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Advanced treatment strategies for challenging radioactive Wastes: Recent Developments and future directions

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ABSTRACT

The management of low- and intermediate-level radioactive waste (LILW) presents increasing challenges, particularly for waste streams with complex chemistries, variable radioactivity, or combined toxic and radiological risks. Conventional treatment methods, while effective for conventional waste types, are often inadequate for these problematic streams, which require advanced and tailored approaches. This review evaluates recent progress in thermal (pyrolysis, plasma processes, fluidized bed steam reforming, molten salt oxidation) and chemical technologies (wet and electrochemical oxidation) for treating such wastes. The novelty of this work lies in its integrated analysis, which combines comparative technology mapping with assessments of scalability, regulatory and societal acceptance, and the integration of lifecycle environmental and economic metrics. Cross-technology performance matrices are presented to support process selection, together with a strategic research roadmap that prioritizes secondary waste minimization, flexible acceptance criteria, and the inclusion of Life Cycle Assessment (LCA). The study also highlights future trends such as mobile modular treatment systems, hybrid technologies that integrate multiple treatment approaches, and the increasing use of artificial intelligence (AI) and Internet of Things (IoT) technologies for real-time monitoring and process optimization. Overall, this review aims to provide a practical framework to guide researchers, industry, and regulators toward safe, sustainable, and industrially viable solutions for complex radioactive waste management.

1. Introduction

Low- and intermediate-level waste exhibit significant diversity and variability, encompassing a wide range of radionuclides, half-lives, activity concentrations, volumes, and physical and chemical properties. In addition to radionuclides, these wastes may contain other hazardous elements. This compositional variety makes the selection of appropriate processes for waste treatment and conditioning highly complex. This depends on factors such as the level of radioactivity, the form and characteristics of the waste, and the overall strategy for waste management. Furthermore, each country's nuclear waste management policies and national regulations significantly influence the chosen approach (Marsal et al., 2023).

For the majority of common waste streams, technologies and practices for waste treatment and conditioning are well-established. However, certain problematic waste streams, such as organic waste or reactive metals (Fig. 1), still lack optimized management solutions (Wasselin et al., 2019).

1.1. Challenging wastes

The term "challenging wastes" refers to specific waste streams that exhibit additional complexities due to factors such as their chemical composition, volume, or the presence of non-radiological hazardous materials that complicate their treatment and subsequent conditioning. Although the technologies and practices for treating and conditioning

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most common waste streams are well established, certain problematic waste streams, including organic wastes, reactive metals, legacy wastes, and those associated with future fuel cycles and reactors, still do not have a mature management strategy. Current technologies may not be fully effective or efficient in treating certain challenging waste streams, prompting the need for the research and development of innovative treatment methods. Overall, addressing the scope of the problem requires a comprehensive understanding of the diverse characteristics of LILW and challenging waste streams, evaluating the challenges associated with their management, and designing new management strategies to ensure safe and sustainable disposal. This involves an assessment of the existing infrastructure, technological capabilities, regulatory frameworks, and potential innovations in waste treatment and containment.

Several common types of waste present significant challenges in their treatment and conditioning for further disposal. These include both solid and liquid organic wastes, which often exhibit complex chemical compositions that make their treatment and conditioning difficult. Reactive metals, mainly from D&D operations, pose problems for conditioning due to their corrosion potential in alkaline environments, making their safe treatment and disposal a priority. Legacy waste resulting from past nuclear activities often lacks adequate historical records, which leads to ambiguities in their characterization and consequent management. Additionally, wastes generated from future fuel cycles and advanced reactors introduce new challenges as they may contain novel radionuclide compositions and require innovative treatment technologies. Addressing these challenging waste streams necessitates the development of advanced treatment methodologies that can handle their specificities and ensure a safe and efficient waste management scheme (Marsal et al., 2023).

1.2. Previous R&D initiatives on the treatment of radioactive wastes

Significant advancements have been made in radioactive waste treatment, but several challenges remain unsolved. These challenges are frequently related to numerous variables such as:

- the need of managing secondary waste streams
- obtaining a chemically-stable product, compatible with conventional conditioning systems
- or overcoming the technical and economic issues associated with scaling up from laboratory to industrial facilities while meeting regulatory requirements (Wareing, 2023; Fournier et al., 2024; Pancotti, 2024).

Continued research and development are essential for optimizing existing technologies and developing novel approaches for wider industrial implementation. In line with this, the treatment and decontamination of challenging LILW has been the focus of several EU projects, including EURAD (Marsal et al., 2023), PREDIS (Holt et al., 2022), and THERAMIN (Scourfield et al., 2020), as well as various international experiences (Jantzen et al., 2007; Walling et al., 2021). Across these projects and experiences, several common challenges have emerged, including regulatory issues, environmental impacts, and the need for innovation to address the remaining research gaps.

European initiatives over the past decade have driven significant advances in the management of complex radioactive wastes, particularly through collaborative projects focused on pre-disposal technologies and alignment of research with industry and regulatory standards (EURAD-2 STREAM). Notably, sustained work in these programs has led to the development and demonstration of innovative treatment methodologies and provided frameworks that promote both technical relevance and practical deployment within the EU context.

1.3. Scope, objectives and strategic focus

This review provides a state-of-the-art assessment of established and emerging treatment and decontamination approaches for complex radioactive waste streams. Its specific aims are to: (i) summarize available and developing methods; (ii) evaluate their performance and scalability for different waste types; (iii) assess regulatory, technical, and operational barriers to deployment; (iv) identify research domains requiring further development; and (v) suggest strategies to foster innovation and accelerate the implementation of sustainable solutions.

Emphasis is placed on evaluating the readiness and industrial applicability of emerging processes through comparative technology mapping, performance benchmarking, and analysis of representative case studies. Extensive experience and data accumulated through recent European research efforts have allow identifying most relevant technical and regulatory challenges in the field, as well as the remaining knowledge gaps that limit a wider adoption of advanced waste treatment strategies. Key attention is given to new treatment concepts that are hybrid, modular, or mobile, and to the integration of tools such as life-cycle assessment (LCA) and sustainability metrics.

By integrating scientific advances with stakeholder and regulatory perspectives, this review attempts to provide practical guidance for researchers, waste management organizations, and policy-makers. Ultimately, it presents a strategic framework to guide decision-making and to accelerate the adoption of next-generation radioactive waste treatment technologies.

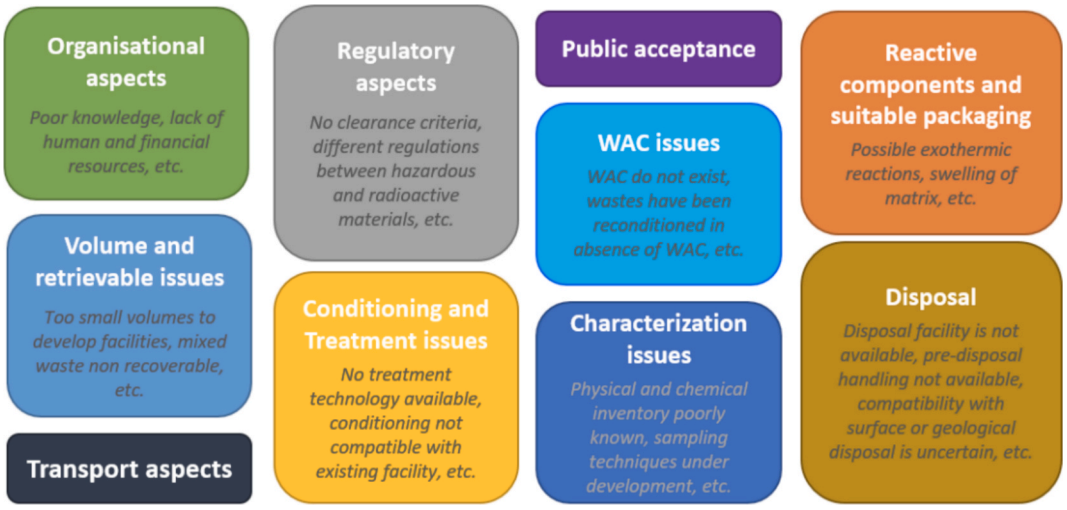


Fig. 1. Reasons leading to consider a waste as challenging one (Wasselin et al., 2019).

2. Overview of radioactive waste treatment technologies

The efficient management of low- and intermediate-level radioactive waste (LILW) relies on the proper classification and characterization of the diverse range of challenging waste streams generated across nuclear operations. This section provides a concise overview of these waste categories and highlights the main challenges that persist in their characterization and subsequent treatment.

2.1. Classification of challenging waste types

Challenging waste types can be classified into several categories, each of which presents unique treatment and management challenges. Fig. 1 summarizes the main causes for considering a waste stream as challenging.

A systematized approach helps ensure that waste management strategies are tailored to the unique technical and safety requirements of each waste stream. The challenging wastes of greatest concern among stakeholders and end users, as identified by previous EU R&D projects, are the following (Wasselin et al., 2019; Abdel Rahman and Ojovan, 2021):

- *Spent Ion Exchange Resins (SIERs)*: Complex organic matrices saturated with radionuclides and diverse chemicals, primarily originating from water purification operations.
- *Radioactive Liquid Organic Wastes (RLOWs):* including oils, solvents, and scintillation liquids, often mixed with both short- and long-lived isotopes and additional hazardous substances.
- *Reactive Metals*: Mainly aluminum, beryllium, and magnesium, whose corrosion in conventional OPC matrices can pose several problems for conditioning and disposal, such as gas generation.
- *Sludges:* Dense, heterogeneous suspension that may contain heavy metals, residual organics, and varying activity concentrations.
- *Evaporator Concentrates:* Saline, often highly active residues formed during liquid volume reduction steps, sometimes requiring further modification to meet conditioning or disposal acceptance.

Table 1 summarizes the physicochemical characteristics of some of the most common challenging wastes (Wasselin et al., 2019; Abdel Rahman and Ojovan, 2021).

Each of these categories requires tailored strategies for treatment and management, considering their specific chemical, physical, and radiological properties. Pre-treatment operations depend heavily on effective waste classification and characterization. For each waste stream, several remaining gaps need to be addressed:

- Uncertainties in the chemical and radiological inventories: Limited documentation and complex natures can hinder reliable radiological and chemical assessment.
- Presence of chemotoxics and hazardous by-products: volatile organics, corrosive agents, or reactive constituents require specialized diagnostics and custom management plans.
- Variable physical characteristics: Factors like viscosity, volume change, or gas generation during interim storage may limit treatment and conditioning options.

Table 2 provides a comprehensive overview of the various aspects and challenges associated with the treatment of different types of challenging radioactive waste, highlighting areas for potential improvement and innovation.

As a conclusion, robust systems for waste classification and characterization are essential for selecting the most appropriate treatment for each type of waste, as well as for achieving regulatory compliance and technical readiness for subsequent treatment steps. Specific treatment options, technology selection, and comparative assessments are addressed in the following sections for each of the waste streams considered.

Table 1
Physical and chemical characteristics of most common challenging wastes.

