2.2.1 Characterisation

Sort, characterise, classify and quantify radioactive waste in accordance with requirements established or approved by the regulatory body (Characterisation)

Theme 2: Pre-disposal

Sub-theme 2.2: Implementing predisposal management of radioactive waste to support key risk and hazard reduction, and to help reduce costs and save space at interim storage and disposal facilities

Authors: An Bielen (SCK CEN)

Reviewers: Paul CARBOL (JRC), Jiri FALTEJSEK (UJV), Alexandru-Bogdan TATOMIR (BGE)

Version issue 28.05.2024

OVERVIEW

Characterisation of radioactive waste is one of the key aspects in its cradle-to-grave management, playing an essential role at each stage of its life cycle. Across the lifetime of a nuclear installation, characterisation includes adhering to regulatory standards according to national and international legislation, ensuring radiation protection for operational workers and ensuring the safety of both population and environment. During the operational and decommissioning phases of nuclear installations, it becomes crucial in dealing with materials and waste streams, and establishing operational procedures. In the pre-disposal stages of radioactive waste management, characterisation aims to identify and classify waste materials. This enables the differentiation between releasing materials from regulatory control, or designating them for additional treatment and conditioning to obtain a stable waste form suitable for future storage and final disposal. Importantly, characterisation of materials and waste packages is crucial for verifying compliance with general waste acceptance criteria for further actions in its management. The objective of this overview document is to provide state-of-knowledge focused on

These projects have received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreements n° 847593 and n°945098.

international characterisation issues in the pre-disposal stage of waste management.

Radioactive waste is not just generated from operation and decommissioning of nuclear facilities, but also from the use of radionuclides in research, health care and industrial applications. Spent fuel is produced by all types of nuclear reactors, and more than 100 000 tHM are stored throughout Europe [IAEA SRIS]. Around 3.0 million m^3 of low and intermediate-level waste has been generated in Europe, of which about 20% has been stored and 80% has been disposed of [IAEA SRIS]. The proliferation of nuclear waste will continue as a result of various activities. Decommissioning will become a more and more important activity, due to the age of many nuclear power plants. The first generation are reaching the end of their design lives, which will be reinforced by changes in nuclear policy in some countries that require early shutdown of reactors. In addition, many countries are making concerted efforts to clean up past nuclear legacy sites [IAEA, 2022].

Waste characterisation is essential at different stages of the waste management process. It involves a comprehensive and accurate assessment of the physical, chemical, radiological, mechanical, thermal, as well as biological properties of the waste. The goal is to obtain a 'quality end product' meeting specified requirements within the entire waste management life cycle, with special emphasis on waste conditioning, storage and disposal [IAEA, 2007]. The characterisation process ensures compliance with acceptance criteria for any subsequent processes by providing the different characteristics, which serves as the basis for determining necessary actions in waste management and selecting a suitable disposal route. Moreover, it must be accomplished in a systematic manner using proven methodologies, technologies and techniques with an overriding emphasis on quality assurance and quality control [IAEA, 2007].

Activities that are performed at various stages of the life cycle may have significant effects on the cost and efficiency of the overall characterisation strategy and programme. Proper control of the radioactive waste parameters within the entire waste management life cycle, and careful testing of the quality of final waste forms and waste packages, are principal components in any waste management strategy. Failure in control procedures at any step can cause important consequences, not only in follow-up steps, but, in some cases, may result in generating waste packages which are not compliant with the waste acceptance criteria for long-term storage or disposal [IAEA, 2007]. To ensure traceability, proper documentation of characterisation records and its retention for a specified duration is crucial. It facilitates review and verification of the accuracy and reliability of the obtained results [NEA, 2017]. Therefore, careful and strategic planning of characterisation and its data management is imperative to ensure effectiveness and compliance with overall requirements.

KEYWORDS

Disposal, life cycle management, predisposal, protection and safety, regulatory body, safety standards, waste acceptance criteria, waste characterisation

KEY ACRONYMS

GBS - goals breakdown structure
DGR - deep geological repository
IAEA - International Atomic Energy Agency
ISO - International Organisation for Standardisation
LABONET - Laboratories for Nuclear Waste Characterization
MS - Member State
NEA - Nuclear Energy Agency
NPP - Nuclear Power Plant
OECD - Organisation for Economic Co-operation and Development
QA - Quality Assurance
RW – radioactive waste
RWM - radioactive waste management
WAC - waste acceptance criteria

1 TYPICAL OVERALL GOALS AND ACTIVITIES IN THE DOMAIN OF CHARACTERISATION

This section provides the overall goal for this domain, extracted from the EURAD Roadmap goals breakdown structure (GBS). This is supplemented by typical activities, according to phases of implementation, needed to achieve the domain goal. Activities are generic and are common to most regional and geological disposal programmes.

