations	1
	Impact on waste management strategy	• Integration of the technology in the waste package or storage facility and commissioning • Removal of the technology after storage • Disposal of the package or technology materials+R[-1]C[2]	None	• Integration of the technology in the waste package or storage facility and commissioning • Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Decommissioning timescale	• The decommissioning timescale is not impacted by the technology. • The technology is easily removed from packages and is immediately reusable. • The only case of contamination is accident/leak, but in such a case the devices would be contaminated instead of the operators. • The technology is quite simple. • There is no decommissioning experience so far, as the technology is reusable.	None	• Integration of the technology in the waste package / storage facility and commissioning • Removal of the technology after storage • Disposal of the package / technology materials	1
Technical Readiness	Maturity of the technology	• The radiation sensors were tested in several projects (at INFN, with companies, with JRC, in EU H2020) and configurations throughout the last 12 years: innumerable lab tests with sources, then with real radwaste from VLLW to HLW and spent fuel in real storage sites. They are also being considered by some companies. The TRL level is reasonably high. • The Wi-Fi electronics developed during the PREDIS project, based on a longstanding experience with similar developments, can still be improved in light of the demo test results. The TRL level is reasonably high. • The technology has not yet undergone normative certification. • There is a reasonably wide range of suppliers for the technology component elements.	None	• Equipment and technology design and manufacture	0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Strategic Cost Impact	Costs of construction, operation and decommissioning, and material costs	• The energy required for sensor powering represents a negligible cost. • The cost of materials for one monitoring unit (which comprises one gamma and one neutron sensor) is about 1000 euros. • For limited production, the cost could be reduced to ≤700 euros. • In cases of mass production, the cost should decrease well below 500 euros per unit. • Additional tests and validation to implement the technology in the storage facility are not expected. • Operating the technology is quite straightforward; short and simple operator instructions are needed; no experts. • Each sensor unit requires a yearly replacement (for battery recharge). • In case of malfunction, the sensor unit can be quickly and easily replaced. • We have a proven track record of the construction of many tens of thousands of sensors in our previous projects since 2009; no decommissioning has occurred so far. • The technology is fully reusable. • Reduced manpower costs • Reduced human health impact	• SciFi+SiLiF is an additional technology. • The baseline is no technology. • Any cost is worse than no cost. • The economic cost must be compared with the human cost of exposing the operators to avoidable radiologic risks.	• Equipment and technology design and manufacture • Integration of the technology in the waste package or storage facility and commissioning • Removal of the technology after storage • Disposal of the package or technology materials	-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Impact on disposal costs (package & secondary wastes / maintenance wastes destined for disposal)	• No secondary activated waste is generated by the technology. • The unlikely case of an activated sensor unit is an accident or leakage, but this would prevent human contamination. • The technology is add-on, external to the package, and easily removable. • The technology is reusable and does not impact package disposal. • The only waste generated by the technology is the exhausted rechargeable batteries (expected no sooner than 10 years at 1 recharge per year).	Disposal of rechargeable batteries	Removal of the technology after storage Disposal of the package or technology materials	0

A.2 Acoustic Emissions for Measuring ASR

Name	Gert Dekkers
Organisation	Magics Technologies
Date	13-Mar-24
WP7 Monitoring technology	Acoustic emissions for measuring ASR
Baseline	Visual inspection

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Operational and Transport Safety	Technology and equipment manufacture, commissioning, and decommissioning	"Reduced" and efficient periodical visual inspection, hereby reducing human labour and potential safety risks.	Manual installation of the technology.	• Equipment and technology design and manufacture • Removal of the technology after storage, disposal of the package / technology materials.	1
	Package or store modification requirements for technology implementation (conventional and radiological safety implications)	None	• Infrastructural changes to the facility are required to mitigate safety hazards. • Changes to the surface of the package are required	• Equipment and technology design and manufacture.	-1
	Storage/monitoring operational safety issues	Data will be collected automatically. No manual intervention needed.	Adds practical constraints to barrel movement as physical sensors need to be disconnected for their cabling	• Monitoring operations	-1
	Transport safety issues	Small size	Risk of transport unknown		0
Environmental impact	Material environmental impacts	Sensors can be re-used	Requires potentially a lot of cabling depending on the number of barrels	• Equipment and technology design and manufacture, • Removal of the technology after storage, disposal of the package / technology materials.	-1
	Technology energy requirements	None	Higher energy consumption	• Monitoring operations	-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Secondary and maintenance waste generated	NA	NA	• Disposal of the package / technology materials	1
Impact on disposability / long-term safety	Ability to meet waste acceptance criteria				2
	Disposability of secondary waste				
Implementation and timescales	Design, construction, implementation and operating timescale			• Integration of the technology in the storage facility and commissioning	-1
	Ease of achieving required data collection by the technology during storage			• Monitoring operations	0
	Potential to monitor a wide range of packages (flexibility) including legacy packages in different storage configurations			• Monitoring operations	2
	Impact on waste management strategy			• Monitoring operations	1
	Decommissioning timescale			• Removal of the technology after storage	
Technical Readiness	Maturity of the technology				-2
Strategic Cost Impact	Costs of construction, operation and decommissioning, and material costs				-1
	Impact on disposal costs (package & secondary wastes / maintenance wastes destined for disposal)				1

A.3 Non-contact Ultrasonic Scanning

Name	Darren Potter
Organisation	National Nuclear Laboratory (NNL), UK
Date	21-Mar-24
WP7 Monitoring technology	Non-contact Ultrasonic Scanning
Baseline	Visual inspection

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Operational and Transport Safety	Technology and equipment manufacture, commissioning, and decommissioning	As with the baseline (visual inspection), this technology does not change the reference package design or add additional internals to the waste packages. The technology is a non-invasive system that can be used to measure perturbations and defects in the circumferential direction of the cylindrical package. No changes are required to the package handling process, and the system can either form part of an existing inspection cell or, as intended, be deployed near the packages while stacked in stillages. Packages can be safely sent for disposal with no post-storage processing requirement.	Technology requires skilled operators for the correct alignment and positioning of transducers and detectors. Added complexity to the current baseline inspection requirements (visual inspection).	Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Package or store modification requirements for technology implementation (conventional and radiological safety implications)	As with the baseline, no modifications to the waste packages are required. Minor store modifications are required, depending on the method of deployment. e.g., the addition of technology to the inspection cell.	Significant development is still required should the in-situ approach to technology be explored. (e.g., technology deployment while packages are still stacked in stillages. (Stacker crane deployment of the system). Typical conventional hazards will be higher during construction and commissioning phases, with overall lower conventional and radiological hazards during operation.	Monitoring operations	0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Storage/monitoring operational safety issues	There are no further conventional or radiological safety implications beyond the current baseline (visual inspection) for in-store inspection technologies.	High-voltage equipment is required in the store. It has no impact on the packages but adds to the potential list of hazards within the store and is something that would need to be addressed via assessment. Data is normally collected in close proximity to the detector, as small changes in incident angles are usually required. Hence, data management would need to be reviewed later. It is expected that this data will need to be transmitted to a secondary location for storage and evaluation. Any deployment method is expected to include the following features to reduce the need for physical operator involvement and reduce possible damage to the packages: -Remote recovery -E-stop -Slow movement speed -Low payload	Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Transport safety issues	There is no change to the safety considerations for the licenced packages. The proposed technology is confined to operations within a store or store inspection bay.	As the proposed technology is confined to operations within a store/store inspection bay, no package transport is expected. This is dependent upon the successful development of a suitable deployment method of the technology.	Equipment and technology design and manufacture	2