Type of waste stream	Physical and chemical characteristics
Spent Ion Exchange Resins (SIERS)	Organic exchangers are primarily composed of polystyrene-divinylbenzene (PS-DVB) or acrylic-based polymers with sulfonic acid, quaternary ammonium, or chelating groups for ion exchange Classified as LILW, SIERs contain major contaminants like fission products (e.g., Cs, Sr), corrosion products, borates, nitrates, and alkali components. Countries have reported that non-conditioned SIERs can have activity up to 10 TBq.
Radioactive Liquid Organic Waste (RLOWs)	Variable organic nature and wide range of contaminants depending on their origin. The characteristics of organic liquid wastes depend on their chemical composition, application, and the extent of hydrolysis and radiolysis. Common radiological features include: – Oils (lubricating oils, hydraulic fluids, vacuum pump oils) are produced in small volumes. Reactor oils are classified as LLW, containing low levels of beta and gamma emitters (e.g., ^{137}Cs, ^{134}Cs, ^{58}Co, ^{60}Co, ^{65}Zn). In PHWRs, spent vacuum pump oils are ILW. – Scintillation liquids, used in radiochemical analysis, contain low-energy alpha and beta emitters, with an activity of around 350 MBq/m^3. – Miscellaneous solvents (e.g., toluene, acetone, alcohols) used in decontamination have activity levels < 200 MBq/m^3. Solvents from nuclear fuel reprocessing are generated in higher volumes.
Reactive metals (Al, Be, Mg, etc.)	Variable reactivity in alkaline media Critical dependence of pore alkaline Ph
Sludges	High Radioactivity & Toxicity: contains long-lived radionuclides requiring shielding and remote handling. Complex Composition: Mix of heavy metals, organic compounds, and unstable colloidal particles, risking gas generation and leaks. Handling Difficulties: Viscous and fast-settling, causing clogging and transport issues. Storage & Disposal Risks: Requires stabilization (drying, vitrification); aging tanks risk leaks, complicating geological disposal. Chemical Reactions: Organic materials and nitrates can generate explosive gases; alkaline sludge reacts with CO_2, forming retrieval-resistant crusts.
Evaporator concentrates	The concentrate or bottoms product can range from 15 wt% solids to a virtually dry powder or cake, depending on the evaporator type and efficiency and on the chemical composition of the waste stream Evaporator concentrates are highly saline solutions with specific activity concentrations of 10^6 –10^8 Bq/L. They contain fission products like ^{137}Cs, ^{60}Co, and ^{54}Mn, along with borates ($NaBO_2$, $Na_2B_4O_7$), nitrates ($NaNO_3$, KNO_3), hydroxides (NaOH, KOH), and organic compounds such as oxalates.

3. Current and emerging treatment technologies

Treatment approaches in radioactive waste management pursue three main goals: maximum volume reduction, efficient radionuclide removal, and stabilization of physical and chemical waste forms for safe repository disposal (IAEA SSG-41, 2016).

IAEA and the NEA have established principles and developed comprehensive guidance to promote the minimization and responsible management of radioactive wastes, providing member states with recognized good practices and strategic recommendations. Recent European syntheses of best practices have emphasized the importance of comprehensive process integration, from the initial collection and segregation of waste streams to the tailored application of advanced treatment methods (Pancotti, 2024; IAEA TRS-427, 2004; IAEA TRS-

Table 2
Challenges and uncertainties in the characterisation, treatment, conditioning and storage/disposal of the challenging wastes included in STREAM (

	Characterisation	Treatment
SIERs	Challenges related to the characterization of SIERs is similar to sludge characterization. Techniques like gamma spectrometry and scaling factors help assess radiological inventories. Regarding chemical composition, chemical additives and corrosive products can also be present.	Increased activity after thermal treatment: While thermal treatments help reduce the volume of SIERs, they can also increase specific radioactivity. This complicates disposal and may require the use of alternative repository sites.
Sludges	Uncertainties in radiological and chemical inventories and varying sludge volumes. Need for extensive characterization of legacy sludges.	(Pre)treatment methods like drying, high-density compaction or thermal treatment are explored to address cementation challenges for specific sludges.
RLOW (Radioactive Liquid Organic Wastes): oils, LSC, decontamination effluents	Problems with the characterization of legacy wastes and complexing agent cocktails, including the ones resulting from plastic degradation.	Organic liquid wastes can be volatile, flammable, and toxic, requiring treatment and/or immobilization. Incineration of RLOWs is one of the options considered. However, certain waste streams are not compatible with incineration due to hazardous chemicals. Transport restrictions may not allow the waste to be transferred to appropriate treatment facilities. In order to overcome these limitations, immobilisation in Nochar polymer is an interesting option.
Evaporator concentrates	Uncertainties in radiological and chemical inventories. Large volumes to characterise	Treatment technologies have focused on boron extraction mainly, in order to decrease borate contents and improve compatibility with OPC matrices (Lerche, 2025; Avramenko et al., 2007)
Reactive metals (Al, Be, U, Mg..)	Characterizing reactive metal waste is challenging due to difficulties in obtaining precise list of activation products.	Reactive metals pose challenges for waste treatment and conditioning due to corrosion, which can cause waste form modifications (such as cracking), and changes in container mechanical properties.

adapted from (Wasselin et al., 2019).

441, 2006; NEA, 2020). These efforts have allowed for the identification of strategies that address the unique physicochemical characteristics and operational requirements of a wide spectrum of radioactive waste types (IAEA GS-G-3.3, 2008; IAEA, 2024; Tochaikul et al., 2022).

3.1. Thermal technologies

Thermal treatments in general, are well developed and commercially available, and can provide high volume reduction (IAEA TECDOC 1527, 2006; Vuorio, 2022; Nieminen et al., 2020). They can be used to treat aqueous liquids, organic liquids, inorganic/organic sludges, ion-exchange solids, organic solids, and metals. Residual ash procured after treatment need to be properly immobilized and stabilized. Some limitations in the application of these technologies are linked to the specific waste acceptance criteria of the available facilities (ANDRA, 2018), the need to limit off-gases, which generate secondary waste, and poor public acceptance for some treatments, such as incineration.

Currently, a wide variety of thermal methods are commercially available, each with specific operational characteristics. Below is a brief overview of both commercially available technologies and the most promising emerging technologies:

- Incineration (TRL 9): Widely implemented for solid and liquid wastes, providing high volume reduction and organics destruction. Requires strict management of emissions and is less economical for small or alpha-rich waste streams due to regulatory and technical constraints.
- Pyrolysis (TRL 9): Applies low-temperature, oxygen-free treatment for diverse wastes, particularly those incompatible with classic combustion. Effective with certain polymers and organics, but non-combustibles and halogenated plastics demand specific system adaptations and control of secondary gas products.
- Plasma (TRL 9): Delivers high-volume reduction and vitrification, applicable to heterogeneous or complex waste. Not suitable for wastes with substantial volatile radionuclides, and generates secondary residues that need further management.
- Molten Salt Oxidation (MSO) (TRL 4–6): Suitable for difficult organics and certain inorganics, retaining acidic off-gases as salts. Application can be limited by certain nuclide content, such as C-14 or tritium.
- Fluidized Bed Steam Reforming (FBSR) (TRL 9): Treats solid and liquid streams, including ion exchange media and oils, efficiently mineralizing the waste and eliminating liquid secondary residues. Operational handling of generated dust is required.
- Metal Melting (TRL 9): Used for volume reduction and stabilization of metallic waste; operations must address volatility of some radionuclides, residual activity, and secondary off-gas or slag management.

The maturity (TRL), strengths, and weaknesses of the different thermal treatment technologies are summarized in Table 3.

3.2. Chemical and hybrid techniques

Chemical treatments can destroy many organic compounds and convert inorganic compounds into more stable forms; but there are some limitations linked to the specificity of the waste stream to be treated and the need for expensive corrosion-resistant materials.

Advanced chemical options offer specific advantages, often with reduced off-gas formation compared to thermal treatments. The most relevant characteristics of some of the most promising chemical treatment methods are:

- *Wet Oxidation* (Fenton process) (TRL 4–6): Operates at moderate temperatures and is suited for volatile radionuclide-bearing waste, achieving high organics destruction with reduced solid residue. The approach is still in development for most radioactive contexts, with numerous implementation trials required before industrial deployment.
- *Acid Digestion* (TRL 9): Employs strong acids to break down organic waste components and is fully mature for select streams. Efficient processing sometimes demands size reduction of waste material and careful management of corrosive by-products—especially hydrochloric acid when handling halogenated inputs.

Table 3
Characteristics of available and emerging thermal technologies.

Technology	Maturity (TRL)	Strength	Weakness
Incineration	Commercially available – TRL 9	Offers high volume reduction for both solid and liquid wastes	It needs to meet environmental discharge requirements and is generally not economical for small amounts of waste. Special regimes are required for treating alpha-bearing waste
Pyrolysis (Eldridge and Prasad, 2024)	Commercially available – TRL 9 (Cyclife, 2025)	Attractive low-temperature, flameless process faces	Constraints with non-combustible waste and requires additional engineering for halogenated plastics. Secondary gases must be filtered and burned before discharge
Plasma (Zabulov et al., 2023; Gonçalves et al., 2022; Ma et al., 2024; Nonnet et al., 2023)	Commercially available – TRL 9 (BELGOPROCESS, 2025)	Provides high-volume reduction and meets safe storage criteria	Unsuitable for wastes with significant volatile radionuclides and produces secondary waste that requires further treatment
Molten Salt Oxidation (MSO) (Rivers et al., 2007; Gray et al., 1992; Hsu et al., 2001)	Demonstrated in the industrial environment and small-scale tests on radioactive waste – TRL 4–6	Flameless process that retains acidic gases as salts	It is constrained by wastes with significant C-14 or tritium radionuclides
Fluidized Bed Steam Refomer (FBSR) (Jantzen et al., 2007)	Commercially available for processing nuclear waste- TRL 9 (Studsvik, 2025)	Process a wide variety of solid and liquid streams including ion exchange resins, charcoal, graphite, sludge, oils, solvents Liquid secondary wastes are not produced	Release of dust during treatment
Metal melting (Slimák and Nečas, 2016; Huutoniemi et al., 2012)	Commercially available – TRL 9 Facilities for melting of radioactive material, e.g.: France: CENTRACO INFANTE Germany:CARLA	Offers high volume reduction Transfer of volatile species, as well as alpha emitting nuclides, to secondary waste. ·Binding of the remaining radioactivity in the metal structure. Potential for free release of material due to the above factors. ·Volume reduction. Reduction of surface-to-volume ratio.	Release of activity during treatment Dose burden Pre-sorting is required due to different melt temperatures, and secondary waste management is complex

- *Supercritical Water Oxidation* (SCWO) (TRL 6): Leverages water above its critical point to achieve rapid and complete oxidation of organic matter, especially in liquid wastes. The process requires size reduction of solid inputs, and the treatment of generated aqueous effluents remains a consideration.

The maturity (TRL), strengths, and weaknesses of the different thermal treatment technologies are summarized in Table 4.

4. Comparative analysis of treatment technologies for a selection of most common challenging wastes

4.1. Assessment of commercial and emerging treatment technologies

The management of challenging radioactive waste streams requires a comprehensive understanding of available treatment methodologies and their suitability for different waste streams. Generally, the assessment of commercial and emerging treatment technologies focuses on the effectiveness of each method by waste type, examining how well the treatment strategies address the specific challenges posed by different waste compositions.

Key considerations include volume reduction capabilities, which are crucial for minimizing the spatial footprint of waste storage and disposal facilities. Treatment selectivity also needs to be evaluated as it determines the ability of a method to target and process specific components within complex waste matrices. Compatibility with the physical and chemical characteristics of waste is another essential factor that influences the feasibility and safety of the treatment process.