Domain Goal	
2.2.1 Sort, characterise, classify and quantify radioactive waste in accordance with requirements established or approved by the regulatory body (Characterisation)	
Domain Activities	
Phase 1: Planning and Programme Initiation	The assessment of waste inventory, waste acceptance criteria and strategic planning to inform safe and effective long-term waste management are underlined during this phase. The critical role of early stakeholder involvement, consideration of available data and proactive development of characterisation strategies are progressed parallel to optimise decision-making and mitigate cost.
Phase 2: Programme Implementation	Incorporating best practices in radioactive waste characterisation for safe and effective waste management. Comprehensive characterisation plans are worked out, covering various activities and safety considerations with guidance from international reports, emphasizing a life cycle approach for optimal efficiency and risk management. The engagement and interactions among various stakeholders are delineated.
Phases 3-4: Programme Operation/Optimisation and Closure	Continuous review and adjustment of characterisation plans in waste management facilities, emphasizing the implementation of new technologies for safety, regulatory compliance, and economic benefits. Thorough assessments, optimisation of cost and safety routes, and minimise worker exposure are essential concerns. Additionally, the importance of characterisation records management, including waste inventory records, is highlighted for repository operation and closure.

2 INTERNATIONAL LEGISLATION, REGULATION, AND REQUIREMENTS

International regulations on radioactive waste (RW) characterisation include guidelines and standards aiming to ensure a consistent and rigorous approach to the characterisation of RW on a global scale and emphasizing the importance of accurate and comprehensive characterisation throughout the lifecycle of RW, from generation to disposal. Adherence to these standards supports the development of safe, environmentally sustainable, and internationally accepted practices for managing RW, promoting global nuclear safety and security.

The International Atomic Energy Agency (IAEA) outlines guidelines and standards, covering various aspects of waste characterisation, including the classification of waste, assessment of radioactivity levels, documentation requirements, and considerations for transportation and disposal. These regulations aim to ensure a consistent and rigorous approach to the characterisation of RW on a global scale. Additionally, the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) contributes to international efforts by facilitating collaboration among Member States (MSs). The NEA provides a platform for sharing best practices, research findings, and expertise related to radioactive waste management (RWM), including characterisation.

It is important to provide a framework for the safe RWM, necessitating the determination of the required characterisation details, which are described in [IAEA, 1996] and typically developed from disposal performance assessment in addition to waste acceptance criteria (WAC), process control and quality assurance (QA) requirements, transportation requirements, as well as requirements for overall safety and environmental protection. A matrix showing where each WAC originates can greatly assist with understanding the philosophy behind the overall characterisation programme and put the elements into context [IAEA, 2007]. Inadequate data acquisition may lead to the selection of an improperly management process, while excessive data collection result in a waste of resources [IAEA, 2007].

Features adopted for waste characterisation and process control should ensure that the properties of waste packages will be maintained; otherwise the long-term safety demonstration of the proposed disposal facility may not be conclusive [IAEA, 2007]. Characterisation of LILW and HLW at various stages in predisposal management is critical for quality control, process verification, and the safe processing and disposal of waste [IAEA 2003a, IAEA 2003b].

The IAEA's Waste Technology Section provides assistance through a wide range of predisposal topics, which includes the Network of Laboratories for Nuclear Waste Characterisation (LABONET). LABONET has been established to increase efficiency in sharing international experience in the application of proven, quality assured practices for the characterisation of RW and waste packages, and to accelerate risk reduction and clean-up of environmental legacies. LABONET has been involved in several activities, including providing training courses and workshops, and holding annual meetings.

The International Organisation for Standardisation (ISO) has several standards relevant to RW characterisation. The international quality standards ISO 9001 [ISO, 2015a] is widely adopted and it is expected that most characterisation projects will be undertaken within this wider framework. Any organisation collecting and

evaluating characterisation data must be concerned with ensuring the right characterisation information has been collected and the results and their evaluation is of an appropriate quality. Many laboratories currently use methods which are independently accredited to ISO 17025 [ISO, 2015b]. Moreover, one of the key outcomes of the EC project INSIDER [INSIDER, 2020] is the thorough mapping of existing standards, resulting in a well-defined summary of guidelines and standards related to this particular field.

Implementation of a QA programme, as recommend in [IAEA, 2003b], along with a system of records for documenting and keeping all the waste data [IAEA, 1995; IAEA, 2005], as well as in accordance with the requirements and recommendations provided in [IAEA, 2005], is crucial. These records should be reviewed against the specifications to determine the acceptability of the waste package. The QA programme for predisposal management should involve activities [IAEA, 2007], such as waste characterisation, specification development for waste packages, approval of the conditioning process, confirmation of waste package characteristics, and the review of quality control records.

