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The MICADO project and its possible upgrades

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Summary. — The radiologic characterization is a very important step in dealing with materials and waste streams generated during operational and decommissioning phases of nuclear installations. Its goal is to determine the waste package radiologic content differenting between materials that can be released from regulatory control and those that require further treatment and conditioning to become a stable waste form suitable for future storage and final disposal, according to its classification. Characterization is also needed in the pre-disposal stages of radioactive waste management to demonstrate compliance with the waste acceptance criteria of the storage facilities. This work presents the strategies developed and implemented by the MICADO EU project for an in-depth and accurate waste characterization and investigation of the different radioactive waste packages considered. It presents its goals, the methods developed and the technologies used contributing to the improvement of the safety. Special emphasis will also be given to complementary approaches highlighting the usability of the technologies and the digitalization and accessibility of the data.

1. – Introduction

The radiological characterization of radioactive waste is one of the key aspects in its management. Accurate knowledge of both the volume and the radiologic and physicochemical content of nuclear waste generated in each national program will influence the strategies and technologies for its further management. Radioactive Waste Packages (RWP) characterization is considered a key procedure required by national and international legislation, ensuring transparency of information for stakeholders. It is also important with respect to safeguards to prevent nuclear proliferation, to ensure adequate radiation protection for workers in the relevant in-field operations, and for the safety of the entire population and of the environment. Radiological and physicochemical assessments are important to determine the type of waste, the safety procedures for its handling, the type of conditioning procedure to be adopted and the resulting modalities of storage. This assessment, obtained in the early stages of waste production, is very important to optimize subsequent waste management (treatment, conditioning, disposal conditions and financial impact) and it significantly reduces the risk associated with waste reconditioning.

Precise information on radiation levels is even more important for RWP with a content that lies at the border between two categories. The accuracy of the information can be critical in determining whether to choose, for example, a surface or geologic repository, which can lead not only to a change in the final location, but also in all activities down to the predisposal phase, resulting in significant cost differences.

In this context, MICADO project was launched under the Euratom call of 2019 with the specific goal to optimize the handling, characterization, and monitoring of RWP, optimizing the data flow, and sharing the acquired knowledge within the community.

2. – European nuclear waste and its sources

More than 60,000 tons of spent nuclear fuel are stored throughout Europe (excluding Russia and Slovakia), most of it in France. High-level waste, which also comes from the reprocessing of spent fuel, accounts for the largest share of radioactive waste. In Europe, more than 2.5 million m^3 of low and intermediate level waste has been generated, of which about 20% (0.5 million m^3) has been stored and 80% (close to 2 million m^3) has been disposed of. The decommissioning of the European reactors may generate more than 1.5 million m^3 of low and intermediate level waste. During the entire lifetime of European nuclear reactors, about 6.6 million m^3 of nuclear waste may be generated. Four countries account for more than 75% of this waste: France (30%), the UK (20%), Ukraine (18%), and Germany (8%) [1, 2].

Excluding fuel chain facilities, the European power reactor fleet alone could generate at least another million cubic meters of low- and intermediate-level waste from decommissioning. This is a conservative estimate, as decommissioning experience is still growing.

There are more than 140 operating nuclear power plants in Europe. The ongoing generation of nuclear waste and the imminent decommissioning of nuclear facilities poses an increasing challenge as storage capacity in Europe will soon be exhausted. Moreover, in countries such as the United Kingdom and France, decommissioning waste is also strongly influenced by activities that are independent of the power reactors.

All countries publish information regularly, but differ significantly in how they define, categorize nuclear waste, and report quantities of nuclear waste. The different national approaches reflect a lack of common standards and coherency in how countries manage some aspects of nuclear waste. To this end, initiatives have been taken, *e.g.*, within the

OECD-NEA, to achieve more consistent and standardized reporting [3, 4].