Operational complexity plays a significant role in determining the feasibility of implementing a treatment method. The maturity of the technology, as indicated by its Technology Readiness Level (TRL), provides insights into the development stage of the treatment method and

Table 4
Characteristics of available and emerging chemical methods for treatment of LILW.

Technology	Maturity (TRL)	Strengths	Weaknesses
Wet Oxidation (Fenton) (Walling et al., 2021)	Trials at laboratory scale and pilot plants for radioactive waste – TRL 4–6 (Brillas, 2020; Feng et al., 2018; Wan et al., 2015)	Effective at lower temperatures, making it suitable for volatile radioisotopes, and significant reduction of solid secondary waste compared to the high temperature treatments. It offers significant volume reduction and destruction of organics	It requires extensive trials for implementation
Acid Digestion (MacKenzie and Kempf, 1986)	Laboratory, bench-scale test and industrial scale – TRL-9	It uses concentrated acids to decompose organic materials	It requires waste sizing for efficiency and produces hydrochloric acid when treating halogenated organics, necessitating additional handling
Supercritical Water Oxidation (Eldridge and Prasad, 2024; Koda, 2009)	Technical maturity for radioactive liquid organic waste and pilot scale for solid radioactive organic waste – TRL 6	Supercritical water serves as an excellent solvent, fully mixing with oxygen and organic liquids, which enables rapid and complete oxidation reactions	Solid waste must be size-reduced, and liquid effluent requires further treatment

its readiness for commercial deployment. Finally, scalability was assessed to understand the potential for these methods to be applied on a broader scale, addressing larger volumes of waste or diverse waste types. By examining these aspects, Table 5 to Table 7 aim to provide a comprehensive evaluation of current treatment methods, highlighting areas where further research and development are needed to enhance the effectiveness and sustainability of existing or under-development management routes.

4.2. Performance metrics

Table 8 presents a comprehensive analysis of key metrics across several treatment technologies. Plasma treatment and fluidized bed steam reforming (FBSR) stand out for their high volume reduction rates and excellent organic destruction efficiency, with over 95–99 % of organics eliminated and the majority of radionuclides immobilised in stable matrices, though plasma requires significantly more energy per unit of waste. Incineration and pyrolysis are both effective and well-established, offering high readiness levels and scalability, but generate notable volumes of secondary residues that require further management. Molten salt oxidation and supercritical water oxidation achieve high organic removal and radionuclide retention but are generally available only at pilot scale and often result in liquid or salt-based secondary waste that needs additional treatment. Metal melting is highly effective for reducing the volume of metallic wastes, though less relevant for organic destruction, while wet oxidation and electrochemical methods provide moderate efficiency and are still largely limited to pilot applications with considerable secondary liquid waste generation. These findings confirm that while advanced methods like plasma and FBSR deliver the best technical performance for difficult wastes, practical factors such as energy use, secondary waste, and technology maturity must be taken into account when selecting the optimal treatment strategy.

4.3. Cost, Environmental, and regulatory considerations

The selection of radioactive waste treatment technologies is significantly influenced by cost, environmental, and regulatory considerations. Optimal technology selection for radioactive waste management strongly depends on the specific characteristics of each waste stream and the unique constraints of each site, making a tailored assessment essential rather than relying on a one-size-fits-all approach.

Each treatment technology offers a different balance of cost, environmental impact, and regulatory feasibility. High-efficiency options such as plasma and incineration deliver excellent performance and significant volume reduction but are often associated with high costs and complex regulatory requirements. In contrast, lower-cost methods like compaction and drying provide simpler implementation but offer only limited stabilization.

Hybrid and advanced oxidation technologies, including FBSR and electrochemical oxidation, hold promise for minimizing environmental footprint and secondary waste generation, yet further demonstration is needed to achieve widespread regulatory acceptance. Investing in technologies that reduce secondary waste and simplify regulatory approvals, particularly those featuring modular and hybrid designs, will be crucial for achieving cost-effective, environmentally responsible, and compliant radioactive waste management over the long term.

To support balanced decision-making technology selection, Table 9 presents a multi-criteria comparison of several treatment technologies. Each technology is evaluated across five categories: treatment effectiveness, cost, environmental impact, regulatory complexity, scalability, and maturity; using a relative ranking system (1 = lowest, 5 = most favorable). This comparative matrix is aimed to quickly assess strengths and limitations, clarifying trade-offs between performance,

Table 5
Review of treatment methods for Spent Ion Exchange Resins (SIERs).

Treatment Method	Effectiveness	Volume Reduction	Treatment Selectivity	Compatibility with Waste Characteristics	Operational Complexity	Maturity (TRL)	Scalability	Commercial Availability
Incineration	High	High	Moderate	High	High	TRL 9	High	Widely Available
Pyrolysis	High	High	Moderate	High	Moderate	TRL 9	High	Widely Available
Plasma Technology	High	High	High	High	High	TRL 9	High	Limited
Fluidized Bed Steam Reforming (FBSR)	High	High	High	High	Moderate	TRL 9	High	Limited
Gasification	High	High	Moderate	Moderate	High	TRL 6	Moderate	Emerging
Molten Salt Oxidation (MSO)	High	High	High	Moderate	Moderate	TRL 6	Moderate	Emerging
Fenton & Fenton-like Oxidation	High	Moderate	High	Moderate	High	TRL 4-7	Moderate	Emerging

Effectiveness: Indicates overall success in treating the specific waste type.
Volume Reduction: extent to which the treatment method can reduce the volume of waste.
Treatment Selectivity: ability of the method to target specific components within the waste.
Compatibility with Waste Characteristics: how well the treatment method aligns with the physical and chemical properties of the waste.
Operational Complexity: technical and logistical challenges involved in implementing the treatment.
Maturity (TRL): Ranges from 1 to 9, with 9 indicating full maturity and commercial deployment.
Scalability: Reflects the potential for the treatment method to be applied on a larger scale.
Commercial Availability: Indicates the extent to which the treatment method is available for commercial use, ranging from “Research Stage” to “Widely Available.”.
Volume Reduction (%): Percent reduction in mass or volume from raw waste to treated residue.
Organic Destruction Efficiency (%): Fraction of organic contaminants destroyed, often measured by total organic carbon (TOC) or specific compound removal.
Radionuclide Retention (%): Fraction of radionuclides immobilized or retained in the solid residue or immobilized.
Energy Use (kWh/kg waste): Electrical or thermal energy consumption normalized per kilogram of processed waste.
Technology Readiness Level (TRL): From 1 (concept) to 9 (fully commercial).
Typical Scale: Approximate throughput capacity per day for industrial or pilot-scale installations.
Secondary Waste Volume: Percentage or fraction of initial waste mass/volume converted into secondary residue requiring treatment or disposal.

Table 6
Review of treatment methods for Radioactive Liquid Organic Wastes (RLOWs).

Treatment Method	Effectiveness	Volume Reduction	Treatment Selectivity	Compatibility with Waste Characteristics	Operational Complexity	Maturity (TRL)	Scalability	Commercial Availability
Incineration	High	High	Moderate	High	High	TRL 9	High	Widely Available
Pyrolysis	High	High	Moderate	High	Moderate	TRL 9	High	Widely Available
Plasma Technology (ELIPSE)	High	High	High	High	High		Low	Emerging
Supercritical Water Oxidation (SCWO)	High	High	High	Moderate	High		Moderate	Emerging
Acid Digestion	High	High	High	Moderate	High		Moderate	Emerging
Electrochemical Oxidation	High	Low	High	High	High		Moderate	Emerging
Direct Chemical Oxidation	High	Low	High	High	Moderate		Moderate	Emerging
Catalytic Chemical Oxidation	High	Low	High	High	Moderate		Moderate	Emerging
Photo Oxidation	Moderate	Low	High	Moderate	Moderate		Low	Emerging

Table 7
Review of treatment methods for metallic materials, sludges and evaporator concentrates.

	Treatment Method	Effectiveness	Volume Reduction	Treatment Selectivity	Compatibility with Waste Characteristics	Operational Complexity	Maturity (TRL)	Scalability	Commercial Availability
Metals	Metal Melting	High	High	High	High	High	TRL 8	High	Limited
Sludges	Drying	Moderate	Moderate	Low	High	Low	TRL 9	High	Widely Available
	High-density Compaction	Moderate	High	Low	High	Moderate	TRL 9	High	Widely Available
	Thermal Treatments (General)	High	High	Moderate)	Moderate	High	TRL 6-9	Moderate	Limited
	Acid Digestion	High	High	High	Moderate	High		Moderate	Limited
	Direct Chemical Oxidation	High	Low	High	High	Moderate		Moderate	Emerging
	Catalytic Chemical Oxidation	High	Low	High	High	Moderate		Moderate	Emerging
	Electrochemical Oxidation	High	Low	High	High	High		Moderate	Limited
	Fenton & Fenton-like Oxidation	High	Moderate	High	Moderate	High	TRL 4	Moderate	Emerging

implementation challenges, and readiness for broader adoption in complex waste management scenarios.

4.3.1. Cost considerations

Cost structures vary widely among the available options. Incineration and plasma technologies have high capital and operational costs, primarily due to advanced emission control requirements, intensive energy consumption, and the need for robust containment systems. Pyrolysis and fluidized bed steam reforming (FBSR) generally offer moderate costs, benefiting from more manageable secondary waste streams and economies of scale. Molten salt and electrochemical oxidation methods can result in moderate to high costs, mainly due to the complexity of materials handling and specific infrastructure requirements. In contrast, processes such as sludge drying and compaction are generally less expensive but may provide only partial stabilization or limited waste minimization, and often require subsequent conditioning. Table 10 summarizes cost-related aspects that condition the deployment of treatment technologies.

4.3.2. Environmental impact

Environmental issues play a major role, especially when it comes to air emissions, secondary waste generation, and the need for efficient off-gas and dust control systems (Table 11). Incineration and plasma processes require advanced scrubbers to capture pollutants such as dioxins, NOx, and heavy metals. Pyrolysis and supercritical water oxidation create secondary residues that must be solidified or otherwise treated. Electrochemical oxidation usually produces less air pollution but still generates liquid and solid waste that need to be managed. Technologies like FBSR and molten salt oxidation reduce liquid waste and effectively trap hazardous contaminants, though managing certain byproducts can still be a technical challenge.

4.3.3. Regulatory considerations

Both thermal and chemical treatment technologies need to comply

Table 8
Comparative performance metrics for radioactive waste treatment technologies.

