

Seeing radioactivity: gamma-ray imaging technique applied to TRIGA RC-1 Research Reactor in ENEA Casaccia

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Abstract—Current radiological characterization protocols applied in nuclear installations provide a valuable set of information used to assess level and distribution of radioactivity, which is a crucial information in the plant management. Nevertheless, typical routines may present limitations that novel technologies can alleviate. In this work, a new-generation 3D pixelated CdZnTe gamma imaging and spectrometer detector has been used at TRIGA RC-1 Research Reactor in ENEA Casaccia Research Centre to assess its performances in several possible tasks and effectively understand this technology readiness. In particular, three possible tasks have been considered: survey of potentially contaminated area (with determination of known and unknown hot spots), source identification and localization (including neutron sources via their gamma emissions), and quantification of isotope-specific activities in generic components thanks to the point-kernel-based algorithm the system is equipped with. The experience has demonstrated the capability to achieve reliable results in these tasks, with consequences that could impact not only the current characterization protocols but also the way some Nuclear Safeguards and Non-Proliferation operations are performed.

Keywords — Gamma imaging, TRIGA research reactor, radiological survey, neutron sources, quantitative gamma spectrometry, nuclear decommissioning, waste management.

1. INTRODUCTION

IN the perspective of proper management of any nuclear site, a comprehensive understanding of the radiological status of buildings and surrounding areas, from identification to localization of radioactive sources and contamination spots, is critical and necessary. Actions that may seem simple, such as planning and executing routine operations, maintenance, and inspection activities, can become complex without full knowledge of the radiological scenario. In line with the ALARA (As Low As Reasonably Achievable) principle [1], having a general overview of the occurring radioactivity can

improve the implementation of action plans in terms of correct procedures, precautions, or restrictions for operators, as long as helping to define specific procedures for managing radioactive sources, and to ensure appropriate radiation exposure of personnel and radiation protection of the environment according to international standards.

The radiological state of a nuclear installation is typically ensured through characterization protocols involving H*(10) dose-rate measurements, total superficial contamination measurements and smear tests, on areas and components with the higher expected risk to be contaminated or activated, possibly complemented by other non-destructive assays (mainly, gamma spectrometry) and destructive analyses for determination of Difficult-To-Measure (DTM) Radionuclides [2]. Such protocols have two main limitations. Firstly, they cannot be applied to every single component or area of the installation (it would require far too much time, money, and personnel efforts), but they are just limited to the main parts of components and areas known/expected to be radioactive, i.e. some radioactivity spots may remain unidentified (e.g. an unknown leakage of radioactive liquid). Secondly, they provide data that “remain on paper” and are even prone to arise difficulties in taking them into account: a nuclear installation is a complex and spatially wide environment, where, for example, the irradiation due to a high-radioactivity hot spot may influence operations done in far area, for which that hot spot has not been taken into account. Another example is the cutting of a pipe, where eventual hot spots should be ensured to not be cut. In both cases, radiological data can be available, but their accounting is entrusted completely to the technicians planning the task to be perform, which may commit a trivial clerical error and neglect them.

These aspects are in contrast with the indication of the state-of-art in plant management [3], whose requirement is to integrate as many details as possible in a unique digital environment where all data are easy to be accessed, understood and taken into account. Such environment, for example, would permit to define the approach to be followed

in a specific task (e.g. cutting a pipe or move a high-activity source) in terms of dose conferred to operators and potential release of radioactivity. Finally, radioactivity distribution in waste can affect the reliability of other quantitative measurement techniques, thus its knowledge is crucial for a proper waste route definition [4].

In this perspective, nuclear industry is seeking novel characterization systems exploiting modern technologies to improve the level of details current characterization procedures can provide. System equipped with imaging capabilities, for example, can provide results in a data format naturally easy to be understood and integrated in digital models. Moreover, modern electronics and algorithms allow for measuring in a large (or even in the entire) field of view, ensuring the possibility to detect radioactivity located in unexpected areas or components.

A new-generation gamma-ray imaging and spectrometric system has been tested in the real-world case of a TRIGA research reactor to assess its performance in a variety of tasks and effectively understand this technology readiness, for potentially taking part in standard characterization tasks and routines.