The MICADO [5] project contribute to improving the characterization of radioactive waste at different stages of the waste management process in order to reduce the impact of final disposal. The project focus on the largest part of the existing waste volumes, which are mainly composed of low and intermediate level packages, legacy waste and waste from European *D&D* activities with RWP of different volumes from 50 l to 400 l.

The future optimization of the waste management process towards final repository is a combination of multiple activities: monitoring, handling, conditioning, packaging, and characterization with the digitization of key information, most of them covered within the project and obtained following a predefined characterization procedure.

3. – The MICADO project

The MICADO [5] (Measurement and Instrumentation for Cleaning And Decommissioning Operations) project of H2020 Research and Innovation Program aims to propose a cost-effective and comprehensive solution for non-destructive characterization of nuclear waste by the implementation of different detection and software technologies as well the integration if procedures and the digitalization of all data available.

It started in 2019 and will run until the end of Feruary 2023 with an overall budget of 5 million euros and the involvement of 9 partners from 5 different countries. Partners are CAEN (It), CEA (Fr), ENEA (It), ORANO (Fr), SCK CEN (Be), INFN (It), Sogin (It), CTU (CZ), XIE (Ge). The aims of the project are focused on changing the manual procedures used for the non-destructive assay (NDA) characterization techniques of the waste packages. To better qualify the waste package to be analyzed, a waste type-dependent analysis procedure is applied and information from different relocatable detection stations is combined. The project established a characterization procedure, data analysis, and information storage suitable for different types of waste activities (VLLW, LLW, ILW, legacy waste), matrix types (metallic, organic, and concrete fillings), and drum dimensions, including unconditioned waste but excluding high activity level waste (HLW) packages. A second objective is to design and demonstrate the transportability of the measurement stations to reduce operational and maintenance costs associated with multiple fixed stations on the waste production sites, or alternatively to overcome the difficulty of transporting radioactive waste in the case of a large centralized characterization facility.

The infrastructure for data collection and visualization of the data provided by each technology represents another innovative approach in addition to the newly developed technologies. The RCMS software infrastructure can collect, store, display all data and integrate results of the advanced error calculations (such as Monte Carlo calculations, machine learning or Bayesian inference). This software allows a new approach to data management and more secure data processing. These aspects and the mobility of the detection devices are included in the list of topics prepared by CHANCE in Deliverable D2.3. These topics demonstrate the importance and complementarity of the projects, which provide continuity in the nuclear waste characterization field.

The innovations behind the project not only refer to the detection technologies considered and developed, but it is their integration in a waste management procedures that can improve the RWP characterization itself and that can be considered another element of innovation. These processes under study combine information from the different detection techniques to improve the knowledge of the package contents as it happens with big data analysis.

4. – The MICADO investigated technologies

The RWP characterization is a complex analysis that involves not only the qualification and quantification of the radiologic content, but also the analysis of the physical (density, volume, shape, mechanics, cracking, etc.), chemical (element composition, toxicity, presence of reactive substances, gas production, liquid, solid materials, etc.) and radiological (dose rate, spectroscopy, isotopic composition, spectrometry, calorimetry, etc.) parameters required to optimize the waste management. Destructive and non-destructive methods are used to measure and verify these parameters.

Destructive Analysis (DA) offers the most accurate and unbiased activity determination, and the sampling provided should represent the whole package. This technique is mandatory to verify the presence of pure alpha and beta emitters. These radionuclides or those emitting gamma or X-rays with a too small intensity or energy are extremely difficult to measure even in already conditioned waste packages.

Non-destructive analysis (NDA) [6] and testing methods are used to minimize the radiation dose to personnel, avoid secondary radioactive waste production, minimize costs, and provide comprehensive characterization of the RWP in reasonable measurement times with respect to DA. Despite the methods employed today, there is a need for the development of new non-destructive methods focused on conditioned waste and the MICADO project is focused on NDA techniques of investigation to determine the presence, to quantity, and localize radioisotopes in the RWP.

