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REVIEW

Reviewing the Role of the Radiological Characterization Laboratory in Nuclear Facility Decommissioning

D. Gurau*

Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), 30 Rectorului, Magurele, POB MG-6, 077125, Romania

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*e-mail: daniela.gurau@nipne.ro

The process of radiological characterization involving all the systems, structures, equipment, and components resulting from the decommissioning of the VVR-S nuclear research reactor at the Horia Hulubei National Institute for Physics and Nuclear Engineering was a continuous journey marked by ongoing research, specialized training, and the accumulation of invaluable experience. Recognizing the significance of protecting the expertise gained during this effort, this paper aims to share several key insights collected from the radiological characterization process. In particular, the focus is placed on elucidating various methodologies and techniques utilized in gamma-ray spectrometry. The aim of delving into these specific aspects is to offer practical lessons that can serve as valuable guidance for future efforts in radiological characterization within similar contexts. Through the dissemination of these insights, it is hoped that the collective knowledge and expertise amassed during the radiological characterization of the VVR-S nuclear research reactor decommissioning can be effectively preserved and utilized for the benefit of future projects in the field.

topics: radiological characterization, gamma-ray spectrometry, decommissioning expertise

1. Introduction

Established in 2005 within the Reactor Decommissioning Department (DDR) at the Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH) in Magurele, near Bucharest, Romania, the Radiological Characterization Laboratory (LCR) emerged as a pivotal entity in the Institute's operations. Led by a team comprising a dosimetrist, three dedicated researchers, and the laboratory's head, LCR swiftly became instrumental in driving forward the objectives of the decommissioning project [1]. The main objective was radiological characterization — a process that was of paramount importance in the decommissioning project [1, 2]. Through meticulous analysis and assessment, LCR played a critical role in identifying, quantifying, and characterizing radiation levels within the facility and its surrounding environment [3, 4]. This comprehensive approach not only facilitated the effective management of resulting materials, but also served as a stepping stone for addressing crucial considerations related to the protection of workers, the general public, and the environment [5]. By providing invaluable information on the radiological landscape of the decommissioning site, LCR enabled informed decision-making and strategic planning, ensuring that all actions taken remained in strict compliance with established safety protocols and regulatory standards. Thus, the establishment of LCR was proof of IFIN-HH's commitment to excellence in nuclear research and its unwavering dedication to the highest standards of safety and environmental management.

In 2006, as part of a United States Department of Energy (DOE) project, a thorough initial characterization process [6] was conducted utilizing equipment available at that time, which included a NaI(Tl) detector and portable radiation monitors. A pivotal aspect of this process was engaging in discussions with both current and retired personnel from the Reactor Decommissioning Department (DDR) from IFIN-HH. These discussions aimed to gain comprehensive insights into the operational history, thereby facilitating a deeper understanding of past activities and their potential implications. Throughout the subsequent decommissioning project, initiated in 2010 and successfully completed in 2020, the Radiological Characterization Laboratory (LCR) conducted an effective and meticulous characterization process. This process was critical in identifying the nature and precise locations of contamination within the facility. By providing invaluable data, LCR's efforts played a crucial role in the planning, preparation, optimization, and ultimately the execution of the installation's dismantling and decommissioning phases. This comprehensive approach ensured that all necessary precautions were taken to safeguard both workers and the environment while efficiently managing the project's scope and resources.

The main activities of the Radiological Characterization Laboratory (LCR) included several critical tasks: (i) carrying out the radiological characterization of the nuclear facility and the workspaces associated with the VVR-S nuclear research reactor, in strict compliance with the predefined radiological characterization plans; (ii) expanding radiological characterization efforts to include all systems, structures, equipment, and components (SSEC) resulting from the decommissioning project; (iii) facilitating the free release of materials considered to be within acceptable radiological limits; (iv) carrying out the radiological characterization of the drums with radioactive waste materials generated during the decommissioning of the VVR-S nuclear research reactor.

It is noteworthy that the LCR activities were carried out in strict accordance with the established system procedures and work instructions outlined in the Integrated Management Manual of the Reactor Decommissioning Department. It is important to emphasize that a significant part of the personnel involved in both the radiological characterization and the decommissioning process had never been engaged in such activities before. The decommissioning of the VVR-S nuclear research reactor in Magurele marked a pioneering step in Romania. While the experience gained by personnel throughout the operational lifetime of a nuclear facility has proven invaluable for both radiological characterization and decommissioning processes, it has become apparent that new skills are needed to effectively and safely manage the decommissioning project. Therefore, despite the rich experience gained from previous nuclear facility operations, the unique challenges generated by the decommissioning process required the acquisition of additional skills to ensure the safe and successful execution of the project.