Multiple characterisation projects may be needed over the lifetime of such programmes. In line with good practice, such programmes generally use integrated management systems, aligned to international standards and guidelines, to manage aspects such as project, people, assets, safety, environment, quality and knowledge. Collaboration with stakeholders, partners or contractors is paramount for successful implementation, as highlighted in [NEA, 2017].

The European Union Directive "Radioactive Waste and Spent Fuel Management" [European, 2011] outlines the European Union's framework for the responsible and safe management of RW and spent fuel to avoid undue burdens on future generations. EU MSs are transposing the directive into their national laws and take measures to comply with its provisions. It is important to note that various MSs adopt different principles for waste categorisation, based on their nationally different repository concepts, considering different waste characteristics and radiological impacts. Consequently, the deliverables and characterisation requirements may vary among MSs, reflecting their specific national disposal concepts and geological conditions. Any characterisation scheme and QA assessment shall accommodate individual national legal frameworks.

Accurate characterisation is imperative, as inaccuracies in data collection may result in non-compliant packages discovered late in the life cycle, incurring expensive corrections. Undetected errors may result in unsafe disposal, potentially causing severe, long-term environmental consequences. The adherence to international regulations, therefore, serves as a cornerstone for the responsible and sustainable management of RW on a global scale.

3 GENERIC SAFETY ISSUES FOR CHARACTERISATION

This section describes the safety precautions associated with radioactive material characterisation issues during each of the three phases noted in the table of Section 1. They are described with respect to a waste management programme, addressing pre-disposal activities (prior to final geological disposal). It shall be noted that the characterisation safety and regulation issues do not change during the three phases

yet are reviewed iteratively through each phase and with progressively greater detail.

3.1 Planning and Programme Initiation

In the early phases of pre-disposal programme initiation, it is essential to assess the current and future anticipated RW inventory with regard to material types, radioactivity and volume. This involves analysing the waste's physical and chemical properties, assessing its radiological characteristics, and categorising it according to origin and type. Accurate waste characterisation is crucial for designing appropriate storage, handling, and disposal strategies, ensuring compliance with regulatory standards, and laying the foundation for a safe, effective and sustainable long-term waste management programme.

Planning for waste characterisation should take place in advance of waste generation to ensure that waste collection, segregation, containerisation and storage are all accomplished in a controlled manner which best supports the waste characterisation programme. Strategic characterisation planning plays a pivotal role in RWM, supporting proper segregation and enhancing the accuracy of the characterisation of homogenised raw waste. Segregation of RW reduces uncertainties associated with mixing different waste types, thereby facilitating more precise analysis and classification of waste materials.

Obtaining regulatory approval for the characterisation methods in the processing of waste is crucial, making early engagement with the regulators beneficial. The quality of waste packages may be investigated by non-destructive and, infrequently, also by destructive methods, aiming to obtain specific and measurable data [IAEA, 2007]. However, sampling and inspection may be complemented by indirect methods based on mathematical models and theoretical frameworks for the assessment and understanding of hard-to-detect radionuclides. The scaling factor methodology is a very widely used technique to characterise RW [IAEA, 2009], allowing for the inference of hard-to-measure radionuclides.

Strategic planning of RWM schemes enhances the efficiency of waste characterisation and enables the execution of characterisation under optimal analytical conditions. Moreover, it mitigates the risk of inadvertent mixing characterised and non-characterised waste, and avoids cross contamination of already characterised streams, ensuring the integrity and traceability of waste management processes. In general, the better the planning, the more cost effective and successful the characterisation programme.

In order to elaborate a strategy for characterisation, it is crucial to critically understand and assess:

- the waste acceptance criteria (and the rationale behind it),
- the safety assessment for the cradle-to-grave RWM (e.g. assumptions made, assessment of what is measurable, essential information),
- the public and environmental safety aspects,
- the incorporated quality within integrated management systems to ensure regulatory compliance, meeting metrology requirements, data accuracy, consistency across MSs, effective communication and long-term safety considerations,

- the ISO standards, due to its role in standardising processes, ensuring quality, promoting compliance, providing global recognition, supporting risk management and fostering continuous improvement.

Subsequently, gathering information on waste type, regulatory regime, available process knowledge and characteristics to be measured is essential. Efficiency and effectiveness rely on meeting the criteria with appropriate technologies and strategies, consulting relevant stakeholders, addressing knowledge gaps, and obtaining approval from competent authorities.