Technology	Volume Reduction (%)	Organic Destruction Efficiency (%)	Radionuclide Retention (%)	Energy Use (kWh/kg waste)	Technology Readiness Level (TRL)	Typical Scale (t/day capacity)	Secondary Waste Volume
Incineration	80 – 95	>99 (organics)	>95 (solid radionuclides remain in ash)	~10 – 50	9	0.1 – 10	5 – 10 % of input mass as ash and solid residues
Pyrolysis	70 – 90	85 – 95 (organics converted to syngas/ tars)	>90 (radionuclides largely retained in char)	~5 – 20	9	0.1 – 5	~10–30 % char residue volume
Plasma Treatment	90 – 99	>99 (complete mineralization organics)	>98 (immobilized in vitreous slag)	50 – 200	6 – 9	<1 – 2	<5% vitrified solid residue volume
Fluidized Bed Steam Reforming (FBSR)	80 – 95	>95 (organics converted to mineral waste)	>95 (radionuclides tightly bound in mineral matrix)	~30 – 50	9	~1 – 5	<5% secondary dust and mineralized solids
Molten Salt Oxidation (MSO)	85 – 98	>98 (organics oxidized to salts)	>90 (radionuclides captured in salts)	40 – 100	4 – 6	Pilot scale (<1)	Salt residues approx. 5 – 10 % input mass
Metal Melting	85 – 95	Not applicable (metal volume reduction)	>95 (radionuclides partially retained in slag/metal)	20 – 50	8	1 – 10	Secondary slag 5 – 15 % of initial mass
Wet Oxidation (Fenton)	30 – 70	80 – 95 (organics)	Retention depends on process; generally > 80	1 – 5	4 – 7	Pilot scale	Secondary liquid wastes 5 – 20 % of initial volume
Supercritical Water Oxidation (SCWO)	60 – 90	>98 (organics)	>90	20 – 40	6	Pilot scale	Liquid effluent requires secondary treatment
Acid Digestion	50 – 90	>90 (organic decomposition)	Depends on radionuclide chemistry	2 – 10	6 – 9	0.1 – 1	Acidic secondary liquid wastes produced
Electrochemical Oxidation	10 – 40	75 – 90 (depends on organics and treatment time)	Generally high retention (>90)	5 – 15	6	Pilot scale	Concentrated liquid residues needing further treatment

Table 9
Multi-criteria comparison of waste treatment technologies.

Treatment	Cost	Environmental Impact	Regulatory complexity	Scalability	Maturity
Incineration	(2)	(2)	(5)	(5)	(5)
Pyrolysis	(3)	(3)	(3)	(5)	(5)
Plasma	(1)	(2)	(1)	(3)	(3)
Fluidized Bed Steam Reforming (FBSR)	(2)	(4)	(2)	(4)	(4)
Molten Salt Oxidation (MSO)	(2)	(3)	(2)	(3)	(3)
Metal melting	(1)	(2)	(2)	(5)	5)
Wet oxidation (Fenton)	(4)	(3)	(3)	(2)	(3)
Acid digestion	(3)	(3)	(3)	(3)	(4)
SuperCritical Water Oxidation (SCWO)	(2)	(3)	(2)	(3)	(3)
Electrochemical Oxidation	(3)	(4)	(4)	(2)	(3)

(5) = most favorable; (4) = very good; (3) = good; (2) = moderate; (1) = least favorable.

with national and international regulatory frameworks. Fundamental requirements include licensing, safety assessments, and comprehensive monitoring (IAEA SSG-12, 2010). When waste exhibits both radioactive and hazardous chemical properties (mixed waste), dual regulation comes into play, involving both nuclear regulatory bodies and environmental protection agencies.

Thermal treatment processes are subject to intense regulatory oversight on air emissions and must ensure the long-term durability of the solidified waste form, due to volatilization risks of radionuclides and hazardous chemicals at high temperatures.

Chemical/electrochemical processes face more rigorous regulation of effluent quality and the management of hazardous by-products, with relatively less emphasis on air emissions because these processes produce fewer combustion by-products.

Overall, the regulatory framework applied to each type of facility should be tailored to the specific operational and risk characteristics of the chosen treatment technology. But, in any case, the emphasis of applicable regulations should be shaped by the hazard profile, air and solid form stability for thermal, effluent and chemical management for chemical processes. The key differences in regulatory requirements for thermal and chemical treatment technologies are summarized in Table 12 below.

So, from a regulatory perspective, incineration and metal melting are the most established, with clear licensing precedents and defined waste acceptance criteria, provided emissions and residues meet regulatory limits. Emerging technologies such as plasma, FBSR, and electrochemical oxidation may face more complex and extended approval processes, often requiring pilot demonstration and detailed performance validation. For all methods, strict traceability, documentation, and demonstration of waste form performance are essential for repository acceptance. Table 13 summarizes most relevant regulatory issues and approval paths for each treatment technology.

4.4. Summary of the comparative analysis

Table 14 summarizes the preferred treatment options for each major type of challenging radioactive waste, highlighting their main advantages and limitations. For spent ion exchange resins, methods like plasma, FBSR, pyrolysis, and incineration achieve strong destruction of organics and significant volume reduction, though they often result in high energy use and generation of secondary waste. Radioactive liquid organic wastes are best treated with pyrolysis, supercritical water oxidation, or electrochemical oxidation, which are effective at breaking down organics but still present issues with secondary waste and

Table 10
Influence of cost-related factors on the Deployment of treatment technologies.

Technology	Estimated Cost Level	Main Cost Drivers	Notes
Incineration	Moderate to High	Emission control, permits, operational manpower	Economically less viable for small waste volumes due to fixed costs
Pyrolysis	Moderate	Equipment maintenance, off-gas treatment	Economies of scale achievable
Plasma	High	Energy consumption, complex control systems	High capital and operational expenses
FBSR	Moderate to High	Reactor materials, dust control	Produces minimal secondary waste
Molten Salt Oxidation	Moderate to High	Molten salt handling systems, corrosion materials	Currently limited industrial experience
Electrochemical Oxidation	Moderate	Power consumption, electrode replacement	Potentially lower secondary waste treatment costs
Metal Melting	High	Shielding, off-gas management	Infrastructure intensive
Sludge Drying/ Compaction	Low to Moderate	Equipment and energy costs	Often integrated with larger management scheme

Table 11
Impact of Environmental Issues on the Deployment of Treatment Technologies.

Technology	Environmental Considerations	Secondary Waste Generation	Emissions Control
Incineration	Air pollutants (dioxins, NOx, heavy metals), ash disposal	Fly ashes requiring stabilization	High—incinerators need advanced scrubbers
Pyrolysis	Off-gas treatment for tars and syngas	Char and tar residues, often solidified	Moderate—typically combustion/gas-cleaning
Plasma	Energy intensive, off-gases, vitrified slag generation	Secondary solid residues	Advanced scrubbers required—high energy footprint
FBSR	Dust release during operations	Minimal liquid secondary waste	Dust control crucial
Molten Salt Oxidation	Salt waste secondary management	Salt residues with concentrated contaminants	Retains acidic gases as salts
Electrochemical Oxidation	Lower emissions of gaseous pollutants	Concentrated liquid and solid residues	Relatively low gaseous emissions
Metal Melting	Volatile radionuclide release risk	Secondary solid and gaseous wastes	Requires robust off-gas treatment

handling safety. Metallic wastes benefit from metal melting or thermal treatments, which both shrink waste volume and stabilize radioactive content, although these require careful management of gases released during the process. For sludges and evaporator concentrates, drying, compaction, and thermal treatments offer moderate volume reduction, but challenges remain due to chemical reactivity and diversity of the wastes. In summary, selection of the most suitable treatment technology should be based on the specific characteristics of the waste, while also considering cost, environmental impact, and regulatory requirements to ensure safe and effective long-term management.

Table 12
Comparative regulatory aspects between thermal and chemical treatment technologies.

Aspect	Thermal Treatment	Chemical/Electrochemical Treatment
Main Regulatory Bodies	Nuclear & environmental regulators	Nuclear & environmental + chemical safety
Key Environmental Concern	Off-gas emissions (airborne radioactive + non-radioactive)	Liquid effluent quality; some gases
Safety Assessment	Long-term waste form stability, air monitoring	Effluent stability, residue/ chemical safety
Waste Acceptance Criteria (WAC)	Vitrified/solid waste meets disposal regulations	Treated solutions/residues meet discharge/disposal regulations
Mixed Waste Regulation	Required if waste is both hazardous & radioactive	Required if waste is both hazardous & radioactive
Monitoring	Emission stack; leaching tests of solid forms	Effluent and residue characterization, air as needed

Table 13
Regulatory issues and approval paths for radioactive waste treatment technologies.

Technology	**Regulatory Challenges**	**Licensing and Approval Path**	**Waste Acceptance Criteria (WAC) Implications**
Incineration	Strict air emissions limits, ash disposal standards	Well established for licensed plants	Ash must meet leaching criteria
Pyrolysis	Air emission monitoring, secondary waste characterization	Typically considered under existing frameworks	Requires confirmation of stable residues
Plasma	Complex safety case due to high temperature and energy	Emerging tech often requires pilot demonstrations	Vitrified slags must meet disposal acceptance
FBSR	Dust emission and secondary residue safety	Demonstrated in limited commercial facilities	Mineral waste accepted by many repositories
Molten Salt Oxidation	Handling of molten salts, high-temperature operation	Limited licensing examples	Salt residues require careful containment assessment
Electrochemical Oxidation	Chemical handling safety, electrical safety	Regulator acceptance in progress	Residues and treated liquids must meet disposal/ discharge limits
Metal Melting	Worker protection, volatile radionuclides	Well-established in several countries	Secondary wastes evaluated under WAC

5. Scalability and transferability

Scalability and transferability are critical considerations in the deployment of novel technologies for radioactive waste management. These aspects help assess not only the potential for upscaling a technology from pilot-plant to full industrial operations, but also its adaptability to different facility types, waste streams, and regulatory environments. Comprehensive evaluation of both scalability and transferability ensures that innovative solutions can be widely and effectively implemented, thereby supporting the long-term resilience and sustainability of radioactive waste management strategies.

5.1. Scalability

Scalability is a fundamental consideration in the industrial adoption

Table 14
Overview of Treatment Selection, Key Performance Metrics, and Implementation Challenges for Radioactive Waste Types.

Waste Type	Preferred Treatment(s)	Advantages	Main issues
Spent Ion Exchange Resins (SIERs)	Plasma, FBSR, Pyrolysis, Incineration	High volume reduction & effective organics *destruction*	High energy use, regulatory approval, secondary wastes
Radioactive Liquid Organic Wastes (RLOWs)	Pyrolysis, Supercritical Water Oxid., Electrochemical Oxidation	High organics destruction, moderate to low volume reduction	Secondary waste management, chemical handling safety
Metallic Wastes	Metal Melting, Thermal Treatments	High volume reduction & radionuclide stabilization	Volatile radionuclides, off-gas treatment
Sludges, Evaporator Concentrates	Drying, Compaction, Thermal treatments	Moderate volume reduction; stabilization critical	Heterogeneity, chemical reactivity, remote handling

of novel technologies, dictating whether promising laboratory or pilot-scale processes can be viably implemented for routine or large-volume waste streams. Highly scalable technologies, such as incineration, pyrolysis, and fluidized bed steam reforming (FBSR), have demonstrated the capacity to process a wide range of waste volumes, ranging from small batches typical of research reactors to the massive inventories generated during decommissioning of large nuclear facilities.

These technologies benefit from modular or continuous processing designs, allowing them to be upscaled by multiplying process lines or increasing reactor volume. For example, FBSR and incineration plants can be constructed in modular units, each capable of handling a set daily throughput, enabling facilities to incrementally expand as waste volumes dictate.

On the contrary, some emerging technologies (e.g., plasma, molten salt oxidation) have thus far seen most success at pilot or small demonstration scales, with comparatively limited experience at commercial or multi-site deployment. In these cases, their scalability is influenced by technical factors (e.g., thermal management, off-gas cleaning) and by the complexity of the feed preparation required for specific waste types.