2. Radiological characterization advancements

In 2006, during the initial stages of radiological characterization, three types of in-situ measurements were conducted: dose rate measurements, contamination assessments, and gamma-ray spectrometry. Portable radiation monitors, in particular the Eberline E-600, were used to measure both dose rate and contamination. The following probes were employed in conjunction with these monitors:

(i) SHP-380 AB probe — used for alpha/beta surveys; this probe features detectors tailored for specific purposes, i.e., ZnS(Ag) for alpha detection and NE102 plastic scintillator for beta detection;
(ii) SHP-360 probe — designed for alpha/beta/gamma surveys; this probe includes a Geiger–Müller detector with a mica window;
(iii) SSPA-3 probe — employed for high sensitivity gamma measurements; this probe uses a sodium iodide (NaI(Tl)) detector;
(iv) SHP-210 T probe — similar to the SHP-360; this probe is suitable for alpha/beta/gamma surveys and features a Geiger–Müller detector with a mica window.

These instruments and probes facilitated comprehensive data collection, allowing for a thorough assessment and characterization of radiation levels and contamination within the research reactor. Their deployment was essential to ensuring accurate and detailed radiological assessments, which were essential for effective planning and management throughout the decommissioning process.

During that period, in-situ gamma-ray measurements were conducted using a portable gamma-ray spectrometry system manufactured by ORTEC [7–9]. This system comprised a ScintiPack Photomultiplier Base with Preamplifier and High Voltage Supply, type 296, along with a Digital Portable Multichannel Analyzer, type digiDART. Sampling and subsequent laboratory analyses were employed to gather information regarding contamination and activated materials. Since the laboratory did not possess at that time high-resolution gamma-ray spectrometry systems, samples were analysed in laboratories at IFIN-HH accredited by Romanian Association for Accreditation (RENAR) in accordance with the standard SR EN ISO 17025.

The contamination observed in the VVR-S reactor originated from various sources, including reactor operations, radioisotope production in hot cells, depleted uranium processing, and research activities. After the shutdown of the VVR-S reactor in 1997, only radionuclides with a half-life of more than one year contributed significantly to the inventory of radionuclides made in 2006. In light of these considerations, radionuclides were categorized into three groups: beta/gamma emitters, alpha emitters, and hard-to-detect radionuclides. Hard-to-detect radionuclides presented unique challenges in the VVR-S research reactor due to their low-energy emissions, low abundance, or complex chemical properties. These characteristics made their detection and measurement difficult. Examples in the reactor context included ^{3}H, a low-energy beta emitter, ^{14}C, and ^{63}Ni. The majority of radioactive contaminants generated by reactor operations were classified as beta/gamma emitters. These contaminants were relatively easy to measure using techniques such as gross beta/gamma counting and gamma-ray spectrometry. It's worth noting that this classification was essential for prioritizing monitoring and decontamination efforts, ensuring that appropriate measures were taken to address the most prevalent and easily detectable contaminants. By understanding the nature and distribution of radioactive materials within the reactor and its surroundings, effective strategies could be implemented to mitigate potential risks to personnel, the environment, and public health.

Due to the extensive use of gamma-ray spectrometry measurements in radiological characterization, significant investments were made in subsequent years to improve capabilities. These actions included:

(i) Acquisition in 2007 of a gamma-ray spectrometry laboratory system comprising a HPGe detector model GMX50P4;
(ii) Purchase of an ISOCART system, used for measuring radioactive waste drums, with a HPGe detector model GEM25P4;
(iii) Acquisition in 2009 of another gamma-ray spectrometry laboratory system, equipped with a HPGe detector model GEM60P4-95;
(iv) Addition of another ISOCART system in 2014, equipped with a HPGe detector model GEM100P4-95-SMP.

The acquisitions significantly enhanced the LCR capabilities, enabling more accurate and comprehensive radiological characterization throughout the decommissioning project. The radiological characterization carried out by LCR, which included not only the initial stages, but all the activities within the decommissioning project, strictly followed the stringent quality assurance requirements. These requirements needed that personnel involved in the characterization be properly qualified and trained, ensuring competence in their roles. Furthermore, expert input was sought to select appropriate measurement tools, all of which were subjected to rigorous testing and certification prior to use. Sampling and measurement procedures were meticulously followed and data diligently recorded and archived for future reference. By adhering to these rigorous quality assurance standards, LCR ensured the reliability and accuracy of all radiological characterization activities, thereby contributing to the successful execution of the decommissioning project while meeting the highest standards of safety and regulatory compliance.