Accurate evaluation of available data, including facility documentation, operational history, staff information, characterisation results, and inventory data, can reduce time and costs, significantly influencing the entire decommissioning approach. When dealing with scaling factors, it is valuable to critically assess similar waste streams at similar facilities. It provides insights into the behaviour and characteristics of radionuclides under comparable conditions, and one can better understand trends, identify patterns and establish pertinent scaling factors that enhance the accuracy and reliability of assessments and predictions for waste management practices. It is advisable to anticipate future characterisation needs early on, aligning with downstream work or associated projects, to ensure maximising the use of generated characterisation information, and minimising the need for future measurement campaigns. Another important aspect is the estimation of the quantity of waste generated to facilitate proper planning for storage, transportation, and disposal.

In order to achieve the characterisation objectives and formulate a strategic plan, it is essential to thoroughly plan and identify the characteristics to be assessed, the required resources, expertise, equipment, accuracy and total uncertainty, facilities for performing accurate waste characterisation, as well as data records and knowledge (set-up, scaling factors, etc.). The major assets are associated with the contaminants concerned, in situ measurement techniques, sampling strategy and laboratory analytical equipment. Equally crucial is the early involvement of stakeholders, considering their opinions and expectations in the decision-making process to optimise outcomes and minimise the risk that the characterisation work will not meet its objectives. Securing acceptance from all stakeholders and contributors is paramount in ensuring success.

A characterisation strategy provides an opportunity to consider characterisation across the entire lifetime of a programme or enterprise, considering the inter-relationships between characterisation campaigns, and to set down or reference out to standard approaches defining how characterisation projects will be carried out. Key characterisation objectives focus on understanding the composition and form of radioactive and hazardous substances so that appropriate worker safety protective measures can be put in place during decommissioning or waste handling operations. Radiation doses to workers must be below legal limits, therefore measures as time, distance, shielding, etc. must be applied.

There is increasing recognition that developing characterisation strategies in parallel with major programmes (e.g. decommissioning or waste management strategies) allows a more proactive (EC project INSIDER) and optimised approach to be taken to the initiation of characterisation projects and ensures that the right characterisation information is available at the right time to inform decisions regarding the development and implementation of the major programme.

During the planning phase, characterisation issues closely link to the other EURAD Roadmap Domains of Inventory (2.1.1) and Waste Acceptance Criteria (2.1.2).

3.2 Programme Implementation

Getting closer towards actual operation of facilities and handling of RW streams, it is critical to incorporate the best practices, enhancing the accuracy of RW characterisation and contributing to the safe and effective management of such waste. As part of a characterisation plan, one need to ensure that all aspects meet the regulatory requirements, a commitment to responsible and legalised practices, contributing to the overall safety and environmental protection. Safety considerations, including health, radiological exposure risks and hazardous risks, are highlighted as fundamental prerequisites. With regard to radiological aspects, adequate dose monitoring, specifying limits, supplying dose recording and alarmed equipment, are emphasized. Thorough identification and justification of hazards, both conventional (such as chemical and physical) and radiological, are crucial before proceeding with any characterisation plan. This comprehensive approach aims to address the potential dangers, promoting a safe working environment and minimising adverse effects.

The importance of a comprehensive waste characterisation approach must be highlighted and a wide range of characterisation activities must be outlined, such as area preparation, in situ measurements, sample collection and laboratory analysis. Work instructions need to be developed covering definitions, responsibilities for field and laboratory personnel, equipment calibration and usage, sample-taking procedures and custody transfer processes and required analytical measurements with expected accuracy and total uncertainty. Furthermore, workers undertaking characterisation activities must be suitably trained and qualified. Development of the operational procedures will be informed by the information contained in the characterisation plan, including the number, type and location of sampling and measurements to be undertaken. Documentation, records management and reporting requirements should also be clearly specified.

The report of [NEA, 2017] aims to provide guidance on implementing characterisation, emphasizing collaboration, regulatory compliance, and a commitment to safety and environmental protection. It is important to understand the area to be characterised and adapt the original characterisation plan if necessary. The life cycle approach to characterisation is supported, spanning the entire nuclear facility life cycle from design, construction, operation, transition, decommissioning, waste management, to end states for materials and waste. This approach ensures optimal use of relevant information at each stage, considering multiple characterisation objectives and varying risks. The final destination of the material/waste needs to be considered, to optimise the efficiency and effectiveness of characterisation. In addition, the technical report of [IAEA, 2007] provides a complete examination of methodologies and strategies for waste characterisation, considering waste origin, different streams, laboratory situations, and available analytical technologies. The importance of quality control strategies and policies for RW characterisation is stressed, along with a review of standardisation activities and information for harmonisation of characterisation procedures.

