Enhanced Radioactive Waste Drum Monitoring: A Sensorized LoRa-Based Network for Identification and Integrity Assessment

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Abstract

A reliable monitoring and oversight system is essential to guarantee the safe operation and eventual closure of radioactive waste disposal facilities. With recent technological advancements, there is now the capability to deploy distributed wireless sensor networks that are cost-effective and low in power consumption. Such networks are versatile, finding applications in several civil, environmental, and industrial sectors. This work presents a novel system and method for identifying and continuously monitoring the integrity of stored radioactive waste packages. The proposed approach, developed by the University of Pisa in the context of the H2020 European Project PREDIS, employs a network of wireless node devices, provided with solid-state micro-power radiation detectors tasked with the measurement of gamma-rays and thermal neutrons coming from within cemented waste drums. Collected data are automatically transmitted across the storage site via Long Range radio technology and forwarded to cloud-based or offline platforms, allowing for further visualization, data processing, and safe storage. The system highlights the feasibility of autonomously and passively gathering data from radioactive waste drums over extended distances (more than 250m in non-line-of-sight conditions), decreasing the reliance on portable or automated scanning mechanisms. In line with its capability for autonomous, long-range data collection, the system satisfies the requirement for structural integrity, containment, and confinement of packaging throughout both interim and long-term disposal of radioactive wastes, thereby playing a key role in reinforcing the safe management of radioactive waste.

Keywords: Radioactive Waste Drum, Non-Destructive Techniques, Wireless Sensor Networks, Long Range Radio, Long Term Monitoring, Integrity Assessment

1. Introduction

Radioactive wastes (RWs), produced as a result of nuclear technologies and power generation processes, require storage in appropriate packaging systems to comply with international standards for safe disposal. Throughout the interim or long-term disposal period, the packaging must ensure structural integrity, containment, and confinement functions over its entire lifespan. Consequently, for the safe management of RWs, it is critical to confirm the durability of both the packaging and the waste form, and to continuously ensure compliance with the fundamental principles of radiation protection and established acceptance criteria (Lowenthal, 1998; IAEA, 2007). For this purpose, a robust and potentially passive monitoring system needs to be developed, ensuring the essential and ongoing surveillance of storage conditions at disposal facilities.

To assess and determine the properties of the waste form and its packaging, both non-destructive testing (NDT) and destructive testing (DT) techniques are commonly employed (Morichi et al., 2023; NEA, 2014). Many of these methods enable the determination of the ambient dose equivalent rate in raw or conditioned waste (Tavčar et al., 2007; Maringer et al., 2013), the measurement of alpha and beta-emitting radionuclides' activity, analysis of isotopic composition (Pérot et al., 2018), and the assessment of the mass of nuclear and fissile materials (Dighe et al., 2019). Typically, NDT methods are favored over DT ones because they help to minimize radiation exposure for operators, reduce or prevent the generation of secondary waste, and decrease overall costs.

Among the various NDT methods, passive gamma and neutron counting techniques are most used for on-site and long-term radiological monitoring and characterization. These methods are easy to deploy and economically advantageous. Passive counting's effectiveness in detecting photons and neutrons in waste packages (NEA, 2017) is

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challenged by low-energy emissions from radionuclides like Cl-36 and Am-241. However, correlating these with gamma emitters such as Cs-137, detectable through 511 keV annihilation photons, is possible (IAEA, 2009), with neutron counting providing essential complementary data, especially when gamma emissions are obscured (Jallu et al., 2011).

In this paper, we introduce a novel and smart device designed for providing data on the durability of waste forms under conditions likely to be encountered in a repository setting both during operation and after closure. The chemical and mechanical stability of the waste form is vital for the overall integrity of the packaging system. For instance, the waste form, in conjunction with the packaging, must possess adequate long-term mechanical strength to endure the various stresses encountered in repository environments. The capability of this system to deduce package deterioration and degradation, such as thinning, localized corrosion, or changes in the waste form, from the measured activity data, sets it apart from other developed and tested methods, both destructive DT and NDT.

The University of Pisa (UniPi) designed, characterized, and validated this platform within real storage environments as part of the activity on sensing technology performed in WP7 of the H2020 European project 'PREDIS – 'The Pre-Disposal Management of Radioactive Waste' (PREDIS, 2020). Noteworthily, it was specifically engineered for use in complex storage facilities, where it faces challenges such as limited internet connectivity and significant structural attenuation. Furthermore, the adaptability of the platform significantly extends its applicability, enabling its use not only with standard waste packages but also with those of larger or more complex geometries.

In the subsequent sections, we first introduce the technology specifically designed for identifying and continuously monitoring the radiological levels in conditioned RWDs. Following this, we delve into a detailed description of the methodology, which is expected not only to track the radiation intensity on the surface of the package, but also to potentially unveil alterations in the structural integrity of the package. Lastly, we offer a comprehensive description of the Wireless Sensor Network (WSN), which comprises numerous independent devices (sensor nodes), devised for the long-term monitoring of the packaging. This is followed by a critical analysis of the results obtained, encompassing both the validation and verification of the sensor's functionality and efficacy.

2. Waste Drum Monitoring Network

To address the need for monitoring many waste packages and the challenges of limited accessibility and real-time data requirements, the device has been integrated into a WSN. This network consists of multiple independent sensor nodes, each equipped with solid-state gamma-ray and thermal neutron detectors, ensuring dependable performance in diverse monitoring environments.

