The MICADO Integrated Gamma Station for Radioactive Waste Packages radiological characterization

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***Abstract* — The MICADO (Measurement and Instrumentation for Cleaning And Decommissioning Operations) Project of the H2020 Research and Innovation Programme aims to propose a cost-effective solution for non-destructive characterization of nuclear waste, implementing a digitization process that could become a referenced standard facilitating and harmonizing the methodology used for the in-field Waste Management and Dismantling & Decommissioning operations. It employs instruments based on different technologies: an active and passive neutron measurement system, a photo-fission facility, and the 'Integrated Gamma Station'.**

Within the MICADO Project, an entire work package has been dedicated to the design and realization of the 'Integrated Gamma Station' obtained by combining different gamma detection technologies supporting each other to a comprehensive and effective non-destructive gamma characterization, able to accommodate Radioactive Waste Packages of different sizes. The techniques implemented are i) dosimetry measurements, count rate inspection and raw spectroscopy with the CAEN RadHAND, ii) gamma imaging in open geometry with the CEA Nanopix gamma camera, iii) high resolution gamma spectrometry with the ENEA Tomographic Gamma Scanner (TGS). The latter able to carry out different characterization methodologies, i.e., Open Geometry, Segmented Gamma Scanning, Angular Scanning, and Tomography.

This paper describes the layout of the Integrated Gamma Station conceived, its features and detection capabilities, and part of the measurement campaign realized during the MICADO Project.

***Keywords*— Radioactive Waste, Integration and Digitization, Gamma Spectrometry Characterization.**

I. INTRODUCTION

THE main aim of MICADO (Measurement and Instrumentation for Cleaning And Decommissioning Operations, Project of the H2020 Research and Innovation Programme) has been to define an innovative methodology for the characterization and long term monitoring of Radioactive Waste Packages (RWP), with a toolbox of measurement devices, simulation, software and analysis tools providing a comprehensive solution for the global digitization in real-time of all nuclear waste relevant information dose-rate, gamma spectroscopy, gamma imaging-hot spot identification [1] [2], active and passive neutron measurements [3] [4], photofission techniques [5] [6], long term monitoring grid [7] [8], sample description, origin, scaling factor, etc.) and define a global procedure for waste characterization and uncertainty management [9].

Along with technical implementation, study and integration of RWP characterization and monitoring methodologies, the RCMS (Radiological Characterization & Monitoring System) DigiWaste Platform is the main output of the MICADO Project, a completely independent database connected to all measurement stations and monitoring systems [10]. It allows:

- to provide a data continuum and a single digital identity (ID) to each RWP. Data resulting from characterization actions collected on different sites/techniques are integrated in a single database record,
- faster execution of radiological measurements (cross-combination of technical information, e.g., weight, waste matrix content and density, expected radionuclides from other methodologies, etc.),
- optimized characterization of a RWP results with lower uncertainties, by combining outputs of all non-destructive methods and tools already used as reference,
- accurate tracking and long-term monitoring of RWP neutron and gamma emission,
- efficient digitization of the full characterization and logistical processes.

Within the MICADO Project, an entire work package has been dedicated to the realization of the 'Integrated Gamma Station' (IGS), to accommodate Radioactive Waste Packages of different sizes, obtained by combining different gamma detection technologies, supporting each other to a comprehensive non-destructive gamma characterization. The techniques implemented are i) raw spectroscopy and dosimetry, ii) gamma imaging in open geometry; iii) high resolution gamma spectrometry to different characterization methodologies, i.e., Open Geometry, Segmented Gamma

Scanning, Angular Scanning, and Tomography.