The data required for characterisation and methods for collecting data may vary depending on the type and form of the RW. Whenever waste streams are processed, characterisation may be performed by sampling and analysing the chemical,

physical, radiological, biological, thermal and mechanical properties of the waste. As mentioned in previous section, the quality of waste packages may be investigated by non-destructive and destructive characterisation methods. The most efficient and effective approach frequently involves a combination of these methods [IAEA, 2007; NEA, 2017]. However, these methods may be complemented by indirect characterisation methods based on process control and process knowledge to minimise occupational exposure. The scaling factor methodology is widely used to characterise RW, especially for difficult-to-measure nuclides [IAEA, 2009]. Throughout the implementation phase, it is important to update and verify the accuracy of scaling factors, by ensuring that control samples remain within statistically defined limits, thereby validating the scaling factors. As part of the authorisation process, all waste processing characterisation methods must be approved by the regulatory body.

Defining the organisational structure into which the characterisation efforts fit, will take into account the relationships between the various bodies involved: those responsible for waste management, the disposal organisation, the regulator, the various waste producers and operators, and the independent (or accredited) laboratory [IAEA, 2007]. Given the prolonged nature of RWM projects, it is imperative to emphasize the importance of maintaining metrological consistency, particularly when implementing changes in devices or methods, to ensure the reliability of collected data and decision-making throughout the entire project's duration.

During the implementation phase, characterisation issues closely link to the other EURAD Roadmap Domain of Treatment & Processing (2.2.2).

3.3 Programme Operation and Closure

During operation of (pre-disposal) waste management facilities there is a continuous process of reviewing characterisation records and making necessary adjustments to the characterisation plan based on lessons learned. There are opportunities to take into practice new technologies and strategies with regard to ensure safety (including radiological protection), streamline regulatory compliance and realise economic benefits. Optimisation of routes for costs and safety can be enhanced by conducting thorough assessments and by improving efficiency and resource management. To minimise worker exposure, it is advised to explore and employ remote and automated characterisation techniques. Additionally, evaluation of any re-processing and/or re-packaging needs of wastes in interim storage to meet updated final disposal requirements or repository detailed designs is essential.

Regulatory oversight is crucial for waste characterisation to ensure adherence to global safety in a manner that supports long-term sustainability. For this reason, and due to the significant time intervals between characterisation campaigns and the generation of waste and final disposal, characterisation records management and its retention is of great importance to ensure traceability, enabling easy tracking back to specific procedures, methodologies and results. It is imperative to collect, record and transfer this data according to a quality plan, ideally outlined within operational procedures [NEA, 2017]. Key information that is needed for repository operation and closure is the waste inventory records, containing the radionuclide and hazardous waste inventory, waste form/package information and location in the repository. Efficient data documentation of waste characteristics and

consistent labelling practices are critical elements in maintaining traceability throughout the waste life cycle.

Typical records generated could include:

- waste inventory records managed by a WIRKS [IAEA, 2001],
- general WAC,
- waste package procurement and quality control,
- waste generator technical reports,
- waste profiles prepared by generators (pre-qualification records),
- approval of waste profiles by the repository operator and/or regulators,
- waste characterisation procedures and approvals, including calibrations and control measurements,
- shipping manifests - paperwork that arrives with a shipment, and
- contracts and correspondence with waste generators.

During the operation phase, characterisation issues closely link to the other EURAD Roadmap Domains of Quality & Management Systems (2.3.1) and Optimisation (2.3.2).

4 CRITICAL ISSUES, INFORMATION, DATA OR KNOWLEDGE IN THE DOMAIN OF CHARACTERISATION

The key critical issues for characterisation are summarised by the regulatory objectives, which may vary between countries. Understanding and adhering to these regulatory objectives are essential for ensuring compliance and effective waste characterisation. However, differences in these objectives between countries can pose challenges, as they may require adjustments or additional considerations when implementing characterisation strategies across international borders. The key critical issues are:

- Identifying the characteristics of the wastes (physical, chemical, radiological, biological, mechanical and thermal properties) in order to sort, classify and quantify RW in accordance with the requirements established and approved by the regulatory body and next RWM procedures. Characterisation of wastes applies throughout the life cycle (e.g. for processing, storage, transport and disposal) and need to comply with the regulations to ensure proper handling and final safe disposal.
- Confirming compliance with the general WAC, to ensure that sufficient safety measures are in place for managing the waste.
- The accessibility and capability of laboratories characterised by well-equipped and properly staffed laboratories is essential for performing accurate and timely assessments.
- Establish comprehensive data reporting and recordkeeping systems to ensure transparency, traceability and compliance with regulatory requirements.
- Promote public awareness and education regarding waste characterisation and proper disposal practices to elevate community involvement.

- Encourage waste segregation at the source and minimise waste generation to reduce the environmental footprint.

Challenges include a lack of standardised classification systems, inadequate testing methods, insufficient expertise, and barriers to public engagement. Addressing these issues is vital for effective waste management, ensuring the selection of a safe management route for RW while minimising environmental and health risks.