In waste management applications, deploying sensor networks presents clear benefits. These networks facilitate distributed monitoring across extensive areas, diminishing reliance on intricate cabling infrastructure or mechanical scanning systems (Manzano et al., 2021; Ahmad et al., 2021). Consequently, this approach can substantially reduce the inconsistencies and human errors that typically arise during the information management of RWDs throughout the disposal process. Furthermore, with the inclusion of a long-range wireless interface, the network's applicability extends to transportation scenarios (Brincat et al., 2019). The integration of these technologies with decommissioning machinery, such as conveyor belts, robotic arms, and specific demolition equipment, may provide real-time radiation data during all stages of the decommissioning process (Marques et al., 2021).

In the presented WSN, the selection of Long-Range Radio (LoRa) technology as the wireless communication protocol of choice is attributed to its inherent benefits: minimal energy requirements, economic viability, superior transmission distance—effective in direct line-of-sight and penetrating impediments, network flexibility, and secure data encryption. Whereas protocols for shorter and intermediate distances fulfill their respective niches (Noor-A-Rahim et al., 2023), long-range protocols like LoRa are particularly adept in scenarios demanding comprehensive and continuous network coverage (Bahashwan et al., 2021). Additionally, LoRa's decentralized framework enhances data handling efficiency, significantly reducing the reliance on continuous centralized or cloud-based network connections.

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This characteristic is particularly valuable in environments where consistent network availability is difficult, like radioactive waste storage facilities or nuclear power stations. Economically, LoRa generally offers a more feasible option relative to other technologies. Its versatility in adapting to diverse environmental circumstances and the flexibility it provides in configuring network topologies often result in financial advantages, both in terms of initial setup costs and ongoing maintenance (Sun et al., 2022).

2.1. Overview

The proposed WSN is structured into three distinct layers (Fig. 1):

- LoRa Nodes: provided with a unique identifier on the network, they are responsible for periodically or continuously gathering radiation data coming from within the package. Changes over time in radiation signals provide a method for tracking the structural condition of the waste drums. This collected radiation information is then automatically transmitted to LoRa gateways, using direct communication or through repeaters as required by the operational environment.
- LoRa Gateways: they handle the LoRa traffic and forward data to local storage or an Azure IoT Central application via Wi-Fi through a Message Queuing Telemetry Transport (MQTT) broker. Additionally, they maintain synchronization across all nodes using acknowledgment (ACK) radio payloads, mitigating the potential for data transmission collisions.
- Cloud-based Platform: implemented through an Azure IoT Central application, this platform allows for remote access and data processing. Data is visually represented on interactive dashboards, streamlining analysis and interpretation. Metadata has been defined in JSON format, detailing all the network components, including sensors, nodes, and gateway configurations. Leveraging cloud storage capabilities ensures that end-users can access the sensor network remotely. Although this remote access necessitates internet connectivity, it's important to note that the network remains fully operational even without an internet connection.

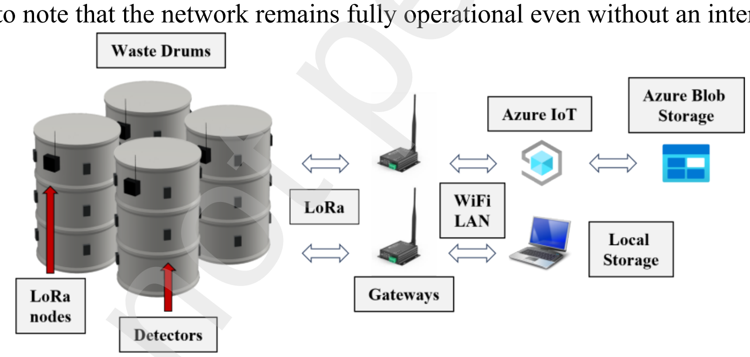

Fig. 1: Architecture of the LoRa-based WSN for the identification and monitoring of cemented RWDs proposed by UniPi.

2.2. LoRa nodes and detectors

The wireless sensor nodes at the heart of the system combine a high-precision, temperature-compensated Real Time Clock (RTC) with a power-efficient microcontroller (MCU) for task scheduling and operations control (Fig 2). For communication, nodes utilize UART-interface LoRa transceivers capable of wake-on radio functionality, which allows them to conserve energy by remaining in a sleep state until triggered by incoming radio signals—ideal for intermittent or responsive data transmission scenarios. This setup forgoes integration with LoRaWAN but achieves a balance in cost, dependability, and simplicity of use.

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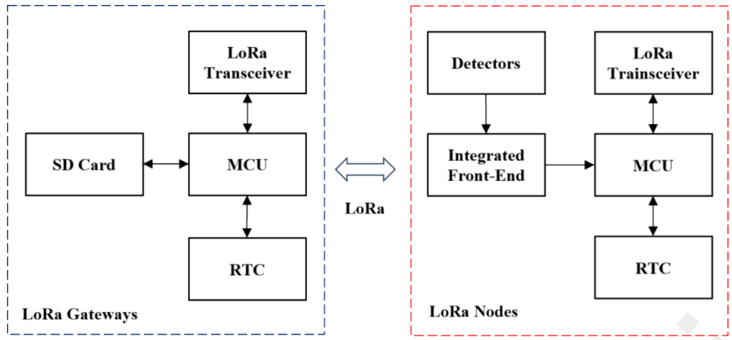

Fig. 2: Architecture of the sensorised LoRa nodes and gateways comprising the WSN.