Taking into account all the factors mentioned above, the staff of the Radiological Characterization Laboratory (LCR) remained actively involved in a multitude of professional development activities. These included regular participation in exchanges of experience, scientific visits and events organized by the International Atomic Energy Agency (IAEA). In addition, staff members benefited from various training courses and undertook research projects. Some even pursued higher education, obtaining masters and doctorate degrees. This ongoing commitment to professional growth and knowledge acquisition significantly advanced methods for the radiological characterization of materials derived from nuclear decommissioning. By keeping abreast of the latest developments in the field and actively participating in collaborative efforts and educational opportunities, LCR staff played a crucial role in increasing the effectiveness and efficiency of radiological characterization practices. Their dedication not only contributed to the success of the decommissioning project, but also encouraged continuous improvement in the broader field of nuclear decommissioning and environmental remediation.

3. Gamma-ray spectrometry experience

In the field of activity measurement by gamma-ray spectrometry, obtaining accurate results relies heavily on the knowledge of the maximum energy efficiency (photopeak) for the specific source–detector configuration used [10]. The quality and accuracy of gamma-ray spectrometry measurements are directly influenced by the accuracy of the detection efficiency under specific measurement conditions. Typically, calibration involves establishing a relationship between the detection efficiency and the energy of gamma rays emitted by various isotopes. This calibration process often involves the use of a range of gamma-ray energies relevant to the experiment, allowing the construction of an experimental efficiency curve as a function of energy. National standards laboratories play a crucial role in providing isotopes with accurate gamma-ray emission rates, typically with an accuracy of 0.5% to 2.5% for a 1σ standard deviation. Detector efficiency calibration is commonly performed using single sources containing specific radionuclides, as these sources emit well-known gamma-ray peaks whose areas can be used for calibration purposes. However, if the energy scale of interest extends beyond the capabilities of a single source, it may be necessary to use multiple sources. Despite these established methods, challenges can arise when a suitable set of calibrated sources is not available or fails to adequately represent the geometric conditions of the experiment. In such cases, alternative calibration approaches or adaptations may be necessary to ensure accurate and reliable measurements with gamma-ray spectrometry.

3.1. LCR experience with NaI(Tl) detector

Although it is among the oldest and most practical detectors used for gamma-ray spectroscopy, the NaI(Tl) detector remains the scintillation material of choice for measuring gamma energies exceeding several hundred keV. Its widespread use stems from its effectiveness in identifying and quantifying nuclides during gamma-ray measurements. Typically, NaI(Tl) detectors are used in various scenarios, including the evaluation of individuals, soil samples,

Fig. 1. Examples of in-situ measurements with NaI(Tl) detector.

containers (such as cans and boxes), and other objects. In radiological characterization works performed by LCR, the NaI(Tl) detector served primarily to evaluate surface activity and perform in-situ measurements.

In Fig. 1, some examples of in-situ measurements performed using the NaI(Tl) detector are presented, showcasing practical applications of the device.

Radu and colleagues detailed in their papers [7–9] an innovative method that combines efficiency measurements derived from point sources with theoretical calculations. This approach allowed them to determine the peak efficiency $\varepsilon(E)$ for disk sources measured using a NaI(Tl) detector. Subsequently, these efficiency curves found practical application in the assessment of surface activity levels on materials resulting from the VVR-S nuclear reactor decommissioning project, especially those undergoing the non-restrictive release process. Their analysis assumed that the activity was uniformly distributed over the surface. Figure 2 provides a visual representation of the surface contamination geometry, providing insight into the spatial distribution of detected activity.

The equation used to compute the surface activity $\Lambda_s(i)$ for a given radionuclide i using the NaI(Tl) detector is expressed as follows

$$\Lambda_s(i) = \frac{R_{net}(E)}{Y_i(E)\left(\dfrac{\varepsilon_i(E)}{F_{ci}(E)}\right) S}. \tag{1}$$

Here, $R_{net}(E)$ denotes the net count rate, $Y_i(E)$ stands for the yield, $F_{ci}(E)$ is the coincidence correction factor, $\varepsilon_i(E)$ is the efficiency of the NaI(Tl) detector evaluated for surface samples at energy E emitted by the radionuclide i using ETNA (Efficiency Transfer for Nuclide Activity measurements) software [11], and S represents the sample's area.

The coincidence correction factor $F_{ci}(E)$ was determined using either the ETNA code or the GESPECOR Monte Carlo simulation code [12]. These sophisticated computational tools enable accurate calculation of the coincidence correction factor, ensuring precise adjustments to the measured data for enhanced reliability in the assessment of surface activity.

