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ICARUS: development, optimization, and harmonization of innovative characterization techniques for large volumes of radioactive waste

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Abstract. In the framework of the EURAD-2 partnership, the ICARUS (Innovative ChARacterization techniques for large volUmeS) work package aims at further developing, optimizing and harmonizing innovative techniques for the radiological, physical and chemical characterization of large volume of low/intermediate-level mixed waste, as it could be critical for the safe implementation of radioactive waste management programmes of the member states. Destructive Techniques (DT), Non-Destructive Techniques (NDT), and Scaling Factors (SF) will be investigated. Four use cases will be considered according to the end users' needs: (i) enabling fast and sufficiently accurate characterization of gamma activity distribution by NDT in complex large packages, including mixed wastes as heterogeneous legacy waste; (ii) improving and simplifying NDT for determining physico-chemical properties; (iii) improving sensitivity, accuracy, and uncertainty and replacing the expensive and time-consuming radiochemical analysis of long-lived Difficult To Measure (DTM) radionuclides by DT; (iv) improving accuracy, uncertainty, and reliability of the SF approach to estimate DTM radionuclides in raw mixed waste. Specific education and training materials and opportunities will be provided to foster career advancement of young professionals and researchers. The research activities will be carried out by 29 organizations from 17 countries.

1 Introduction

A key step of waste management is the radioactive waste characterization, which provides the necessary information for the safe and effective collection, segregation, storage, treatment, conditioning, packaging, transport, and disposal of the waste itself. For example, radiological characterization is a pivotal step to ascertain if a material under regulatory radiological control might be released for unrestricted use [1]. For several reasons, waste characterization is a multidisciplinary and challenging operation. Indeed, radioactive waste is generated by a plethora of different activities and processes, not limited to the nuclear energy sector, as it may come from nuclear research facilities, nuclear medicine, and non-nuclear industrial facilities, i.e. facilities handling naturally occurring radioactive materials. Therefore, radioactive waste may possess such a wide range of physical, chemical, and radiological characteristics, all relevant for the development and identification of the most appropriate waste route. Non-exhaustive examples of physical parameters to be assessed are shape, volume, dimensions, density, heterogeneity, distribution of waste and contaminants within the conditioning matrices, presence of liquids or cracks, mechanical and thermal properties, heat generation, hydrogen production and

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release, gas permeation, and diffusion coefficients. Among the chemical and radiological properties, elemental composition, content of toxic or reactive substances, presence of organics such as flammable or explosive compounds, dose rate, distribution of gamma and neutron emitters, concentration of alpha and beta emitting radionuclides, isotopic composition and amounts of nuclear materials should be considered [2]. Characterization of radioactive waste or packages can be performed by Destructive Techniques (DT) or Non-Destructive Techniques (NDT). Some techniques may be difficult to implement, or may provide results with low accuracy and precision, or may be too time-consuming and expensive, given the nature of the waste and its radioactivity content. For economic and practical reasons, waste characterization consists in a compromise between the complete knowledge of all waste properties, the need for high accuracy and precision, cost-effectiveness, and rapidity demands [3]. Besides the technical and financial challenges posed by the waste properties and the characterization procedures, compliance with the waste acceptance criteria (WAC) should always be demonstrated along all waste management stages, including during decommissioning. A systematic complication is added by the country-specific regulations and waste-dependent diversity of the WAC.

Hence, there is need for developing better solutions to bridge the gaps and overcome these issues, as described in the EURAD Roadmap and Strategic Research Agenda [4,5]. These are the founding documents of EURAD-2, the European partnership on radioactive waste management co-funded by the European Commission. The EURAD-2 partnership is built on the previous experience of the EURAD Programme and PREDIS project, and aims to implement the Waste Directive 2011/70 in the EU member states [6,7]. More than 140 organizations, afferents to waste management organizations, technical safety organizations, or research entities, participate in the partnership as mandated actors, affiliated or associated entities [8]. Among the 17 EURAD-2 work packages (WP), WP5 – ICARUS (Innovative ChARacterization techniques for large volUmeS) focuses on the development, optimization and harmonization of innovative techniques for the radiological, physical and chemical characterization of large volume of low/intermediate-level mixed waste. ICARUS has its roots in several previous research projects, hence a comprehensive state-of-the-art will be performed to identify the most promising characterization techniques for industrially relevant decommissioning situations [9]. Over the 5 years duration, the WP – ICARUS has set itself the following objectives:

- Identification of relevant use cases to develop cutting-edge techniques and methods for an industrial application.
- Development of characterization methodologies for mixed wastes as heterogeneous decommissioning, to acquire accurate radiological and chemical inventory necessary for defining pre-disposal management.
- Identification of most relevant radionuclides, considering the main limitations and difficulties that remain for their proper characterization.