Operational parameters, such as the timing of data collection and transmission intervals, are governed by the RTC. The nodes operate mostly in a power-saving mode, awakening as programmed to perform tasks or transmit data, thus extending battery life to several years. Communication is organized via time-division multiple access (TDMA) and listen-before-talk (LBT) protocols, ensuring orderly data traffic and energy-efficient transmissions. Each node's RTC is routinely re-calibrated to maintain network-wide timing precision, supplemented by an inbuilt MCU RTC checking for system integrity every few seconds. In case of a system hang, a record of the current state of the program is stored in non-volatile memory before initiating a system reset issued by a Watchdog Timer (WDT), ensuring data preservation and system reliability.

Radiation data is captured during predetermined intervals, known as measure windows, which can be fine-tuned for their occurrence and length to balance power efficiency, data detail, and measurement precision. After the designated number of measure windows, the system transmits the collected data. Moreover, if the radiation fluence surpasses a predefined threshold, the system promptly raises an alert and conducts an expedited data transmission, ensuring the information is relayed with no more than an 8-second delay (Fig. 3).

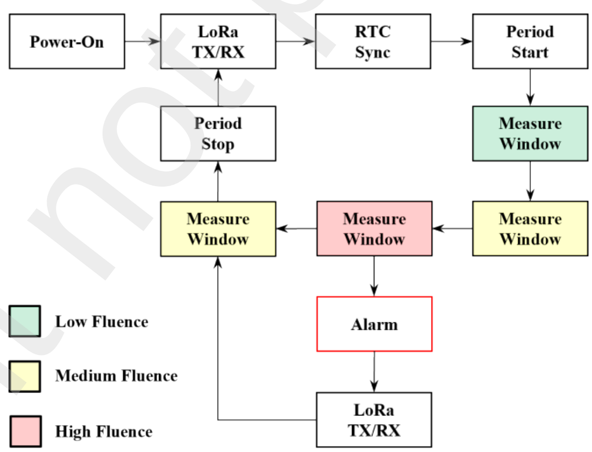

Fig. 3: Scheduling of the activities conducted by a sensorised LoRa node. Duration, frequency, and number of windows are custom.

Within this system, each node is engineered to support up to eight detectors in parallel, optimized for low-power operation and specifically designed to detect gamma rays or thermal neutrons (Fig. 4). For gamma-ray detection, Teviso BG51 detectors were chosen, which utilize a modified silicon PIN diode array as its sensing element. These detectors can identify gamma radiation up to 2 MeV, feature an active area of 0.54 cm2, and provide TTL pulse outputs for data communication (Teviso, 2023). In contrast, the Domino v5.4 model from Radiation Detection Technologies is employed for thermal neutron detection, incorporating Microstructured Semiconductor Neutron Detector (MSND) technology that combines a ^{6}Li converter with silicon diodes, covering a 4 cm^2 detection area. These thermal neutron

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detectors are characterized by gamma insensitivity and can detect thermal neutrons with up to 30% efficiency (Radectech, 2022).

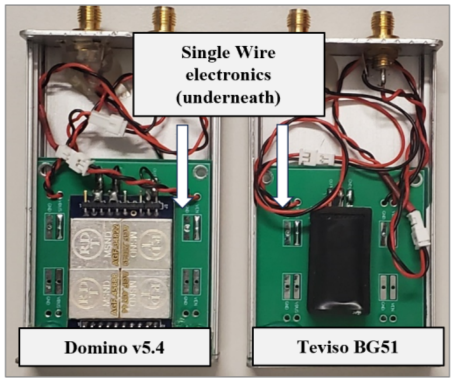

Fig. 4: Solid state detectors for thermal neutrons (Domino v5.4) and gamma rays (Teviso BG51).

2.3. LoRa gateways

In the WSN, LoRa gateways are essential for communication, handling data reception from nodes, sending ACKs, and maintaining the accuracy of node clocks to ensure precise measurement and transmission schedules under Time-Division Multiple Access (TDMA) and Listen Before Talk (LBT) protocols.

Data is locally preserved on SD cards within the gateways and concurrently sent to a web router that communicates with an MQTT broker, which allows to upload of telemetry data to an Azure IoT Central application. This integration streamlines the WSN by combining gateway and router functions into a single device, powered by an Espressif ESP32 MCU.

The system's cloud infrastructure supports customized monitoring dashboards through the addition and configuration of nodes. This allows for advanced data management and presentation, with minimized human error due to the system's automated processes, ensuring a reliable radiation monitoring workflow (Fig. 5).