The effective surface area S [cm^2] is defined as follows: (i) $S = S_0(1 + \frac{d}{4.4})$, if $S > S_0$ (more precisely $R > R_0 = \sqrt{S_0/\pi}$); (ii) S is equal to sample surface, if $S < S_0$ (more precisely $R < R_0 = \sqrt{S_0/\pi}$). Now, R_0 is the radius corresponding to S_0 [cm^2] and $S_0(E) = 12E^3 - 21E^2 + 21E + 44$ represents the gamma-ray energy-dependent parameter defining the sample's surface area, while d denotes the distance from the collimator to the contaminated surface. These equations account for variations in surface area due to distance and energy-dependent detector response.

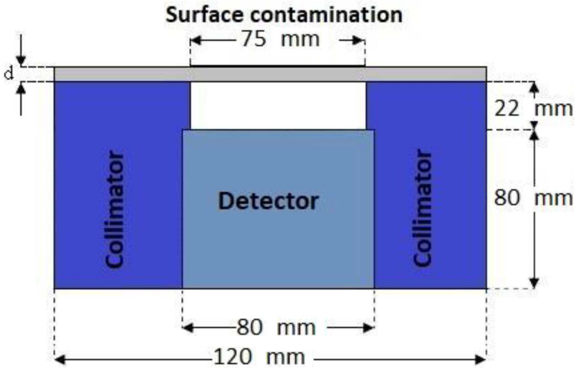

Fig. 2. Surface contamination geometry.

In Fig. 3, the effective surface area $S_0(E)$ is shown as a function of energy E. This visual representation elucidates the correlation between S_0 and energy values across a specified range. By graphically plotting $S_0(E)$ against energy, observers can discern patterns and trends in the behavior of S_0 as energy varies. This graphical illustration facilitates the interpretation and analysis of the function's characteristics and its energy dependence. Moreover, Fig. 3 serves as a visual aid for researchers and readers, enhancing their comprehension of the S_0 properties across different energy values.

The efficiency transfer method was not only applied to point sources but also extended to volume sources. For assessing the efficiency of small volume sources, the ETNA software served as a valuable tool. Within this evaluation process, the activity was assumed to be uniformly distributed throughout the volume, ensuring a comprehensive analysis of the efficiency transfer. Figure 4 illustrates the volume contamination geometry, offering valuable insights into the spatial distribution of detected activity.

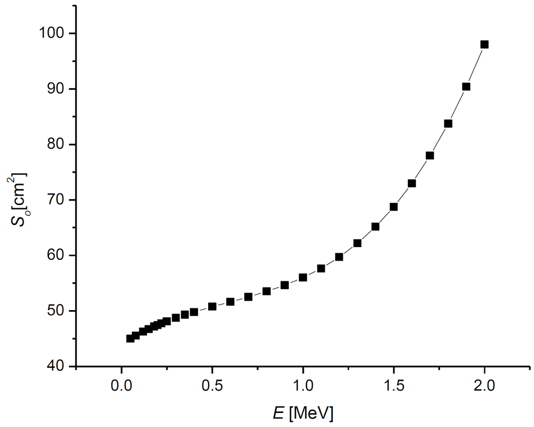

Fig. 3. Behavior of S_0 as a function of energy.

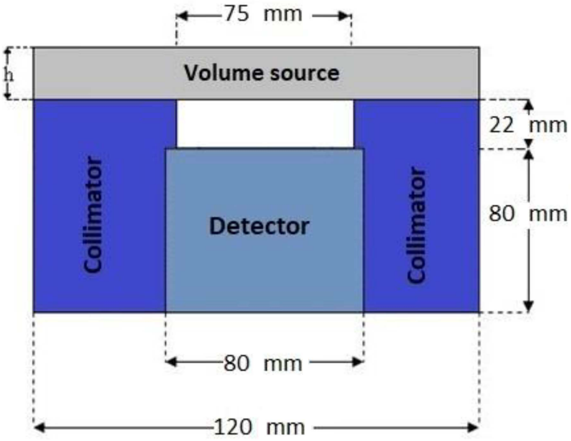

Fig. 4. Volume contamination geometry.

The equation used to calculate the specific activity, denoted as $\Lambda_m(i)$, for a given radionuclide i using a NaI(Tl) is as follows

$$\Lambda_m\left(i\right)=\frac{R_{net}\left(E\right)}{Y_i\left(E\right)\left(\dfrac{\varepsilon_i\left(E\right)}{F_{ci}\left(E\right)}\right)m}, \tag{2}$$

where m is the product of the volume V and the density ρ of the sample. The volume is calculated as

$$V=\frac{S_0h}{3}\left[2+\frac{h}{4.4}+\sqrt{1+\frac{h}{4.4}}\right], \tag{3}$$

and h represents the height of the sample.