Within the MICADO project it was established a working package structure that can be easily described as related to 4 different detection stations, a software tool for uncertainty assessment and a software digitalization platform, all acting as individual building blocks but integrated in a single platform, based on precedures, to be adapted to different types and volumes of RWP.

The gamma station. – The first element is the MICADO Gamma station, represented on the left of fig. 1, used as the first and mandatory step for the full radiologic characterization of all RWP under evaluation. The station is not a single detection technology, but the integration of three technologies and a characterization procedure. Each RWP passes through it, for an initial identification based on the RFID (Radio Frequency Identifier) tag applied to the drum and the RFID antenna able to recognize the tag id, which uniquely identify the RWP, the package is also weighted and a pictures is also saved. The second part of the gamma station working procedure foresees the complete gamma characterization based on the three radiologic systems equipping the station itself:

- *The RadhHAND system* [9] used for dosimetry and spectroscopic measurements at contact and in open geometry. It performs gamma dose rate measurements mainly for safety reasons: They are performed at contact and at a distance of 1 meter from the RWP surface. They are used for the first radiologic assessment and planning of the handling of the RWP by the operators. The dose rate can be converted into activity if the isotopic vector of the radioactive waste is known;

- *The Nanopix* [10, 11] gamma imaging system for localization and identification of hot spots in open geometry and working, in this configuration, in parallel with the RadHAND system;

- *The SEA Radioactive Waste Gamma Analyzer (SRWGA)* [12] is a tomographic segmented gamma scanner performing spectrometry and tomographic measurements

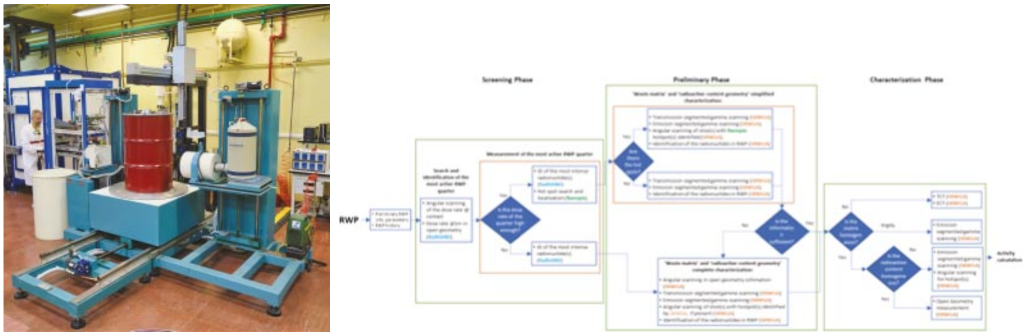


Fig. 1.: The Gamma station on the right and its working procedure scheme on the right.

of the package. Gamma spectroscopy and spectrometry techniques are based on HPGe detectors and are used to detect, identify, quantify, and localize gamma radioisotopes. They are suitable for scanning open, segmented, and angular geometries. Tomographic systems are also able to reconstruct radiologic emission and hot spots inside the RWP in 3D. The system is equipped with a gamma radiation source to perform transmission measurements to obtain density information on the contents. These gamma results are also used in combination with neutron detection techniques.

Although gamma spectrometry and tomography are considered traditional techniques, the main innovation is the procedural integration of the three techniques. The procedure consists of four steps (see fig. 1): identification, screening, preliminary, and characterization phases. As described before, the identification phase starts with an UHF-RFID tag used to tag the waste package, providing a unique identifier, and to associate its EPC number to the entry in the database identifying the package and its characteristics. During the inspection phase, an initial dose rate at contact is taken for safety reasons and radiation protection activities. The preliminary characterization phase consists of measurements of radiologic homogeneity/dis-homogeneity of the contents, identification of higher intensity radionuclides, and acquisition of package picture recordings using the Nanopix and RadHAND systems, and identification of the tag on the package. During characterization, SRWGA will complete the gamma characterization phase. The SRWGA measurement type will be decided based on the results of the preliminary phase helping to select the best measurement technique for a complete package characterization. The result provided by the gamma station is used to determine the second step of the characterization process and select the measurement to be performed (neutron or photofission measurements).