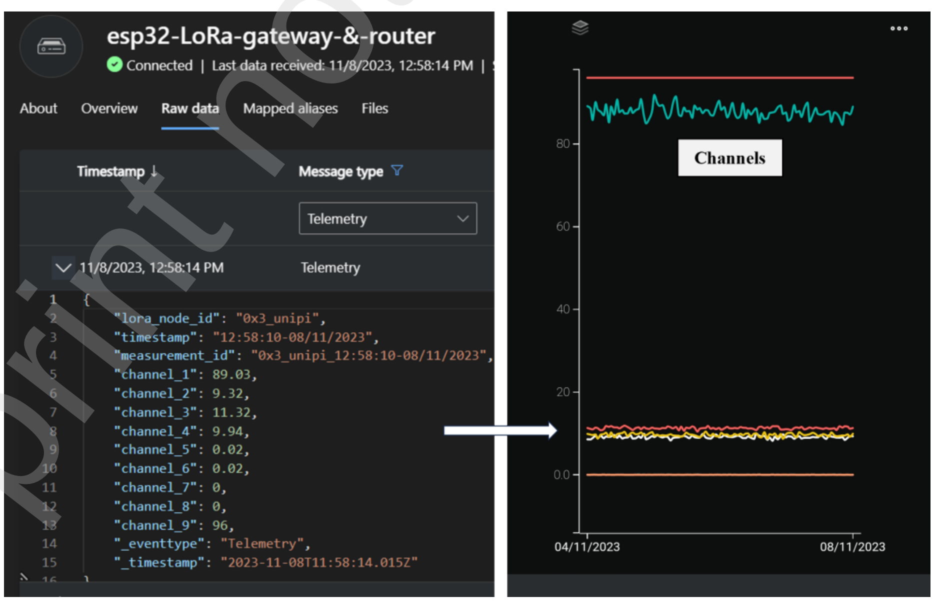

Fig. 5: Telemetry data upload on Azure IoT Central and dashboard visualization

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While our current research emphasizes the use of passive gamma and neutron counting within our WSN, it's important to note the versatility of the framework. This system can be adapted to incorporate a variety of other passive detection technologies, thereby broadening the scope of data acquisition, and enhancing the comprehensive assessment of the status and integrity of radioactive waste packages.

3. Results and discussion

3.1. LoRa node performance assessment

Initial testing to investigate the functionality of the sensorised LoRa nodes was conducted at the University of Pisa's Laboratory of Nuclear Measurements (LNM) (Fig. 6).

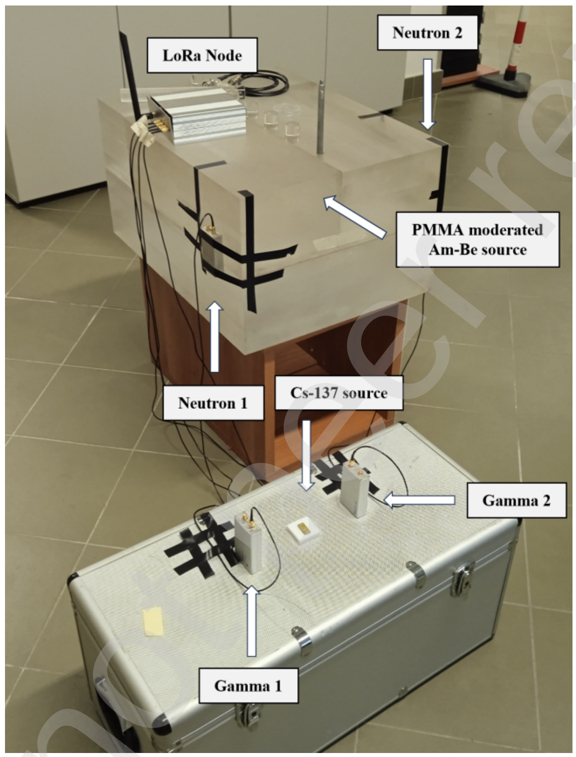

Fig. 6: Performance evaluation setup of the sensorised LoRa node at the LNM of the University of Pisa.

This stage primarily involved verifying the sensitivity and efficiency specifications provided by the detector manufacturers. Additionally, the long-term reliability of the system was assessed, with particular attention paid to its sustained performance in executing predetermined tasks like data acquisition, data transmission, and the cycling between active and deep-sleep states.

For the evaluation, the integration window ΔT for all detectors was established at 1 hour, with a repetition period of 6 hours. Over a month's worth of background radiation data was utilized to estimate metrics such as the minimum detectable count rate (MDCR) and minimum detectable fluence rate (MDFR).

Subsequently, a 140.4 kBq Cs-137-pointlike source was used to expose the gamma-ray detectors stationed atop an unoccupied aluminum support, elevated 50 cm above ground to mitigate scattering influences. The detectors were positioned 10 cm away from the gamma-ray source, aligning with the mid-height of the detectors' active zone.

Moreover, a 1.1 GBq Am-Be neutron source, moderated with 25 cm of PMMA, was used to produce a measurable thermal neutrons fluence rate (up to 0.5 eV) of 100 ± 12 cm^{-2} min^{-1} in the air at 25 cm from the source itself. Thermal neutron detectors were positioned in line with the PMMA moderator, 25 cm distant from the neutron source, and

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centered at the mid-height of the detectors' active region. For the analysis, errors from Monte Carlo simulations were accounted for, in addition to considering the inherent uncertainties associated with counting statistics.

The characterization results are shown in Fig. 7 and Fig. 8 and summarized in Table 1.

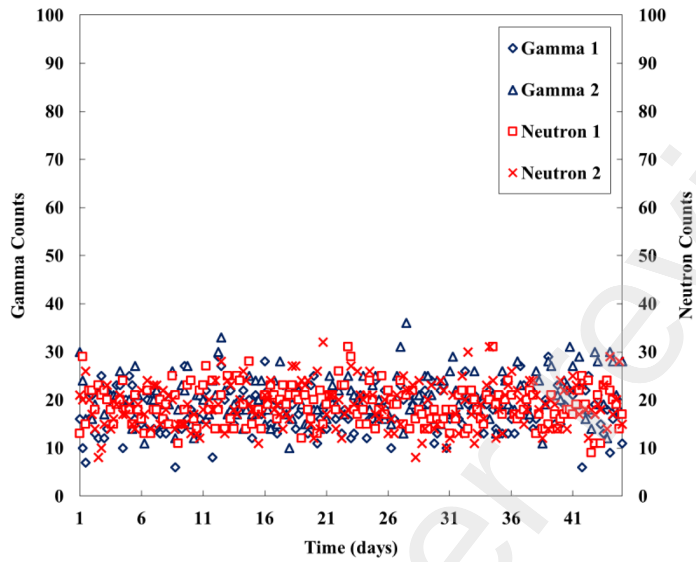

Fig. 7: Background radiation data gathered by the LoRa node with gamma and neutron detectors for a duration exceeding one month. Collection intervals were established at one-hour durations, recurring every six hours.