An examination of the waste characterisation strategies and practices in various countries indicates that many different or modified control methods are in use. Insufficient harmonisation of testing methods and different interpretation of the obtained results, especially in the area of quality control of the final waste forms and waste packages, constrain application of unified safety rules and requirements [IAEA, 2007]. In [NEA, 2017] some areas are highlighted that could benefit from further development through international co-operation and co-ordination. It is worth considering the role of internationally organised round-robin tests. These tests involve distributing identical samples to multiple laboratories for independent analysis, aiming to evaluate both inter-laboratory variability and accuracy. This approach is organised by Nuclear Physical Laboratory (NPL) [NPL, website], which facilitates collaborative efforts to enhance consistency and reliability in waste characterisation methodologies on a global scale.

Knowledge management involves processes and methodologies that allow maintaining, sharing, accessibility and development of object-oriented knowledge. In the context of characterisation processes, organisations must maintain characterisation information and records, with defined retention periods based on business, legal and national/international obligations, ensuring resilience by storing records in different formats and locations.

Authorities responsible for regulating the management of RW have a designated and unchanging role. Demonstration of efficient and accurate characterisation helps prove to regulators and stakeholders that RW is managed safely. The generator of raw waste and the operators (treatment and conditioning, storage and disposal) are obligated to perform waste characterisation. The waste generator retains responsibility and ownership of the waste, and operators must implement an auditable QA management system for quality control during the process. Taking into account the particular activities involved in each step and in the whole life cycle can help fulfil all requirements in a more effective way. Each body has to obtain regulatory agreement/approval as well as agreement from the next body (operator or authority) to transfer the waste to its next life cycle phase. It is crucial that information about the waste (including its characterisation results) from generator to disposal operator is traceable and shared between bodies [IAEA, 2007].

5 MATURITY OF KNOWLEDGE AND TECHNOLOGY

This section provides an indication of the relative maturity of information, data and knowledge for the domain of characterisation. It includes the latest developments for the most promising advances, including innovations at lower levels of technology maturity where ongoing RD&D and industrialisation activities continue to improve.

5.1 Advances in characterisation issues

New technologies related to characterisation that are being implemented or could be applicable to the radioactive waste domain include for instance:

- Development of new, remote, integrated and automated methods for in-situ identification, characterisation and segregation of material waste streams for better informed decision-making on next steps for efficient remediation, dismantling, treatment resulting in lower costs, greater time savings and improved safety with less exposure risks.
- Challenges persist in developing fast, cost-effective, and straightforward methods for measuring difficult-to-measure radionuclides, as the available technology has not reached the required maturity level, as well as transitioning from destructive techniques to more sustainable and safer non-destructive characterisation techniques. The main outcomes of these efforts would be a reduction in characterisation time and cost, with the main goal to enhance availability, reliability, accuracy, robustness and efficiency.
- Due to the complexity of the characterisation of conditioned RW, more advanced non-destructive techniques and methodologies are required. These technologies primarily aim to minimise uncertainties in radionuclide inventory and enable non-destructive control of the content of large volume RW types.
- Enhancing the comprehension of non-radiological properties and inventory of radioactive waste is a key focus. A more detailed understanding of the chemical component of wastes will enable the implications for processing, transport, storage and disposal to be identified and assessed. Additionally employing non-destructive testing methods for characterisation of the physico-chemical content and properties is crucial. The aim is to decrease conservatism with respect to waste inventory assessments.
- Innovative methods for validating scaling factors are essential to enhance the accuracy and reliability of characterisation results. There is a pressing need to develop scaling factors considering heterogeneity in terms of time and space, along with a more effective quantification and treatment of uncertainties.
- The development of mobile monitoring and characterisation systems, especially for containerised RW and unconventional legacy waste, aims to enhance on-site, non-destructive analyses, and even radio-chemical assessments. This strategy reduces the challenged linked to transporting radioactive waste packages, particularly those with high radioactivity or limited knowledge of the characteristics.
- Improve sampling techniques, by optimising sampling strategies, using statistical methods and by emphasizing sampling representativeness for result precision, accuracy and uncertainty assessment.

5.2 Optimisation challenge and innovations

Challenges exist with regarding to efficient (time and cost) and safe characterisation of RW, especially in implementing advanced non-destructive techniques and methodologies that can provide accurate assessments of both radiological and non-radiological properties. Legacy RW characterisation and transportation from their interim storage to a final safe repository pose extra challenges. Additionally, the enhance use of robotics including drones and sensors is highlighted from both standardisation and regulatory implications points of view.

Another challenge emerges in the throughout planning of cradle-to-grave RWM. It involves mapping out the entire life cycle of the RW, from its generation to its final disposal. This process includes identifying key points where waste characterisation is essential to ensure safe handling, transportation, treatment and disposal. Strategic planning ensures that characterisation activities are strategically integrated into the entire process to facilitate informed decision-making, regulatory compliance, and protection of human health and the environment.