The neutron station. – The neutron station presented in the left picture of fig. 2 combines passive neutron coincidence counting and active neutron interrogation techniques. RWP with fissile or fertile material, but also large metallic waste packages, which are difficult to characterize by gamma spectroscopy, are processed in this station. The designed structure is mobile and can be rapidly deployed in different locations as demonstrated within the MICADO project, and can process packages of different sizes up to 400 l. Moreover, this technique is combined with data analysis based on matrix characteristics (material, density, filling) using artificial intelligence with trained data (based on a arge number of MCNP simulations) to apply signal attenuation corrections (also called "matrix effect" corrections) based on internal monitors and neutron transmission measurements to characterize the matrix. Monte Carlo simulations [13] were performed initially to optimize the design and, in a second phase, evaluate the final detection efficiency of the system based on technical drawings.

The station was designed in order to achieve a good compromise between the performances in passive neutron coincidence counting and in active interrogation mode with the differential die-away technique. Since the latter strongly depends on the thermal neutron absorption properties of the nuclear waste drums to be measured, the matrix effect correction is mandatory to limit the measurement uncertainty.

Passive neutron measurement is used to quantify actinides, mainly plutonium. This type of measurement allows separating neutrons from spontaneous fissions, where several correlated neutrons are emitted per fission, or (α, n) reactions with only one emitted neutron per reaction. The measurements foresee both a total neutron count and a time correlation analysis. Looking at event coincidence allows to distinguish the signal due to fission neutrons from the accidental background due to (α, n) reactions and hence the type of isotopes in the RWP (*e.g.*, ^{240}Pu *vs.* ^{241}Am). For medium size drums, this technique is less sensitive to high atomic number materials (metals) than to low atomic number materials (especially those containing hydrogen). Another limitation is the presence of curium, because its very high specific activity of spontaneous fission can totally mask the passive neutron coincidence signal of plutonium in the RWP, as in the case of highly active metallic residues from spent fuel reprocessing. In such instance, an active neutron interrogation is needed.

Active neutron interrogation technique has been used industrially for decades, for instance at the spent fuel reprocessing plant of ORANO La Hague (France), where four measurement stations currently in operation for the characterization of highly active metallic residues (hulls and end pieces) in the T1, R1 [7] and ACC facilities [8]. The measurement uses the die-away method to quantify the fissile material inside the package when plutonium gamma rays are masked by the intense emission of fission and activation products and when the passive neutron coincidence count signal is dominated by curium spontaneous fission neutrons or when the (α, n) accidental background is too intense. It uses the flux of a pulsed neutron generator. The MICADO neutron cell uses DT deuterium-tritium pulsed generator emitting bursts of 14 MeV neutrons that are thermalized in polyethylene walls and induce fissions in the presence of fissile material, the useful signal being the total counting of fission prompt neutrons. The prompt neutron signal is detected a few hundred microseconds after the generator neutron pulse and is proportional to the fissile material mass. This is the key advantage of this technique for safety-criticality purpose, although it is more affected than passive neutron counting by the waste package matrix effects. The fission-delayed neutrons could also be recorded between the pulses from the neutron generator, but after the prompt neutron signal has disappeared. The delayed signal is sensitive to ^{238}U due to fast fissions, in addition to the fissile isotopes ^{235}U, ^{239}U, ^{241}Pu (thermal fissions as in the prompt signal). Using both prompt and delayed neutron signals could be used to discriminate of U and Pu contributions.