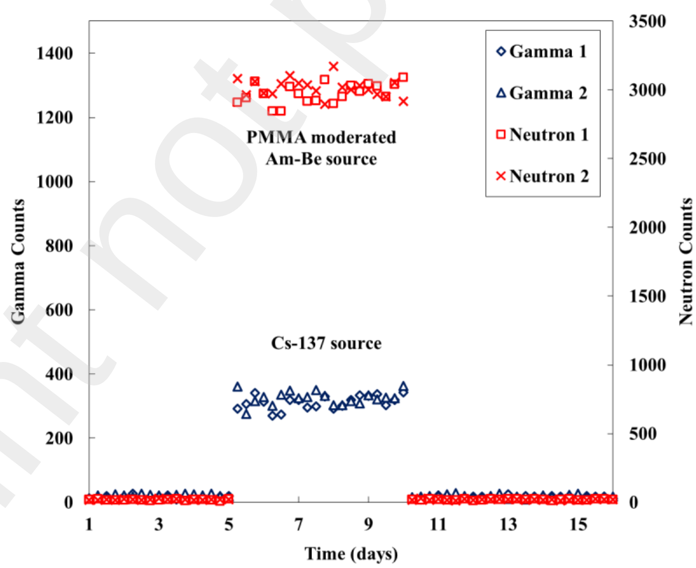

Fig. 8: Radiation data gathered by the LoRa node with gamma and neutron detectors in the presence of Cs-137 and PMMA-moderated Am-Be sources. Collection intervals were established at one-hour durations, recurring every six hours.

The results align with the manufacturer's specifications that cite a sensitivity for gamma detectors equal to 5 (± 15%) CPM/µSv/h at 662 keV (Teviso, 2023), and an efficiency of up to 30% for thermal neutrons (Radectech, 2022).

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Additionally, no significant discrepancy was observed between the tested detectors. The high efficiency of the Domino sensors enables a swift identification even of minimal thermal neutron contamination (an ambient dose equivalent rate of 0.01 μSv/h can be reliably detected in a matter of seconds). In contrast, gamma detectors necessitate an extended integration time to obtain statistically significant results. For example, a 0.1 μSv/h ambient dose equivalent rate can be reliably detected in 1 hour, but this value roughly doubles if ΔT is reduced to 12.5 minutes. However, thanks to the neglectable power consumption, these detectors are particularly well-suited for long-term monitoring of RWDs, or radioactive contamination spread in a nuclear facility.

Table 1: Summary of the characterization of gamma and neutron detectors in terms of Efficiency, Sensitivity, and Minimum Detectable Fluence Rate.

Detector ID	Efficiency (%)	Sensitivity (CPM/μSv/h)	MDFR (n cm^{-2} min^{-1})
Gamma 1	0.18 ± 0.01	5.2 ± 0.3	522.8 ± 26.5
Gamma 2	0.18 ± 0.01	5.2 ± 0.3	588.7 ± 29.2
Neutron 1	13.0 ± 0.3	757.9 ± 6.5	1.01 ± 0.03
Neutron 2	13.1 ± 0.3	759.7 ± 6.5	1.02 ± 0.03

Notes: MDFR = Minimum Detectable Fluence Rate

In a preliminary study, the LoRa node was also tested for electrical power consumption, communication efficiency under NLOS conditions, and EMI immunity. Its power consumption was notably low, averaging 15 μA, and even less during deep sleep mode. Communication tests revealed strong transmission capabilities over 250 meters in NLOS scenarios; additionally, the node's performance remained stable amidst high-power radio transceivers, indicating robust EMI resistance (Chierici et al., 2023).

3.2. Installation in Nucleco S.p.a

The system underwent installation and evaluation in an operational context at the radiation waste storage site of Nucleco S.p.a. in Rome, Italy. A LoRa node, furnished with 2 gamma ray and 2 thermal neutron detectors, was affixed to a 380L cemented overpack containing sources totaling over 100 GBq of Am-Be and 9 GBq of Cs-137. Given the pronounced radiation levels from the cemented package, measurements were programmed at 1-hour intervals with integration windows of 12.5 minutes. A total of 19 hours of measurements on the overpack was recorded. For redundancy and to address potential inhomogeneities within the container, the 4 detectors were positioned at 90-degree intervals from one another (Fig. 9).

Significantly, the tests confirmed the unit's proficiency in relaying data through four buildings laden with cemented waste drums. The data, reflecting background radiation outside the storage facility and the specific emissions from the overpack sources, is presented in Fig. 10. Both gamma rays and thermal neutrons were detected, and relevant data was transmitted to the Azure IoT Central application successfully. Observed discrepancies in count rates among comparable detectors are attributed to the heterogeneity of the concrete matrix and the spatial distribution of the sources. This was validated with calibrated reference detectors furnished by the LNM of the University of Pisa.