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Environmental impact	Material environmental impacts	Minimal environmental impact, the system is compact and requires direct mains connectivity for power because of the voltage requirements. No material changes to the packages are required. System maintenance would take the form of a hot spare. It is more cost-effective to replace the system than to go into the store and repair it. The system is composed of electronics, metals, and plastics. It is assumed that the device would be disposed of as waste in the event of failure or the end of its life. The anticipated operating life would be 2 to 3 years before the system would be swapped out. Literature implies that the transducer itself may be rad-hardened to increase its lifetime. No package modifications are required for this technology. The system may be reusable after life in the stores, but further assessment would be required.	Weakness against the baseline for material considerations comes from the method of deployment. For the PREDIS project, we have demonstrated the deployment of non-contact ultrasonic using robotic 6-axis manipulators. This is just for demonstration purposes, but any deployment method would present a material need. This would not change the packages, but a deployment technique would add further devices and systems that would eventually require disposal.	Disposal of the package / technology materials	1
	Technology energy requirements	Technology is a wheel-in, wheel-out solution for stores. So all energy requirements are associated with the build of the technology, the operation of the technology, and the final disposal of the technology.	Energy consumption unknown, as deployment method for the transducers would likely comprise most of the power consumption.	Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Secondary and maintenance waste generated	Air-coupled transducers, meaning no need for contact or fluid media. There were no changes to the packages. Transducers can be interchanged, meaning that the full system does not need to be replaced as part of the maintenance schedule. Activity associated with maintenance activities is not expected to be any different from the levels within the stores. Waste can be disposed of via traditional waste routes.	Maintenance strategy is required and would be additional to current baseline activities. Secondary wastes would be produced where components fail and must be disposed of.	Equipment and technology design and manufacture	1
Impact on disposability / long-term safety	Ability to meet waste acceptance criteria	This technology has no impact on the waste acceptance criteria. Technology supports the assessment of package integrity for store operations. The system would highlight package integrity issues for waste reconditioning, if required. Technology supports package integrity, not the evolution of the package content. Technology builds on the structural integrity design of the package and looks to support the inspection requirements to ensure package integrity remains for the duration of interim storage.	This technology has no impact on the waste acceptance criteria.	Monitoring operations	0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Disposability of secondary waste	No secondary waste is expected for the technology other than operator PPE for maintenance, should this be required.	None	Disposal of the package / technology materials	1
Implementation and timescales	Design, construction, implementation and operating timescale	The technology is a commercially off-the-shelf system that would be adapted for our deployment. The main consideration would be the method of deployment, which is outside the scope of the works to date (system for in-situ package assessment vs. inspection cell approach). Licencing of the technology is not expected to be an issue. The system tested for the works is CE-marked and conforms to the required safety standards for the NNL non-active tests when reviewed via risk assessment. No regulatory approval is required for the proposed technology, as the waste package is unchanged, and the store operations are unchanged. The system would be viewed as a task and would undergo standard PUWER assessment before deployment. Maintenance timescales are low, with limited moving parts for the detectors. Timescales to obtain measurements are in the order of minutes.	The system would require additional modules for deployment, whether this be robotic arms, stacker crane deployment, inspection turntables, etc. All would add further complexity to the COTS system. Operating timescales are short for obtaining information but do require expert knowledge for interpretation. The systems would need development to ensure the correct positioning of the ultrasonic transducer and receiver for the analysis. It is expected that a standard design and development study would conclude with a detailed design stage, HAZOP, and safety case evaluation. The lifetime of the technology is partially determined by the deployment route.	Equipment and technology design and manufacture	2

	Ease of achieving required data collection by the technology during storage	"Parameters measured include: waste package wall thickness, waste package perturbation, waste package corrosion (general and localised), and discontinuities for waste package integrity. Technology provides assurance of the structural integrity of waste packages with quantitative measurements. This is typical of what the end user seeks for the management of waste in interim storage. The duration of measurement is in the order of a few minutes, but results will be visible after a few seconds. These quantitative measurements may be compared with previous measurements of the same drum. The technology can be used to assess the full outer skin of the package. The measurements obtained are quantitative and have a have a very small error range. Technology is interoperable and can be used in conjunction with other technologies, such as stereo imaging, to produce a full digital representation of a package, even if direct line of sight is not available for all surfaces. The technology offers no constraints on the storage or disposal of waste packages. The technology is compatible with the low levels of radiation expected in ILW and LLW waste stores."	"Unlike the baseline technology (visual inspections), this technology cannot measure any other visible defects. Commercial software is required to post-process the information from the UT scans. This then requires interpretation by a trained operative. Depending on the method of deployment, the technology may only be able to assess certain parts of the waste container. E.g., circumferential direction. Data collection is not continuous, and effort is required to deploy the technology to the stacked packages or bring the packages to the inspection facility."	Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Potential to monitor a wide range of packages (flexibility) including legacy packages in different storage configurations	The technology is applicable to a wide range of waste packages beyond our reference package geometry. The technology is independent of waste content. Legacy waste packages can be monitored without new conditioning processes. The purpose of the technology's design intent is to produce a 3D digital representation of the waste package.	Technology does not monitor waste evolution, although the current baseline for inspection technologies does not currently offer this solution. The technology may be less effective when measuring the diameter of a drum in which the contents are pressed against the inside of the drum shell (due to the wave travel being inhibited). Further testing will confirm the exact difference.	Equipment and technology design and manufacture	1
	Impact on waste management strategy	A limited impact on the waste management lifecycle is expected.	Skilled operators are required to interpret data, upskilling the current workforce. An operative may also be required for operation of the deployment mechanism for the technology. This may be the same person depending upon the complexity of the design.	Disposal of the package / technology materials	0
	Decommissioning timescale		Technology is not part of current systems. Further work would be required to understand the impact on the decommissioning operation.	Disposal of the package / technology materials	-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Technical Readiness	Maturity of the technology	PREDIS project scope was to progress the technology to TRL5; however, non-contact ultrasonic detectors on their own are at TRL9 and would require trials to confirm their technology maturity. The assessment for TRL 5 was for the combination of UT measurements with stereo imaging techniques. This shows much promise but is still undergoing active research.		Equipment and technology design and manufacture	-1
Strategic Cost Impact	Costs of construction, operation and decommissioning, and material costs	Non-contact UT sensors are commercially off-the-shelf systems that require very little further development prior to deployment. The main costs associated with further R&D are linked to the interoperability of these systems with other sensor data to build a more comprehensive model of waste package integrity. Installation costs are low for UT methods. Running costs for energy consumption are low. Decommissioning costs are low for a single item, which generates no secondary waste. Potential for technology reuse. Cost-saving benefits in the applicability of technology across nuclear waste management and decommissioning.	There is limited use of this technology within store environments. Typically, the system is deployed with expectant operators on plant inspection tasks. Interoperability with other systems looks promising but will require R&D, which has cost implications.	Equipment and technology design and manufacture	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Impact on disposal costs (package & secondary wastes / maintenance wastes destined for disposal)	No secondary waste is generated. No change to the package disposal route is required.	N/A	Disposal of the package / technology materials	1

A.4 RFID Embedded Sensors

Name	Ernst Niederleithinger, Christian Koepp
Organisation	BAM Federal Institute for Materials Research and Testing
Date	15-Mar-24
WP7 Monitoring technology	RFID Embedded Sensors
Baseline	Visual inspection