II. EXPERIMENTAL EQUIPMENT AND METHODS

The measurements were conducted at the TRIGA RC-1 research reactor in the ENEA Casaccia Research Centre (Rome). It is a pool-type, natural-convection cooled, 1 MW_{th} maximum power reactor, operated for running irradiations and experiences using thermal neutron spectra and fluxes in several experimental channels available. An H3D, Inc. H420 3D-pixelated CdZnTe gamma-ray imaging and spectrometer was used for acquisition and analysis [5]. It has roughly 20 cm³ of CdZnTe crystal with better than 1.1% full-width-at-half-maximum energy resolution at 662 keV (see Fig. 1). Images of moderate/high- and low-energy photons were generated using Compton imaging and coded aperture imaging (CAI) respectively. The H420 has an angular resolution of $\approx 5^\circ$ FWHM in coded-aperture field of view (CAI imaging) and $\approx 20^\circ$ FWHM for all 4π (Compton imaging). Quantitative analysis of H420 gamma-ray spectra was conducted using SourceTerm tool in Visualizer software [6] SourceTerm estimates geometry-specific measurement efficiency for required energies, via a point-kernel-based calculation and measured detector efficiency, to convert photopeak count rates to absolute activities, with reliability close to the one ensured by the golden standard of detectors based upon High Purity Germanium (HPGe) crystals [7].

The combination of the CdZnTe crystal's good energy and angular resolution, isotope-specific imaging and quantification capability, and detector compact design, allowed to realize an accurate survey and characterization campaign of the most radiologically significant zones and components within TRIGA-RC1 facility. Measurements were conducted in areas where a more relevant radioactivity is to be expected. As a first step once entering in a new area, some preliminary acquisitions are taken to collect general information about the

level of environmental background and radiological condition, allowing for proper planning of following detailed measurements. Then, based on the information obtained from these preliminary investigations, the focus shifted on individual components and more confined areas, physically bringing the detector closer to the objects suspected/detected to be radioactive. This approach aimed to optimize the time of each measurement and to locate the radioactivity more precisely within the components.

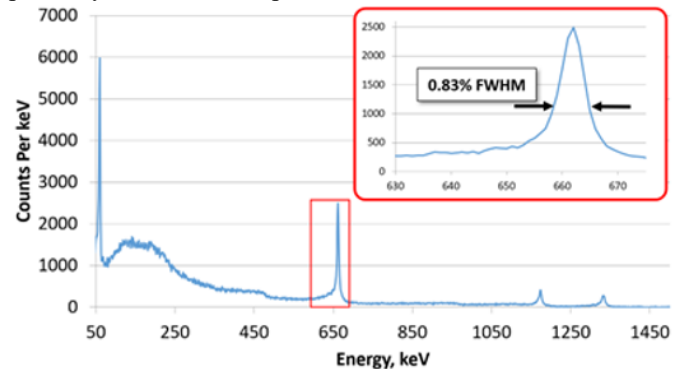


Fig. 1. Background-subtracted H420 gamma-ray spectra with mixed radionuclides. ¹³⁷Cs energy resolution was measured at 0.83% FWHM.

III. THE TRIGA RC-1 RESEARCH REACTOR

The TRIGA RC-1 at the ENEA Casaccia Research Centre is a thermal neutron spectrum, pool-type, water-cooled Research Reactor, with MARK III type containment, originally having a thermal power of 100 kW when built in 1960, increased to 1 MW based on an in-house developed ENEA design in 1967.

TRIGA RC-1 utilization has covered in the past, and covers currently, a wide range of fields:

- Neutron Activation Analysis (NAA).
- Neutron imaging.
- Forensic studies and food traceability.
- Material studies via neutron scattering and diffractometry.
- Stress-test for materials and electronic components for space applications.
- Radionuclide production, e.g., for industrial applications or precursor of radiopharmaceuticals such as of ^{99m}Tc, ¹⁷⁷Lu, ¹⁶¹Tb.
- Detector testing.
- Education and training.

Many experimental channels are available, i.e.:

- Thermal Column: used for validation of novel detectors.
- Tangential Piercing Channel: optimized for performing neutron radiography and tomography.
- Radial Channels: historically used for neutron diffraction experiments. Channels A, B and C are undergoing refurbishment before various new activities can occur.
- Lazy Susan: activities include NAA, tests for space applications, and food traceability mainly.
- Central Thimble: activities include precursor

radionuclides production for radiopharmaceuticals, NAA, tests for space applications, and food traceability.

- Rabbit Channel: used for NAA mainly.