A significant challenge of scalability lies in maintaining process stability, QA/QC of process and products, and safe operation as system size increases. Complex waste streams and heterogeneous input compositions can cause variability at the industrial scale and can required of advanced process control or hybrid pre-treatment steps. Flexible and robust process engineering, as well as continuous monitoring, are thus critical when scaling up novel technologies.

5.2. Transferability

Transferability refers to how well a treatment technology can be implemented across different national infrastructures and regulatory frameworks or geographic locations. While many of the advanced methods reviewed (e.g., incineration, FBSR, metal melting) have demonstrated successful implementation in countries with established nuclear industries, successful transfer to other regulatory or infrastructural environments is not always straightforward.

Key factors affecting transferability include:

- *Regulatory Compatibility:* Mature technologies like incineration and metal melting benefit from established licensing precedents and harmonized international guidance (e.g., from IAEA and NEA) (NEA, 2020; IAEA GS-G-3.3, 2008; IAEA TRS-402, 2001). Newer processes such as FBSR or plasma frequently require case-by-case regulatory review, pilot demonstrations, and the development of facility-specific safety cases, particularly where mixed (radioactive and hazardous) waste streams are involved.
- *Infrastructure Requirements:* Some processes, such as pyrolysis or FBSR, require robust energy, off-gas treatment, and waste handling infrastructure, which may not be available in all sites or facilities. Modular or mobile system designs (increasingly available for emerging methods) can lower the infrastructure barrier, enabling deployment at sites with smaller inventories or less-developed waste management infrastructure.
- *Geographical and Societal Contexts:* Local factors, including public acceptance, availability of skilled personnel, and proximity to waste storage or disposal sites, can also impact technology adoption.

6. Challenges for industrial implementation

Addressing the challenges of radioactive waste management requires robust, scalable, and commercially viable methodologies for processing and treating diverse forms of waste, including organic substances, metals, concentrated residues, and sludge (Wang et al., 2018). The progression from experimental techniques developed in laboratories to large-scale industrial applications involves overcoming a multitude of obstacles, including technical complexities, regulatory requirements, and financial considerations.

Upscaling radioactive waste treatment operations requires a methodical approach to ensure dependability, effectiveness, and adherence to the safety protocols (Ma et al., 2023). Upscaling involves increasing the size of operations from the laboratory to the industrial scale, which is essential for efficiently managing substantial quantities of waste. This process encounters technical obstacles such as preserving process stability with larger equipment and financial hurdles, including substantial initial investments. Regulatory adherence is vital for guaranteeing that safety standards are upheld. The methodology encompasses laboratory-scale development, pilot testing, and design of full-scale facilities with ongoing monitoring for continuous enhancement. Scaling up is crucial for efficiently handling large volumes of waste while addressing the associated technical, economic, and regulatory challenges.

6.1. Key steps and considered factors

To upscale a treatment and conditioning process, a systematic approach is necessary:

- *Process selection:* Identify an appropriate method based on waste characteristics. For HLW, vitrification is often chosen; for LLW, cementation/polymerization or incineration may suffice. Waste characterization, including composition and activity levels, is critical to inform this choice.
- *Lab-scale development:* Develop and characterize the process on a small scale and understand chemical reactions and physical transformations. This stage ensures feasibility and identifies initial parameters.
- *Pilot plant testing:* Conducted tests at a larger scale to optimize the process, identify issues such as heat transfer inefficiencies or equipment scaling limitations, and optimize the processes.
- *Design and construction:* Design a full-scale facility and select equipment capable of handling increased volumes. Safety measures, such as shielding and remote handling, must be integrated. Environmental considerations, such as minimizing the release, were also addressed.
- *Regulatory engagement and economic analysis:* Collaborate with regulatory bodies to establish standards, as the IAEA does for geopolymers (IAEA CRP T21029). This includes demonstrating compliance by extensive testing and documentation. Conduct cost-benefit analyses considering the initial investment and long-term savings.

- *Operation and continuous improvement:* Implementation of the scaled-up process with continuous monitoring for quality control (e.g., glass durability tests) and efficiency. Adjustments may be required based on the operational data to ensure compliance and safety.

6.2. Challenges of upscaling

Upscaling treatment processes presents several challenges:

- *Technical challenges:* Scaling up requires maintaining process stability and efficiency. For vitrification, ensuring glass quality (durability and stability) at larger scales is complex, with equipment such as furnaces needing to handle increased volumes while managing high temperatures (up to 1100 °C for vitrification) (Walker et al., 1992). Material handling of radioactive waste requires specialized equipment and remote operations to minimize worker exposure, particularly for HLW. Variability in waste streams can affect the process consistency, which requires flexible systems.
- *Economic challenges:* The initial investment in large-scale facilities is significant, with vitrification plants having high operational costs owing to energy consumption and the need for qualified personnel (NDC-NEA, n.d.). Economic viability is crucial, especially for locations with stable and large waste volumes, as smaller or variable streams may not justify investment.
- *Regulatory challenges:* Compliance with local, national, and international standards is essential, with strict requirements for emissions (e.g., incineration gases must meet standards) and waste form stability. Regulators impose rigorous disposal criteria, and upscaling often requires additional permitting, increased complexity, and a timeline (IAEA SSG-40, 2016).

In summary, scaling up and industrial implementation of new treatment processes for radioactive waste require interdisciplinary collaboration, technological innovation, and adherence to strict regulatory frameworks. By leveraging advancements in materials science, process engineering, and automation, industries can achieve safer and more efficient long-term waste-management solutions. Drawing upon previous experiences from organizations, such as the IAEA and national waste management agencies, continued collaboration and knowledge sharing will be crucial to further refine these technologies and ensure their successful deployment on an industrial scale.

7. Case studies

7.1. The Hanford waste treatment and immobilization plant (Vit Plant)

The Hanford Site in Washington State contains about 200,000 m3 of radioactive and chemical waste stored in 177 underground tanks. The Waste Treatment Plant (WTP), under construction since 2002, is designed to immobilize this heterogeneous waste through vitrification. This approach provides long-term immobilization and significantly reduces the risk of radionuclide release compared to continued liquid or sludge storage in aging tanks.

7.1.1. Industrial implementation

The Hanford Vit Plant represents one of the world's largest nuclear waste vitrification projects (Hanford, 2025), with a construction start in 2002 and continuing challenges in scaling up from pilot demonstrations to a full industrial facility. Technical problems, including waste stream variability, facility design complexities, and safety concerns, led to construction pauses in 2012. Work started again in 2022, but large-scale implementation remains technically challenging. The Direct-Feed Low-Activity Waste (DFLAW) approach has been introduced as a phased strategy, prioritizing vitrification of low-activity waste before addressing the more complex high-level waste streams. Despite progress, the project illustrates the difficulties of upscaling laboratory-proven technologies to an unprecedented industrial scale (Einan and Schleif, 2025).

7.1.2. Environmental and regulatory considerations

In the Hanford Site, of the 177 tanks, more than 60 have leaked, contaminating the subsurface and posing risks to groundwater and the Columbia river, where it sits. Vitrification has been selected to meet U.S. Department of Energy (DOE) regulatory requirements and long-term safety goals. However, oversight agencies, including the U.S. Government Accountability Office (GAO, 2024), have flagged deficiencies in DOE's alternatives analysis, noting insufficient evaluation of potentially more cost-effective methods, such as mixing waste with grout or concrete. These findings highlight the importance of independent assessments, robust regulatory oversight, and early mitigation of technical risks to avoid environmental and safety setbacks during prolonged project execution.

7.1.3. Economic aspects

The Vit Plant has become one of the most expensive cleanup efforts in U.S. history. Initially projected in the early 2000 s at a fraction of today's estimates, the project has experienced significant cost increases, with recent projections suggesting that overall cleanup could cost about $341 billion and extend beyond 2084. By 2022, more than $200 million had been spent without the facility being operational. The Government Accountability Office (GAO) has estimated that alternative approaches, such as partial grout immobilization, could potentially save tens of billions of dollars, but DOE's limited analysis of alternatives has restricted the consideration of such options. The Hanford case exemplifies the financial risks involved in scaling up large-scale technologies, and highlights the need for thorough upfront planning and flexible strategies that balance cost, risk, and environmental safety.

7.2. Kozloduy plasma treatment plant

The Kozloduy plasma treatment facility, operating since 2018, is equipped with a 500 kW plasma torch and can process up to 250 tonnes of LILW annually, originating from operation and D&D activities. The typical specific activity of processed waste is approximately 5x105Bq/kg (NEI, 2018).

7.2.1. Advantages and performance outcomes

The plant can treat a diverse range of waste streams, including high-volume, physically heterogeneous debris, bituminized wastes, and materials such as concrete, asbestos, and certain metals that are otherwise difficult to manage using conventional methods.

A key advantage of this facility is that waste can be fed directly into the system without pre-treatment or sorting, thereby improving worker safety and reducing contamination risks. The plasma process melts inorganic materials into inert slag and gasifies organic compounds, producing a final product that is free of organics and liquids, and suitable for long-term storage or disposal.

The facility achieves significant volume reduction, ranging from a factor of 1.3 for concrete wastes up to 10 for bituminized drums, depending on the composition (Deckers, 2021). Treated waste packages typically have surface dose rates below 2 mSv/h, aligned with international transport standards. Furthermore, advanced shielding, process automation, and emissions control systems contribute to enhanced operator safety and environmental protection.

7.2.2. Industrial implementation

Among the challenges of industrial deployment, it is important to emphasize the need to optimize feed and off-gas cleaning systems for diverse waste forms, as well as to integrate real-time process monitoring and automated slag handling to ensure operator safety.

7.2.3. Regulatory and environmental considerations

The facility operates in full compliance with national and European regulations, including thorough environmental impact assessments, stakeholder engagement, and transboundary notifications, particularly with Romania. Continuous environmental monitoring (e.g., emissions and gamma background) confirms that background radiation levels remain unchanged, while the off-gas cleaning systems ensure continued compliance with environmental standards.

7.2.4. Economic aspects and funding

The plant was built at a cost of approximately €31 million, with 65 % funding from the Kozloduy International Decommissioning Support Fund managed by the EBRD and 35 % from the Bulgarian government. Initial cost estimates increased by 23 % due to technical challenges, schedule extensions, regulatory compliance requirements, and integration with other plant systems. However, flexible co-financing and strong national commitment mitigated financial risks (European Bank for Reconstruction and Development, 2018).

7.3. Framatome Oxidation treatment technology for SIERs

Framatome has developed a pilot plant based on a hybrid and modular oxidation technology for the treatment of spent ion exchange resins. The system combines mild advanced oxidation processes (Fenton-like and electrochemical reactions) at low operating temperatures (60–85 °C). This hybrid approach enables efficient decomposition of organic matter while liquefying the resin structure, making subsequent conditioning easier. The modular nature of the technology allows tailored configuration for site-specific needs and future scalability.

The treatment converts organic-rich spent resins into organic-free aqueous solutions. Concentrated residues are then immobilized and solidified, achieving residual total organic carbon levels below 100 g/m^3. The process is compatible with a wide range of waste streams, including resins from PWR, BWR, and PHWR operations, decontamination residues, and legacy or mixed organic wastes requiring stabilization.

