# The Euratom project MICADO and its innovative characterization process of the Nuclear Waste Packages

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## INTRODUCTION

All over the world the nuclear waste management sector is always part of public debate, mainly due to complexity and costs arising from storage and management of the waste produced. It is important to underlying that this waste is not only produced by the nuclear power industry, but also by hospitals, universities, and non-nuclear industries. Regardless from its origin, the main concern is the radiation emission, which makes it a particular hazard for human health and the environment. It must therefore be managed with special care, from production to final disposal with a specific focus on the radiological waste characterization which determine the waste categorization and the consequent storage and radiological waste treatment and management.

Another relevant aspect to consider is the existence of a RWM (radiological waste management) country dependent legislation. It is not only defining the category levels, this means to have different definition of waste categories and activities (ex. Free release), but also their management and storage. For this reason, RWP (radiological waste package) are often characterized at each site with different detection systems generating a large amount of off-line data to be manually analysed.

It is in this framework that in 2019 the MICADO (Measurement and Instrumentation for Cleaning And Decommissioning Operations) project started under the H2020 Euratom call, aiming to demonstrate the feasibility of an improved characterization of nuclear waste packages.

This paper describes the MICADO structure, the technologies under integration and the software infrastructure under development to increase the characterization efficiency and to limit the human errors. All aspects that will improve the Non Destructive Assay (NDA) characterization measurement will be touched along with a quick status update of the project after two years from its starting point.

## The MICADO project

The MICADO [1] (Measurement and Instrumentation for Cleaning And Decommissioning Operations) project funded under the H2020 Research and Innovation Program.

MICADO aims to change the manual operations used for the NDA characterization of the RWP. It applies an analysis procedure, waste type dependent, and combines information from different relocatable detection stations to better qualify the waste package under analysis represented in Figure 1. The project has established a characterization process, data analysis and information storage able to cope with different types of waste activities (VLLW, LLW, ILW, legacy waste), types (Metallic & concrete filling) and drum dimensions.

This is done with a toolbox of up to date and novel gamma and neutron detection technologies, working as modular elements, and a digital software platform used as a base for the digitalization of detector information and the off-line analysis for the uncertainties assessment. The procedure was defined to try to reduce the measurement time in each step and being able to select the required detection technology, thus avoiding multiple identical measurements of the RWP itself. The combined data analysis, like any other big-data study, fuses different measurements results to extract information not available by the individual systems and to reduce the individual uncertainties. This reduction is a possible solution to the problem of proper categorization of complex waste packages, sometimes with high density, for free release or more accurate disposal. The software platform aims to reduce operator cost and radiation dose, decreasing the time spent on field by operators and promises a simpler and easier data control on historical basis of all already characterized waste packages.

MICADO is a comprehensive solution for non-destructive characterization of nuclear waste that implements different technologies such as gamma cameras, gamma-ray spectroscopy, passive and active neutron measurements, and photofission interrogation described hereafter.

Diagram

Description automatically generated

Figure 1 General layout of the MICADO Radiological Characterization System

### The gamma spectrometric station

The necessary characterization is performed by the gamma emitters detection station. It aims at the gamma radiological characterization of the RWP, the first step of the radiological procedure conceived within the MICADO project. All RWPs to be characterized have to pass through this first station. It combines several non-destructive techniques based on gamma-ray detection systems in a single station. The selected techniques are the upgraded RadhHand system [2] used for dosimetry measurements at contact, followed by dosimetry and spectroscopic measurements in open geometry; Nanopix [3], a gamma imaging in open geometry detector for the localization and identifications of hot spots; SEARadioactive Waste Gamma Analyzer (SRWGA) [4], a tomographic segmented gamma scanner performing spectrometry measurements (segmented gamma scanning, angular scanning, emission and transmission tomography) of the RWP.

The station is designed to fit inside an ISO container so it can be transported to different locations and able to characterize multiple RWP sizes, estimate the matrix material and density according to linear attenuation coefficients, hot-spot localization and radioisotopes identification.

The main innovation comes from these measurements provided by three separate and independent systems, properly integrated to work together. Different techniques can complement each other by sharing information and results, improving the overall characterization quality and speeding up the full analysis process.

To optimize the operation these three technologies provide information used to define further measurements, so they their number can be reduced and the time optimized. This is done introducing a three steps procedure: inspection, preliminary and characterization phases.