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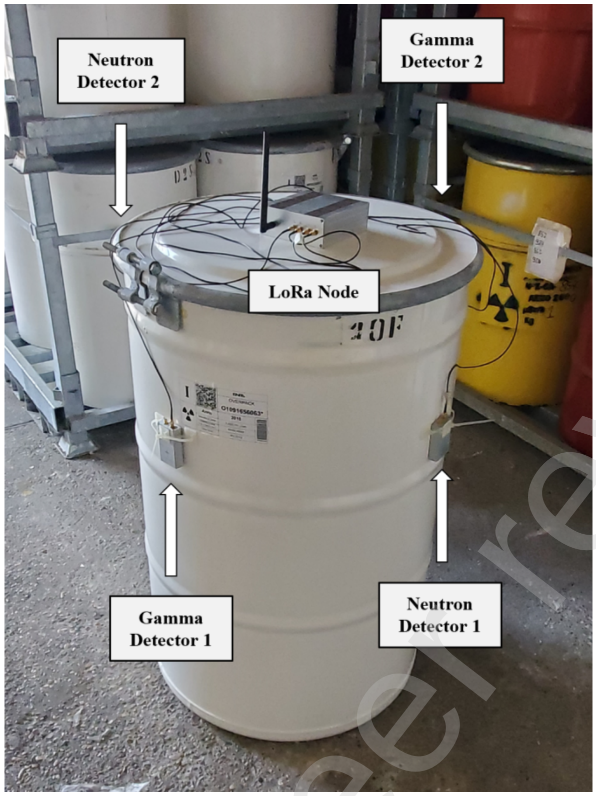

Fig. 9: LoRa node equipped with four detectors installed on a 380L cemented overpack at Nucleco S.p.a.

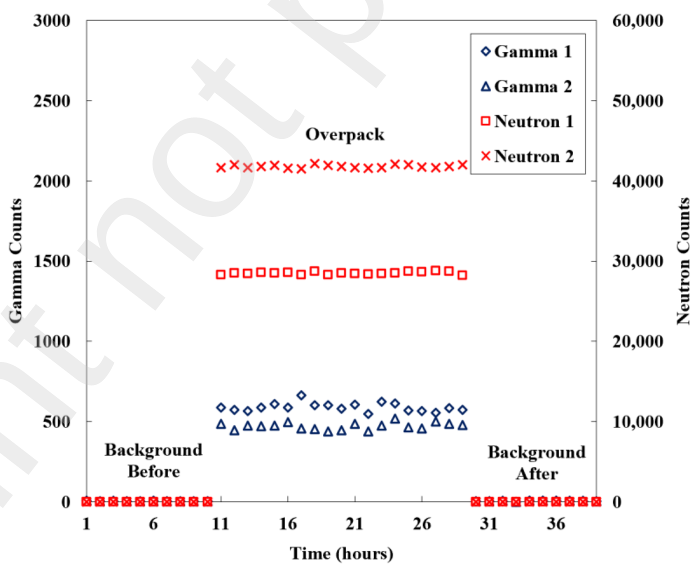

Fig. 10: Data collected from gamma and neutron detectors placed on the 380L cemented overpack in Nucleco S.p.a.

The collected data underscores the potential for discerning activity distribution within the package or pinpointing inhomogeneities, particularly when leveraging multiple interconnected detectors for enhanced container coverage. Deploying a network of these units in a waste storage facility can offer an automated and remote method for long-

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term radiological monitoring, thanks to its minimal power consumption. Furthermore, it can serve as a valuable source of radiological data pertinent to waste acceptance criteria and the improvement of safety protocols.

3.3. PREDIS demonstration test

In alignment with T7.6's objectives of WP7 of the European Project PREDIS, a joint demonstration test was prepared, and it is currently ongoing to evaluate the longevity and efficacy of technologies developed by involved partners. The test, with the organization and coordination managed jointly by NLL (National Nuclear Laboratory, UK) and ORANO (France), is currently being conducted at ÚJV Řež, a.s. (Nuclear Research Institute Rez, Czech Republic).

At ÚJV, drums with a standard capacity of 200L (model 0485, 820 mm in height, 1.2 mm thick galvanized steel) were cemented using a concrete formula provided by SCK-CEN (Belgium), emulating the typical waste drums found in real waste storage facilities. Based on the stipulated specifications, the layout for the three-month test was arranged, as depicted in Fig. 11 and Fig. 12.

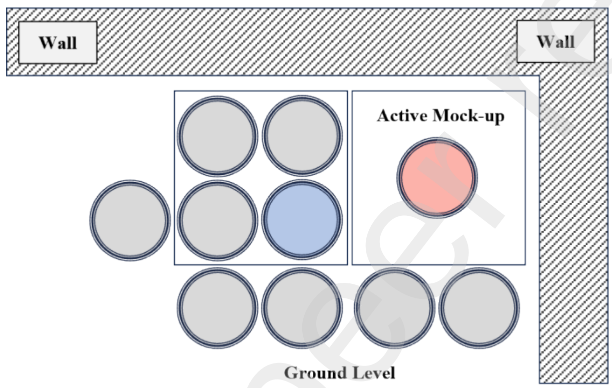

Fig. 11: Ground-level configuration chosen to conduct the joint PREDIS demonstration test at ÚJV Řež, a.s. In red is highlighted the active mock-up to test the technologies developed by UniPi, while in light blue the mock-up used to host non radiological technologies.

Fig. 12: Configuration used during the demonstration test, with an extra layer of drums placed on top of the inspected mock-ups.