2 Description of the work

The research & development activities of ICARUS will be focused to:

- Identify the best available characterization techniques for large volume raw waste in industrially relevant decommissioning situations, a comprehensive State-of-the-Art (SotA) is needed.
- Achieve fast and sufficiently accurate gamma activity distribution in complex large packages (1st use case), NDTs require innovation and optimization to be proficiently implemented in industrial applications, encompassing decommissioning and ongoing operational processes.
- Improve and simplify the inventory of physico-chemical properties and alpha emitters compared to current expensive DT and high uncertainty SF methods (2nd use case), the optimization of NDT needs to be investigated in relevant industrial scenarios (decommissioning/operational processes).
- Improve sensitivity, accuracy, uncertainty and replace expensive and time-consuming conventional radiochemical analysis (3rd use case), cutting-edge DTs need to be developed for determining critical long-lived Difficult To Measure (DTM) radionuclides (C-14, Cl-36, Ca-41, Se-79, Zr-93, Mo-93, Tc-99, Pd-107, Cs-135, Cm-243, Cm-244) in decommissioning/operational samples to develop a comprehensive inventory.
- Lower the uncertainties and improve accuracy and reliability to meet ever stringent requirements set by national regulators for raw mixed waste (4th use case), the SF approach needs to be thoroughly investigated.

2.1 Partners, end-users and stakeholders

The research activities will be carried out by 29 organizations from 17 countries (see Tab. 1). Beneficiaries and affiliated entities participate in ICARUS respectively with or without an official mandate by the respective government. Both have a similar obligation to implement action tasks and the right to charge costs and claim contributions. Associated partners from non-EU countries contribute to ICARUS, but without the right to charge costs or claim contributions. Moreover, ICARUS has already received interest from end users and stakeholders (see Tab. 2), which will be actively engaged through surveys and meetings to keep the use cases adjourned on real industrial needs and organize prototype demonstrations in real scenarios. The large participation of research entities and technical support organizations fosters a complementary and innovation-based approach to identify innovative cutting-edge solutions for the full-scope characterization of radioactive waste. The participation of waste management organizations and the engagement of end users from several member states ensure that relevant use cases are considered to address relevant industrial needs. Moreover, the large participation of universities ensures the involvement of young professionals, as Ph.D. candidates and postdoctoral researchers.

Table 1. List of ICARUS partners grouped per country. A: mandated actors, i.e. beneficiaries; B: affiliated entities; C: associated partners.