When conducting in-situ gamma spectrometry, the accuracy of activity measurements can be substantially compromised by substantial interference from high-energy external gamma radiation sources. In cases where regions with elevated activity levels exert a notable impact on measurements, it becomes imperative to implement shielding measures. By identifying and effectively shielding areas of heightened activity, the integrity and reliability of the measurements can be preserved, ensuring more accurate and trustworthy results.

The laboratory's extensive experience with the NaI(Tl) detector reaffirms its enduring significance in gamma-ray spectroscopy. Despite its age, the detector remains the material of choice for measuring gamma energies exceeding several hundred keV, owing to its reliability and practicality. Through innovative methodologies and the use of sophisticated computational tools, LCR has demonstrated its commitment to accuracy and reliability in surface activity assessments in decommissioning project. The laboratory's expertise in evaluating surface contamination levels underscores the practical applications of the NaI(Tl) detector in radiological characterization efforts. By assuming uniform activity distribution over surfaces and employing robust computational methods, the laboratory enhances the accuracy and reliability of surface activity assessments. Furthermore, the laboratory's proficiency in analysing various contamination geometries, exemplified by the extension of the efficiency transfer method to volume sources, reflects its depth of expertise in gamma-ray spectroscopy. Overall, the laboratory's experience serves as a testament to the enduring significance and practicality of the NaI(Tl) detector in gamma-ray spectroscopy, paving the way for advancements in radiological characterization.

3.2. LCR experience with HPGe detectors

Due to their poor resolution, NaI(Tl) detectors may not always be suitable for effectively identifying complex mixtures of gamma-rays. In such scenarios, detectors with higher resolution are preferred for accurate identification. Consequently, the Laboratory of Radiological Characterization (LCR) has explored the utilization of high-purity germanium (HPGe) detectors to address these challenges and enhance gamma-ray spectroscopy capabilities.

In this section, the experiences gained by the Laboratory of Radiological Characterization (LCR) with high-purity germanium (HPGe) detectors is explored. HPGe detectors offer superior resolution compared to NaI(Tl) detectors, making them well-suited for discerning intricate gamma-ray spectra and identifying nuances in complex mixtures. This heightened resolution facilitated for more precise identification and quantification of radionuclides present in various samples, extending from environmental matrices to industrial materials. The use of HPGe detectors in LCR's analytical processes facilitated advancements in radiological characterization efforts. By harnessing the superior resolution capabilities of HPGe detectors, LCR has been able to achieve increased sensitivity and accuracy in identifying trace contaminants and quantifying their concentrations. This is particularly crucial in scenarios where precise identification of radioactive isotopes is essential for assessing environmental contamination levels or ensuring compliance with regulatory standards. Furthermore, experiences gained from the use of HPGe detectors have provided valuable information for optimizing measurement protocols and data analysis techniques. LCR has developed tailored methodologies to effectively leverage the capabilities of HPGe detectors, including calibration procedures, spectral deconvolution algorithms, and quality assurance protocols. These refined methodologies contribute to the reliability and validity of gamma-ray spectroscopy results obtained using HPGe detectors.

Drawing from experience, insight can be provided into the challenges encountered during radiological characterization activities undertaken during the dismantling and decommissioning of the 30 m^3 buffer tank [13] from the VVR-S nuclear research reactor. A noteworthy aspect of this undertaking was the diverse range of samples measured by gamma-ray spectrometry. One of the primary objectives during radiological characterization of the buffer tank and its surroundings was to identify the radionuclide composition of the contamination. This necessitated a multifaceted approach involving various types of measurements. Contamination measurements were conducted to determine the surface activity of potentially contaminated materials and areas. Additionally, gamma-ray spectrometry analyses were performed to further elucidate the radionuclide composition of the contamination. Samples, including smears and small pieces taken from pipes or the tank itself, were collected for laboratory measurement, providing valuable data for analysis. This diversity underscores the complexity of the radiological characterization process and the need for versatile analytical techniques capable of accommodating various sample types. Navigating through these challenges required a combination of expertise, state-of-the-art instrumentation, and methodological innovation. The experience gained from addressing the complexities encountered during the dismantling and decommissioning of the buffer tank has provided valuable insights into effective strategies for radiological characterization in similar contexts.

