ISSN 1392-3730/eISSN 1822-3605

JOURNAL of CIVIL ENGINEERING and MANAGEMENT

2026
Volume 32
Issue 5
Pages 700–723
https://doi.org/10.3846/jcem.2026.26131

NUCLEAR WASTE MANAGEMENT STRATEGIES, ADVANCEMENTS AND ITS IMPACT ON INFRASTRUCTURE

Fathima NIFLA [1], Satheeskumar NAVARATNAM [2], Pathmanathan RAJEEV [1]✉, Jay SANJAYAN [1], Emad GAD [1]

[1] *Swinburne University of Technology, Hawthorn, VIC, Australia*
[2] *Institute of Innovation, Science and Sustainability (IISS), Federation University, Mt Helen Campus, Ballarat, Australia*

Article History:
- received 10 January 2025
- accepted 9 November 2025

Abstract. Nuclear waste management has become a critical issue due to growing concerns about the long-term safety and sustainability of radioactive waste disposal and its impact on infrastructure. Insufficient knowledge and regulations surrounding nuclear waste management are significant challenges to sustainable development. This review provides an in-depth categorisation of nuclear waste, with particular emphasis on high-level waste (HLW), which requires extensive pre-disposal treatments, and explores its impact on infrastructure and structures. Recent innovations, such as thermal treatment, partitioning and transmutation, are highlighted for their effectiveness in reducing HLW volume and radiotoxicity. The review also examines the detrimental effects of radiation on containment materials, especially concrete and steel. Notably, containment infrastructure is vulnerable to degradation, with studies showing a loss of up to 50% in compressive strength in concrete exposed to extreme neutron irradiation and reductions of up to 70% in Young's modulus. Advanced materials, such as fibre-reinforced concrete and oxide-dispersion-strengthened steels, offer promising solutions by mitigating these effects and improving durability by 10–30%. Furthermore, the review identifies significant strides in international collaboration on nuclear waste management, which have led to advancements in minimising hazards and improving waste processing. These efforts are further supported by the integration of digital tools and material innovations, ensuring continued progress in managing nuclear waste safely and sustainably.

Keywords: high level waste, compressive strength, radioactive materials, radiation effects, concrete durability.

✉Corresponding author. E-mail: *prajeev@swin.edu.au*

1. Introduction

The advancement of nuclear technology in recent decades has undoubtedly contributed significantly to the global energy sector, providing a substantial portion of electricity in many countries. The significance of nuclear power lies in its ability to generate large amounts of energy with almost zero greenhouse gas emissions, making it an essential part of the global effort to combat climate change (Nuttall, 2022). However, with this progress comes the inevitable challenge of nuclear waste management, a complex and multifaceted issue that demands attention and comprehensive solutions.

Nuclear waste, a byproduct of nuclear power generation and various industrial processes like weapon reprocessing operations involving radioactive materials, poses a significant challenge due to its hazardous nature and long-lasting radioactivity (Rosenfeld & Feng, 2011). The generation of nuclear waste could be a result of nuclear weapons production, nuclear power generation, and the use of radioactive materials in industry, medicine, agriculture, and academia (Gee et al., 2005). Nuclear waste generation takes place in various stages of the nuclear fuel cycle (Nuclear Energy Agency & Organisation for Economic Co-operation and Development, 2008). These stages encompass mining and milling, fuel cycle operations, nuclear reactor operation, and reprocessing and decommissioning (Nuclear Energy Agency & Organisation for Economic Co-operation and Development, 2006; Ojovan & Lee, 2014; Choi et al., 2022). During the mining and milling stages, uranium ore extraction leads to the production of low-level waste, including tailings that contain radioactive material (Nuclear Energy Agency & Organisation for Economic Co-operation and Development, 2008). Uranium conversion, enrichment, and fuel fabrication, which are the activities that fall under the process of fuel cycle operation, generate intermediate-level waste, which includes chemical byproducts and contaminated materials (Nuclear Energy Agency & Organisation for Economic Co-operation and Development, 2006). Spent nuclear fuel, which is regarded as highly radioactive, is primarily generated during nuclear reactor operation (Nuclear Energy Agency & Organisation for Economic Co-operation and Development, 2008; Ojovan & Lee, 2014). Additional waste streams, including fission products and actinides, are produced while reprocessing spent fuel, and structural and decommissioning waste are produced as a result of decommissioning plants (Ojovan & Lee, 2014; Choi et al., 2022). While high-level waste from reactors often attracts attention mostly, it is crucial to recognize that all the stages contribute towards the overall generation of nuclear waste, emphasizing the importance of management strategies (Darda et al., 2021). Hence, understanding these processes is vital for effective waste management, subsequently leading towards environmental protection.