The combination of three separate and independent systems based on gamma detection, the i) dosimeter and raw spectroscopy CAEN RadHAND, ii) CEA Nanopix gamma camera, iii) ENEA Tomographic Gamma Scanner, could provide:

- increased reliability of the characterization results, by comparing and sharing information and different outcomes, improving the overall characterization quality and speeding up the full analysis;
- more automated procedures reducing human intervention, minimizing the possibility of human error in the whole procedure, and increase of conventional safety and radiation protection for the operator or user;
- reduction in the timespan to carry out the complete analysis, because of the integration of techniques and the adoption of an automatic system using "decision parameters" for selecting the most suitable gamma characterization technique to be applied to the RWP, automatically. Expert user intervention will remain an option for those cases the central automatic control system cannot manage by itself.

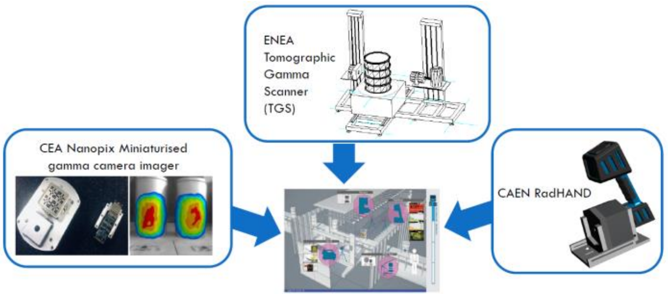

Fig. 1. The combination of CAEN RadHAND dosimetry and spectroscopy, CEA Nanopix gamma camera, ENEA Tomographic Gamma Scanner within the MICADO IGS.

The IGS will be able to provide:

- multiple RWP sizes accommodation and characterization;
- determination of the waste matrix material and density spatial distribution based on the evaluation of linear attenuation coefficients (transmission measurements);
- radioactive "hot-spot" localization and count rate distribution estimation;
- radioisotopes identification, and spatial distribution of the radioactive sources;
- decision about the best characterization technique to be applied, proper detector calibration, and activities estimation based on high resolution gamma spectrometry.

The key issue for the coordination of data is to keep devices and information connected to a central storage unit – the RCMS DigiWaste Database – from which the IGS automatic control system can retrieve information from, execute the characterization required for the RWP, and upload the obtained results.

II. THE MICADO CHARACTERIZATION CAMPAIGN

During the MICADO Final Demonstration Event (FDE) on 2023 January 23rd–27th, all MICADO technologies available at the ENEA Casaccia Research Center site (Rome, Italy), have been tested on some mock-up RWPs just prepared.

In particular, at the ENEA Radiochemistry Laboratory, the IGS was installed (Work Package 4) along with the neutron measurement system (Work Package 5) by CEA DEN Cadarache. The latter focused only on the passive mode because of licensing limitations relative to use of the neutron generator.

The main aim of the test was to demonstrate that different techniques can cooperate to a comprehensive and complete characterization of the Radioactive Waste Package to be analysed.

Radioactive Waste packages adopted to test the full procedure are described in the following section, and they are targeted to cover effective needs of the nuclear industry, reproducing typical wastes from:

A. Reprocessing Plant/MOX Fuel production facility (U and Pu in metal and burnable materials, essentially),
B. Research Reactor/Research Laboratory (fission and activation radionuclides within burnable materials),
C. Legacy Waste (various radionuclides in different matrices).

For the sake of brevity, just the 'Legacy Waste' mock-up drum C is illustrated in this work. Its main characteristics are the following:

- Waste matrix: metal, burnable (paper, plastic, cotton, etc.) simulated with the ENEA mock-up Multi-material Reference Drum, Fig. *2*;
- Radiological content:
    - Plutonium, ~5 g di Pu, at R3 (Fig. *2*) in wood slice (~55 cm from bottom),
    - Plutonium, ~5 g di Pu and Uranium, ~7 g with 10% enrichment in U-235, at R0 (Fig. *2*) in metal slice (~33 cm from bottom),
    - Cs-137 linear source, ~10 MBq at R2 (whole height),
    - Co-60 point source, ~300 kBq at R4 (Fig. *2*) in metal slice (~55 cm from bottom),
    - Eu-152 point source, ~700 kBq (Fig. *2*) at R5 in metal slice (~55 cm from bottom).