Given the limited availability of point calibration sources and the need to address numerous parameters such as coincidence-summing effects, self-attenuation, and all the effects of photon interactions in both the source and materials, the task faced by the Laboratory of Radiological Characterization (LCR) was definitely a challenging one. To cope with these complexities, LCR commonly used two software tools: ETNA (Efficiency Transfer for Nuclide Activity) and GESPECOR. The ETNA software [11] played a pivotal role in the laboratory's operations by facilitating the computation of efficiency transfer factors for a wide range of counting geometries in routine measurements. Specifically, it was used to calculate the efficiency of a high-purity germanium (HPGe) detector for both point sources placed at different distances and volume sources with different compositions and densities. The analysis revealed that the ETNA software accurately computed efficiency transfer factors from a point source to other geometries, provided that all measurement details were accurately known. Additionally, it helped to assess the uncertainties associated with close-to-detector measurement geometries, particularly when using high-efficiency detectors, by incorporating important coincidence summing effects into the measured data. In conclusion, the ETNA software proved to be a useful tool for routine gamma spectrometric measurements, as its application for efficiency computation saved time and eliminated the need for tedious and expensive experimental calibration for different sample geometries [8–10].

The GESPECOR software [12], known for its user-friendly interface, served as a robust Monte Carlo tool within the laboratory's toolkit, significantly contributing to gamma-ray spectrometry with HPGe detectors. It possesses the capability to compute efficiency, matrix effects, and coincidence summing corrections, thereby enhancing the accuracy and reliability of the analytical process.

In LCR's gamma-ray spectrometry studies, GESPECOR was used for various critical purposes. Firstly, it played a pivotal role in computing efficiency transfer factors, crucial for precise measurements in routine laboratory settings. This included analysing different counting geometries to ensure reliable computation of these factors, essential for obtaining accurate peak efficiencies. By utilizing Monte Carlo simulations through GESPECOR, researchers could assess the dependence of detector efficiency on specific geometries, providing valuable insights into performance changes. Moreover, GESPECOR facilitated the correction of experimental efficiency values through Monte Carlo simulations and analytical procedures. Researchers were able to calculate correction factors to improve the accuracy of peak efficiency values. Additionally, the software was instrumental in efficiency calibration for high-resolution gamma-ray spectrometers based on HPGe detectors. It provided procedures for efficiency calibration, enabling computations using either correction factors or direct calculations based on complex detector models and physical processes [14–16]. Furthermore, GESPECOR aided in optimizing detector parameters to ensure optimal correspondence between simulated and experimental outcomes, leading to adjustments in parameters such as crystal length, radius, window thickness, and crystal-window distance. Using GESPECOR, researchers could accurately evaluate photon interaction probabilities, thereby contributing to the reliability of efficiency calculations and enhancing the overall quality of gamma-ray spectrometry analyses.

Another challenge that LCR faced was the radiological characterization of packages containing radioactive waste. While gamma-ray spectrometry measurements for such investigations are advanced worldwide with various methods and technologies being developed to measure large volumes of radioactive materials [17–19] intended for radioactive waste management, the technology based on the tomographic method has significantly gathered attention of researchers [20]. However, it is worth noting that this method is associated with high costs, which makes its application limited, particularly for the characterization of fissionable materials, even in the wealthiest countries. Despite the potential benefits, the prohibitive expense associated with tomographic methods has prevented their widespread adoption, thus necessitating the exploration of more cost-effective alternatives for the efficient characterization of radioactive waste.

The standard practice for radioactive waste assay of 220-liter drums typically relies on the assumption that both the drum matrix and radioactivity are uniformly distributed within the container. To establish an accurate detection efficiency calibration curve, a computational procedure based on Monte Carlo simulation is often employed for such samples. This approach involves accurately representing both the geometry and characteristics of the sample, as well as any intermediate attenuating materials, within the simulation model. However, implementing this procedure is not straightforward and requires a lot of information. In response to this challenge, several studies conducted by LCR have deepened phenomena specific to gamma-ray spectrometry under various working conditions. By researching these phenomena, the laboratory aimed to improve their understanding of the complexities involved and to refine the methodologies used in the characterization of radioactive waste. Through meticulous exploration and analysis of gamma-ray spectrometry phenomena, LCR sought to optimize detection techniques and calibration procedures for assessing the content of radioactive waste in 220-liter drums. This proactive approach underscores the laboratory's commitment to advancing methodologies in nuclear waste management and ensuring the accuracy and reliability of radioactive waste assessment practices. Some methodologies developed by LCR are presented in the next paragraph.

A new model was developed for calculating the peak efficiency of unshielded HPGe detectors using a semi-empirical approach, which integrates the virtual point detector model and the attenuation factor concept to account for various factors influencing efficiency [21]. The model incorporates volume sources, employing the integral of the product of the efficiency for a point source in a vacuum, the attenuation factor, and the activity distribution function over the sample volume. Correction factors for angular and axial dependence were determined through Monte Carlo simulations facilitated by GESPECOR software. Additionally, a MATLAB program was created to enable online numerical calibration of gamma waste systems. This program was designed to compute peak efficiency for rotating and fixed drums perpendicular to the detector axis, accommodating photon energies ranging from 60 to 1500 keV and source-to-detector distances exceeding 10 cm.