7.3.1. Volume and dose rate reduction

The pilot plant demonstrates significant performance in reducing waste volume. While conventional cementation achieves a factor of 3–4, the hybrid oxidation system achieves volume reduction factors between 3 and 20, depending on decomposition efficiency and drying. By breaking down the organic fraction before solidification, the process also reduces contamination risks and lowers dose rates. The final waste form is stable, resistant to leaching, and avoids the problems associated with untreated organic sludges or swelling of resin beads (Valveuser Magazine, 2023; Framatome).

7.3.2. Industrial implementation

The pilot plant has been designed as a scalable and compact modular system with a throughput of approximately 200 L per day. It is remotely operated in accordance with ALARA principles. Industrial deployment requires site-specific adjustments, including integration with utilities, management of resin swelling, and optimization of secondary waste handling. Ongoing advancements within the hybrid platform include optional selective C-14 removal, real-time waste tracking, and blending of resins from different inventories to optimize conditioning.

7.3.3. Environmental and regulatory considerations

The oxidation process achieves nearly complete conversion of organics to carbon dioxide and oxygen, with emission streams engineered to meet strict environmental standards. The use of cost-effective and non-toxic chemicals minimizes secondary impacts. The resulting solidified residues are organic-free and suitable for long-term storage, and depending on the national regulations can be even classified as “evaporator concentrate”.

7.3.4. Economic aspects

As a pilot plant technology, funding is generally provided through client operational waste management budgets, with support for demonstration and upscaling projects. The modular hybrid approach drives cost efficiency by enabling flexible deployment, reduced disposal volumes, and minimized repository demand. Comparative studies show that oxidation-based processes can achieve significant cost reductions compared with direct solidification or incineration.

8. Regulatory aspects

8.1. Licensing of novel treatment technologies

The development and implementation of novel treatment technologies for challenging wastes, particularly those involving non-radiologically hazardous components, require a comprehensive and complex licensing process. Licensing ensures that these technologies meet national and international safety, environmental, and regulatory standards before being deployed on an industrial scale.

8.1.1. Regulatory framework

The licensing of novel treatment technologies is governed by a complex regulatory framework that varies from country to country. Technologies must comply with the national and international regulations. These standards ensure that technologies are safe and effective. Regulatory Agencies such as environmental protection agencies and nuclear regulatory bodies are responsible for evaluating the safety of these new technologies, including factors such as technology design, safety assessments, and operational and emergency plans.

8.1.2. Safety and environmental assessments

A critical component of the licensing process involves conducting comprehensive safety and environmental assessments to evaluate potential risks associated with the technology. A detailed safety case that demonstrates the technology’s ability to effectively manage risks is required for licensing. This Safety Case must include hazard identification, risk assessment, and implementation of safety measures to prevent accidents and mitigate their consequences. Additionally, an Environmental Impact Assessment (EIA) is required to assess the potential environmental impact of the technology. This involves evaluating factors such as emissions, waste generation, and resource consumption, as well as their potential effects on local ecosystems and communities.

8.1.3. Demonstration and validation

Before full-scale deployment, novel technologies typically undergo demonstrations and validations to confirm their performance and safety (Oh, 2001):

- *Pilot trials:* Conducting pilot trials allows the evaluation of technological performance under real-world conditions. These trials provide valuable data on operational reliability, safety, and environmental impacts, which are critical for licensing decisions.
- Independent verification: Independent verification by third-party experts or organizations may be required to validate the performance of the technology and safety systems, which provides an extra level of assurance for regulatory bodies and stakeholders.

8.1.4. Stakeholder engagement and public involvement

Engaging stakeholders and the public is an essential aspect of the licensing process, ensuring transparency, and building trust. Effective communication with stakeholders is a key issue for public acceptance. Public consultations provide opportunities for stakeholders, including local communities, to express concerns and provide input for the proposed technology. Such feedback can inform regulatory decisions and foster public acceptance.

8.2. Harmonization and flexibility in waste acceptance criteria (WAC) for treated waste

Effective management of challenging wastes requires a detailed approach to waste acceptance criteria, which are the specifications that treated waste must meet before being accepted for disposal or further processing (ANDRA, 2018). Harmonization and flexibility in WAC are crucial for ensuring that novel treatment technologies can be effectively integrated into waste management systems while also maintaining safety and environmental standards.

8.2.1. Importance of harmonization

The harmonization of WAC is essential for several reasons. Harmonized WAC ensure that waste management practices meet consistent safety and environmental standards (Nachmilner and Karásková-Nenadálová, 2021; Harvey, 2024; ERDO, 2022). This approach can also facilitate the transfer and implementation of novel treatment technologies across countries by providing a clear and consistent framework for compliance. An internationally accepted WAC system can encourage innovation and adoption of advanced waste treatment methods (De Bock et al., 2023).

In the context of increasing global collaboration in waste management, harmonized WAC systems can support joint international projects and partnerships by providing a common understanding of waste acceptance requirements. This can enhance cooperation and practice sharing among countries (HARPERS project).

8.2.2. Need for flexibility

While harmonization is important, flexibility in WAC is equally important for tailoring the capabilities of novel treatment technologies to the specific characteristics of each waste stream. As new treatment technologies have been developed, WAC must be sufficiently flexible to incorporate these advancements by adjusting existing criteria to account for new methods of waste stabilization, volume reduction, and contaminant removal.

Challenging wastes often has complex and variable compositions that require tailored management approaches. Flexible WAC allow for the customization of criteria to address specific waste characteristics, ensuring that the treated waste meets safety and environmental requirements. Flexible WAC systems can also encourage innovation by allowing pilot projects and experimental treatments that might not fit existing criteria. This can drive the development of more effective and sustainable waste-management solutions (Harvey et al., 2020).

8.2.3. Implementing harmonization and flexibility

Harmonization and flexibility in WAC are key issues in the effective management of challenging waste. By ensuring consistent standards, while allowing for adaptability to new technologies and waste characteristics, WAC can support the safe, efficient, and innovative treatment of complex waste streams.

Achieving a balance between harmonization and flexibility in WAC involves several strategies:

a) *Stakeholder engagement:* Engaging with stakeholders, including regulators, industry experts, and the public, is essential for developing WAC that reflects diverse perspectives and needs. This collaborative approach can help identify areas where flexibility is required while maintaining overall safety standards.
b) *Regulatory frameworks:* Developing regulatory frameworks that incorporate harmonized standards and mechanisms for flexibility is key. This can include establishing baseline criteria with provisions for case-by-case adjustments, based on specific waste characteristics and treatment technologies.
c) *Continuous review and adaptation:* Regularly reviewing and updating the WAC in response to technological advancements and emerging scientific knowledge ensures that the criteria remain relevant and effective. This iterative process supports continuous improvements in waste-management practices.

9. Environmental impact and sustainability

9.1. Minimization of secondary wastes and recycling

Effective management of secondary wastes, such as off-gas scrubbing residues, is increasingly important in radioactive waste treatment. Recent technical advancements enable facilities to minimize secondary waste generation and increase potential opportunities for recycling and resource recovery (Mennecart, 2023).

9.1.1. Process design and optimization

Modern treatment systems are engineered to limit secondary waste at the source. By carefully selecting process steps, optimizing parameters, and reusing liquids like scrub solutions, facilities significantly reduce the total volume of waste needing further treatment or disposal (Abdel Rahman et al., 2011).

9.1.2. Recycling and resource recovery

Once clearance limits are met, certain materials such as metals can be recovered from different waste streams. This recovery reduces the volume of waste requiring final disposa (IAEA TECDOC-1130, 2000; NEA, 2017). Other residues, including sludges, spent filters, and ion-exchange materials, may be reused within facility operations or assigned to less critical roles.

9.1.3. Integrated waste management

Modern waste management programs incorporate full lifecycle assessments and apply the waste hierarchy principle, prioritizing prevention, reduction, and recycling before disposal. Enhanced waste characterization enables facilities to select efficient, tailored treatments for each waste stream (Holt et al., 2022; Kvashnina et al., 2024).

9.1.4. Industry examples

Facilities now routinely recycle off-gas scrub solutions and employ advanced membrane and ion-exchange technologies to concentrate contaminants. The use of plasma and vitrification technologies are other options to reduce secondary waste volumes These practices improve sustainability, reduce environmental impact, and lower costs across the industry.

9.2. Life cycle assessment (LCA) and life cycle Costing (LCC)

LCA is a systematic approach that assesses the environmental impacts associated with all stages of a product's life, from raw material extraction to processing, manufacturing, distribution, use, and disposal. For novel radioactive waste treatments, LCA helps identify potential environmental benefits and drawbacks, such as reductions in greenhouse gas emissions or resource consumption.

LCC complements LCA by focusing on economic aspects. It involves calculating the total cost of ownership over the life of an asset, including the initial investment, operation, maintenance, and disposal costs. For radioactive waste treatment, LCC can help determine the cost-effectiveness of new technologies compared to existing methods.

When applied to radioactive waste management, these tools can help stakeholders make informed decisions by providing a comprehensive understanding of the environmental and economic impact of new treatment technologies. By considering both LCA and LCC, decision makers can select solutions that offer sustainable and cost-effective management of radioactive waste, ensuring safety and compliance with regulatory requirements (Clayton et al., 2024; Stamford, 2024).

9.3. Alignment with EU Green deal and circular economy principles

Aligning new treatments for challenging waste and decontamination methods with the EU Green Deal and circular economy principles requires several key considerations:

a) *Resource efficiency:* New treatments should aim to maximize resource efficiency by minimizing waste and promoting the reuse and recycling of materials. This aligns with the circular economy model, which seeks to close the product lifecycle loop through greater resource efficiency.
b) *Reduction in environmental impact:* The EU Green Deal emphasizes reducing pollution and greenhouse gas emissions. Therefore, innovative waste treatments should focus on minimizing environmental impacts, such as emissions and energy consumption, throughout their lifecycle.
c) *Innovation and technology:* Developing and implementing advanced technologies that enable better waste management and decontamination align with the EU's focus on innovation. These technologies should facilitate cleaner processes and enable the recovery of valuable materials from the waste.
d) *Sustainability and safety:* Ensuring that the new methods are sustainable and do not pose additional risks to human health or the environment is crucial. This includes adherence to the strict safety standards and regulations set by the EU.
e) *Economic viability:* The circular economy emphasizes economic benefits. Treatments should be cost-effective and create economic opportunities, such as new jobs in the green technology sector, while reducing the dependency on raw materials.
f) *Collaboration and policy support:* Successful alignment requires collaboration between governments, industries, and research institutions. Policies and incentives from the EU can support the development and adoption of new methods, ensuring that they contribute to the Green Deal's broader goals.

10. Emerging trends and strategic directions for future research and implementation

10.1. Emerging trends and innovations

Next-generation systems combine multiple thermal and chemical technologies to address the diverse characteristics of challenging waste. This integrated approach provides more flexible solutions that can be tailored to specific waste types. The incorporation of digital technologies, such as AI and IoT, enables real-time monitoring and improves the control of the treatment processes. This technological enhancement allows for precise adjustments and optimization, increases process efficiency, and ensures compliance with regulatory standards.

The modular design of these novel systems facilitates scalability and adaptability, making them suitable for different operational scales and evolving waste-management scenarios. This flexibility is crucial for accommodating changing regulatory requirements and waste characteristics. The development of mobile treatment units can be of special interest for small volumes and Small Inventory Member States (SIMS). These, which can be deployed directly to waste sites, reducing the need for transportation and the associated risks. Mobile units provide flexibility in addressing waste management needs in remote or temporary locations, and can be particularly useful in emergency response situations or for decommissioning projects (De Bock et al., 2023).