Belgium	1. Belgian Nuclear Research Centre (SCK CEN)[A]
	2. Tractebel Engineering S.A. (TRACTEBEL)[B]
Czech Republic	3. Ceske vysoke uceni technicke v Praze (CTU)[B]
Denmark	4. Danmarks Tekniske Universitet (DTU)[B]
Finland	5. Teknologian Tutkimuskeskus VTT Oy (VTT)[A]
France	6. ORANO[B]
	7. Institut Mines-Télécom-Atlantique (IMT-Atlantique)[B]
Greece	8. National Technical University of Athens (NTUA)[A]
	9. National Centre For Scientific Research Demokritos (NCSRD)[A]
Hungary	10. Radiookologiai Tisztasagert Tarsadalmi Szervezet (SORC)[B]
Italy	11. Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo sostenibile (ENEA)[A]
	12. Politecnico di Milano (POLIMI)[B]
	13. Costruzioni Apparecchiature Elettroniche Nucleari CAEN SPA (CAEN)[B]
	14. Università di Pisa (UNIPI)[B]
Lithuania	15. Valstybinis mokslinių tyrimų institutas Fizinių ir technologijos mokslų centras (FTMC)[A]
Norway	16. Institutt For Energiteknikk (IFE)[C]
Romania	17. Regia Autonoma Tehnologii Pentru Energia Nucleara (RATEN)[A]
Slovenia	18. Institut Jožef Stefan (JSI)[A]
	19. Agencija Za Radioaktivne Odpadke (ARAO)[A]
Spain	20. Empresa Nacional de Residuos Radiactivos (ENRESA)[A]
	21. Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)[A]
	22. Consejo Superior de Investigaciones Científicas (CSIC)[B]
	23. Investigacion y Desarrollo de proyectos sociedad limitada (INGECID)[B]
	24. Universidad de Sevilla (US)[B]
Sweden	25. Svensk Karnbranslehantering Aktiebolag (SKB)[A]
Switzerland	26. Paul Scherrer Institut (PSI)[C]
The Netherlands	27. Nuclear Research and Consultancy Group (NRG PALLAS)[A]
Ukraine	28. State Scientific And Technical Center For Nuclear And Radiation Safety (SSTC NRS)[A]
	29. Limited Liability Company Energorisk (ENERGORISK)[B]

2.2 Task organization

The ICARUS management and activities are organized in 5 tasks. The ICARUS board constituted by the task leaders and co-leaders are reported in Table 3.

2.2.1 Task 1

Through task 1, the ICARUS board will address the overall management of the WP by coordinating, monitoring, reviewing, and disseminating the scientific-technical progress according to the agreed planning. In particular, periodic meetings of the ICARUS board will be aimed to monitor that WP activities remain within the scope and focused on achieving the identified use cases. Moreover, the ICARUS board will arrange dedicated task meetings and annual events with the partners to allow information exchange, monitor work progress, ensure quality control, foster cooperation, dissemination of results, and interaction with end users and stakeholders.

2.2.2 Task 2

Task 2, embedded into each of the project's technical work packages, aims to establish an effective mechanism for knowledge capture and sharing, keeping into account the specific domain and features of each work package. Within Task 2, ICARUS's knowledge capture initiative primarily focuses on creating a SotA report, divided into two parts: (i) gathering existing information available at the start of the work package tasks – the initial SotA, which will be based primarily on scientific research, including previous research projects, and ICARUS partners' experience; (ii) developing the final SotA report that integrates identified innovative radioactive waste characterization techniques into the current framework of

Table 2. List of end users and stakeholders grouped per country, updated in January 2025. The list of end users and stakeholders is being periodically updated. Up to September 2025, 27 end users and 18 stakeholder from 22 countries have manifested their interest for ICARUS. A: end users; B: stakeholders.

Austria	Nuclear Engineering Seibersdorf GmbH (NES)[A]
Belgium	Nationale instelling voor radioactief afval en verrijkte Splijtstoffen (ONDRAF/NIRAS)[A]
Canada	Canadian Nuclear Laboratories (CNL)[B]
Denmark	Dansk Dekommissionering (DEKOM)[A]
Finland	Teollisuuden Voima Oyj (TVO)[A]
	Platom Oy[B]
France	Agence Nationale pour la gestion des déchets radioactifs (ANDRA)[A]
	Cyclife engineering[B]
	Institut de Radioprotection et de Sûreté Nucléaire (IRSN)[B]
Germany	Cyclife Germany GmbH[B]
Hungary	Isotoptech ZRT[B]
International	International Atomic Energy Agency (IAEA)[B]
Italy	Società Gestione Impianti Nucleari Per Azioni (SOGIN)[A]
Norway	Direktoratet for strålevern og atomsikkerhet (DSA)[A]
Romania	Institutul National de Cercetare-Dezvoltare pentru Fizica si Inginerie Nucleara "Horia Hulubei" (IFIN-HH)[A]
South Korea	Korea Atomic Energy Research Institute (KAERI)[B]
Spain	Westinghouse (WES)[A]
UK	Nuclear Waste Services (NWS)[A]
	Environment Agency (EA)[A]
	Lucideon Ltd[B]
	United Kingdom National Nuclear Laboratory (UKNNL)[B]
USA	Pacific Northwest National Laboratory (PNNL)[B]

Table 3. ICARUS board and tasks.