Also, a novel approach to integral gamma scanning of rotating waste drums was developed, aiming to expand the utility of integral gamma scanning to measure waste drums with relatively homogeneous matrices and heterogeneous activity distributions, even requiring multiple measurements [22]. A model for computing peak efficiency was developed to discretize the first-kind Fredholm integral equation [23–25], resulting in an ill-conditioned system of equations solved using Tikhonov regularization [26–28] with non-negativity constraints. Initially, the performance of the approach was assessed using synthetic data, demonstrating accurate results for waste drums with relatively homogeneous matrices and heterogeneous activity distributions, particularly for nuclides emitting two or more gamma rays. Taking into account that the numerical experiments showed reasonable results for multi-gamma emitters, even with highly heterogeneous mass distributions, the approach was applied to measure the activity of a certified linear ^{152}Eu source positioned at various radial positions within a 220 liter drum filled with cement, yielding accurate results with only a few measurements for each source position.

In other studies [22, 29, 30], a computational technique was developed to facilitate the calibration and evaluation of radioactive waste measurements using drum counting systems. Specifically, a realistic Monte Carlo simulation program based on the GEANT3.21 toolkit [31] was created to simulate the response function of the ISOCART gamma-ray spectrometry system for sources distributed over several spatial domains, with the theoretical division of the drum volume. This program was used to generate expected spectra in the energy range from 50 to 2000 keV, along with the full energy peak and total efficiency. These calculations were performed for scenarios where the source was distributed in a single domain, and also when the source was uniformly distributed over the entire drum. It is worth noting that while realistic Monte Carlo simulation is commonly used to calculate the efficiency of point sources or volume-limited sources, such as those encountered in environmental radioactivity monitoring, fully realistic Monte Carlo simulations for the case of the 220 liter drum had not been reported until the study carried out by the LCR researchers. This was mainly attributed to the long calculation time required to reach reasonable levels of uncertainty.

The study also aids in testing whether the spectral shape correlates with the location and distribution of the source and whether it can provide insights into the efficiency [32]. This is crucial due to a specific challenge encountered in gamma-ray spectrometry measurements of large samples, such as 220 liter drums, namely the variability of source distribution within the volume. Because the efficiency varies significantly depending on the source's position, the estimated activity may incur substantial errors if the actual source distribution diverges significantly from the assumed distribution. Therefore, any information regarding the source distribution proves valuable in assessing the activity of such samples.

Through the strategic utilization of these sophisticated software solutions, LCR successfully navigated the complexities inherent in gamma-ray spectroscopy analysis. This approach allowed the laboratory to obtain accurate and reliable measurements despite the multifaceted nature of the task at hand.

4. Conclusions

The experience gained from the radiological characterization activities during the decommissioning of nuclear and radiological installations underscores the necessity of meticulous planning and use of specialized resources. The lessons learned from the application of gamma-ray spectrometry methodologies, particularly in the decommissioning of the VVR-S nuclear research reactor, highlight the importance of expertise, advanced instrumentation, and adaptability in addressing the complexities inherent in such projects. The successful transfer of complex equipment and specialized personnel to the Radionuclide, Physico-Chemical, Mechanical and Structural Characterization Laboratory (DMDR-Lab) from Radioactive Waste Management Department (DMDR) from Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH) after the completion of the decommissioning project marks a strategic move towards consolidating expertise and resources for the national management of institutional radioactive waste. However, challenges persist, especially concerning the decommissioning of older installations lacking operational staff and historical data. The methods and equipment used for radiological characterization must be tailored to the specificities of each facility, emphasizing the need for preserving and disseminating expertise acquired through experience. The use of advanced instrumentation, such as HPGe detectors, has significantly enhanced gamma-ray spectroscopy capabilities, enabling more accurate and comprehensive radiological characterization. This continuous pursuit of excellence in gamma-ray spectroscopy not only contributes to environmental monitoring and nuclear safety but also fosters progress in radiological research.

Overall, lessons learned from radiological characterization activities provide valuable insights into the complexity of decommissioning projects and underscore the importance of expertise, innovation, and collaboration in ensuring the safe and effective management of radioactive materials. Facing the challenges of decommissioning aging facilities necessitates leveraging technological advances and collective knowledge to successfully navigate these efforts. In addition, these perspectives emphasize the need for further development and training of personnel in radiological characterization techniques. Ensuring that expertise is not only maintained but expanded is crucial for future decommissioning projects. This includes fostering partnerships between academic institutions, industry and regulatory bodies to facilitate knowledge transfer and technological advances.