A first non-radioactive mock-up was created to evaluate other technologies developed during the project, while a second mock-up, intended for radioactive studies, was designed to test the technology developed by UniPi. This mock-up has a 2.5 cm lateral slot and a central hole to accommodate a Cs-137 167 MBq source, measuring 3 mm in diameter and 3 mm in height, encased in steel with dimensions of 5.2 mm in diameter and 15.9 mm in height (Fig. 13). The objective was to investigate the radiation detection systems' ability to detect the presence of the slot simulating a large crack based on the increased radiation fluence compared to other drum areas.

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Fig. 13: Realization of the active mock-up with a 2.5 cm lateral slot and several holes to accommodate radioactive sources.

For the test, the LoRa node, equipped with 4 gamma detectors labelled 1 to 4 and 2 thermal neutron detectors labelled 1 and 2, was affixed to the mock-up's side, while the gateway connected to a Wi-Fi network in a data equipment area (DEA) situated two floors above the storage area. The repetition period for data recording was set at one-hour intervals, facilitating detailed data capture but incurring a slightly increased power consumption, roughly estimated at 50 µA. The gamma detectors operated for 12.5 minutes each hour, whereas the thermal neutron detectors operated for 1 minute, considering their high efficiency and sensitivity as reported in earlier characterization studies. In the absence of a neutron source, neutron detectors were installed only to verify the insensitivity to gamma radiation. The positioning of the detectors is illustrated in Fig. 14 and Fig. 15, which also provides the calculated theoretical ambient dose equivalent rate in the measuring points for gammas. The test objectives were multifaceted: firstly, to validate the accuracy of the detectors in measuring the right radiation intensity, as pre-determined through prior simulations. Secondly, to demonstrate the efficacy of data transmission in a complex environment lacking internet connectivity and using wireless methods. Thirdly, to evaluate the longevity of the battery. Additionally, to test the ability to detect structural integrity loss indicated by increased fluence, assuming the slot as an indicator. Furthermore, the test was designed to explore the statistical significance of these measurements in assessing the system's potential to detect gradual integrity degradation over time. This would be achieved by analyzing any increases in the fluence rate recorded by the same detector, a capability we believe to be feasible, although it was not directly tested due to current limitations.

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Fig. 14: Placement of the detectors around the drum together with the calculated theoretical ambient dose equivalent rate in the measuring points for gamma detectors (top view).

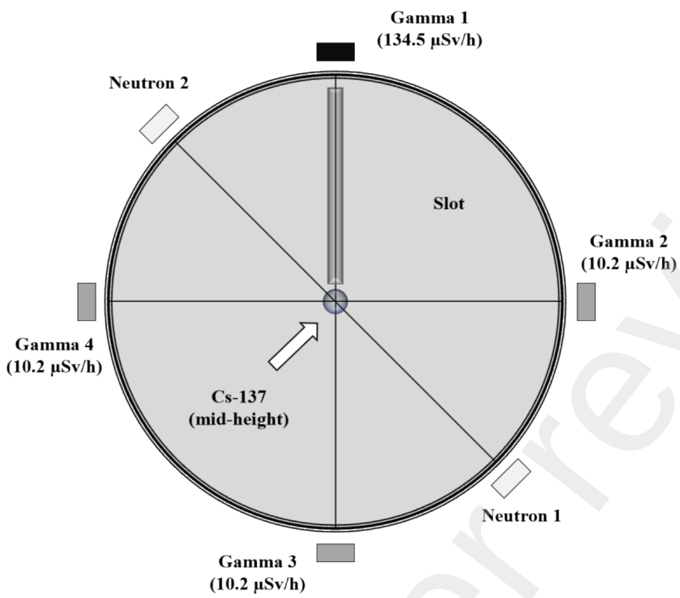

Fig. 15: Gamma and neutron detectors installed on the metallic surface of the drum at mid-height.

Data gathered over more than 10 days are presented in Fig. 16. The count rates were converted to ambient dose equivalent rate using the calibration factor for Cs-137 obtained from prior tests. The thermal neutrons data mainly reflect background measurements.

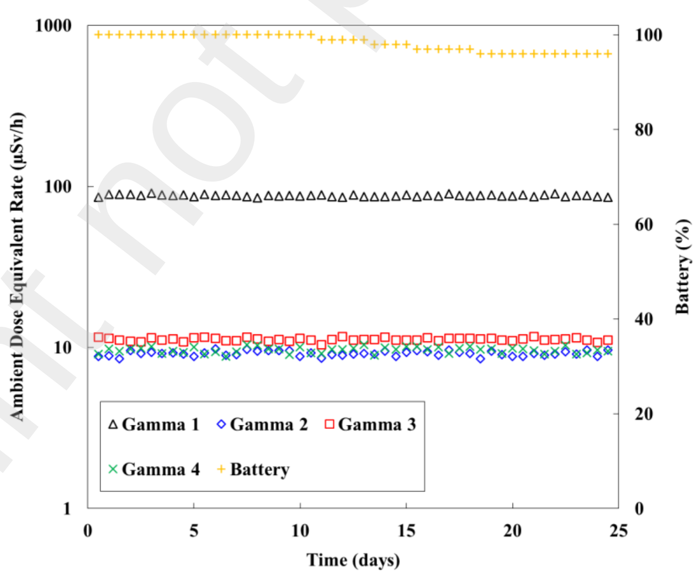

Fig. 16: Data collected for more than 20 days: the gamma detector placed in front of the slot can easily identify an increased dose rate compared to the other 3.

After a month of operation, the system displayed only 3% battery depletion. While initial estimates of battery life were based on a linear voltage-charge correlation, this approach doesn't fully capture the actual discharge pattern. In

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practice, reducing the measurement frequency from the hourly test setting could significantly extend battery life, further reducing power consumption.