The photofission station. – The photofission technique is still an *R&D* technique in this field. It is used to detect and quantify the presence of fissile materials as the active neutron interrogation but focused on large packages and with low density, as concrete, or high density (metal) matrix. This techniques induces fission from an high energy

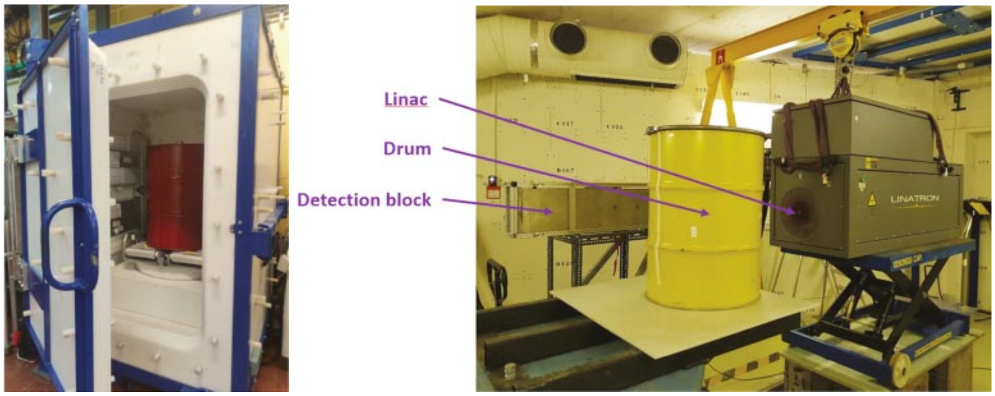
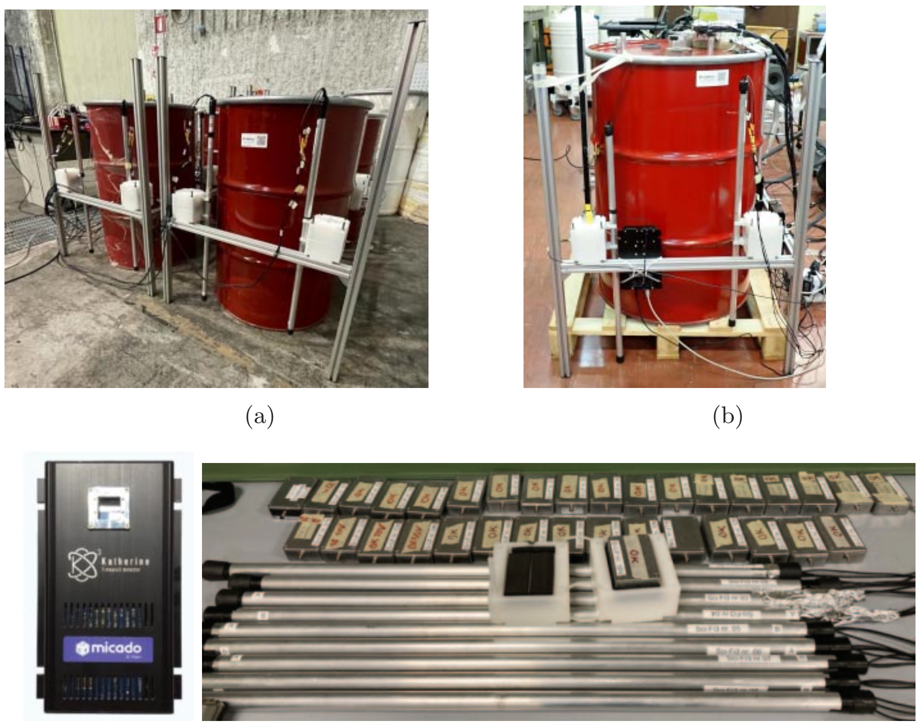


Fig. 2.: Neutron detection system installed at ENEA laboratory on the left and the photofission station at the CEA Saclay laboratory on the right.