During the inspection phase a first dose rate at contact is taken for safety reasons and for radiation protection activities. This phase is followed by the preliminary characterization phase consisting of radiological content homogeneity/inhomogeneity measurements, identification of higher intensities radionuclide(s) and RWP picture recording. It is during this phase that pre-determined and fixed measurement configurations in open geometry will be performed with the Nanopix and the RadHand systems, as well identification of the tag on the RWP. These two elements aim at reducing human mistakes and the predetermination of the most intense Region of Interest (ROI) to be studied in in the final characterization phase. It is in the third or last phase, that the SRWGA will complete the gamma characterization phase. The measurement type will be decided based on results coming out from the preliminary phase, helping to select the best measurement technique to be used for a complete RWP characterization.

### The neutron station

The second station is the neutron measurement station, it combines both passive neutron coincidence counting and active neutron interrogation techniques to characterize a wide range of nuclear waste. For the MICADO project transportable system was designed. The transportability requires an easy-to-move, compact and relatively light weight system, while complying with radiation safety rules and, at the same time, being adaptable to different RWP sizes.

The aim of the station is to estimate the nuclear material mass inside legacy waste drums of low and intermediate radioactivity levels. Monte Carlo simulations [5] have been performed to improve the design with the main objective to reach a good trade-off between the performances in passive mode and in active interrogation mode with the Differential Die-away Technique.

The system strongly depends on the characteristics of the nuclear waste drums to be measured. Presently, the need is focused on technological legacy waste drums up to 400 L with presence of neutron emitters and fissile isotopes. The system is a 10 cm HDPE detection room with a DT neutron generator for the active mode. The neutron detection system is made of lateral blocks of 3He detector tubes placed on the two opposite sides of the drum. The mechanical drawings are completed, and the system is under construction. An update on the detector status will be given at the conference.

### The photofission station

Large volumes of waste with concrete or polyethylene matrices are generated as well during dismantling and decommissioning and they are one of the RPW types that are considered difficult to be characterized. The preferred methodology for verification is based on non-destructive assay techniques that allows qualitative and quantitative analyses of the actinide materials inventories without opening the waste package. RWPs containing concrete are particularly challenging, because the traditional assay methods based on neutron interrogation reach their performance limits for such packages.

One promising technique is based on photofission interrogation. It uses high-energy photons to penetrate thick materials and to induce fission of actinides. Photofission is a threshold process, for most actinides (fissile and fertile) the photofission energy threshold starts at around 6 MeV. The process essentially can be divided in three steps. High-energy photons are used as interrogation radiation to induce fissions in the assaying material. Prompt and delayed fission signatures (neutrons and gamma-rays) are emitted from the sample and finally measured with appropriate detection systems.

An integral part of the MICADO project is the design of a photofission-based system for in-situ nuclear waste assay applications.

### The long term monitoring grid

The proposed system for online real-time monitoring consists of an array of many radiation sensors to be deployed all around several RWP, to collect counting-rate in real time and to make them available to the Radiological Characterization and Monitoring System (RCMS) DigiWaste platform. In order to be suitable for mass deployment these detectors have to be small, reasonably inexpensive, robust, easy-to-use and reliable.

In view of a possible mass deployment the foreseen sensors must be reasonably low-cost. The overall system must be modular to easily modify number and placement of the sensors around the RWP, and it has to be scalable in order to make it possible to tailor it to small, medium and large-scale storage configurations. The proposed system is based on gamma and neutron detectors which can be easily installed and/or reassembled in different geometrical configurations and are based on commercial electronics. Moreover, these detectors do not need special calibration procedures, and their simplicity of use and installation makes them suitable for short, medium and long term monitoring. A continuous automatic monitoring of the RWP after their characterization represents an added value in terms of safety and security, and a tool toward transparency. The two main detection technologies for gamma and neutron detection are:

#### The SciFi detector

There is a wide variety of devices and techniques on the market to monitor gamma radiation, and typically a detector is from moderately to highly expensive, therefore not well suited for a granular monitoring. By exploiting the silicon photomultipliers, along with plastic scintillating fibers, it was designed a new low-cost gamma ray counter capable of fulfilling this task. The plastic scintillating fibers have the advantage of coming in a predefined shape that is suitable for being cut according to needs. The fiber is coupled at each end to a SiPM thus makes it possible to achieve a reasonable sensitivity to gamma radiation. One of the favourable features of the SciFi detector is the linear shape of the sensitive fiber, as it makes possible to monitor uniformly the full height of a drum, provided that the detection efficiency is constant along the fiber.