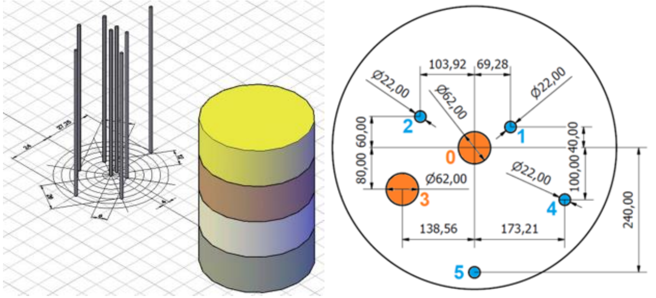

Fig. 2. The ENEA Multi-material Reference 220 liter drum. From the bottom to the top: concrete, metal, wood, neoprene. Penetration channels from the top allow to insert radioactive sources at different R0…R5 positions (dimension in mm).

The ‘Legacy Waste’ mock-up drum C is covering the most complex case, where Special Nuclear Materials are mixed with fission products and activation products, within a heterogeneous waste matrix. Other MICADO mock-up drums are simpler cases in terms of radioactive sources and waste matrix material contained.

The characterization procedure has been divided in three phases, initially.

1) *Screening phase*: RCMS database is filled with RWP information available, and the RFID (Radio Frequency IDentification) is applied to unique identification of the item. The integration of technologies in the station is expecting the RadHAND and the Nanopix gamma camera at the start-up phase mainly. Information about heterogeneity in spatial distribution of the radiological content (e.g., hotspots) is investigated. Dose-rate inspection and raw gamma spectrometry (3-minutes each) at fourteen different positions are carried out, and gamma camera imaging is run for a single 30-minutes acquisition. If heterogeneity in radioactive content is found, decision about the characterization technique to be applied to the RWP (Open Geometry, OG; Angular Scanning, AS; Segmented Gamma Scanning, SGS; Emission/Transmission Tomography, ECT/TCT) can be taken immediately.
2) *Preliminary phase*: information about heterogeneity in spatial distribution of waste materials is searched for with the ENEA TGS transmission measurements, and hypotheses about the characterization technique to be applied to the RWP are complemented with the previous step:
    a. the OG is suitable for homogenous (both waste matrix and distribution of radioactive content) RWPs. The collimation and the detector-to-RWP distance are selected in such a way that the RWP can be seen entirely by the detector in a single shot measurement, while the RWP is rotating;
    b. the AS is performed for a RWP with a homogeneous matrix and a heterogeneous distribution of radioactivity. By acquiring spectra at different angles and height, the variation of the count rate allows the reconstruction of the spatial distribution of the radiological content;
    c. SGS is used for a RWP with a slightly heterogeneous matrix and a heterogeneous distribution of the radioactive source. The RWP is divided into slices, and gamma spectra are acquired measured uninterruptedly while rotating.
    d. ECT/TCT is the most complex and general approach that can be used for any kind of RWP. Transmission tomography can obtain the spatial distribution of waste matrix materials. The Emission tomography allows the reconstruction of the radioactivity spatial distribution by back-projection method reconstruction.
3) *Characterization phase*: it is the execution itself, of the most suitable technique, to determine the activity of those radionuclides identified to occur in the RWP, and results are recorded on the RCMS platform, to be shared with other techniques.

Cooperation of different technologies is achieved not only with the RCMS database, but also by integration of detectors on the IGS by a common National Instrument LabView platform prepared on the PC controlling the automation of the whole IGS station.

III. AN EXAMPLE OF CHARACTERIZATION RESULTS

The section describes the results achieved in radiological characterization of MICADO ‘Legacy Waste’ mock-up drum C. From the initial inspection, the vertical distribution of the dose rate is given by the HPGe detector analysing vertical slices of the drum while it is in rotation, Fig. *3*.