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Operational and Transport Safety	Technology and equipment manufacture, commissioning, and decommissioning	• Embedding sensors in concrete enhances monitoring capabilities for nuclear waste storage. • The technology provides valuable data for assessing the condition of the storage environment over time. • The technology enables safer handling and management of nuclear waste by providing real-time data on potential risks. • **Regarding post-monitoring and disposal:** Depending on regulations, disposal may or may not require technology removal, reducing additional handling risks. The technology provides valuable data for assessing the condition of the storage package before disposal, enhancing safety and regulatory compliance.	• Construction and decommissioning require specialized equipment and expertise, potentially increasing costs. • Decommissioning poses challenges, including contamination risks during sensor removal from concrete-filled barrels. Implementation exposes workers to hazards like concrete and construction chemicals, necessitating strict safety protocols, which add complexity.	• Equipment and technology design and manufacture	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Package or store modification requirements for technology implementation (conventional and radiological safety implications)		Modification would involve cutting into the package, potentially causing contamination or structural damage and is impossible. The invasiveness depends on package design and technology accessibility, complicating disposal procedures. Strict protocols, including radiation shielding and decontamination, ensure worker safety during modification, but may require extra resources and time, increasing overall disposal complexity.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning	-2

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Storage/monitoring operational safety issues	The integration of pressure, temperature, and moisture sensors into concrete-filled barrels for nuclear waste storage significantly enhances safety and risk management. These sensors collect data remotely, reducing operator exposure to radiation and other hazards. They also eliminate the need for package movement, minimizing the risk of accidents. With real-time monitoring capabilities, potential hazards can be detected early, enabling proactive risk management strategies. Overall, this technology improves safety and security in nuclear waste storage facilities.	Introduction of new materials for sensor implementation, such as polymers, may lead to gas release or container corrosion, altering the waste hazard risk. This poses a potential safety concern, especially if the technology exacerbates degradation processes within the storage packages. While the technology itself does not introduce new risks during package movement or stacking, improper handling of packages could still result in accidents or damage. Careful training and handling procedures are necessary to mitigate these risks effectively.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations	2

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Transport safety issues	The presence of embedded pressure sensors in barrels filled with concrete and containing nuclear waste can enhance safety during transport by providing real-time monitoring, early warning capabilities, improved emergency response readiness, and regulatory compliance assurance.	The installation of embedded pressure sensors may introduce vulnerabilities to the structural integrity of the barrels by weakening the integrity of the barrel, potentially increasing the risk of leaks or ruptures during transport. The electronic components of pressure sensors may be susceptible to electromagnetic interference during transport, leading to misinterpretation of provided data.	• Equipment and technology design and manufacture	-1

Environmental impact	Material environmental impacts	The choice of materials for the pressure sensors can influence their environmental impact. Opting for environmentally friendly materials or those with minimal ecological footprint can help reduce potential environmental harm. The manufacturing processes involved in producing pressure sensors may generate waste materials, emissions, or energy consumption. Implementing sustainable manufacturing practices can mitigate these impacts	At the end of their life cycle, pressure sensors may require disposal. Proper disposal methods, such as recycling or appropriate waste management, are essential to minimize environmental pollution and resource depletion. Conducting a life cycle analysis of the pressure sensors, from production to disposal, can help assess their overall environmental impact. This analysis can identify opportunities for improvement and inform decisions to minimize environmental harm. Embedded pressure sensors themselves may have limited direct environmental impact, it is essential to consider their entire life cycle and associated operational practices to ensure minimal environmental harm in the context of barrels filled with concrete and containing nuclear waste. The environmental impact associated with the removal of the sensors (if required) at the end of the interim storage phase and the following cemented waste reconditioning can be high (new conditioning	• Equipment and technology design and manufacture • Removal of the technology after storage • Disposal of the package / technology materials	0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
			operations, old metallic packages generated as wastes, package qualification should be done again,…).		
		A modification would only be a different arrangement of the drums in the storage facility. This would not consume any additional material, but the probable modification of cables.	Sensors cannot be recovered form the waste packages after use. They will most likely break.		
	Technology energy requirements	The energy consumption of the technology is rather low. It does not go beyond any other monitoring or measuring system. No special plugs or fuses are needed, just regular 220V power outlets. If a very large number of waste barrels is to be equipped with the system, energy demand might increase, but since usually there will always only be a limited number of monitored barrels, this is still negligible. The energy consumption of one measurement cycle for each node is about 0.4mAs (20mW x 60ms).	Concrete is a durable material and extracting sensors from it typically requires significant energy input. Methods for extraction may include drilling, cutting, or breaking the concrete. Each of these methods consumes different amounts of energy. Additionally, the type of sensors embedded in the concrete can affect the extraction process. If fragile sensors require more delicate extraction methods to avoid damage, which could impact the energy requirements.	• Equipment and technology design and manufacture • Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Secondary and maintenance waste generated	No secondary waste is produced, unless requirements demand the extraction of the sensors after use.	If removing the sensors from the package is required, the waste associated with these operations will need be considered (drilled cement, cutting tools, …). In addition, the transmitting unit outside the package may also be considered part of secondary waste if disposed of.	• Removal of the technology after storage • Disposal of the package / technology materials	-1

Impact on disposability / long-term safety	Ability to meet waste acceptance criteria	Incorporating sensors into waste packaging represents a technological innovation that could enhance monitoring and safety capabilities. However, it also introduces new considerations and potential challenges that regulators and waste management organizations must address to ensure that the waste continues to meet acceptance criteria and can be safely disposed of in accordance with applicable regulations.	The presence of sensors may need to be evaluated to ensure that they do not interfere with the long-term integrity of the waste package or the disposal facility itself. For example, sensors should not compromise the structural integrity of the concrete or contribute to corrosion. Depending on the type and placement of sensors, they could affect the radiation shielding properties of the waste package. This may require additional evaluation to ensure that the waste package still meets radiation protection requirements. Sensors and their components must be chemically compatible with the waste and packaging materials to avoid potential reactions or degradation over time that could compromise containment. If removal of the embedded sensors from the package is required, then this may impact compatibility of the package with the WAC (e.g., operations and new conditioning may be required, meaning a new package qualification for disposal will be needed).	• Removal of the technology after storage • Disposal of the package / technology materials	-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Disposability of secondary waste	No secondary waste.			0
Implementation and timescales	Design, construction, implementation and operating timescale	• Embedding pressure sensors in concrete for nuclear waste storage is customisable to handle the harsh environmental conditions. • No modifications to storage infrastructure are needed. Securely embedding sensor housing is manageable without major structural changes. • Proper design will help to adapt the technology for the interim storage period, but ongoing monitoring is crucial for reliability.	Obtaining operational licensing involves navigating stringent safety and environmental regulations, which vary by jurisdiction and facility characteristics. The type of waste in barrels can affect sensor lifespan. It is noted that sensor lifespan may be affected by cemented materials nature. It can also be highlighted that although the technology will have no impact on the storage unit it will affect the conditioning unit and conditioning procedures that will be modified in order to implement the technology in the package.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations	0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Ease of achieving required data collection by the technology during storage	The technology measures pressure within concrete barrels, crucial for monitoring storage environment changes and assessing structural integrity and potential leakage. Measurement duration varies depending on user-set monitoring frequency. It controls pressure monitoring in individual packages, providing quantitative readings. Uncertainties in measurements are minimized through calibration and quality control. Data transfer is reliable, enabling secure transmission to designated receivers. Continuous monitoring offers real-time insights into environmental conditions. Collected data can be adjusted for post-processing and analysis beyond pressure measurements. The technology is sensitive to variations in package contents and storage modifications, impacting pressure dynamics. Integration with other technologies can enhance overall monitoring capabilities and provide a more comprehensive understanding.	It may require modelling for interpreting complex pressure dynamics, ensuring accurate results. Additional software might be needed for data processing and display based on user needs.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations • Removal of the technology after storage • Disposal of the package / technology materials	2