10.2. Future strategic research lines and implementation

Future research and implementation strategies must address both technological and systemic barriers to advance the safe and sustainable management of challenging radioactive wastes. The following strategic research directions are proposed:

10.2.1. Raise technology readiness levels (TRLs)

Many promising treatment and decontamination technologies, such as plasma processing, pyrolysis, and fluidized bed steam reforming, remain at the laboratory- or pilot-scale. Coordinated efforts should focus on scaling up these technologies, supported by real-world demonstrations and cross-border collaboration, to validate their performance under operational conditions.

10.2.2. Strengthen waste characterization capabilities

Accurate high-resolution characterization is crucial for selecting and optimizing treatment strategies. Investment in nondestructive and in situ techniques, including digital twins and real-time sensors, can significantly reduce uncertainty and improve treatment process design.

10.2.3. Addressing waste stream specificity and flexibility of treatment systems

One of the challenges that needs to be addressed in the coming years is the heterogeneity of waste inventories resulting from D&D activities and future reactor designs. Therefore, flexible treatment systems and optimized pretreatment processes are required.

Pre-treatment optimization: Development and optimization of robust pre-treatment processes (e.g., characterization, sorting, size reduction, chemical adjustment) that allow increased versatility of the treatment process, capable of treating different types of wastes.

Flexible process design: New treatment technologies should be flexible enough to deal with variability in waste composition (e.g., mixed organic/inorganic sludges and reactive metals in diverse matrices). Tailored solutions must be developed for diverse types of wastes. Research should focus on identifying the optimal combinations of treatment steps, including potential hybrid or sequential processes.

10.2.4. Improve secondary waste management

Emerging treatments often generate secondary waste streams (e.g., off-gas scrubbing residues and spent media). Research should target minimization, safe handling, and, where possible, the recycling or revalorization of these by-products.

10.2.5. Address regulatory and public acceptance challenges

Early engagement with regulators and stakeholders can facilitate smoother deployment. Developing guidance for licensing novel technologies and transparent communication strategies can build trust and streamline the approval pathways.

10.2.6. Integrate environmental and economic assessments

LCA and LCC should be systematically applied to new technologies to ensure that they meet sustainability and cost-effectiveness goals. These tools can guide R&D priorities toward more viable and sustainable options..

10.2.7. Promote cross-sector collaboration and knowledge transfer

Partnerships between research institutions, industries, regulators, and national waste management organizations are vital. Knowledge-sharing platforms, such as those established in EURAD-2 and PREDIS, should be expanded to avoid duplication and accelerate innovation.

11. Conclusions and perspective

Recent advancements in radioactive waste treatment have shown promising results in improving the efficiency, effectiveness, and sustainability of waste-management practices. Novel thermal and chemical technologies are key to the development of new management routes for complex waste streams. Thermal technologies, such as pyrolysis, plasma, and FBSR, are particularly effective for reducing waste volume and stabilizing hazardous components, while chemical processes, such as the Fenton process and wet oxidation, are valuable for the efficient degradation of organic contaminants.

Despite these advancements, several challenges remain, including the need for further research to optimize these technologies for large-scale applications, and the development of cost-effective solutions that align with regulatory requirements and public acceptance. The integration of these advanced strategies with digital technologies, such as AI and IoT, also presents a promising avenue for enhancing monitoring and management processes. Future research should focus on fostering interdisciplinary collaborations that bring together scientists, industry stakeholders, and policymakers to drive innovation. Additionally, aligning these treatment strategies with global sustainability goals, such as the EU Green Deal and circular economy principles, will be crucial for ensuring long-term environmental and economic benefits.

In conclusion, although significant advances have been made in the treatment of challenging wastes, continued innovation and cooperation are essential to overcome existing barriers and develop new safer and more sustainable management routes.

CRediT authorship contribution statement

Elena Torres Álvarez: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Michael Gracey:** Writing – review & editing, Writing – original draft, Conceptualization. **Mark Cowper:** Writing – review & editing, Writing – original draft. **Quoc Tri Phung:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Borys Zlobenko:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Federica Pancotti:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Mafalda Guerra:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Märten Kala:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Janno Torop:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Alan H. Tkaczyk:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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No data was used for the research described in the article.

References

Abdel Rahman, R.O., Ibrahium, H.A., Hung, Y.T. Liquid radioactive wastes treatment: A review, 2011. MDPI AG. https://doi.org/10.3390/w3020551.

Abdel Rahman, R.O., Ojovan, M.I. Toward sustainable cementitious radioactive waste forms: Immobilization of problematic operational wastes, Nov. 01, 2021, MDPI. https://doi.org/10.3390/su132111992.

ANDRA. Theramin D.4.1. Waste Acceptance Criteria and requirements in terms of characterisation, 2018. Accessed: July 10, 2025. [Online]. Available: https://www.theramin-h2020.eu:80/downloads/THERAMIN%20D4_4%20Synthesis%20report%20of%20WP4.pdf.

Avramenko, V., Dobrzhansky, V., Marinin, D., Sergienko, V., Shmatko, S. Novel technology for hydrothermal treatment of NPP evaporator concentrates. In: ICEM'07: 11. International Conference on Environmental Remediation and Radioactive Waste Management, Bruges (Belgium): American Society of Mechanical Engineers - ASME, New York (United States), Sep. 2007. [Online]. Available: https://www.osti.gov/biblio/21156305.

BELGOPROCESS. Thermal treatment technologies. https://www.belgoprocess.be/commercial-services/?lang=en.

Brillas, E. A review on the photoelectro-Fenton process as efficient electrochemical advanced oxidation for wastewater remediation. Treatment with UV light, sunlight, and coupling with conventional and other photo-assisted advanced technologies, Jul. 01, 2020, Elsevier Ltd. https://doi.org/10.1016/j.chemosphere.2020.126198.

Clayton, R., Kirk, J., Banford, A., Stamford, L. A review of radioactive waste processing and disposal from a life cycle environmental perspective, Feb. 01, 2024. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s10098-024-02998-6.

Cyclife. Cyclife Sweden AB - Nyköping facility. https://www.cyclife-edf.com/en/cyclife/governance/cyclife-sweden.

De Bock, C., Harvey, L., Harrison, T. EURAD-ROUTES D.9.9: Suggestions for the management of challenging wastes while maintaining compatibility with options for disposal. ROUTES Task 4 Final Report, 2023. [Online]. Available: http://www.ejp-eurad.eu/.

Deckers, H.J. Treatment of problematic waste by Thermal Treatment Technologies. https://predis-h2020.eu/wp-content/uploads/2021/03/04_Belgoprocess_Hansen.pdf.

Einan, D.S., Schleif, S. Completion of the 2025 Hanford Lifecycle Scope, Schedule and Cost Report. Milestone M-036-01K. p. 2025.

Eldridge, C., Prasad, S. PREDIS D.6.4 Thermal Treatment of Solid Radioactive Organic Wasteforms, 2024.

ERDO. Minimum set of WACs for near-surface disposal of VLLW-LLW, ERDO Technical Note ERDO-WG-LWC project - Task 2, 2022. Accessed: May 28, 2025. [Online]. Available: https://www.erdo.org/app/uploads/2022/10/LWC-Task-2-Report-Minimum-set-of-WACs-for-near-surface-disposal-of-VLLW-LLW.pdf.

EURAD-2. Sustainable treatment and immobilisation of challenging waste (STREAM). https://www.ejp-eurad.eu/implementation/sustainable-treatment-and-immobilisation-challenging-waste-stream. (Accessed 10 July 2025).

European Bank for Reconstruction and Development. Plasma plant at Bulgaria's Kozloduy Nuclear Power Plant starts operation. https://www.ebrd.com/home/news-and-events/news/2018/plasma-plant-at-bulgarias-kozloduy-nuclear-power-plant-starts-operations.html.

Feng, W., Li, J., Jia, S., Wang, Y., Ye, D., Aug. 2018. The Treatment of IRN77/78 Resin using Fenton Oxidation Process. In: IOP Conference Series: Materials Science and Engineering. Institute of Physics Publishing. https://doi.org/10.1088/1757-899X/392/3/032042.

Fournier, M., et al. 2.2.3. Conditioning; Domain Insight, Jul. 04, 2024. Accessed: May 27, 2025. [Online]. Available: https://predis-h2020.eu/wp-content/uploads/2024/08/DI-2.2.3-Conditioning-%E2%80%93-Domain-Insight.pdf.

Framatome. Chemical Treatment of Spent Resins. Decomposition of Organic Matter and Waste Volume Reduction. Accessed: Jul. 28, 2025. [Online]. Available: https://www.framatome.com/solutions-portfolio/docs/default-source/default-document-library/product-sheets/a1747-p-ge-en-202408-chemical-treatmentdc213fe73a314e77b64300f4a946c697.pdf?sfvrsn=e6107107_0.

GAO. HANFORD CLEANUP Alternatives for Treating and Disposing of High-Level Waste Could Save Billions of Dollars and Reduce Certain Risks Report to Congressional Committees United States Government Accountability Office, 2024. Accessed: Aug. 29, 2025. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.gao.gov/assets/gao-24-106989.pdf.

Gonçalves, M.F.S., Petraconi Filho, G., Couto, A.A., da Silva Sobrinho, A.S., Miranda, F. S., Massi, M., Jun. 2022. Evaluation of thermal plasma process for treatment disposal of solid radioactive waste. J. Environ. Manage. 311, 114895. https://doi.org/10.1016/J.JENVMAN.2022.114895.

Gray, L.W., Adamson, M.G., Cooper, J.F., Farmer, J.C., Upadhye, R.S., C. A. Molten salt oxidation as an alternative to incineration. In: 1992 Incineration Conference, Alburquerque, NM, May 1992.

Hanford. Hanford Vit Plant Project, Accessed: Jul. 28, 2025. [Online]. Available: https://www.hanfordvitplant.com/about-project.

HARPERS project. HARmonised PracticEs, Regulations and Standards in waste management and decommissioning. https://www.harpers-h2020.eu/.

Harvey, L. 2.1.2. Waste Acceptance Criteria (WAC): Domain Insight, Aug. 2024. Accessed: May 27, 2025. [Online]. Available: https://predis-h2020.eu/wp-content/uploads/2024/08/DI-2.1.2-Waste-Acceptance-Criteria-%E2%80%93-Domain-Insight.pdf.

Harvey, L., De Bock, C., Bucur, C. EURAD-ROUTES MS 88: Current use of Waste Acceptance Criteria (WAC) in European Union Member-States and some Associated Countries, Nov. 2020. [Online]. Available: http://www.ejp-eurad.eu/.

Holt, E., Oksa, M., Nieminen, M., Abdelouas, A., Banford, A., Fournier, M., Mennecart, T., Niederleithinger, E., 2022. Predisposal conditioning, treatment, and performance assessment of radioactive waste streams. EDP Sci. https://doi.org/10.1051/epjn/2022036.

Hsu, P., Watkins, B., Pruneda, C., Kwak, S. Molten Salt Oxidation: A Thermal Technology for Waste Treatment and Demilitarization. In: 19th Joint Army Navy NASA Air Force, 30th Propellant Development & Characterization and 9th Safety & Environment Meeting, Colorado Springs, CO, USA, Sep. 2001. Accessed: Jun. 30, 2025. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.osti.gov/servlets/purl/15005323.