Globally, as per the Spent Fuel and Radioactive Waste Information System (SRIS), the world has produced approximately 1.4 million tons of nuclear waste since the beginning of nuclear energy production, of which around 750,000 tons of nuclear waste is still in storage and awaiting disposal (Spent Fuel and Radioactive Waste Information System, 2022). The quantities of nuclear waste generated vary depending on the type of nuclear facility and its operational context. Decommissioning of a typical million-kilowatt nuclear power plant generates approximately 12,000 m^3 of nuclear waste, which consists of low-level waste and some high-level waste from reactor components (Li, 2022). In Russia, solid low-level waste and high-level waste are generated at a rate of 0.033 m^3/GW h and 0.00028 m^3/GW h, respectively, during normal operations (Ekidin & Antonov, 2020).

The impacts of nuclear waste are complex, influencing public health, environmental safety, and public perception. Contamination of water, soil, and air leads to long-term ecological risks, which are critical consequences of nuclear waste. The harmful effects of these wastes, particularly on human health including acute injury (damage caused by large doses of toxic waste on human body in a short period of time), chronic injury and long term effects due to exposure and contamination such as leukemia, aplastic anemia, malignant tumors, cataracts and effects on early fetuses and the environment pollution which alters the natural balance of the ecosystem (Liu & Dai, 2019) have led to the growing concern regarding the management of these wastes safely and sustainably. Thus, the impact of inadequately managed nuclear waste on both the environment and human health is undeniable (Fazzo et al., 2017). The potential for contamination, long-term radiation exposure, and the risk of catastrophic incidents necessitate careful consideration of waste management practices (Iqbal et al., 2021).

In the context of Australia, notwithstanding its comparatively modest nuclear presence relative to its prominent international counterparts, the nation confronts challenges inherent to nuclear waste management. Despite the absence of commercially operational Nuclear Power Plants (NPPs), Australia houses a research reactor situated at Lucas Heights, primarily dedicated to the production of radioisotopes integral to medical and research applications. Annually, the nation generates approximately 45 m^3 of radioactive waste stemming from these, comprising approximately 40 m^3 of low-level waste (LLW) and 5 m^3 of intermediate-level waste (ILW) (World Nuclear Association [WNA], 2023). Australia currently exports its high-level wastes (HLW) for overseas reprocessing, notably spent nuclear fuel derived from reactors. As a result of this practice, Australia is presently recognized as a nation that does not internally generate HLW. Currently, the storage of LLW spans over a hundred sites across the country (WNA, 2023). As of 2021, there exists an accumulation of approximately 2490 m^3 of LLW awaiting disposal, alongside 2061 m^3 of ILW awaiting more optimal storage solutions (Australian Radioactive Waste Agency, 2022). The strategy of exporting HLW for processing and disposal abroad presents various challenges and raises sustainability concerns, especially if Australia were to expand its nuclear energy sector. Therefore, Australia needs to develop domestic capabilities for the processing and disposal of HLW and adopt advanced technologies for ILW and LLW.

While previous studies have explored various aspects of nuclear waste management, a comprehensive understanding of the global management strategies with their impact on infrastructure materials remains largely unexplored (Selvam et al., 2025; Alwaeli & Mannheim, 2022). For instance, Selvam et al. (2025) focus on AI's role in optimising nuclear waste classification, treatment, storage, and disposal, highlighting improvements in accuracy, risk assessment, and regulatory compliance. Similarly, Alwaeli and Mannheim (2022) assess nuclear waste management strategies, particularly for high-level waste (HLW) and spent nuclear fuel (SNF) disposal in European countries, integrating a life cycle assessment (LCA) approach to evaluate abiotic resource depletion and the environmental impact of nuclear electricity in the production process.

Existing reviews predominantly focus on individual waste treatment methods, disposal strategies or country-specific policies (Alwaeli & Mannheim, 2022; Fernández-Arias et al., 2023; Jain et al., 2025). Terranova and Tavares (2024) review innovative spent nuclear fuel treatment methodologies, emphasizing chemical and physical processes for recovering and reusing valuable isotopes. Fernández-Arias et al. (2023) analyzes specialised literature on HLW management technologies and their international implementation. Meanwhile, Jain et al. (2025) investigate the encapsulation of cesium and strontium in cementitious materials, assessing immobilisation strategies and material durability. While it provides an in-depth discussion on waste encapsulation and material performance, it does not extensively explore the broader impact of nuclear waste on infrastructure materials beyond immobilisation.