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
		If properly and safely placed inside the barrel, the sensors are protected against usual mechanical impacts that might occur during handling of the barrels in the storage facility. Re-arranging the placement of the barrels for whatever reason is not hindered by the presence of the monitoring system at all.	Still some care has to be taken for example during handling of the barrels by robot manipulators, especially on top of the barrel lid, where the transmitting unit is placed.		2
	Potential to monitor a wide range of packages (flexibility) including legacy packages in different storage configurations	Technology is very flexible for use in different configurations.		• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations	2

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Impact on waste management strategy	If the technology affects waste conditioning, it may necessitate adjustments to infrastructure to ensure compatibility with movement in storage and package qualification criteria. Changes in waste conditioning processes could potentially impact waste generation rates and overall waste management practices. If the technology requires operators to make measurements, there may be implications for the number of operators needed and their qualifications. Depending on the complexity of the technology, qualified operators or experts may be necessary, potentially affecting staffing requirements and operational costs.	Embedded technologies that remain within the package could pose challenges for disposal if they are not compatible with disposal criteria. This may require additional steps for package disposal or could potentially limit disposal options, impacting overall waste disposal strategies. The implementation of the monitoring technology could impact the available storage area, particularly if it requires a dedicated area or changes in storage configuration that reduce storage capacity. This could influence the overall efficiency and effectiveness of the storage facility.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations	0
	Decommissioning timescale	With proper planning the additional time needed for the application of the sensor systems can be spent in parallel to other needed preparatory procedures.	Equipping a number of waste barrels with sensors requires additional time, skilled personnel and careful application of the sensor system. This is definitely affecting the timescale of the decommission, but not to a very large extend.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations	-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Technical Readiness	Maturity of the technology	The technology is at a pilot scale. While it has been developed and tested within the PREDIS project, it still requires further refinement and optimization before widespread implementation. Full-scale implementation of the technology in a storage facility would likely require further research and development efforts. This includes refining the monitoring technology itself, addressing compatibility issues with waste conditioning and disposal criteria, optimizing storage area impact, and ensuring operator readiness. The technology is mature on the sensor	Limitations in the number of suppliers can affect the technology's maturity and reliability. If there are few suppliers offering the technology, it may indicate a less mature market with potential reliability concerns.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations	-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Strategic Cost Impact	Costs of construction, operation and decommissioning, and material costs	The costs for the technology on a laboratory level and/or experimental stage are relatively low. Besides personal costs for the construction and manufacturing of the prototypes, material costs are negligible. The procedure of embedding the sensors in the concrete in the barrels requires technical skills and can only be achieved by experienced personnel.	Scaling up the installation would of course increase the costs drastically. Depending on how many waste barrels need to be monitored in a storage facility, the factor goes up with every additional waste package considered. It requires a strategy, where in the repository waste packages should be monitored and how many of them to get a useful and reliable result. Again, necessary manpower to set up the installation would be the determining cost factor. The sensors themselves could be produced in larger numbers by small companies.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations • Removal of the technology after storage • Disposal of the package / technology materials	-1
	Impact on disposal costs (package & secondary wastes / maintenance wastes destined for disposal)	Since there is no secondary waste, except when the sensors need to be extracted due to regulations (and then only very small amount of material), these costs are negligible.		• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations • Removal of the technology after storage • Disposal of the package / technology materials	0

A.5 Sensorised LoRa Wireless Sensor Network

Name	Andrea Chierici
Organisation	University of Pisa
Date	21-Mar-24
WP7 Monitoring technology	Sensorised LoRa wireless sensor network for identification and integrity assessment of radioactive waste drums
Baseline	Visual inspection and manual dose rate measurement

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Operational and Transport Safety	Technology and equipment manufacture, commissioning, and decommissioning	**Reduced Complexity and Hazard Exposure (Slightly Better):** - Technology Construction: less complex, no extensive wiring or new buildings needed. Sensors attach to waste drums via magnets, minimizing construction hazards. - Decommissioning Simplicity: modular sensors allow for easy removal, reducing decommissioning risks and exposure to contaminated materials. **Minimized Hazards (Better):** -Minimal direct contact is needed for sensor deployment, reducing non-radiological (infrastructure for installation) and radiological exposure (easy to install) to hazardous materials. -Long-term, maintenance-free operation and automated, remote calibration decrease worker interaction with contaminated areas. **Enhanced Safety During Post-Monitoring Steps (Slightly Better):** -Disposal Process Simplification: sensors are detachable and non-invasive, easily removed without compromising waste drum integrity, simplifying disposal and enhancing safety.	**Initial Technology Complexity (Worse):** -Technical Knowledge Required: installation of a private network for a large number of packages needs planning, which could delay deployment in facilities lacking wireless tech expertise. **Potential for Radiological Hazards during Initial Setup (Slightly Worse):** -Initial sensor installation may increase proximity to radioactive materials, raising the risk of higher worker doses. Careful management is essential to minimize this risk. **Decommissioning and Post-Monitoring Considerations (Slightly Worse):** -Technology Removal Challenges**: r**emoving sensors could add steps to waste management, especially for inaccessible packages. Requires careful planning to reduce exposure to hazardous materials	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning. • Removal of the technology after storage	-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Package or store modification requirements for technology implementation (conventional and radiological safety implications)	**Minimal Modification Requirements (Slightly Better):** -Non-Invasive Installation: small detectors and antennas mean minimal modifications to storage/packages, preserving waste container integrity. -Flexibility in Deployment: allows for flexible sensor placement with minor or no modifications needed, enhancing adaptability without compromising safety. **Reduced Conventional Hazards (Slightly Better):** -Lower Physical Injury Risk: minimal modifications reduce risks of burns, mechanical injuries, or exposure to hazardous materials. Simplified sensor attachment lowers installation-related hazards. **Decreased Radiological Exposure (Better):** -Limited Handling/Exposure: installation requires less handling of waste drums, reducing close and frequent worker interactions with radioactive materials, thereby decreasing radiological exposure.	**Requirement for Initial Modifications (Worse):** -Potential Structural Impact: minimal modifications for antennas/sensors could affect storage site layout, especially for unprepared drums. -Installation Safety Hazards: even small modifications carry risks of mechanical injuries from installation tools/materials. **Radiological Hazards During Installation (Worse):** -Increased Exposure Risk: initial setup/modifications may temporarily raise radiological exposure for workers, particularly with direct container interaction. **Complexity of Compliance and Safety Protocols (Worse):** -Regulatory Review Needed: modifications may require revisiting safety protocols and regulatory compliance, adding to the implementation complexity. -Necessary adjustments could slow deployment and necessitate extra safety measures to maintain container integrity and facility safety.	• Integration of the technology in the waste package / storage facility and commissioning	-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Storage/monitoring operational safety issues	**Reduced Worker Exposure to Radiation (Better):** -Remote monitoring capabilities reduce physical presence near waste, lowering radiation doses for workers. **Minimal Need for Package Handling (Better):** -Designed for long-term, maintenance-free operation, eliminating the need for package movement and reducing injury and exposure risks. **No Additional Shielding Required (Same):** -Sensors operate without introducing new radiation sources, negating the need for extra shielding in storage facilities. **Elimination of Risks Associated with Radioactive Source Handling (Slightly Better):** -Passive emission detection eliminates the need for active radiation sources, reducing the risk profile compared to technologies like x-ray systems.	**Potential for Unintended Radiological Exposure (Worse):** -Initial calibration/testing may require closer proximity to waste, possibly increasing radiological exposure temporarily. **Risk of Technological Malfunction (Worse):** -Sensor network failures requiring manual intervention can elevate conventional and radiological hazard exposure risks, necessitating robust design and contingency plans. **Introduction of New Materials (Slightly Worse):** -Sensor components may degrade under irradiation, potentially impacting the waste environment. Long-term material stability must be assessed to prevent new hazards. **Impact on Storage Facility Operations (Worse):** -Installation may lead to temporary facility rearrangements or access needs, causing operational disruptions or safety issues	• Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Transport safety issues	**Reduced Need for Waste Package Transport (Better):** -In-Situ Monitoring: eliminates or significantly reduces waste package transport for monitoring, lowering accident risk. -Long-Term Data Collection: decreases movement within or outside the facility, minimizing transport operations. **Minimal Monitoring Technology Transport Requirements (Better):** -Compact and Lightweight Sensors: easy and low-risk transport to and within storage facilities due to small size and non-hazardous nature. -Single Transport Operation: -monitoring technology typically transported once, minimizing transport-related accident chances.	**Initial Transport of Technology to Facility (Same/Slightly Worse):** -Handling and Logistics Challenges: standard logistics risks during initial transport, including potential road or rail accidents, albeit lower due to non-hazardous, compact nature of the equipment. **Potential for Transport During Installation or Maintenance (Slightly Worse):** -Occasional Movement Risks: reduced transport need, yet initial setup, calibration, or rare maintenance may necessitate minimal equipment or waste package movement, introducing nominal transport-related safety risks.	• Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations	1