photon beam, above 6 MeV, produces via bremsstrahlung from an initial electron beam accelerated using a Linac (linear accelerator) and interacting on a target. The detection technique consist on detecting neutrons from fission reactions and gamma rays to determine the presence and content of the fissile material. The advantage are the low gamma sensitivity to low density materials and the possibility to characterize very large RWP compared to neutron stations. For this reason the photofission station is used to characterize large volumes packages with concrete or polyethylene matrices, which are considered difficult to characterize with both passive and active neutron measurements. Within MICADO, the possibility of using a mobile photofission system based on "low energy" X-rays (7 MeV) has been studied to minimize the hazard and safety shielding usually required for this technique. To provide this information, simulations and laboratory tests are performed to test two photon beam energies, 7 MeV and the 9 MeV [14]. It is common practice to use 9 MeV [15] and it is shown in the right picture of fig. 2. However, the ability to perform a package characterization using a 7 MeV beam as well will facilitate the use of a mobile system. This will require a more flexible shielding structure that is transportable or can be easily prepared on site to ensure safety procedures.

The uncertainty reduction technique. – Within MICADO it was included the pipeline data assessment technique for the evaluation of uncertainty reduction obtainable combining results from different detection technology measurements. The Data Analysis Pipeline (DAP) is not a detection technology for characterizing a waste package, but rather a software infrastructure capable of propagating the uncertainties related to the individual techniques and combining the results of the individual techniques to reduce the global uncertainty of the final inventory. One of the main goals is to better determine the levels of radioactivity to optimize the waste package classification. This concerns in particular radioactive waste packages being close to the boundary between waste for geological disposal and surface disposal. This software infrastructure uses Monte Carlo Particle Transport (MCPT) simulations [16] and surrogate models to evaluate the effects on the efficiencies of different uncertainty parameters related to matrix composition and source distribution within the probabilistic model. For uncertainty quantification, a Bayesian inference approach is applied, using a probabilistic programming language for MCMC [17] sampling. Combining the different techniques enables to integrate all results



(a) (b)

(c) (d)

Fig. 3.: (a) SiliF & SciFi sensors deployed at the Nucleco storage site. (b) Timepix3, SciFi & SiliF under test at the ENEA laboratory during the Final Demonstration tests. (c) Timepix3 device. (d) SiliF & SciFi sensors

and merging the probabilistic outcomes, propagating into a global uncertainty.

The combined data analysis extracts information that is not available within the individual systems to reduce the final uncertainty on the waste inventory. This reduction is a solution to the problem of properly categorizing complex waste packages, for release or more accurate disposal. Full-scale testing of the data processing and uncertainty quantification was based on virtual cases defined at the beginning of the project based on real situations.

The Long monitoring techniques. – MICADO not only included the characterization technologies, but provided different type of sensors that can be used to monitor the radiologic situation of the RWP in their storage facilities or the final repository. The idea behind is to have a complete solution covering most of the aspects of the nuclear waste production till their final state.

For this reason, small and affordable gamma and neutron sensors are developed under MICADO. Unlike the other systems, the main aim of these sensors is the long-term monitoring of waste packages (*e.g.*, in intermediate storage facilities) deployng sensors in agrid form covering the full area of the repository.

A first system that was realized and tested in two different storage facilities in La Hague and at the Nucleco storage site fig. 3(a) in Casaccia is made of two types of