All such activities involve the irradiation of samples, container capsules, supports and metal parts of the reactor and experimental setup both. Neutron activation is carefully evaluated case by case during the design phase of the experiment (to understand feasibility) and verified during and after the experience by direct measurements. Moreover, neutron activation of fluids (liquids, and air mainly) and dust could produce further contributions to the personnel exposure, external irradiation, and contamination either.

The rationale is that in the normal life of the TRIGA RC-1 reactor, more than half of the day is a rest-time that could be used to set gamma imaging inspections to manage events before, eventually.

IV. RESULTS

The H3D H420 pixelated CdZnTe gamma camera was used at the ENEA TRIGA RC-1 Research Reactor for an experimental campaign from January 2023 to June 2023. More than 50 spectral acquisitions were carried out, with a duration spanning from few minutes up to almost 70 hours depending upon the level of occurring radioactivity and the desired sensitivity.

Measurements covered the ‘Reactor Top’ and related equipment, several views of the Reactor Hall ground floor, some views of the Pump Room in the basement, and direct measurements of a fresh fuel element (known quantity of low-enriched uranium mass) at the Fresh Fuel Storage Room.

According to the experience achieved along the whole campaign, three main goals have been demonstrated to be accomplished by means of modern gamma imaging systems:

- Survey of potentially contaminated areas and identification of radioactive items.
- Identification and localization of radioactive sources.
- Quantification of gamma-emitting radionuclides in generic components.

These tasks will be addressed in detail in the following discussion.

A. Survey of potentially contaminated areas

Knowing the radiological state of a nuclear installation is typically ensured through characterization protocols involving $H^*(10)$ dose-rate measurements and smear test on areas and components with the higher expected risk to be contaminated or activated, eventually complemented by other non-destructive assays (mainly, gamma spectrometry) and destructive analyses for determination of DTMRs.

In this context, gamma imaging has been investigated as a supporting technique to help reactor operators in manage risks regarding activated materials, to check and “look for” unexpected activations or contaminations events especially once the experience is done. Gamma imaging could become a

novel protocol in safety management to deepen and improve the knowledge of radiation fields, and to enhance radiation protection definitively.

Regarding this last aspect, the most interesting outcomes obtained are related to the items that were not expected to be radioactive but turned out to be, as reported for example in the case of a cabinet storing samples and materials from reactor experience over decades (see Fig. 2).

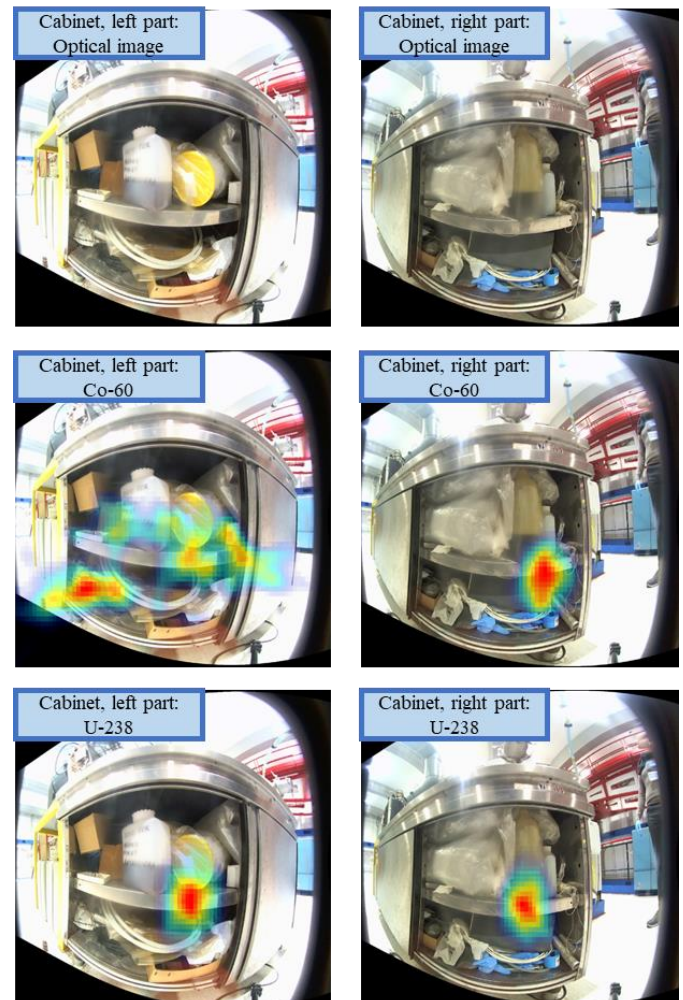


Fig. 2. Unexpected localization of radioactive items in the cabinet, with identification of ^{238}U and ^{60}Co (both reconstructed via Compton imaging).