Huutoniemi, T., Larsson, A., Blank, E., Nuclear, S. Svensk Kärnbränslehantering AB R-12-07 Melting of metallic intermediate level waste, 2012. [Online]. Available: www.skb.se.

IAEA. Handbook on the treatment of solid LILW radioactive waste: Annex I Applied industrialized technologies on the treatment of solid LILW radioactive waste, vol. To be published. IAEA, Vienna, 2024.

IAEA CRP T21029. Geopolymers as an Immobilization Matrix for Radioactive Waste. https://www.iaea.org/projects/crp/t21029.
IAEA General Safety Guide GS-G-3.3. The Management System for the Processing, Handling and Storage of Radioactive Waste for protecting people and the environment Safety Guide, 2008. Accessed: May 27, 2025. [Online]. Available: https://www-pub.iaea.org/mtcd/publications/pdf/pub1329_web.pdf.
IAEA-SSG-12. IAEA Safety Standards Licensing Process for Nuclear Installations, 2010. [Online]. Available: http://www-ns.iaea.org/standards/.
IAEA Specific Safety Guide SSG-40. Specific Safety Guide Predisposal Management of Radioactive Waste from Nuclear Power Plants and Research Reactors, 2016. Accessed: May 27, 2025. [Online]. Available: https://www-pub.iaea.org/MTCD/publications/PDF/Pub1719web-85295015.pdf.
IAEA Specific Safety Guide SSG-41. Predisposal Management of Radioactive Waste from Nuclear Fuel Cycle Facilities, 2016. Accessed: May 27, 2025. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1720web-34641098.pdf.
IAEA-TECDOC-1130. Recycle and Reuse of Materials and Components from Waste Streams of Nuclear Fuel Cycle Facilities, 2000. Accessed: May 27, 2025. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/te_1130_prn.pdf.
IAEA TECDOC 1527. Application of thermal technologies for processing of radioactive waste, IAEA, 2006. Accessed: May 27, 2025. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/te_1527_web.pdf.
IAEA Technical Reports Series TRS-402. Handling and Processing of Radioactive Waste from Nuclear Applications, 2001. Accessed: May 27, 2025. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/TRS402_scr.pdf.
IAEA Technical Reports Series TRS-427. Predisposal Management of Organic Radioactive Waste, 2004. Accessed: May 27, 2025. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/TRS427_web.pdf.
IAEA Technical Report Series TRS-441. Management of Problematic Waste and Material Generated during the Decommissioning of Nuclear Facilities, 2006. Accessed: May 27, 2025. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/TRS441_web.pdf.
Jantzen, C.M., Lorier, T.H., Pareizs, J.M., Marra, J.C., 2007. Fluidized Bed Steam Reformed (FBSR) mineral waste forms: Characterization and durability testing. In: In Materials Research Society Symposium Proceedings, pp. 379–386. https://doi.org/10.1557/proc-985-0985-nn10-04.
Koda, S. Oxidation reactions of solid carbonaceous and resinous substances in supercritical water, Jan. 2009. https://doi.org/10.1016/j.supflu.2008.08.006.
Kvashnina, K., Claret, F., Clavier, N., Levitskaia, T.G., Wainwright, H., Yao, T., Dec. 01, 2024. Long-term, sustainable solutions to radioactive waste management. Nat. Res. https://doi.org/10.1038/s41598-024-55911-y.
Lerche, M. NURES® & BORES® usage at Paks Nuclear Power Plant. https://www.fortum.com/media/2025/03/nures-bores-usage-paks-nuclear-power-plant.
Ma, H., Shen, M., Tong, Y., Wang, X. Radioactive Wastewater Treatment Technologies: A Review, Feb. 01, 2023. MDPI. https://doi.org/10.3390/molecules28041935.
Ma, Y., Chu, H., Zheng, B., Apr. 2024. Research progress of plasma melting technology in radioactive waste treatment of nuclear power plants. Ann. Nucl. Energy 198, 110307. https://doi.org/10.1016/J.ANUCENE.2023.110307.
MacKenzie, D.R., Kempf, C.R., 1986. "Treatment methods for radioactive mixed wastes in commercial low-level wastes - technical considerations," in Waste management 86. Low Level Waste vol. 3.
Marsal, F., et al., 2023. EURAD EC project – Overview of the routes work package: Identified key issues and open questions about waste management routes in Europe, from cradle to grave. EDP Sci. https://doi.org/10.1051/epjn/2022024.
Mennecart, T. DI-2.3.3-Secondary-Waste-Management, 2023. Accessed: Aug. 29, 2025. [Online]. Available: https://predis-h2020.eu/wp-content/uploads/2024/08/DI-2.3.3-Secondary-Waste-Management-%E2%80%93-Domain-Insight.pdf.
Nachmilner, L., Karásková-Nenadálová, L., 2021. "Deliverable 2.4 International approaches to establishing a waste acceptance system version Final Dissemination level. Public.
NDC-NEA, n.d. Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). https://www.oecd-nea.org/jcms/c_12089/committee-for-technical-and-economic-studies-on-nuclear-energy-development-and-the-fuel-cycle-ndc.
NEA. Recycling and Reuse of Materials Arising from the Decommissioning of Nuclear Facilities, 2017. Accessed: May 23, 2025. [Online]. Available: https://www.oecd-nea.org/jcms/pl_15012/recycling-and-reuse-of-materials-arising-from-the-decommissioning-of-nuclear-facilities?details=true.
NEA. Optimising Management of Low-level Radioactive Materials and Waste from Decommissioning, 2020. Accessed: May 23, 2025. [Online]. Available: https://www.oecd-nea.org/jcms/pl_47447/optimising-management-of-low-level-radioactive-materials-and-waste-from-decommissioning?details=true#:~:text=Recognising%20the%20important%20role%20of%20an%20effective%20waste,low-level%20radioactive%20waste%20and%20materials%20arising%20from%20decommissioning.
Nieminen, M., et al., 2020. Thermal treatment for radioactive waste minimisation. EPJ. Nucl. Sci. Technol. 6, 25. https://doi.org/10.1051/epjn/2019040.
Nonnet, H., Mabrouk, M., Argote, S.G., 2023. Development of innovative Plasma Treatment Processes for the Management of Radioactive Organic Liquid Waste. In: 7th Fukushima International Forum.
Nuclear Engineering International (NEI). Kozloduy's plasma plant. Accessed: July 25, 2025. [Online]. Available: https://www.neimagazine.com/advanced-reactorsfusion/kozloduys-plasma-plant-6230627/.
Oh, C.H., 2001. Hazardous and Radioactive Waste Treatment Technologies Handbook, first ed. CRC Press, CRC Press.
Pancotti, F. 2.2.2. Treatment & Processing, Domain Insight, 2024. Accessed: May 27, 2025. [Online]. Available: https://predis-h2020.eu/wp-content/uploads/2024/08/DI-2.2.2-Treatment-Processing-%E2%80%93-Domain-Insight.pdf.
Rivers, T., Kwak, S., Moosavi, M., Wallace, J. Waste Treatment Using Molten Salt Oxidation Technology. In: 15th Annual Global Demilitarization Symposium & Exhibition, Parsippany, NJ, Dec. 2007. Accessed: May 29, 2025. [Online]. Available: https://ndia.dtic.mil/wp-content/uploads/2007/global_demil/SessionIVA/0800Rivers.pdf.
Scourfield, S.J., Kent, J.E., Wickham, S.M., Nieminen, M., Clarke, S., Frasca, B. Thermal treatment for radioactive waste minimisation and hazard reduction: Overview and summary of the EC THERAMIN project. In: IOP Conference Series: Materials Science and Engineering, Apr. 2020. Institute of Physics Publishing. https://doi.org/10.1088/1757-899X/818/1/012001.
Slimák, A., Nečas, V., Sep. 2016. Melting of contaminated metallic materials in the process of the decommissioning of nuclear power plants. Prog. Nucl. Energy 92, 29–39. https://doi.org/10.1016/J.PNUCENE.2016.06.008.
Stamford, L., 2024. Deliverable 2.9 Synthesis report on predisposal LCA studies version Final Dissemination level. Public.
Studsvik. FBSR - Fluidized Bed Steam Reforming. Accessed: May 23, 2025. [Online]. Available: https://www.studsvik.com/key-offerings/waste-management-technology/treatment-technologies/fbsr/.
Tochaikul, G., Phattanasub, A., Khemkham, P., Saengthamthawee, K., Danthanavat, N., Moonkum, N. Radioactive waste treatment technology: a review, Apr. 01, 2022, Walter de Gruyter GmbH. https://doi.org/10.1515/kern-2021-1029.
Valveuser Magazine. Framatome's nuclear spent resin waste management solutions. https://www.valveuser.com/4200-framatomes-nuclear-spent-resin-waste-management-solutions.htm.Oct.23.
Vuorio, M. EURAD-ROUTES D.9.12: A review of past and present studies and plans for developing shared solutions for radioactive waste management in Europe, 2022. Accessed: May 23, 2025. [Online]. Available: https://igdtp.eu/wp-content/uploads/2022/06/EURAD-D9.12-Studies-and-plans-for-developing-shared-solutions-for-radioactive-waste-management-in-Europe.pdf#:~:text=The%20objective%20of%20this%20report%20is%20to%20summarise,also%20identified%20%28e.g.%2C%20in%20IAEA%20studies%29%20where%20relevant.
Walker, S., Hyde, R.A., Piper, R.B., Roy, M.W., EG, I. F. I. D. United S. G Idaho Inc. An overview of in situ waste treatment technologies. In: Nuclear and Hazardous Waste Management International topical meeting. (Spectrum '92), Idaho Falls, ID (United States), Aug. 92.
Walling, S.A., Um, W., Corkhill, C.L., Hyatt, N.C. Fenton and Fenton-like wet oxidation for degradation and destruction of organic radioactive wastes, Dec. 01, 2021, Nature Publishing Group. https://doi.org/10.1038/s41529-021-00192-3.
Wan, Z., Xu, L., Wang, J., Sep. 2015. Disintegration and dissolution of spent radioactive cationic exchange resins using Fenton-like oxidation process. Nucl. Eng. Des. 291, 101–108. https://doi.org/10.1016/J.NUCENGDES.2015.05.009.
Wang, P., Zhan, J., Li, Y., 2018. Improving the scaling problem of Qinshan 320MW waste liquid evaporator. Sci. Technol. vis. 27, 38–40.
Wareing, A. PREDIS MS 2.4 Strategic Research Agenda, 2023. Accessed: May 23, 2025. [Online]. Available: https://predis-h2020.eu/wp-content/uploads/2023/05/PREDIS-SRA_Milestone-Report-2.4_May-2023.pdf.
Wasselin, V., Maître, M., Kutina, I. EURAD-ROUTES D.9.5 Overview of issues related to challenging wastes, 2019. Accessed: May 23, 2025. [Online]. Available: https://www.ejp-eurad.eu/sites/default/files/2022-08/EURAD%20-%20D9.5%20Overview%20of%20issues%20related%20to%20challenging%20wastes.pdf.
Zabulov, Y., Puhab, A., Zlobenko, B., 2023. Plasma gasification of solid organic radioactive waste. In: International Conference on Nuclear Decommissioning: Addressing the past and Ensuring the Future.