The system maintained robust communication, evident from an RSSI value greater than 190 dBm with the gateway located in the DEA. Accordingly, the system resulted well-suited for long-term radiation monitoring of waste drums even in absence of internet connectivity.

Moreover, the observed ambient dose equivalent rates align well with the anticipated values. Gamma 1 detected a notably higher dose rate, identifying the presence of the slot due to the elevated radiation fluence. Dose rate measurements on the drum's exterior were corroborated by ÚJV technicians utilizing calibrated handheld detectors.

As detailed in Table 2, for a given count rate (or dose rate), the minimum significative (99.7%) count rate increase ΔCR (for example due to a loss of integrity of the matrix or cracks) depends on the duration of the measuring window ΔT (integration time), and it can be approximated as $\Delta CR \approx 3 \times (CR \times \Delta T^{-1})^{1/2}$ for large count values, where CR is the current count rate. Thus, by increasing the integration window, the capability of the system to resolve a small increase in the count rate due to increased radiation fluence can be improved, at the cost of increased power consumption and lower granularity.

Table 2: Summary of Count Rate and Ambient Dose Equivalent Rate measurements for gamma detectors.

Detector ID	**Angular Position**	**CR (CPM)**	**ΔCR (CPM)**	**ADER (µSv/h)**	**ΔADER (µSv/h)**
Gamma 1	0°	440.3 ± 5.9	17.8	88.1 ± 1.2	3.6
Gamma 2	90°	46.0 ± 1.9	5.8	9.2 ± 0.4	1.2
Gamma 3	180°	56.6 ± 2.1	6.4	11.3 ± 0.5	1.5
Gamma 4	270°	48.4 ± 2.0	5.9	9.7 ± 0.4	1.3

Notes: CR = Count Rate; ΔCR = Minimum Significative CR Increase (99.7%); ADER = Ambient Dose Equivalent Rate; ΔADER = Minimum Significative ADER Increase (99.7%).

As previously shown, the detector positioned on the slot can effectively discern its presence. While this representation is deliberately pronounced, in real-world scenarios, cracks would likely be more subtle in both size and spread. Nevertheless, this capability underscores the system's potential to autonomously detect substantial structural degradation within the drum's matrix. Beyond mere detection, prolonged monitoring combined with accurate dose rate evaluations can provide essential insights into drum integrity, containment, and confinement capabilities.

4. Further developments

To ensure the platform's durability and resilience, its radiation hardness is currently under examination. While the unit is aimed to be used within low-level or intermediate-level radioactive waste environments, understanding the tolerance to different radiation levels will enhance its reliability and longevity in various radioactive settings. Beyond radiation hardness studies, several factors, that need to be understood and modeled, may influence the accuracy and efficiency of the detection process. The aging of materials, particularly under radiation exposure, can influence their characteristics, and in turn, affect the measurement outcomes.

Another essential aspect of any technological deployment is its economic and bureaucratic feasibility, both during the initial implementation and long-term maintenance. This will ensure that the system remains cost-effective while delivering optimal performance.

Regarding data analysis, advanced modeling needs to be generated to predict future waste behavior, potential vulnerabilities, or areas requiring attention; models can then be used to refine and enhance safety protocols, ensuring

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proactive risk mitigation and at the same time provide valuable information to stakeholders to define or refine waste acceptance criteria. Moreover, the data's utility is enhanced when made easily accessible to stakeholders. Dedicated dashboards and analytical tools, currently under development, will facilitate more informed decisions.

5. Conclusions

This paper introduced a novel device and methodology based on IoT and WSNs to identify and monitor the structural integrity of stored RWDs. The proposed approach utilizes fixed sensor nodes, entirely developed by the University of Pisa, which are either attached to the RWDs or strategically positioned in critical locations, to facilitate automated and remote data collection. This innovation aims to enhance the efficiency of storage management and minimize the likelihood of errors associated with manual data handling.

The integrated network employs LoRa technology as the wireless communication interface, selected for its low power consumption, cost-effectiveness, and extended range capabilities, which make it an optimal choice for the intended application in challenging operational environments.

After an initial characterization to determine the sensors' sensitivity, efficiency, and minimum detectable fluence rate, the system's capacity for long-range communication was confirmed to be highly reliable, even under adverse conditions.

The successful concurrent deployment of multiple sensor nodes demonstrated the system's ability to handle simultaneous data transmissions effectively. This underscores its potential as a passive, long-term monitoring solution in waste storage facilities, where simultaneous monitoring of numerous packages is required.

In a preliminary field trial, the system was deployed at the Nucleco S.p.a. site in Rome on a 380L cemented overpack containing gamma and neutron sources of significant entity, where the technology proved its effectiveness in delivering insights into the activity distribution within the overpack. Additionally, the system's ability to identify anomalies within waste containers highlights its value for long-term, automated, and remote monitoring, as shown in joint demonstration tests currently being conducted at ÚJV Řež, a.s. These developments are in line with the objectives of the European Project PREDIS, which aims for comprehensive monitoring solutions.

Overall, the system demonstrated its suitability for long-term radiation monitoring of RWDs, functioning well without an internet connection and providing reliable data aligned with anticipated dose rates. The system's design allows for adjustments in measurement precision and power use, ensuring flexibility to meet specific site needs. Ultimately, this system's ability to infer package deterioration and degradation, including thinning, localized corrosion, or alterations in the waste form, based on the activity data measured, distinguishes it from other existing methods, encompassing both DT and NDT.

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CRediT author statement

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