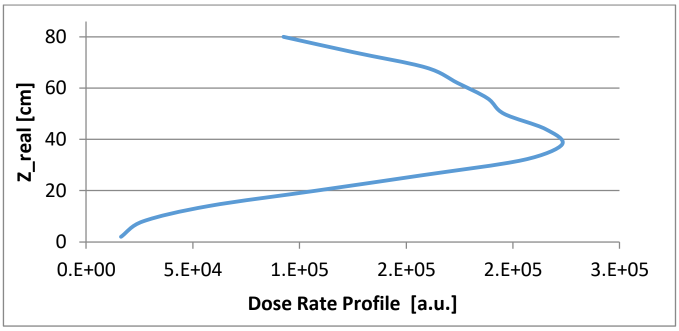

Fig. 3. Mock-up drum “C”. Vertical dose profile by HPGe detector.

The vertical coordinate of the hotspot identified is ~40 cm from the bottom. At this height, a rotational inspection gave the rotational dose profile, Fig. *4*.

Fig. 4. Mock-up drum “C”. Angular dose profile by HPGe detector at the vertical coordinate of the hotspot identified.

The angular coordinate of the hotspot is found at ~140 °. The identified maximum surface dose-rate hotspot point is placed in front of the RadHand, to determine:

- the maximum dose rate at contact;
- the maximum dose rate at 1m (once the RadHand is placed 1 m away from the drum surface).

RadHand inspection of 12 sectors followed (the drum is conceptually divided in 3 slabs and 4 angular sectors), giving for each position:

- one dose rate value, 3-min averaged;
- one gamma spectrum (acquisition of 3 min) for initial radionuclides identification and to qualitative activity distribution estimation, Fig. *5*.

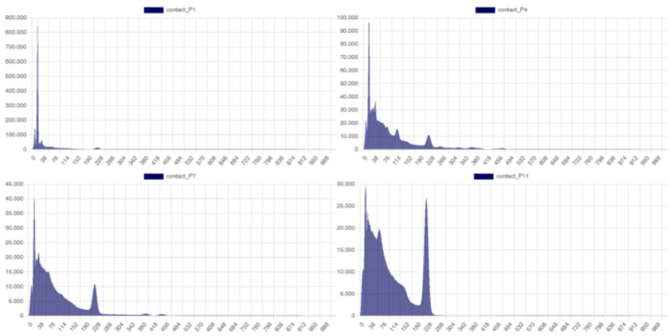

Fig. 5. Mock-up drum "C". Some of the spectra collected from CAEN RadHand. Heterogeneity in spatial distribution of radionuclides is clearly evident: the 4 plots qualitatively illustrate the spectral variation vs. some detector positions.

Then RadHand and the Nanopix Gamma Camera are then placed 1 m away from the surface of the drum (corresponding to the hotspot position identified) at the middle height of the drum and a 30 min acquisition is adopted for both detectors.

The 30 min acquisition by RadHand retrieves a quick and global identification of present radionuclides, while Nanopix gamma camera estimates the surficial extension of the radioactive source, if the gamma rate emission is strong enough. Am-241, Eu-152, U-235, Co-60 and Cs-137 are identified, and the gamma distribution by Nanopix is reported below, Fig. 6.