Prioritising knowledge-sharing is crucial for developing and maintaining technical expertise in nuclear decommissioning programmes. Despite international organisations' efforts, regulatory harmonisation remains a challenge, impacting multinational cooperation in decommissioning and waste management. Various reports [IAEA, 2007; NEA, 2017] and EC project HARPERS emphasize the need for harmonisation to facilitate benchmarking the efficiency of strategies, identify best practices, and address public risk perception and acceptance.

Future developments to enhance characterisation safety are related to:

- The implementation of educational and training programmes to ensure sufficient and skilled staff are available for the sector with a special focus on the use of new technologies for characterisation.
- Identify opportunities to improve the exchange of experiences and identification of MS' regulatory differences regarding clearance and acceptance criteria. Alignment and harmonisation based on EU standards for an efficient benchmarking of best available techniques.
- Evaluate the regulatory implications of using advanced technologies including robotics, automated site mapping and digital twin technology.
- Digitalisation, modelling and simulation. Best practices and guidelines on the implementation of digital technologies to improve key tasks in the decommissioning.
- Development of methodologies for characterisation data treatment and (measurement) uncertainty management (e.g. statistical approaches), and improved interpretation of characterisation results using artificial intelligence or machine learning methods, especially for challenging or heterogeneous waste streams.

6 PAST RD&D PROJECTS ON CHARACTERISATION

Past IAEA and/or European Commission funded projects that have partially addressed radioactive waste characterisation have included:

- CHANCE project – Characterisation of conditioned radioactive waste, funding from Horizon 2020 Euratom Work Programme under grant agreement n° 755371, 2017–2021, https://www.chance-h2020.eu/.
- INSIDER project – Improved nuclear site characterisation for waste minimisation in decommissioning and dismantling operations under constrained environment, funding from the Euratom Research and Training Programme under grant agreement n° 755554, 2017-2021, https://insider-h2020.eu/.
- MICADO project – Measurement and instrumentation for cleaning and decommissioning operations, funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 847641, 2019-2023, https://www.micado-project.eu/.
- PLEIADES – PLatform based on Emerging and Interoperable Applications for enhanced Decommissioning processES, funding from Horizon 2020 Euratom Work Programme under grant agreement n° 899990, 2020-2023, https://cordis.europa.eu/project/id/899990.
- CLEANDEM project – Cyber physical equipment for unmanned nuclear decommissioning measurements, funding from Horizon 2020 Euratom Work Programme under grant agreement n° 945335, 2021-2024, https://cordis.europa.eu/project/id/945335.
- SHARE project – Creating a strategic plan for the research focused on enhancing safety, reducing environmental impact, and cutting costs in the decommissioning process, funding from European Union's Horizon 2020 Research and Innovation Programme under grant agreement n° 847626, 2019-2022, https://share-h2020.eu/.

7 UNCERTAINTIES

The absence of final WAC for waste disposal in many countries contributes to uncertainties in RW characterisation. The lack of clear guidelines and standardised criteria hinders the consistent and universally applicable assessment of waste properties, potentially leading to varied interpretations, methodologies, and safety measures. Additionally, changes in regulatory framework can introduce uncertainties in the standards and requirements for RW characterisation. Adapting to new regulations may pose challenges for effective waste management practices and disposal strategies.

Predicting the long-term behaviour of RW materials, especially over thousand years, is challenging. There is uncertainty about how these materials will interact with the environment and potential changes in geological conditions. Another issue that can introduce inaccuracies in assessing the nature and potential risks of RW are human errors during the characterisation process, as well as accidents or incidents during handling, transportation or storage could lead to unexpected consequences.

The exact composition and characteristics of RW may not always be fully known or understood, leading to uncertainties in how to handle, process and dispose it safely. Also, uncertainty will arise as a result of the variability of contamination and activation products in the materials or waste being examined. Since it is impossible in every situation to measure the residual radioactivity at every point in space and time, the results will be incomplete to some degree. Uncertainty is also associated with measurement, sampling and analysis techniques, and includes random and systematic errors. Random errors affect the precision of the measurement system and present as variations among repeated measurements. Systematic errors in measurements are biased giving results that are consistently higher or lower than the true value.

In most cases underestimation of contaminants tends to be the greatest concern however, overestimation can be costly. This area is commonly overlooked which can lead to significant problems. To avoid such matters, the variability in a population of characterisation results needs to be considered taking into account all significant sources of uncertainty. The main sources of uncertainty arise in checking the homogeneity of a waste stream and sampling, selecting the key nuclides and non-radioactive elements, measuring the easy and difficult-to-measure radionuclides, and calculating the hard/impossible to measure radionuclides (IAEA 2007).