Task	Leader	Co-leader
1 – Management/coordination of the WP	Eros Mossini (POLIMI)	
2 – Knowledge Management	Yevheniia Kudriashova (SSTC NRS)	
3 – NDT design for industrial implementation	Bas Janssen (NRG PALLAS)	Ferdinando Giordano (CAEN) An Bielen (SCK CEN)
4 – DT design for DTM radionuclides	Jixin Qiao (DTU)	Marko Štrok (JSI) Anumaija Leskinen (VTT)
5 – Scaling Factor optimization	José Luis Leganés Nieto (ENRESA)	Arturas Plukis (FTMC)

physical, chemical, radiochemical, and radiological characterization methods, enabling convenient search and implementation of methodologies through relevant use cases. The work package partners' expertise will also contribute to creating Domain Insight documents, Guidance documents, and information bulletins targeted at various stakeholder groups in the nuclear waste management field, aligned with the EURAD Roadmap [4].

Knowledge sharing activities focus on engaging students and young scientists in work package and project-related activities, developing specialized training modules, organizing workshops and seminars, and creating social media content. The practical implementation of combining theoretical achievements and experience sharing is planned through prototype-based training (NDT), radionuclide workshops (DT), and specialized SF seminars during decommissioning phases. This will be integrated with member states' experience assessment and documented in the final SotA deliverable on innovative NDT, DT, SF for current and new use cases. These combined efforts, along with an open searchable database, will ensure that the knowledge can be effectively applied in practice.

A well-balanced and structured approach to knowledge management, building on experience gained during the EURAD programme implementation, aims to develop innovative approaches, optimize existing methodologies, comprehensively disseminate knowledge, and sustain expertise development in radioactive waste management, particularly for the large volumes of low/intermediate-level mixed waste characterization [10].

2.2.3 Task 3

The task 3 aims to develop innovative devices for the radiological, chemical and physical characterization of large waste volumes, extending the solutions for drum monitoring solutions [9]. Utilizing NDT (subtask 3.2), these solutions will be used either to address the waste container (metallic boxes, containers) or the waste before filling the container. Additionally, the research focuses on enhancing waste management approach through centralized data processing and in-situ information before and during decommissioning, with a focus on answering WAC (Data management subtask 3.1). The result will be to answer WAC on waste inside a large volume package for real decommissioning cases in a fast, cheap, accurate enough and an approach fit for on-site usage (on-site assessments subtask 3.3).

Subtask 3.1 main target is to aid the characterization issues via a comprehensive decommissioning-site data management [11]. This involves developing site-specific novel approaches on waste management, innovating to produce data in an automated, real-time, and centralized manner, like implementing advanced tracking systems and Machine Vision (MV) with Artificial Intelligence (AI). By linking SotA-techniques to the practical use cases of ICARUS, the techniques will be designed into a modern waste management approach using all available data. This data produced and processed, before and during waste management up to on-site storage, will support key decisions for characterization. The assessment of the best techniques and their data-streams will focus on providing real-time info for automation, AI-driven solutions and more efficient, accurate characterization by subtask 3.2, such as the use of machine learning (ML) algorithms for spectra-data analysis to distinguish activation from contamination. This real-time data management approach will also use information during waste handling before filling packages, in order to optimize non-destructive measurements opportunities.

Subtask 3.2 explores the practical application of NDT techniques for comprehensive decommissioning, focusing on the development of flexible, modular, and usable in-situ NDT systems during raw waste processing. These systems will be designed for use in various scenarios, such as on conveyor belts, buffer storages monitoring, data collection during demolition, and waste handling equipment with sensors. NDT on packages can be further developed to better suit the industrial applications by making the process faster, more cost-effective, and capable of addressing several missing WAC. Although the start of the exploration is a broad spectrum of known options, the added value will now be the holistic, on-site waste management approach supported by advanced data management in subtask 3.1. The research aims to innovate NDT techniques for their applicability to large waste packages and also explore options during the management of the raw waste on-site, ensuring the assessment of radiological, chemical, and physical properties.

- Physical condition properties.