Environmental impact	Material environmental impacts	**"Reduced Material Usage (Better):** -Simplified Construction: minimal materials needed due to compact, simple design. Avoids extensive wiring or large structural additions. -Minimal Maintenance Materials: long-term design reduces need for maintenance materials, with minimal to no battery replacements. **Reusability and Minimal Decommissioning Waste (Better):** -High Reusability: components designed for reusability, extending lifecycle and reducing decommissioning waste. -Simplified Decommissioning: less material-intensive decommissioning, with easy detachment and potential repurposing of sensors and gateways. **Eco-friendly Material Choices (Better):** -Preference for Less Harmful Materials: focus on materials with lower environmental impact and better recycling profiles. -Minimal Use of High-Impact Materials: operation avoids extensive use of water, cement, or concrete, reducing ecological footprint."	"Initial Material Use for Setup (Worse): -Material Consumption: initial setup requires materials for nodes, gateways and servers, contributing to environmental footprint, especially for a large number of drums. Potential for Toxic Material Use (Slightly Worse): -Batteries: use in some sensors may involve environmental risks, especially with toxic substances in batteries. -Printed Circuit Boards (PCBs): materials PCBs may pose environmental risks as well. Environmental Risk from Decommissioned Materials (Slightly Worse): -Decommissioning Process: non-reusable/recyclable materials need proper disposal to avoid releasing harmful substances. Limited Impact from Necessary Package Modifications (Slightly Worse): -Materials for Modification: accommodating sensors might require additional materials with potential environmental impacts if not easily removable or recyclable."	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations • Removal of the technology after storage • Disposal of the package / technology materials	1

	Technology energy requirements	**Low Energy Consumption Across Lifecycle (Better):** -Efficient Construction and Implementation: minimal energy required for setup due to compact technology; gateways and servers optimized for efficiency. -Minimal Modification Energy: energy for waste package modifications is low, often limited to sensor attachment. **High Operational Energy Efficiency (Better):** -Low Storage Operation Energy Requirements: sensors designed for low power consumption, battery-operated, resulting in minimal operational energy use. -Decommissioning Energy Efficiency: energy-efficient decommissioning with minimal energy needed for sensor removal and modifications. **Environmental Impact and Energy Source (Better):** -Renewable Energy Potential: low energy needs allow for potential use of renewable sources, reducing carbon footprint and enhancing sustainability. -Energy Usage Normalization: energy use significantly lower when normalized to volume of package monitored or facility lifetime, underscoring efficiency.	**Initial Setup Energy Consumption (Worse):** -Construction Energy Use: the energy used in constructing network infrastructure, although minimal, contributes to the technology's energy footprint. Efficiency may vary depending on the machinery or equipment used. **Battery Use and Disposal (Worse):** -Battery Consumption: environmental impacts stem from the production, use, and disposal of batteries. The lifecycle of batteries, particularly those with toxic substances, includes energy-intensive processes. **Potential for Increased Energy Use in Specific Scenarios (Same/Slightly Worse):** -Adaptation Energy Costs: specialized sensors or additional data processing required by certain waste package properties or storage conditions could lead to an increase in energy requirements. **Dependency on Energy Sources (Same/Sligthly Worse):**	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations • Removal of the technology after storage • Disposal of the package / technology materials	0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
			-Source of Electricity: the environmental benefits of the technology are heavily dependent on the source of electricity. Using non-renewable sources could undermine some of the technology's environmental advantages.		

	Secondary and maintenance waste generated	**Minimized Secondary Waste Production (Better):** -Low Volume of Secondary Waste: minimal waste from durable, long-term components, reducing replacements or disposals (also thanks to minimal user interaction). -Primarily Solid Waste: easier management, treatment, and recycling of solid waste like sensors and batteries. **Sustainable Waste Management (Better):** -Recycling and Reuse: components are recyclable or reusable, aligning with sustainable practices and minimizing disposal needs (at least integrated circuits, antennas and other components). -Pre-Existing Facility Utilization: secondary waste can typically be managed at existing facilities, negating the need for new infrastructure. **Low Contamination Levels (Slightly Better):** -Minimal Contamination Risk: low activity/contamination levels in secondary waste due to minimal direct contact with waste package contents, facilitating easier management and disposal.	**Battery Disposal (Slightly Worse):** -Battery Waste Management Challenges: disposal of batteries used in sensors poses environmental risks, requiring careful recycling and handling. **Decommissioning Waste (Slightly Worse):** -Material Waste from Decommissioning: generates recyclable but potentially contaminant-containing waste like electronics and batteries, needing careful processing. **Management of Infrequent Liquid or Gas Wastes (Slightly Worse):** -Specialized Treatment Needed: rare liquid/gaseous waste from maintenance/decommissioning, such as solvents, requires specific waste management approaches. **Impact of Waste Package Monitoring (Worse):** -Potential Contamination Concerns: direct contact for prolonged periods with waste package contents may elevate contamination levels in secondary waste, necessitating careful disposal assessment.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations • Removal of the technology after storage • Disposal of the package / technology materials	-1