#### The SiLiF detector

For detection of thermal or low energy neutrons, as a viable alternative to 3He tubes, semiconductor-based detectors can be used in combination with a neutron reactive film, usually called neutron converter (6Li, 10B), which converts neutrons into charged particles. Fast neutrons can be detected by inserting such detectors inside a suitable moderator box. 6Li was chosen because after capturing a neutron it has a unique decay channel, with no gamma rays, with a higher available kinetic energy and with lighter particles produced, therefore easier to detect than in the case of 10B. Based on these assumptions we have shown that moderately inexpensive solid-state neutron detectors with good gamma/neutron discrimination can be built. The SiLiF were tested in laboratory with moderated AmBe sources, with neutron beams, and with spent fuel. The corresponding data were compared with GEANT4 MonteCarlo simulation results and with efficiency calibration data taken with a certified neutron source at the PTB metrology institute, showing a good mutual agreement. These detectors can be fruitfully exploited for permanent online monitoring of neutron radiation; they can represent a viable ingredient for both safety and security in a nuclear waste storage facility.

### The pipeline assessment

This working group aims to develop the Data Analysis Pipeline (DAP). This pipeline should be able to: propagate the uncertainties related to the individual techniques part of the RCMS DigiWaste, using tools that overcome the limitations of conventional first-order Taylor expansion, at the same time identifying the most relevant contributors to the final inventory uncertainty, and combine the results of the individual techniques to reduce the global uncertainty on the final inventory.

Several issues can be identified in current characterization practices, related to the uncertainty quantification for radiological measurements of waste packages. The systematic uncertainties related to e.g. scaling factors [6] are nearly always not accounted for, and those for calibration factors and efficiencies are often still neglected. While for very favourable laboratory conditions the latter might not result in tremendous errors, larger systematic uncertainties can easily dominate the overall uncertainty on the final results [7]. Uncertainties related to the distribution of activities within the RWP do impact the results considerably [8]. The error propagation that is done is often based on first-order Taylor expansion [9] but the physical variables and parameters related to measurement setups frequently violate the assumptions, which can give rise to errors or the occurrence of nonphysical results.

The above-mentioned issues are tackled knowing all sources of uncertainty for each measurement technique. An analysis of the feedback mechanisms between different measurements, to enable integrating all results and reducing the overall uncertainty is also done. All uncertainties are quantified using Monte Carlo particle transport (MCPT) simulations.

Furthermore, MonteCarlo (MC) error propagation [10] allows working with the proper probability distributions for all relevant parameters and provide full distributions for the variables of interest. As plain error propagation precludes feedback of the measured data on the prior beliefs, it is for instance not straightforward to account for multiple observations informing the same parameters within this framework. We use a full Bayesian uncertainty quantification through a probabilistic programming language (PPL) for Markov chain Monte Carlo (MCMC) sampling, also rarely encountered in radiological characterization literature. Once this uncertainty quantification (UQ) framework is present, it is straightforward and will allow further optimization of the approach by helping experts focus on the most relevant uncertainties.

## The digitalization

All the above-mentioned technologies have in common the digitalization of the information. All data outputs are saved in a commons software framework able to store, elaborate and display information of required during and after the characterization of an RWP: this software infrastructure is the RCMS DigiWaste Software Platform.

One of the key elements of the RCMS software is the database from which the organized collection of stored data from MICADO can be accessed to from several computers and by different operators. Three technologies are suitable to be used on the measurement of both macroscopic and microscopic waste characteristics. Additionally, the monitoring grid that is not a characterization technology but provides useful information will be included in the database. The uncertainties assessment is a key part of the process. The hypothetical changes or updates of the RWP information over time are registered and considered to define the database design, making possible the tracking of waste evolution. The system must be able to work with one or all the elements allowing the full monitoring according to each technology and manage all data and results coming out from each of them for an on-line or an off-line reprocess of the data. The RCMS DigiWaste Database output will be a series of results that can be transferred to the competent authorities and to the owner to better classify the characterized element. As mentioned above, the RCMS DigiWaste Database will be based on a double layer structure: the basic structure of the framework is a combination of a database storing and sorting data and a second layer, the GUI, allowing the operator to use, visualize, and manage the data stored.

Another important feature is the integration of the RFID tag technology to help the logistics of the RWP monitoring and a unique and simple identification of each RWP. The database is used to store data autonomously and the RFID technology is used to uniquely identify the RWP under exam and store information in it thanks to its internal memory. [2]

## Conclusion

The MICADO project aims at the deployment of the RCMS Platform for the nuclear waste characterization and management. The platform consists of the integration of a series of hardware and software technologies to improve the safety and the characterization quality of the waste package content based on multiple measurements. The goals of the identified procedure are to limits human errors, mainly due to manual operations, to reduce characterization time and the exposition time of operators.

This is obtained combining multi-measurements and multi-technologies procedure driving the sequence of measurements based on the ones previously performed, another advantage is the new hardware design structure for having relocatable detection systems that can be used in different location, and finally the use of combined measurement results based on error propagation studies to improve the overall measurement errors.

All these elements will be tested in the second part of the MICADO project to validate the procedure with real waste packages and performing a demonstration in an almost-real life scenario.

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