Understanding the waste matrix materials and density distribution in a waste package is a preliminary and fundamental property used during radiological characterization. Better knowing the waste matrix materials and density distribution allows to reduce conservative assumption on reported activities per nuclide (i.e., higher activity values for radionuclides reported). Materials and density are related to the linear attenuation coefficient distribution within the package, inferred by transmission measurements. In relation to subtask 3.1, the SotA results and ICARUS use cases, best matched techniques will be developed like transmission scanning with dual high energy X-rays or using ultrasound. Physical conditions that change over time must also be addressed, for the chemical and radiolysis modelling related to answering WAC or aid the accuracy during analysis with properties as weight, volume, and humidity.

- Radiation detection.

Radiological analysis approach will start with focus to develop multidetector systems positioned at multiple locations to handle large volume packages. In addition to the package measurement, we will also explore options to have detector systems positioned at different locations on-site. These extra NDT locations generate more measurement moments, e.g. like during the generation of raw waste, temporary storage on-site transport movements. Several devices obtaining distinctive characteristics of the same item will be considered and correlated. Advanced, high-sensitivity detectors will be compared with more cost-effective and robust alternatives via experts aided with ML, expert systems techniques and in collaboration with subtask 3.1. Understanding the waste matrix within the package allows more specific selection of the most suitable characterization methodology and proper calibrations of these systems. The robustness of the characterization methodologies can be deepened by means of sensitivity analyses of critical parameters in subtask 3.1, allowing to focus on all experimental NDT efforts.

- Chemical composition.

Chemical aspects of waste are becoming of interest due to the presence of toxics, hazardous as well as the potential chemical processes that could occur during disposal, impacting both the environment and the public safety. Additionally, chemical changes may arise from degradation processes within the waste form and engineered waste barriers. For example, the release of alkali and amorphous silica from the wastes and aggregates in cemented waste forms can induce alkali-silica reactions (ASR) leading to the formation of expansive phases, particularly in humid environments. Long-term chemical and radiolysis modelling related to answering WAC, it is essential to assess also the condition of the waste within packages. External excitation sources will be used to temporarily alter the physical, chemical, and radiological state of the waste and measure the generated results (e.g. radiation, gas). Techniques such as X-ray fluorescence (XRF) will also be explored in this project as NDT for chemical characterization. To help the use cases we explore solutions to minimize the need for destructive analysis of samples or other remote laboratory solutions.

In subtask 3.3 the results of new NDT techniques connected to theoretical data models [12] in subtask 3.1, will be assessed on practical issues and their added value to the use cases of ICARUS. Based on these assessments, different prototypes will be devised and developed to demonstrate each novel technique and its added value. They will represent in the model of subtask 3.1 an added value in the entire waste treatment process on-site from packaging, to transport and potentially still add value to interim storage and final disposal. The developed prototypes will be compared to reference systems from the SotA to test their accuracy and reliability for the intended applications. Each prototype candidate will be analyzed using before- and after-data, to quantify its contribution to the overall approach, incorporating insights from task 4 (sample taking), and task 5 (nuclide vector methodology). The goal is to test the prototypes for accuracy and reliability in real waste management situations as if on-site to highlight the new options. Only if needed, the test will mix modelled data and dummy experiments. Selection to be used in the use cases of ICARUS, will be based on their impact on in-situ demonstrations, ensuring they align with the need for a fast, cost-effective and sufficiently accurate approach across all decommission stages while fully meeting the answers of WAC.

2.2.4 Task 4

This task focuses on the development of sensitive and accurate techniques for completing the radiological inventory estimation of waste and packages by the quantification of long-lived DTM radionuclides usually present in low activity concentrations. The aim is developing sensitive and reliable analytical methods to improve the detection limits and to replace the conventional expensive and time-consuming radiochemical analysis. The methodological development of radiochemical separation and purification will be focused on the effective removal of interferences for the measurement of target radionuclides by radiometric or mass spectrometry methods.

This task is divided into three main activities.

- Development of new radiochemical methods.