An even more interesting result is obtained by looking carefully at the distribution of ^{60}Co in the measure of the left part of the cabinet: the tail in the distribution exceeding the physical cabinet space is, in fact, not due to a poor-statistics reconstruction, but to another contaminated component placed on the back of the detector, as clearly visible in Fig. 3: looking to the opposite direction with respect to the cabinet, a small canister containing a ^{60}Co contaminated liquid is dominating the reconstruction, although a spot corresponding to the contribution of left part of the cabinet is still present.

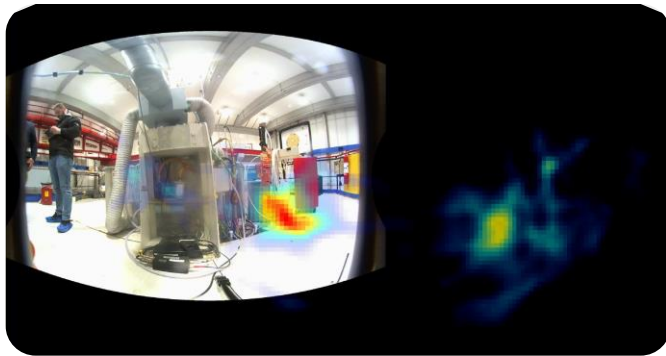


Fig. 3. Distribution of ^{60}Co obtained pointing the detector in the opposite direction with respect to Fig. 2. The spot in the dark region on the right is corresponding to the ^{60}Co reconstructed on the left part of the cabinet.

B. Source identification and localization

Within the TRIGA RC-1 Reactor Hall, radioactive materials generating radiation fields exceeding the ambient $H^*(10)$ dose rate are stored in a specific area called ‘the Bunker’. This structure has concrete walls and no ceiling, allowing to move items in and out by means of the Reactor Hall crane. The Bunker contains activated materials (steel components, essentially) coming from reactor operations, and radioactive sources in their storage cans. Among those items, there are both known sources (present in the installation radiological inventory) and radioactive objects whose information is not available. Moving those items, as well as entering in the area, would imply a significant exposure for the operators by external irradiation, meaning that such operations have to be optimized as much as possible. This is possible only if the components generating the higher dose rate and the sources’ locations are known.

In order to seek this information using the imaging system, several acquisitions have been taken from different sides and positions, and looking inside the Bunker from the top. Fig. 4 reports some of setups used and the main results. The presence of one ^{226}Ra and two ^{241}Am hot spots can be easily distinguished. Furthermore, a higher photon yield in the energy region from 1.7 MeV up to 3 MeV is detected (probably dominated by Compton continuum due to the 4.4 MeV delayed gammas emitted after Beryllium transmutation), as long as the 2.2 MeV photon characteristic of a (n, γ) reaction on hydrogen (deeply used for shielding of neutron sources, e.g., paraffin or polyethylene): both these ranges images are spatially matching the reconstruction of ^{226}Ra and ^{241}Am , thus strongly suggesting the fact the sources are actually RaBe and AmBe neutron sources, which is in agreement with the radiological inventory of the installation. Moreover, the reconstruction of 2.2 MeV line is actually bigger, suggesting the presence of more neutron shielding in the area (and so possibly another low-activity or highly shielded neutron source). Finally, ^{137}Cs is imaged as widely spread over components present in the Bunker, while ^{60}Co reconstruction is dominated by a single activated item (the photon yield is high enough to permit the reconstruction using the Coded Aperture Mask for such high energy).