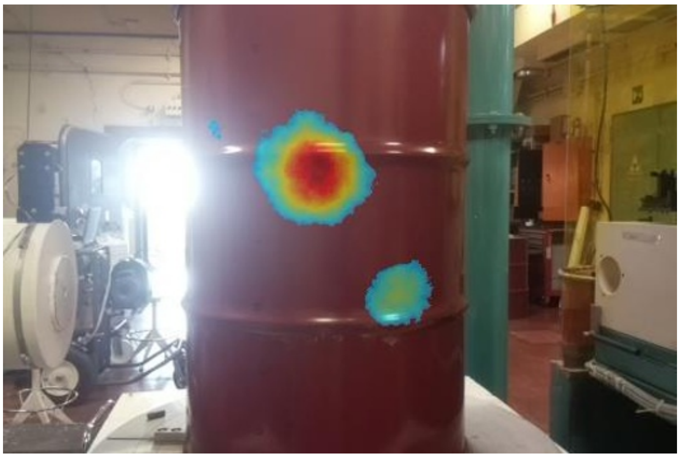

Fig. 6. Mock-up drum "C". CEA Nanopix imaging.

Because of the heterogeneity of the activity distribution inside the drum, it is decided to perform ECT as final radiological characterization technique. The 3-D view and some 2-D sketches of results obtained are reported in Fig. *7* and Fig. *8*.

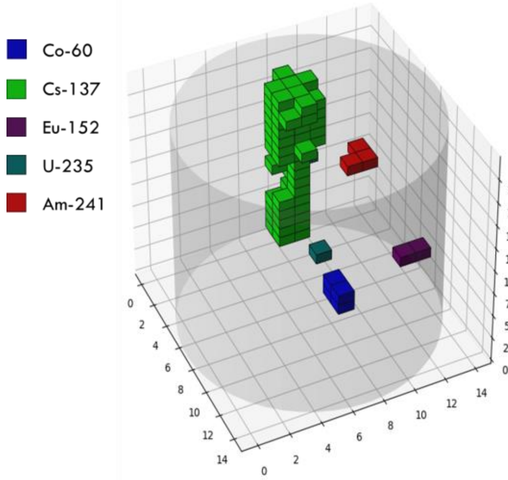

Fig. 7. 3D view of sources identified within the mock-up drum "C".

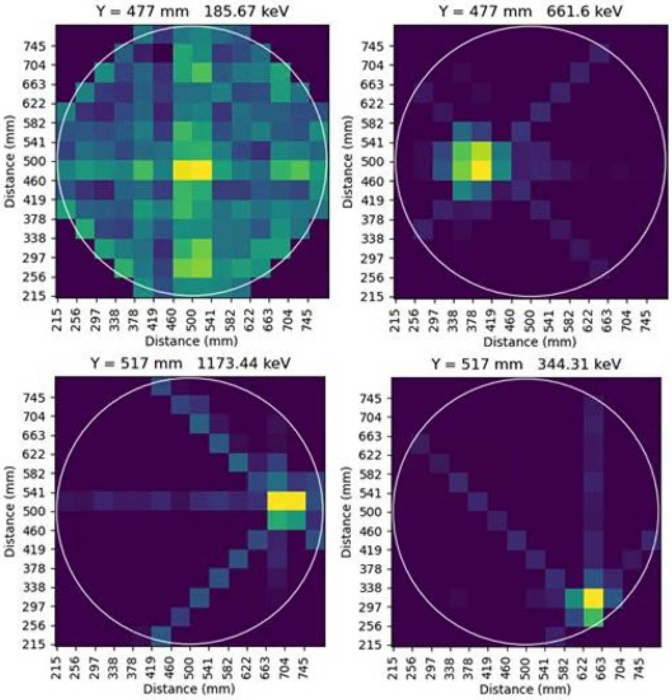

Fig. 8. Mock-up drum "C". Mock-up drum "C". 2-D plot from tomography. Four of the twenty-five hotspots identified: in the order U-235, Cs-137, Co-60, and Eu-152.

Table I reports the calculated activity values for identified radionuclides against the corresponding certified values. The largest bias identified is for the Eu-152, due to the calculation method: at the current stage of development the tomography is considering the 344 keV-line only, instead of using all statistically significant peaks of Eu-152. The other large bias is for the Am-241, mainly due to its low energy 59 keV line that is strongly suffering the waste matrix attenuation effects. Anyway, the order of magnitude of the activity is well reproduced.