One of the main objectives of this sub-task is the development of rapid and effective methods to extract DTM analyte radionuclides from the sample matrix and purify them from all interfering elements and isotopes. The pure beta emitting radionuclides C-14, Cl-36, Ca-41, Se-79, Zr-93, Tc-99, Mo-93, Pd-107, Cs-135 and pure alpha emitting radionuclides Cm-243, Cm-244 are selected as DTM radionuclides in this work, because these radionuclides are important for radioactive waste repository due to their long half-lives, high mobility in the repository site and environment as well as their relative high radioactivity in the waste after a long time storage. The selection of these radionuclides has been driven by the lack of reliable analytical methods (Se-79, Zr-93, Pd-107), or by the challenges of current methods being excessively time consuming (C-14, Cl-36, Tc-99) or difficult to be standardized (Ca-41, Mo-93, Cs-135) [13].

Alloys, metals, concrete, graphite, and ion exchange resin are selected as relevant samples for analysis because these materials are primary waste types from decommissioning or operation of nuclear facilities and difficult to handle in radiochemical analysis. Innovative sample decomposition and pre-concentration methods will be investigated to effectively extract target radionuclides from each type of matrix by acid digestion, alkaline fusion or volatilization, and rapid concentration using coprecipitation or extraction. Sequential separation methods will be designed and investigated to achieve rapid and effective separation of selected radionuclides from the preconcentration to achieve optimal chemical yields and decontamination factors for all possible interferences. For this purpose, different ion exchange or extraction chromatographic resins will be used. The emphasis will be on the simple and fast procedure to be able to separate target radionuclides from the interferences. The method development will be implemented using simulated samples or real samples with known amount of target radionuclides.

- Development of new measurement methods.

The main objective of this sub-task is the development of quick, sensitive, and accurate methods for measurement of long-lived DTM radionuclides (e.g., C-14, Cl-36, Ca-41, Tc-99, Se-79, Zr-93, Mo-93, Cs-135, Pd-107, Cm-243, Cm-244). Methods with liquid scintillation counting (LSC) and mass spectrometry, e.g., triple quadrupole inductively coupled plasma mass spectrometry (ICP-MS/MS), accelerator mass spectrometry (AMS) and multi-collector inductively coupled plasmas mass spectrometry (MC-ICP-MS), will be developed and optimized. Development in LSC will improve efficiency calibration for radionuclides which have no commercially available standards, by using modelling or triple-to-double coincidence ratio (TDCR) LSC techniques [14,15]. Development in mass spectrometry will focus on elimination of spectral interferences such as isobars, hydride and polyatomic interferences by using reaction/collision cell techniques with innovative reaction/collision gases in combination with chemical separation [16,17].

Both mass spectrometric and radiometric methods will be tested and compared to each other to find the optimum one with respect to detection limits, measurement time, as well as costs for analysis. New method for rapid analysis of C-14 activity in challenging waste samples such as graphite will be developed, using combustion with online purification, trapping and radiometric measurement for C-14 to speed up the analysis.

- Implementation of DT on real waste.

Validation, demonstration and harmonization of the developed analytical methods for determination of DTM radionuclides will be implemented by analysis of real waste samples from decommissioning or operation of nuclear facilities provided by project partners. Validation of analytical method is often implemented by analysis of some certified reference materials or intercomparison samples, however DTM method validation is problematic due to the lack of commercial reference materials. Therefore, intercomparison exercise among participating laboratories will be organized for determination of DTM radionuclides in few selected real samples (e.g., ion exchange resin, concrete, graphite) collected from nuclear facilities and homogenized prior to distribution. Meanwhile, this intercomparison could be also used for performance assessment of the participating laboratories and fostering interlaboratory collaboration and harmonization on DTM analysis. Intercomparison exercises on DTM analysis in real radioactive waste has been organized via Nordic Nuclear Safety Research (NKS) community since 2019 and collaboration with NKS is foreseen [18].

2.2.5 Task 5

This task, Scaling Factor optimization, seeks to explore methods for enhancing the accuracy, reliability, and precision of scaling factors, as well as their impact on activity packages and inventory assessment.

This task is divided into four main activities.

- Theoretical analysis of waste streams and identification of conducive parameters.