Impact on disposability / long-term safety	Ability to meet waste acceptance criteria	**Enhanced Monitoring for Compliance (Better):** -Comprehensive Data Collection: enables early detection of package degradation through detailed monitoring of condition over time. -Durability and Ageing Insights: offers data on long-term stability and safety for proactive maintenance decisions. **Safety and Compliance Enhancements (Better):** -Improved Waste Package Management: enhances safety through better management of stacking, impact, and fire performance without the need of inspecting the waste. -Secondary Waste Minimization: reduces the generation of secondary waste, promoting sustainability compared to more complex detecting solutions. **Advanced Data Management and Labelling (Better):** -Effective Data Management: ensures accurate, accessible, and secure information on package condition and compliance. -Continuous Repository Monitoring Potential: sensors may remain with waste packages for ongoing repository monitoring, offering continuous condition data.	**Potential Modifications to Waste Package (Worse):** -Sensor Integration Requirements: slight modifications for sensor attachment could impact handling and integrity. -Integrity and Corrosion Concerns: even minimal modifications carry risks to package integrity and corrosion resistance. **Sensor Disposal and Secondary Waste Generation (Worse):** -Disposal of Sensors: non-permanent sensors create secondary waste, needing careful management. -Chemical and Physical Impacts: sensors could introduce new elements, affecting package chemistry and durability. **Data Management and Quality Control (Slightly Worse):** -Data Overload and Management: extensive data generation may overwhelm systems, requiring improved management solutions. -Sensor Accuracy and Reliability: dependence on sensor performance for critical	• Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations • Removal of the technology after storage • Disposal of the package / technology materials	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
			safety decisions; failures could impact waste acceptance.		
	Disposability of secondary waste	**Disposability of Secondary Waste (Better):** -Minimized Generation of Secondary Waste: technology minimizes secondary waste through durable, long-lasting design and minimal maintenance. -Highly Manageable Waste Forms: solid, non-hazardous secondary waste (e.g., spent sensors, batteries) simplifies disposal processes. -Ease of Recycling and Reuse: recyclable components allow recovery and reuse, aligning with sustainable practices. -Compatibility with Existing Disposal Routes: non-hazardous nature permits disposal through existing infrastructure, avoiding new disposal site development. **Compliance with Waste Acceptance Criteria (Same/Slightly Better):** -Secondary Waste Meeting Acceptance Criteria: often meets generic criteria without need for additional treatment, integrating efficiently into disposal processes.	**Requirement for Specific Treatment and Conditioning (slightly Worse):** -Some components, especially batteries or parts with contamination, require special treatment, adding complexity to disposal. **Potential for Increased Disposal Costs (same/slightly Worse):** -Specialized treatment or disposal of secondary waste could raise waste management costs, impacting economic assessments. **Environmental Impact of Disposal Processes (same/slightly worse):** -Intensive processing of secondary wastes may lead to significant environmental impacts, including energy use and emissions, necessitating thorough evaluation.	• Monitoring operations • Removal of the technology after storage • Disposal of the package / technology materials	0

Implementation and timescales	Design, construction, implementation, and operating timescale	**Rapid Deployment and Scalability (Better):** -Many off-the-shelf components (detectors and transceivers). Easy assembly. Easy installation. Once done operators are not needed. -LoRa allows to develop easy scalable network topologies. -Effort for industrial scale is lower compared to baseline thanks to automatization. -Minimal modifications. Compat and in-situ w/o package movements. **Commissioning Process (Better):** -Licensing and Regulatory Approval: low impact on storage operations and safety, and w/o exposure to operators licensing might speed up. -LoRa supports private networks. No access to LAN of the infrastructure. Works on a different layer. -Short Active and Inactive Commissioning Periods: private network can contribute to shorter commissioning times, both inactive (setup without operational testing) and active (operational testing). **Durability and Long-Term Operation (Better):** -Sensors are radiation hard. Other electronics can be shielded (even in low to intermediate level storages). Main limits are batteries (5-10 years). -Maintenance should be minimal. Devices not used by operators, this could extend lifetime.	**Complexity and Customization Needs (Worse):** -Newly developed. Customization beyond off-the-shelf may be required. Time consuming, also for the large number of units installed. -Infrastructure requirements: repeaters, gateways, data management and processing system. Potential delay. **Licensing and Regulatory Approvals (Worse):** -Newly developed technology. Infrastructures may not approve installation of wireless devices. Manual may look "safer", since are not connected and already certified. **Technology Lifetime (Worse):** -Continuous exposure to radiation may wear off components. Currently under assessment. Manual reduce exposure time to measurement time. -Batteries have limited shelf-time (even w/o current draw). This may affect negatively commissioning periods or maintenance.	• Equipment and technology design and manufacture • Integration of the technology in the waste package / storage facility and commissioning • Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
		Operational Efficiency and Compatibility (Better): -A wireless sensor network is designed for efficiency by nature compared to manual solutions. -Movement of packages is not required for monitoring.			

	Ease of achieving required data collection by the technology during storage	"**Collected Data (Better):** -Long term changes of gamma, neutron dose rates and distribution on surface, reflecting loss of integrity or changes in internal structure. Fully automated, in multiple areas, w/o user manual intervention. -Relevance to end-users: data can be used to achieve ageing indicator after modelling. Automatization and no human errors make this process simpler. **Data Processing and Interpretation (Better):** -Edge Processing and inclusion of Machine Learning/AI tools directly on the sensing devices. Not easily achieved on baseline. Very simple models are available. -Dose rates are quantitative in nature, loss of integrity needs modelling and interpretation to be quantitative. Same is true for baseline. **Scalability and Flexibility (Better):** -Modular, compact design: from single packages to whole storage without substantial changes to core units. -Other tools, measuring devices can be integrated on demand to widen the spectrum of measurements. -continuous vs Discrete measurements: discrete in nature. But frequency of measurements is custom. **Reliability and Precision (Better):** -Calibrated in ISO9001 and ISO17025 Labs (Pisa and Milan). Integration	"**Complexity of Data Management (Same):** -Large amount of data. Extra layer of complexity for data management, processing and interpretation. **Measurement Challenges (Slightly Worse):** -Time-Intensive: solid state detectors are less sensitive compared to scintillators. -Limited Package Coverage: this is also true for manual inspection. -Data quality and uncertainty: certified instruments may provide more reliable and comprehensive data (spectrum). **Changes to Storage and Movements (Worse):** -Sounds/Vibration: detectors detachment, but noise was not observed. -Movement of packages: dose rates from other packages may affect performance. Baseline radiation levels must be reacquired. Manual inspection, if package is removed, do not require this. -Modification to storage to account for detectors and antennas."	• Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
		windows (customizable, currently 12.5 mins for gamma and 1 min for neutrons) to achieve a minimum detectable DR of 1 uSv/h. Precision depends on actual DR (Poisson). Improved precision by extending windows w/o the need for operators. -Sub GHz LoRa: reliable, even in harsh environments and through obstacles. **Interoperability (Better):** - Data are continuously updated w/o the need for operators. If increase DR is observed, other NDT can be used. "			

	Potential to monitor a wide range of packages (flexibility) including legacy packages in different storage configurations	**Versatile Package Monitoring (Slightly Better):** -Adaptation to a diverse array of package geometries and waste contents. No limitation on cementation matrices (e.g., Portland, BFS/OPC) and container materials (metallic, cemented). -Compact detectors can be installed in different areas or surfaces of the waste, and remotely monitored. This may not be possible with baseline. -Legacy waste packages can be monitored, also with heterogeneous contents. Only if still radioactive. **Non-Destructive Analysis (Same):** -Non-destructive by nature. -Prior knowledge of the content may help (to account for natural decays), but not required. -Technology monitors both gammas and neutrons. Baseline solutions may only allow gammas. **Stacking (slightly Better):** -Indirect stacking is functional (for antennas and transceivers). Baseline might require removal and/or full access to the package. **Range of Activities (slightly Better):** -Detectors for both gammas and neutron emitters. -Customizable integration time for different activity levels leads to optimized power consumption. **Digital Twin (Better):**	**Measurement Capabilities with complex packages (worse):** -Complex and very heterogenous packages may require advanced spectral analysis, not available on the platform. **Stacking (depends):** -Manual inspection requires access to packages, but when not monitored all stacking configurations can be used.	• Monitoring operations	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
		-As an IoT solution, the technology can be more easily integrated with digital twin technology. -Extra benefit if digital twins use data from other technologies.			
	Impact on waste management strategy	**Minimal Operators Need (Better):** -Operators are needed for installation only. Automated and remote data collection. **Movements of Packages (Better):** -Packages do not need to be moved for monitoring, decreasing complexities of waste management.	**Space Needed and Storage Configuration (Worse):** -Small space between drums for sensor attachment (probably space already present at 90° may be enough) -Antenna placement. **Disposal (Worse):** -Detectors and transceivers should be removed when packages are disposed off. **Movement (Worse):** -Harsh movements of the packages may detach sensors.	• Monitoring operations • Removal of the technology after storage • Disposal of the package / technology materials	0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Decommissioning timescale		**Contamination (Worse):** -Long term exposure. If contaminated, equipment must be considered a secondary waste and disposed accordingly. **Operations (Worse):** -Detachment of detectors and transceivers is needed. Fast, but needed. **Decommissioning (Slightly Worse):** -No experiences available, however the infrastructure (repeaters, gateways, data management framework) do not need to be disposed of.	• Removal of the technology after storage • Disposal of the package / technology materials	-1