In conclusion, nuclear decommissioning involves a complex range of challenges that require a well-coordinated approach, leveraging advanced technologies and specialized expertise. By learning from past experiences and continuously improving methodologies and tools, the efficiency and safety of decommissioning processes can be improved. A continued commitment to innovation and collaboration will be essential in managing the safe disposal of radioactive materials and addressing the evolving challenges of the nuclear industry.

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References

[1] R. Deju, I. Iorga, D. Gurau, *Acta Phys. Pol. A* **131**, 82 (2017).

[2] C. Tuca, A. Stochioiu, D. Gurau, *Rom. Rep. Phys.* **68**, 1048 (2016).

[3] I. Iorga, R. Deju, A.O. Pavelescu, D. Gurau, *Acta Phys. Pol. A* **134**, 311 (2018).

[4] I. Iorga, R. Deju, D. Gurau, M. Mincu, *Acta Phys. Pol. A* **31**, 541 (2017).

[5] C. Tuca, A. Stochioiu, M. Sahagia, D. Gurau, M. Dragusin, *J. Environ. Rad.* **148**, 130 (2015).

[6] E. Ionescu, D. Gurau, D. Stanga, O. Duliu, *Rom. Rep. Phys.* **64**, 387 (2012).

[7] D. Radu, D. Stanga, O. Sima, *Rom. Rep. Phys.* **61**, 203 (2009).

[8] D. Radu, D. Stanga, O. Sima, *Appl. Radiat. Isot.* **67**, 1686 (2009).

[9] D. Radu, D. Stanga, O. Sima, *Rom. Rep. Phys.* **62**, 57 (2010).

[10] G.F. Knoll, *Radiation Detection and Measurement*, 3rd Ed., Wiley, 2000.

[11] M.C. Lepy, M.M. Be, F. Piton, ETNA (Efficiency Transfer for Nuclide Activity measurement): Software for efficiency transfer and coincidence summing corrections in gamma ray spectrometry, Note Technique LNHB 01/09/A, 2004.

[12] O. Sima, D. Arnold, C. Dovlete, *J. Radioanal. Nucl. Chem.* **248**, 359 (2001).

[13] I. Iorga, R. Deju, A.O. Pavelescu, D. Gurau, *Acta Phys. Pol. A* **134**, 311 (2018).

[14] O. Sima, D. Arnold, *Appl. Radiat. Isot.* **56**, 71 (2002).

[15] O. Sima, C. Dovlete, *Appl. Radiat. Isot.* **48**, 59 (1997).

[16] O. Sima, D. Arnold, *Appl. Radiat. Isot.* **53**, 51 (2000).

[17] T.Q. Dung, N.D. Thanh, L.A. Tuyen, L.T. Son, P.T. Phuc, *Appl. Radiat. Isot.* **67**, 164 (2009).

[18] Y.F. Bai, E. Mauerhofer, D.Z. Wang, R. Odoj, *Appl. Radiat. Isot.* **67**, 1897 (2009).

[19] M.C. Yuan, C.H. Yeh, J.J. Wang, I.J. Chen, C.F. Wang, *Appl. Radiat. Isot.* **67**, 931 (2009).

[20] R. Venkataraman, M. Villani, S. Croft, P. Mcclay, R. Mcelroy, S. Kane, W. Mueller, R. Estep, *Nucl. Instrum. Methods Phys. Res. A* **579**, 375 (2007).

[21] D. Stanga, D. Radu, O. Sima, *Appl. Radiat. Isot.* **68**, 1418 (2010).

[22] D. Stanga, D. Gurau, *Appl. Radiat. Isot.* **70**, 2149 (2012).

[23] D. Yuan, X. Zhang, *SN Appl. Sci.* **1**, 1178 (2019).

[24] I.G. Burova, V.M. Ryabov, *WSEAS Trans. Math.* **19**, 699 (2021).

[25] R. Kress, *Linear Integral Equations*, Springer Science & Business Media, 2013.

[26] A.N. Tikhonov, *Sov. Math. Dokl.* **4**, 1624 (1963).

[27] A.N. Tikhonov, *Sov. Math. Dokl.* **4**, 1035 (1963).

[28] A. Neubauer, *SIAM J. Numer. Anal.* **34**, 517 (1997).

[29] D. Radu, O. Sima, *Rom. Rep. Phys.* **62**, 744 (2010).

[30] D. Gurau, O. Sima, *Appl. Radiat. Isot.* **70**, 305 (2012).

[31] R. Brun, F. Bruyant, M. Maire, A.C. McPherson, P. Zanarini, *GEANT3*, DDD/EE/84-1, CERN Data Handling Division, Geneva 1987.

[32] D. Gurau, O. Sima, *Appl. Radiat. Isot.* **70**, 2141 (2012).