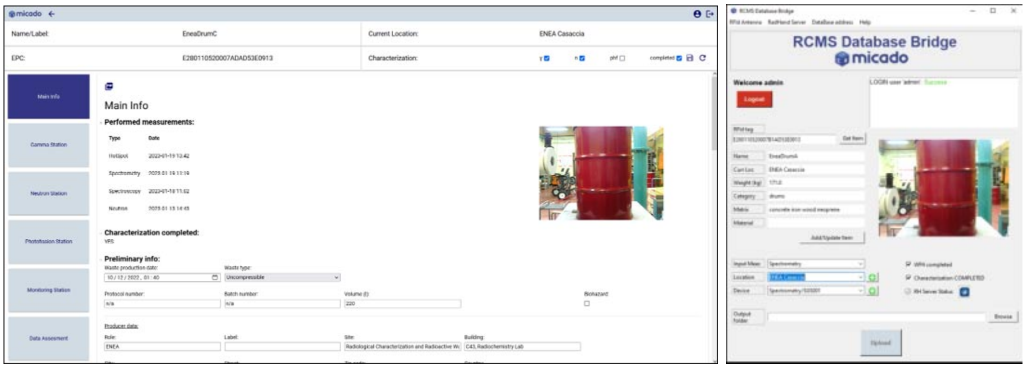


Fig. 4.: GUI, on the left, and Bridge App, on the right, of the RCMS DigiWaste Software

sensors. The sensors are a scintillating fibers for gamma detection (SciFi) [18] and a solid-state detector with lithium (SiLiF) for detection of neutrons [19] and a very high insensitivity (up to 10^{-10}) to gamma radiation. The sensors are coupled either directly to the package or to a surrounding framework and provide continuous trends of neutron and gamma count rates to monitor the status of the stored package in real time.

In the framework of the MICADO project, an *R&D* system for an active long-term nuclear waste monitoring system based on Timepix3 technology [20] was also proposed. It is capable of particle type discrimination and provide spectrometric information in combination with precise timing information. To maximize the versatility of the setup, the Timepix3 sensor was designed as a network of 9 detectors based on Si, as well as CdTe sensors. To enable measurement of neutrons, two quadrants of the silicon detectors are covered by neutron converters. Thermal and epithermal neutrons are detected below a ^{6}LiF foil through products of a $^{6}\mathrm{Li}(n,\alpha)^{3}\mathrm{H}$ reaction and fast neutrons are detected through recoil protons under a polyethylene (PE) layer. The readout software was specifically developed in-house to handle simultaneous operation of all devices, cluster analysis and data visualization.

These sensors where initially characterized in laboratory and at the end of the project where tested at the ENEA Casaccia laboratory in fig. 3(c) with mockup drums in parallel with the Scintillating fibers and the SiliF detectors during the final demonstration test phase of the project as shown in the right picture fig. 3.

The RCMS DigiWaste Software Platform. – All data produced by all stations and technologies of the MICADO framework are digitilized and trasferred to the RCMS (Radiological Characterisation & Monitoring System) DigiWaste Software designed and developed inside the project. All MICADO technologies, software, and hardware, provide data that is saved in a common software framework. This framework stores, processes, and displays the information required during and after the characterization of an RWP. A key element is the RCMS database, from which the organized collection of stored data can be accessed by multiple computers and operators. Using blockchain technology this data is securely stored to ensure the reliability of the data content.

Its structure is made of 3 different layers: the Bridge application, the database and the GUI (graphical User Interface). The Bridge application with its graphics is represented on the right picture of fig. 4 is used to read and connect to the RFID antenna available at the station level and acquire the EPC number of the related RFID tag attached to the RWP to be characterized. This is used to identify the package and connect all data acquired by the station to the related item on the database. This application is valid for all station except the Long term monitoring grid system able to send data in real time directly on the database. The second element is the intermediate level, the database storing RWP information acquired.

The last important element is that the GUI is accessible by all registered users. They have access to all available items, each item corresponds to a RWP, and selecting one of the items the information on the characterization status with expert data and final results is available. The main page of a specific item is shown in the left screenshot of fig. 4.

5. – Conclusions

This paper has reported the innovations coming from the MICADO Euratom project. The technologies developed or under development have been described, but also the procedures and statistical approaches used to improve RWP qualification and its content. Better determination of the radiological content of RWP the key point for better handling and storage of the packages. Improving the current characterization results will not only help stakeholders and end users to reduce costs and operational work.

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