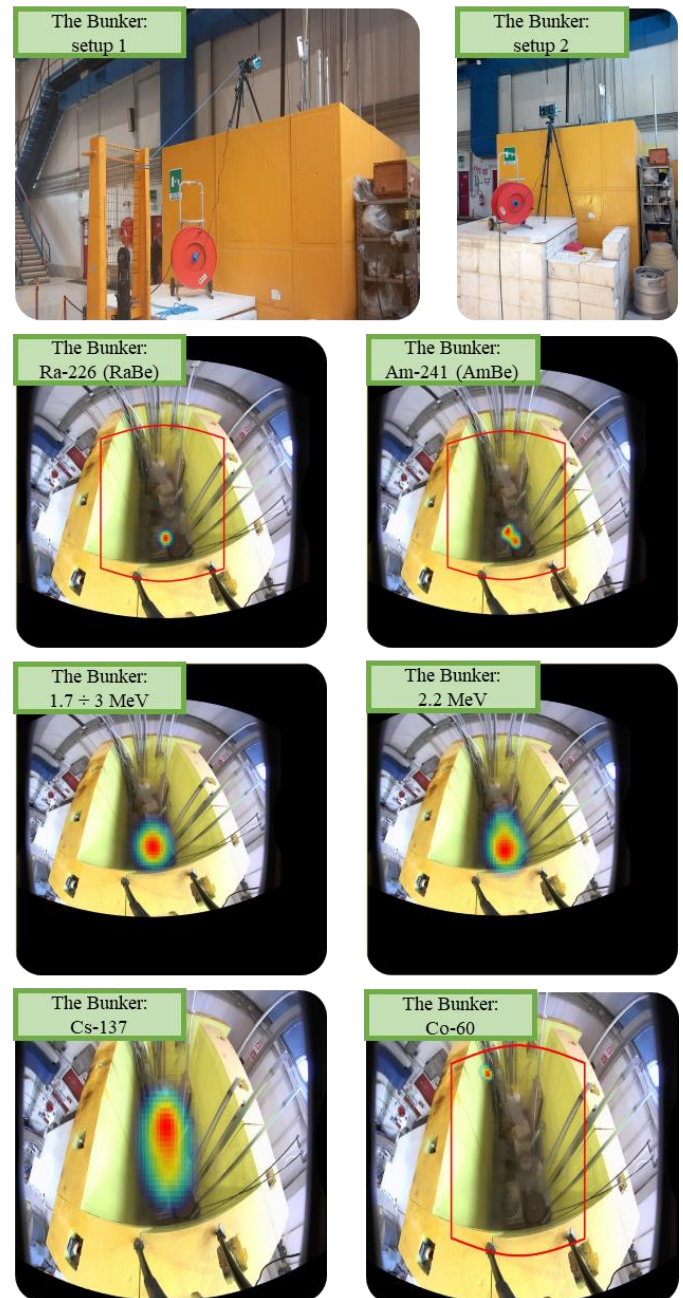


Fig. 4. Detected radionuclides inside the Bunker area.

The Bunker reserved other two ‘‘lessons learned’’ while pursuing the goal of surveying in its surrounding. The first was the capability to detect a small ^{60}Co signal (turned out to come from a source stored in a small shield) in a reconstruction dominated by the signal coming from activated item before (see Fig. 5).

The second was the detection of a steady signal coming from a large polyethylene shielding (measurement done in setup 2 of Fig. 4). Three clues suggest this signal is coming from a AmBe neutron source (see Fig. 6): the presence of the 2.2 MeV peak characteristic of (n, γ) reaction on hydrogen (i.e. a neutron source interacting in polyethylene) and a large count rate in the high-energy range (due to the continuum of 4.4 MeV delayed photons), both being reconstructed in the same position (corresponding to the polyethylene shield), and

the absence of any other identified gamma peak (a significant ^{226}Ra activity would be easy detectable, thus the alpha emitter is expected to be ^{241}Am according to the installation inventory).

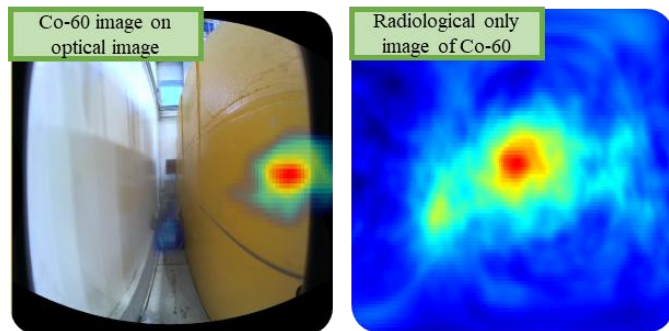


Fig. 5. Detection of a small ^{60}Co source placed in a shield outside the Bunker area as a tailing effect of the main reconstructed dominated by the activated components.