8 GUIDANCE, TRAINING AND COMMUNITIES OF PRACTICE

This section provides links to resources, organisations and networks that can help connect people with people, focussed on the domain of characterisation.

Guidance
• INTERNATIONAL ATOMIC ENERGY AGENCY, Characterization Handbook, Characterization of Radioactive Waste and Waste Packages, IAEA LABONET, Vienna, under review (only available via members area) (https://nucleus.iaea.org/sites/nefw-projects/IMMONET/Handbook_Project/Shared%20Documents/Forms/Characterization.aspx) • INTERNATIONAL ATOMIC ENERGY AGENCY, Pre-disposal Management of Radioactive Waste. General Safety Requirements Part 5, IAEA GSR Part 5, Vienna (2009) (https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1368_web.pdf)
Training
• **IAEA e-learning** (Global search (iaea.org)). Opportunity for following a wide range of courses regarding radioactive waste characterisation.
Active communities of practice and networks
• **ENTRAP** (European Network of Testing Facilities for the Quality Checking of Radioactive Waste Packages) (No website available, but activities are outlined in https://www.cambridge.org/core/services/aop-cambridge-core/content/view/5D156B0382D8835AB7EBC1B8F28296EB/S0026461X00001444a.pdf/entrap-and-its-potential-interaction-with-european-networks.pdf) • **IAEA Labonet** (Laboratories for Nuclear Waste Characterization) (https://nucleus-qa.iaea.org/sites/connect/LABONETpublic/SitePages/Home.aspx)

Key competences that are needed in the area of radioactive waste **characterisation** include radiation safety, chemistry and physics knowledge, nuclear engineer, analytical skills, measurement and monitoring techniques, shielding, communication (stakeholder engagement), data management, quality assurance, risk management, project management.

9 ADDITIONAL REFERENCES AND FUTURE READING

Improved Nuclear Site characterization for waste minimization in DD operations under constrained EnviRonment (INSIDER), Guidelines and Pre-standards on Sampling Strategy, Laboratory Analysis and on Onsite Measurements in Constraint Environments, Deliverable D7.10 (2020).

INTERNATIONAL ATOMIC ENERGY AGENCY, Quality Assurance for Radioactive Waste Packages, Technical Reports Series No. 376, IAEA, Vienna (1995).

INTERNATIONAL ATOMIC ENERGY AGENCY, Requirements and Methods for Low and Intermediate Level Waste Package Acceptability, IAEA-TECDOC-864, Vienna (1996).

INTERNATIONAL ATOMIC ENERGY AGENCY, Characterisation of radioactive waste forms and packages, Technical Reports Series No. 383, Vienna (1997).

INTERNATIONAL ATOMIC ENERGY AGENCY, Waste inventory record keeping systems (WIRKS) for the management and disposal of radioactive waste, IAEA-TECDOC, Vienna (2001).

INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of Low and Intermediate Level Radioactive Waste, IAEA Safety Standards Series No. WS-G-2.5, IAEA, Vienna (2003a).

INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of High Level Radioactive Waste, IAEA Safety Standards Series No. WS-G-2.6, IAEA, Vienna (2003b).

INTERNATIONAL ATOMIC ENERGY AGENCY, Methods for Maintaining a Record of Waste Packages during Processing and Storage, Technical Reports Series No. 434, IAEA, Vienna (2005).

INTERNATIONAL ATOMIC ENERGY AGENCY, Strategy and Methodology for Radioactive Waste Characterisation, IAEA-TECDOC-1537, Vienna (2007).

INTERNATIONAL ATOMIC ENERGY AGENCY, Determination and Use of Scaling Factors for Waste Characterization in Nuclear Power, IAEA Nuclear Energy Series No. NW-T-1.18, Vienna (2009).

INTERNATIONAL ATOMIC ENERGY AGENCY, Status and Trends in Spent Fuel and Radioactive Waste Management, Series No. NW-T-1.14 (Rev. 1), IAEA, Vienna (2022).

IAEA SRIS: The Spent Fuel and Waste Information System. Website: https://sris.iaea.org/home (Access on 07-03-2024).

National Physical Laboratory (NPL), Radioactivity services: Nuclear industry proficiency test exercises. Website: https://www.npl.co.uk/products-services/radioactivity/nuclear-industry-pte (Access on 12-03-2024).

Nuclear Energy Agency (NEA), Radiological Characterisation from a Waste and Materials End-State Perspective: Practices and Experience, Radioactive Waste Management, NEA No. 7373 (2017).

International Organisation for Standardisation, Quality Management Systems – Requirements, ISO 9001, ISO, Geneva (2015a).

International Organisation for Standardisation, General Requirements for the Competence of Testing and Calibration Laboratories, ISO 17025, ISO, Geneva (2015b).