A theoretical study of SF involves modelling the mechanisms responsible for radionuclide production (via activation and fission) and their subsequent transfer into the associated waste stream. Examining the source term within the analysed system and understanding how isotopes integrate into the waste–considering physical and chemical factors such as transport processes, solubility, and other relevant aspects–will help identify the key steps occurring in the stream. Once the theoretical study establishes the primary mechanisms governing radionuclide production and transfer to the waste stream, it becomes possible to quantify the significance of each step in the overall uncertainty analysis. The goal is to determine the dominant processes affecting SF uncertainty for each studied stream and enhance SF analysis by implementing the most relevant parameters, such as the physical state of the sample or the sampling method used in the stream.

- Sampling design for accuracy improvement: trueness/precision.

The primary objective of this task is to define the optimal sampling method to minimize uncertainty and obtain a representative SF applicable to a broader waste classification. Beyond conventional approaches to improve precision and reduce bias, advanced statistical data processing techniques will be employed for specific data grouping and analysis. These methods aim to systematically filter out insignificant or unstructured data while identifying key factors influencing both SF accuracy and uncertainty, along with their respective impact levels [19]. By gaining a clear understanding of these influencing aspects, it becomes theoretically more feasible to design a sampling method that minimizes uncertainty as much as possible while ensuring a representative SF across a wider waste classification. Additionally, outlining the key considerations in sampling, such as the required number of samples, statistical methodologies supporting the procedure, and the relevant radionuclide properties will help establish the most effective approach to follow.

- Package-Disposal-Storage activity accuracy.

The uncertainty associated with SF is relatively high, as their derivation originates from multiple sources, including radiochemical analysis of small samples. Additionally, when SFs are applied to estimate the activity of DTM isotopes in waste packages, the calculation is based on Easy-To-Measure (ETM) isotopes assessed from the entire package [20]. However, the mass and activity distribution of ETM radionuclides within the package do not necessarily match the distribution from which the SFs were originally derived. To address this discrepancy, adjustments in SF uncertainty for waste packages should be developed to prevent excessive conservatism and provide a more realistic uncertainty assessment. Furthermore, the analytical techniques used to determine ETM isotopes introduce additional uncertainty when applied to waste packages. The feasibility of applying SF based on the heterogeneity of the waste–particularly for legacy waste–and WAC before disposal will be evaluated. Ultimately, the total uncertainty in interim storage or final disposal must be accounted for to ensure compliance with the total allowed inventory. The primary objective is to determine a more accurate representation of DTM isotope uncertainty in waste packages and throughout storage or disposal processes to enhance total inventory control.

- Analysis of optimized scaling factors on real waste.

Several models will be developed within this subtask, incorporating many findings from the previous subtasks as possible to evaluate the improvements achieved. New SF will be established using different key nuclides, including cases with more than one key nuclide– an approach not previously implemented. Additionally, multiple linear correlations involving more than one radionuclide are being considered. Furthermore, scaling factors will be explored not only between DTM isotopes but also between one of them and ETM isotope. This multiparametric nuclide vector approach will enable a broader characterization of radioactive waste composition by determining the activity of selected ETM radionuclides. Ultimately, the approval and implementation of a multiparametric nuclide vector model will enhance the categorization of radiological waste streams.

3 Conclusion

The main outcomes of the ICARUS work package, grouped per use cases, will be:

- 1st use case: improved NDT methods and approaches for radiological characterization (including in-situ and remote characterization, gamma and neutron analyses) of complex large packages (including mixed wastes as heterogeneous legacy waste) to safely implement subsequent stages of waste management lifecycle strategy.
- 2nd use case: improved NDT methods for characterization of physico-chemical properties and chemicals inventory to optimize waste segregation, treatment and conditioning and enhance pre-disposal safety.
- 3rd use case: development/optimisation/innovation of fast and cheap DTs to characterise DTM radionuclides identified as critical and for which limitations/ difficulties remain in the available characterization techniques, to improve the sensitivity, accuracy, uncertainty and obtain a comprehensive radiological inventory.
- 4th use case: development of innovative methods for the optimization and validation of SF methodology to improve accuracy, uncertainty, and reliability of DTM radionuclides estimation in raw mixed waste.

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Conflicts of interest

The authors declare that they have no competing interests to report.

Data availability statement

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Author contribution statement

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