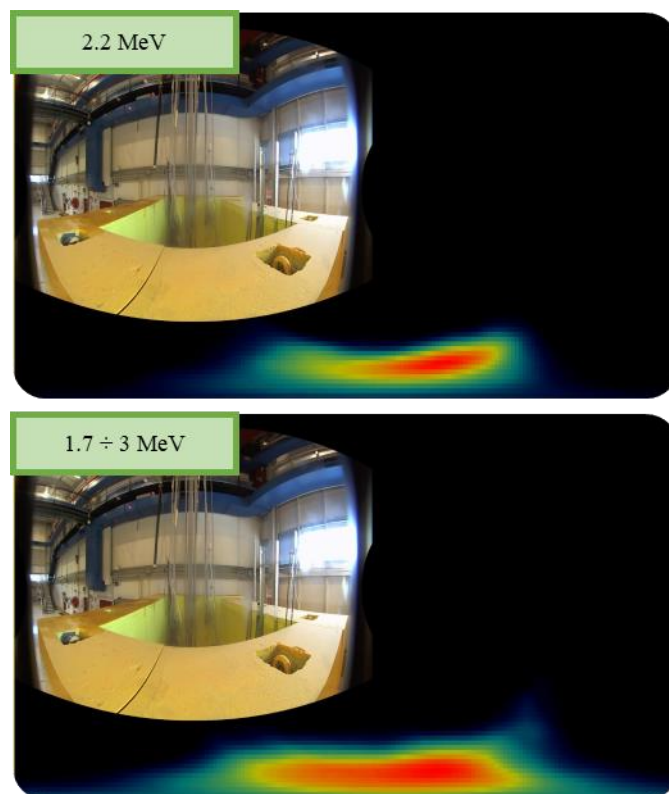


Fig. 6. Meaningful reconstructions due to a AmBe neutron source at the external side of the Bunker.

In the reactor building there is another shielded well, on the Reactor Top actually, used for storing radioactive sources and small hot samples. In particular, two spaces are filled with radioactive materials according to the installation historical data. As Fig. 7 shows, ^{60}Co and ^{137}Cs are identified: the first is clearly located in one pit, while ^{137}Cs is spread over a larger area suggesting (despite the spreading effect due to the scattering introduced by the shield) its presence in more than one pit

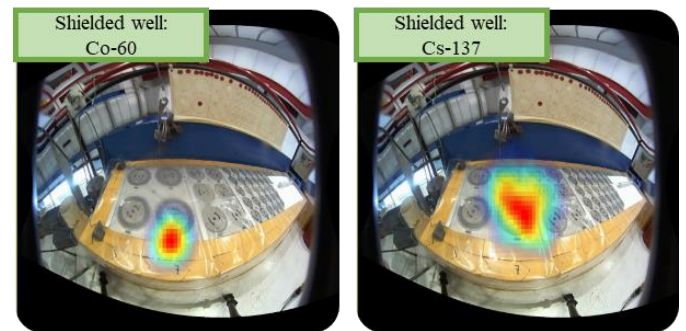


Fig. 7. Identification of ^{60}Co and ^{137}Cs in the shielded well located on the Reactor Top.

C. Quantitative characterization of components

As already mentioned, the gamma-ray imaging system is equipped with a post-processing tool capable of spectrum analysis and efficiency calculation by means of a point-kernel based algorithm. Its performance is close to the industrial standard available for other characterization system, e.g. ISOCS by Mirion Technologies [8]. This feature is worth to be further explored, thanks to the imaging systems native capability to determine the geometrical distribution of radioactivity, which is one of the main unknowns affecting gamma spectrometry uncertainties in assaying components of generic complexity.

Two interesting cases were studied. The first is the analysis of a tank containing ion exchange resins placed in a small, separated room and measured from the top (see Fig. 8): ^{137}Cs and ^{60}Co were identified and quantified assuming a standard resins compound uniformly filling the tank. The quantified activity $8.02 \pm 0.38 \text{ MBq}$ for ^{137}Cs and $1.29 \pm 0.06 \text{ MBq}$ for ^{60}Co will be validated when the tank will be replaced and then characterized.