Technical Readiness	Maturity of the technology	**Maturity of the Technology:** -Deployed at pilot scale: Lab Tests -> Sogin Interim Storage and UJV Demo Test. -Ease of Installation: attachment/detachment of detectors to/from package, installation/retrieval of gateway outside storage area (different building). -Reliability: no packet loss, no loss of accuracy over 4 months. Maintenance/intervention was not required. -Model: gamma 2 calibration factors (low/high energies), neutrons single calibration factor (thermal). Validated through Lab tests. -Suppliers: integrated circuits availability is likely to be high and constant over a long period (minimal modifications required, ex: new MCU of the same family). **Technology Normative and Feasibility:** -Implemented at Industrial Level as LoRaWAN (ERC-REC-70-3E subGHz at European Level). -Several publications available on the feasibility of implementing LoRa networks in industrial facilities. **TRL: 5 / 6** -6: A large-scale pilot of the technology is being tested on the full range of intended applications. Operations not yet at an industrial throughput and likely only with inactive analogues. -5: Technology is being tested at the pilot scale to refine the design. Operations likely to be inactive and at low throughput.	**Maturity of the Technology:** -Deployed at pilot scale: not deployed in a real storage facility over large number of packages. -Ease of Installation: management of large number of units is not straightforward (data collision, management). Interface between LoRa and LAN not implemented. -Reliability: to assess over a real network and in a real storage (movement of packages). -Model: dose rates changes/distribution to loss of integrity and structural changes need more accurate modelling. -Suppliers: micro-power detectors have limited suppliers, but many others are available. **Technology Normative:** -Steps are still required to move from a LoRa private network to LoRaWAN. -Industrial solutions already available, but not strictly targeting the Nuclear Industry.		-1

Strategic Cost Impact	Costs of construction, operation and decommissioning, and material costs	**Construction Costs (per unit):** - Not all packages may need a unit (representative sampling), especially for the same type of waste and matrix, containers. - Cost of a single unit (hardware & software): roughly 2000 euros. Expected lifetime 5 - 10 years (limited by battery). - Cost for R&D needed to achieve full industrial scale (personnel/material): roughly 100'000 euros. - Cost of a single unit is still lower than many commercially available radiation detectors (ex: Inspector for gammas/neutrons = 35'000 euros per unit). **Operational Costs:** - Commissioning: physical installation (< 1000 euros per unit, including personnel cost), software development (data management, network infrastructure): > 50'000 euros. - Maintenance Costs: materials (< 1000 euros per year, per unit), personnel (few operators are needed for maintenance w/o specific expertise, < 5000 euros per person), calibration (every few years). - Energy Costs: < 5 kW for the whole network infrastructure (mainly for servers, databases). Batteries. - Preliminary test of the units may be needed after installation. - Data Interpretation: personnel to assess modelled data will be needed for decision making (few for whole network). - Decommissioning: units are easily detachable from packages, can be	**Construction Costs (per unit):** - Baseline solution requires only a few handheld detectors. - While more expensive, commercial detectors offer more flexibility and features (more value per money). - Certified, maintenance often included in cost. - No extra R&D. **Operational Costs:** - Baseline solution does not require installation on packages, or network implementation. - Data Management software may be simpler and less expensive (not IoT solution). -Technology can be reused, and it is not exposed all the time so contamination risks and costs are lower.		-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
		reused and eventually repurposed/upgraded. - Personnel costs related to constant monitoring of personnel involved in inspection of packages, radioprotection issues, and dosimetry services are lower.			
	Impact on disposal costs (package & secondary wastes / maintenance wastes destined for disposal)		**Secondary radioactive wastes:** - Compared to baseline, detectors, components, batteries that are in contact for long periods of time may become radioactive/contaminated. - LLW, ILW. Activation/contamination risk is low, but still higher than baseline. - Secondary waste are in contact with the package until detached. - Detachment, assessment, decontamination will add steps and costs to waste disposal route.		-1

A.6 Muon Tomography

Name	Enrico Conti, Paolo Checchia
Organisation	INFN Padova
Date	25-Mar-24
WP7 Monitoring technology	Muon Tomography
Baseline	X-ray imaging

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Operational and Transport Safety	Technology and equipment manufacture, commissioning, and decommissioning	• Construction: similar complexity than baseline. • Probably it requires crane. • Requires specific/dedicated space. • No radiation safety rules/protocols are required. • No radiation dose for worker. • Decommissioning: simpler because no radiation hazard. • Direct disposal is possible			1
	Package or store modification requirements for technology implementation (conventional and radiological safety implications)	Same as baseline. Drum must be moved from storage to the detector and vice versa. Hazard for both connected to the waste movement. Same hazard for the baseline.			0

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Storage/monitoring operational safety issues	• Mechanical hazard: same as baseline. • No radiological hazard for exposure for workers. • No radiation hazard respect to the X-ray tech (baseline). • No necessity of operator close to the detector: total control from remote. No additional shielding. • Both technologies do not alter the waste hazard risk.			1
	Transport safety issues				0
Environmental impact	Material environmental impacts	Difficult to answer for the baseline tech. • For Muon tomography: materials used are only Aluminium and stainless steel. Very little plastics for cabling and HV insulation. • Gas mixture Ar+CO2(15%) both extracted from atmosphere. • Electronics is based on very standard components. • No batteries. • Detectors can be reused in other contexts and also with different geometry. • All materials can be recycled.			
	Technology energy requirements	• No answers for baseline, but likely similar to MT. • For MT we give the electric consumption during its operational life: electric power for detector operation (electronics + High Voltage + cooling) and data acquisition (PC + monitor) = 1kW electric power for data storage and data analysis = =0.5-1.=0 kW			**0**

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Secondary and maintenance waste generated	For both systems: no waste during the operational cycle. Perhaps replacements of failed electronics boards, which sometimes could happen.			**0**
Impact on disposability / long-term safety	Ability to meet waste acceptance criteria	• MT and baseline detect and measure the (metallic) content inside the cemented drum. • MT cannot detect cracks nor voids, unless they are very large (studies needed). Similarly for the baseline option.			**0**
	Disposability of secondary waste	• Very limited secondary waste production. • Possible replacements of failed electronics boards, which can be treated as standard electronics waste. • Computers, monitors, and data storage devices which you could change when they become obsolete.			**0**
Implementation and timescales	Design, construction, implementation and operating timescale		Muon Tomography is not at full industrial scale, yet		-1
	Ease of achieving required data collection by the technology during storage	• Both technologies make images of the metallic content of a cemented drum. Both need offline data analysis after the data taking for the 3D reconstruction. • Impact on storage policy because of the need to move the drums from the storage area to the detector. • Transport and handling hazard.	Only difference is that Muon tomography requires much longer data taking time		-1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Potential to monitor a wide range of packages (flexibility) including legacy packages in different storage configurations	• Muon Tomography has large flexibility to accept different geometries, large dimensions, wide range of materials (also mixed materials), different cementation matrix, maybe better than baseline. • MT does tomography without moving the object under inspection, and this is a plus wrt the baseline. No need to know the content of the waste.			1
	Impact on waste management strategy	• MT and baseline both require movements of drums for their inspection. This has an impact of the waste storage management. • A dedicated area for the detector is requires. • Qualified personal is required for the measurement and data analysis (1 person is enough).			**0**
	Decommissioning timescale	• No difficulties in decommissioning. • As for the installation, baseline and MT probably require a crane to lift the large and heavy detectors.			**0**
Technical Readiness	Maturity of the technology		Muon Tomography TRL = 6		-1
Strategic Cost Impact	Costs of construction, operation and decommissioning, and material costs	When at industrial level, we presume a cost for Muon Tomography around 1 MEu.	From TRL = 6 to industrial implementation cost --> difficult evaluation. Also software (computing) optimization must be improved.		