Table II is reporting the Minimum Detectable Activities and Critical Level achieved for radionuclides identified in mock-up drum "C" vs. drum waste matrix material.

Table I
Activity values determined in mock-up drum "C" with the MICADO WP4 Integrated Gamma Station vs. certified values. The last column is providing biases

Radio nuclide	Calculated Activity (Bq)	Certified Activity (Bq)	Bias (%)
Co-60	$(2.68 \pm 0.69) \cdot 10^5$	$(2.50 \pm 0.03) \cdot 10^5$	+7.2
Cs-137	$(8.97 \pm 0.49) \cdot 10^6$	$(11.1 \pm 0.8) \cdot 10^6$	-19.2
Eu-152	$(7.31 \pm 0.41) \cdot 10^5$	$(4.46 \pm 0.05) \cdot 10^5$	+63.9
U-235	$(6.68 \pm 0.80) \cdot 10^4$	$(6.70 \pm 0.47) \cdot 10^4$	-0.3
Am-241	$(12.40 \pm 0.80) \cdot 10^{10}$	$(9.04 \pm 0.30) \cdot 10^{10}$	+37.2

Table II
Minimum Detectable Activities and Critic Level for radionuclides identified vs. drum waste matrix material

Radio nuclide	Matrix	MDA (Bq)	Critical level (Bq)
Co-60	Metal	$5.99 \cdot 10^3$	$2.98 \cdot 10^3$
Cs-137	Neoprene	$4.13 \cdot 10^2$	$2.06 \cdot 10^2$
	Wood	$3.17 \cdot 10^2$	$1.58 \cdot 10^2$
	Metal	$7.88 \cdot 10^2$	$3.93 \cdot 10^2$
	Concrete	$7.53 \cdot 10^3$	$3.76 \cdot 10^3$
Eu-152	Metal	$3.53 \cdot 10^3$	$1.77 \cdot 10^3$
U-235	Metal	$1.26 \cdot 10^3$	$6.29 \cdot 10^2$
Am-241	Wood	$8.89 \cdot 10^6$	$4.44 \cdot 10^6$
	Metal	$4.76 \cdot 10^7$	$2.38 \cdot 10^7$

IV. Conclusions

Within the MICADO Project, an entire work package has been dedicated to the realization of the Integrated Gamma Station, to accommodate Radioactive Waste Packages of different sizes, obtained by combining different gamma detection technologies, supporting each other to a comprehensive and thorough radiological characterization.

The combination of three separate and independent systems based on gamma detection at the MICADO IGS (CAEN RadHAND dosimeter and raw spectroscopy, CEA Nanopix gamma camera, ENEA Tomographic Gamma Scanner) has allowed to develop a new approach to RWP non-destructive gamma characterization. obtaining increased reliability of the results by comparing and sharing information and outcomes among different measurement techniques.

Implementation of the IGS has been driven by the following general criteria: i) automation of measurement procedures, ii) reduction of the human intervention and minimization of the human error, iii) increasing of conventional safety and radiation protection for the operator or user, iv) increased quality and reliability of the characterization results with, at the same time, reduction of the timespan for carrying out the complete analysis of the drum. Expert user intervention (e.g., manual actions and human decision) will remain an option for those cases where the automatic control system might potentially fail.

To test the IGS capabilities and performances, several characterization campaigns have been set up during the development of the MICADO Project, and part of the results obtained have been presented here.

The realization of suitable mock-up drums representing real RWPs occurring in the nuclear industry has allowed to demonstrate that the IGS is fully operative and cooperation of different techniques can speed-up the characterization phase and increase the quality of results, truly.

The MICADO IGS is installed at the ENEA Radiochemistry Laboratory at the Casaccia Research Center, Rome, Italy. It is currently used as an experimental prototype to develop and strengthen gamma-based methodologies applied to non-destructive RWPs characterization techniques.

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