Looking carefully, ^{137}Cs and ^{60}Co distributions are slightly different, with the first one showing a spreading toward the floor below the tank also. Although very small, assuming mass and radioactivity distributions are uniform in the tank, this effect is not expected to be a statistical uncertainty: in fact, ^{137}Cs has more than doubled the statistic of ^{60}Co , whose high-energy photons penetrate more in matter (i.e. generating a “more uniform” image than ^{137}Cs over the tank volume), which cause also a slightly higher intrinsic uncertainty in the imaging reconstruction. These considerations point toward the fact that (assuming the uniformity in tank) would imply the ^{60}Co reconstruction should be larger than ^{137}Cs one, whereas the result is the opposite. This effect could be explained assuming a loss of water is happened from time to time from the tank and has contaminated the floor below: the higher activity of ^{137}Cs in the resins would explain why its presence is more relevant than ^{60}Co and thus influence more the reconstruction.

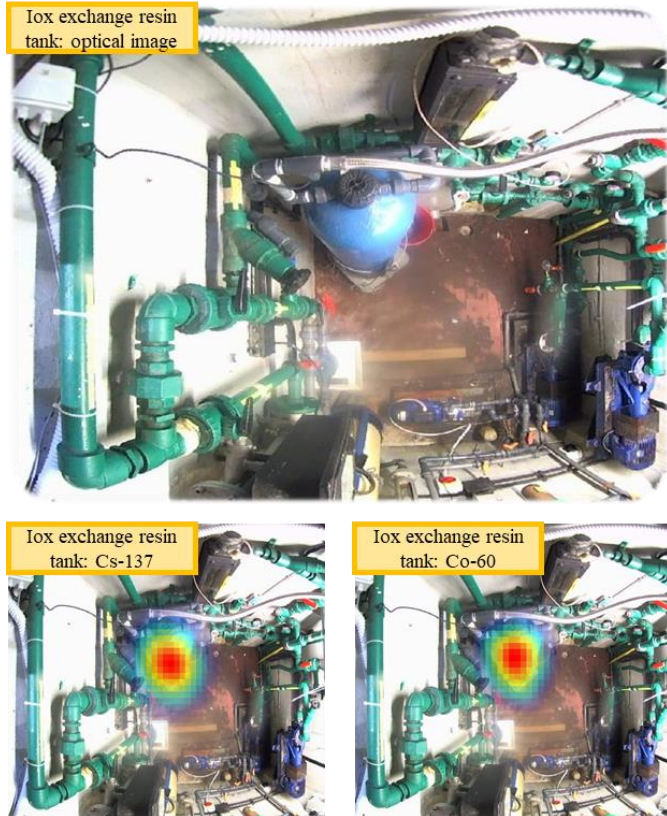


Fig. 8. Imaging and quantification of radioactivity in a tank containing ion exchange resins for primary loop water purification.

The second interesting case is a fuel element from the 100-kW operation phase measured in the Fresh Fuel Storage Room. The element weights 3.4 kg and is made of HZr-U expected to contain 34 gr of ^{235}U . Other details about the elements and its assembly are known from the historical knowledge of the TRIGA reactor [9]. The reconstructions are reported in Fig. 9: ^{235}U (key line at 185.7 keV) is imaged at the center of the element in agreement with the reconstruction of low-energy emissions from ^{234}Th (a ^{238}U son in secular equilibrium) decay. The non-uniformity in the ^{235}U vertical distribution is expected to be due to a non-corrected distance-effect and low-energy gamma-ray self-absorption. Differently, the image of high-energy emissions from $^{234\text{m}}\text{Pa}$ (another son of ^{238}U in secular equilibrium) are instead reconstructed in the backward direction because of the presence of a large amount of natural uranium elements stored in a the immediate surrounding.

The quantitative analysis returned a mass of ^{235}U of 37.02 ± 0.49 g against the 34 g expected, whilst the quantification of ^{238}U was not possible because of the interferences and will be done once a proper background acquisition will be acquired. Analysis and imaging were performed without subtracting any background, which is known to be non-negligible and could explain the ^{235}U overestimation (although the agreement level is more than enough for many applications) and the interference in ^{238}U imaging via $^{234\text{m}}\text{Pa}$ (its high energy emissions are less affected by the absorption due to walls than ^{234}Th and thus are largely detected by the detector).