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Impact on disposal costs (package & secondary wastes / maintenance wastes destined for disposal)	Both MT and baseline: • Maintenance: Possible replacements of failed electronics boards, which can be treated as standard electronics waste. • Other waste are computers, monitors, and data storage devices which you could change when they become obsolete.			

A.7 Digital Twin

Name	Rainer Dähn, Dan Miron
Organisation	Paul Scherrer Institute (PSI), Switzerland VTT, Finland Institute for Energy Technology (IFE), Norway
Date	21-Mar-24
WP7 Monitoring technology	Digital twin
Baseline	Combination of paper records and limited digital archiving of data, but no DT or decision framework used.

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Operational and Transport Safety	Technology and equipment manufacture, commissioning, and decommissioning	DT are non-destructive and contain no hazard to the waste packages	none	n/a	2
	Package or store modification requirements for technology implementation (conventional and radiological safety implications)	No modification required	none	n/a	2
	Storage/monitoring operational safety issues	No conventional or radiological hazards	cybersecurity and data backup	DT can be installed or removed at any time	1
	Transport safety issues	none	Cybersecurity	n/a	0
Environmental impact	Material environmental impacts	IT equipment needs a local computer or a server	Cybersecurity	n/a	1

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Technology energy requirements	High performance PC needs ~5000 kWh per year	none	n/a	1
	Secondary and maintenance waste generated	n/a	n/a	n/a	n/a
Impact on disposability / long-term safety	Ability to meet waste acceptance criteria	Items mentioned can all be integrated in DT	Getting data to train the DT is not that easy	n/a	1
	Disposability of secondary waste	n/a	n/a	n/a	n/a
Implementation and timescales	Design, construction, implementation and operating timescale	Lifetime of a DT can be indefinite	• DT in this field are still under development. • Data are not freely assessable. • Data belong the waste owners.	n/a	0
	Ease of achieving required data collection by the technology during storage	DT are easy scalable and flexible for any future improvement or development	FAIR principles can be problematic in certain cases	n/a	1
	Potential to monitor a wide range of packages (flexibility) including legacy packages in different storage configurations	DT are very flexible, increase amounts of data can be handled	none	n/a	2
	Impact on waste management strategy	DT help in predicting the long-term evolution of waste packages and can optimize the final disposal	none	n/a	2
	Decommissioning timescale	n/a	n/a	n/a	

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Technical Readiness	Maturity of the technology	Development of DT is mature	Data to train the DT are not available yet. The reals 30-year-old waste drums did not show any alteration processes, which could be integrated in a DT. The lab-based enhanced experiments did not show expansion, which would be indicative for the ASR production, instead shrinkage occurred. Therefore, more R&D is required in this field	n/a	0
Strategic Cost Impact	Costs of construction, operation and decommissioning, and material costs	1 PY of a scientist and 0.2 PY of an IT specialist	No proven track record in this field is existing	n/a	0
	Impact on disposal costs (package & secondary wastes / maintenance wastes destined for disposal)	DT can help to reduce waste packages, where appropriate DT can optimize and efficiency of disposal processes	none	n/a	1

A.8 Data Platform and Decision Framework

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Organisation	Institute for Energy Technology (IFE), Norway
Date	19-Mar-24
WP7 Monitoring technology	Data management decision framework tools
Baseline	Combination of paper records and limited digital archiving of data, but no digital twin or decision framework used.

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
Operational and Transport Safety	Construction and decommissioning of the tools			• Tools design and equipment manufacture. • Integration and commissioning of the tools with the storage system. • Data archiving. • Disposal of the tools.	**2**
	Package or store modification requirements for tool implementation (conventional and radiological safety implications)	No modification required	N/A		**2**
	Storage/monitoring operational safety issues	Early issue detection	IT infrastructure is required that increases cyber security threats. Misinformation caused by bugs or bad design. Cloud usage may be restricted do to regulations or cyber security reasons.	• Monitoring / data analysis	**0**
	Transport safety issues	N/A	N/A		
Environmental impact	Material environmental impacts		May require additional IT infrastructures causing some waste from the equipment.	• Monitoring / data analysis	**-1**

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Technology energy requirements		I assume everything can run on one physical server and power consumption is between 100-500 watts. Running virtualised on the cloud can be more efficient.	• Tools design and equipment manufacture. • Integration and commissioning of the tools with the storage system. • Monitoring / data analysis. • Data archiving. • Disposal of the tools.	**-1**
	Secondary and maintenance waste generated		Some electronic waste from running the infrastructure may be produced.	• Tools design and equipment manufacture. • Integration and commissioning of the tools with the storage system. • Monitoring / data analysis. • Data archiving. • Disposal of the tools.	**n/a**
Impact on disposability / long-term safety	Ability to meet waste acceptance criteria	The decision platform could give the ability to analyse and assess the state of the waste including historical data.		• Monitoring / data analysis.	**2**
	Disposability of secondary waste	The decision platform could give the ability to analyse and assess the state of the waste including historical data.		• Monitoring / data analysis.	**2**
Implementation and timescales	Design, construction, implementation and operating timescale		Man year(s) to set up. Will also require IT resources to run and maintain.	• Tools design and equipment manufacture. • Integration and commissioning of the tools with the storage system. • Monitoring / data analysis. • Data archiving. • Disposal of the tools.	**-2**

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Ease of achieving required performance by the tools during storage		• Very high risk of both software and hardware becoming obsolete. • Renewing/updating/migrating can be even more time consuming than the initial development since you have historical data you want to preserve.	• Monitoring / data analysis. • Data archiving.	**-2**
	Potential to handle a wide range of monitoring data from different technologies in different storage configurations		Many of the technologies scales well but it depends. New types of measurements may require some configuration or development. The more you know when the system is developed the better. Changes can be costly either in initial design and implementation or at time of change.	• Monitoring / data analysis.	**-1**
	Impact on waste management strategy	The system can have beneficial impact on early detection and efficient packing and optimising waste streams.			**2**
	Decommissioning timescale				
Technical Readiness	Maturity of the technology		• Dashboard of single drum TRL 3. • Other decision platform prototypes TRL 2. • Some tech used, like Azure, probably at TRL 9.	• Tools design and equipment manufacture. • Integration and commissioning of the tools with the storage system. • Monitoring / data analysis.	**-2**
Strategic Cost Impact	Costs of construction, operation and decommissioning, and material costs		• Considerable cost to take this to higher TRL. • Will be maintenance costs for licensing software, running hardware and providing support.	• Tools design and equipment manufacture. • Integration and commissioning of the tools with the storage system. • Monitoring / data analysis. • Data archiving. • Disposal of the tools.	**-1**

Assessment Area	Criteria	Strengths vs Baseline	Weaknesses vs Baseline	Relevant Lifecycle Stages	Rating
	Impact on disposal costs (package & secondary wastes / maintenance wastes destined for disposal)	See DT	See DT		**1**