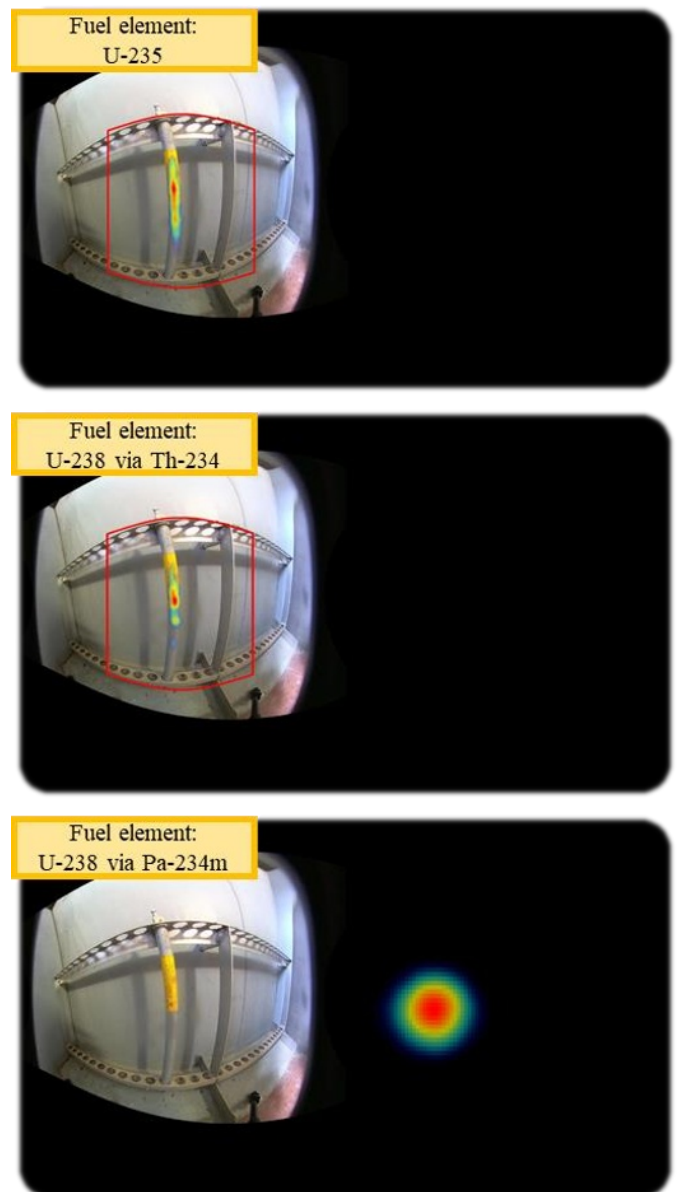


Fig. 9. Image of ^{235}U and ^{238}U (using low- and high-energy lines) for a fuel element used in the 100-kW operation phase.

V. CONCLUSIONS

A 3D pixelated CdZnTe gamma imaging and spectrometry system has been extensively tested at TRIGA RC-1 Research Reactor at the ENEA Casaccia Research Center to evaluate its capability to complement typical Radiation Protection routine. The experience has demonstrated the system is suitable for certain surveying activities (e.g. identifying hotspot and unknown radioactive item, or loss of containment). Furthermore, it has been used to retrieve many detailed information related to radioactive materials (i.e. sources and waste) all around the plant, often inside appropriate shields to reduce their outcome and dose rate. Finally, its post-processing software, thanks to the spectrum analysis and efficiency computation tools, has shown promising

quantification capabilities also in complex and delicate situations like characterizing Special Nuclear Materials (namely, uranium) contained in a fuel element, foreseeing future applications also in the field of Safeguards and Non-Proliferation fields. All these tasks can be considered to be within the capabilities of the used system. Moreover, the native feature to make radioactivity “visible” will enhance the installations safety and reliability in radioactive material management.

Research is still on going to further evaluate system performance in an even bigger variety of situations and tasks, like characterizing the water of the reactor pool, or clearly identifying the radioactive items found during the survey, validating the presence of neutron source (and if the compound effectively has beryllium, because the detection of the 4.4 MeV photons is not possible with the current imaging system due to its analog readout electronics) and verifying the amount of radioactivity circulating in the primary loop water-cooling system during reactor operations.

Moreover, a new hardware and software add-on is currently under development and validation in order to fill some gaps the current 2D imaging system has: this add-on feeds data from a LIDAR and a camera to a SLAM-based algorithm capable to determine at each timeframe detector’s position and pose (i.e. rotation angle respect to the three cartesian axis) in space and also to figure out the space in the format of a point-cloud. This will provide the imaging system the spatial awareness needed for projecting 2D reconstructions in 3D space, thus obtaining 3D distance-corrected radioactivity reconstruction and also useful information for efficiency modelling.

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