Nevertheless, the long-term interaction between nuclear waste components and construction materials, particularly concerning long-term storage and disposal facilities and infrastructure in the close vicinity of waste disposal sites, remains an area of growing concern, especially with the implementation of deep geological repositories for HLW. This review attempts to address this gap in knowledge by examining the nuclear waste management strategies around the world, the composition of HLW and the potential impacts on infrastructure materials. By synthesizing recent advancements and identifying critical gaps in understanding the impact of nuclear waste on infrastructure, this review aims to contribute to the ongoing discourse on nuclear waste management and infrastructure resilience. It is anticipated that this work would enable countries like Australia, with limited hands-on experience in nuclear power management, to understand and select their most viable technologies to promote safe and permanent storage and disposal of their nuclear waste.

2. Methodology

A comprehensive and systematic approach was executed to understand and critically evaluate the literature concerning nuclear waste management strategies, advancements, and their impact on infrastructure construction materials and create new perspectives while ensuring the findings are both reliable and reflective of the current state of the field. Initially, the literature search was conducted to determine studies conducted on nuclear waste management strategies, advancements and impact on infrastructure materials. Online databases such as Scopus, Web of Science and websites of relevant organisations, including the International Atomic Energy Agency [IAEA], World Nuclear Association [WNA], Centre on Global Energy Policy, Nuclear Decommissioning Authority [NDA], country-specific nuclear fuel management organizations, technical reports and journal articles were referred to for the search. Predefined search criteria included two groups of keywords in the identification stage. Group 1 focused on collecting relevant data on the classification and management of nuclear waste and relevant technological advancements, while Group 2 aimed at studies focusing on the impact of radiation on containment infrastructure and the behavior of construction materials such as concrete and steel under neutron and gamma radiation. The search terms used in each group were: Group 1: "nuclear waste classification", "low-level waste", "high-level waste", "waste management strategies", "thermal treatment", "partitioning and transmutation (P&T)", "LLW", "HLW", "ILW", "Nuclear waste" and Group 2: "radiation effects", "concrete degradation", "supplementary cementitious materials (SCMs)".

Following the literature search, the 5245 selected documents were further analyzed and refined using predefined inclusion and exclusion criteria. The inclusion criteria primarily focused on the relevance of studies in the title, abstract and keyword focusing on nuclear waste classification, management strategies including innovations such as thermal treatment and P&T, studies that discuss neutron and gamma radiation's impact on concrete's structural properties, including strength, pore size, and crystallinity of aggregates, and the studies that focus on the effectiveness of remedies to control the impact and improve the durability of concrete against radiation effects. Peer-reviewed journal articles, reputable conference proceedings, and technical reports published only in English were considered. Studies that do not explicitly discuss nuclear waste management strategies or the impact of radiation on infrastructure materials were excluded during the selection process.

Titles and abstracts were examined to apply these inclusion and exclusion criteria as outlined in Figure 1a, which further reduced the articles to 275. Finally, full text screening was carried out, and each article was thoroughly reviewed, and based on their eligibility, 75 articles were selected for qualitative analysis. Thus, the systematic review classification was carried out based on the preferred reporting items for systematic review and meta-analysis (PRISMA) approach (Moher et al., 2015). The data gathered under this study mainly focused on nuclear waste management and the impact of radiation on infrastructure material. A co-occurrence study of keywords was carried out using VOSviewer to identify the trends and understand the structure of scientific knowledge, as well as the state of research in the field of nuclear waste management and infrastructure. A total of 267 keywords were obtained from the database, of which six remained in the articles with an occurrence of at least 4 times. These various topics were divided into 18 groups/clusters as shown in Figure 1b with 267 items, 1239 links and a total strength of 1252. From the figure, several big nodes can be observed, revealing this study's coverage. Under nuclear waste management, nuclear waste classification, management strategies, advancements in technologies, pre-disposal treatment methods, digital tools for waste management, and material advancements were explored. Effects of neutron and gamma radiation on concrete and other containment materials and mitigation strategies involving supplementary cementitious materials (SCMs) and steel fibers were determined under the impacts of radiation on infrastructure materials. A comparative analysis was conducted between traditional nuclear waste management systems and modern advancements covering the major aspects of effectiveness, efficiency, and infrastructure resilience. Finally, the paper synthesizes the findings, presenting the effectiveness of current nuclear waste management strategies and material advancements, which evaluate sustainability and safety.

3. Current nuclear waste management strategies

3.1. Nuclear waste classifications

Nuclear waste management involves the systematic classification and disposal of hazardous materials generated during nuclear activities, which may exist as liquids, solids, gases, or sludges. Most countries, including France,

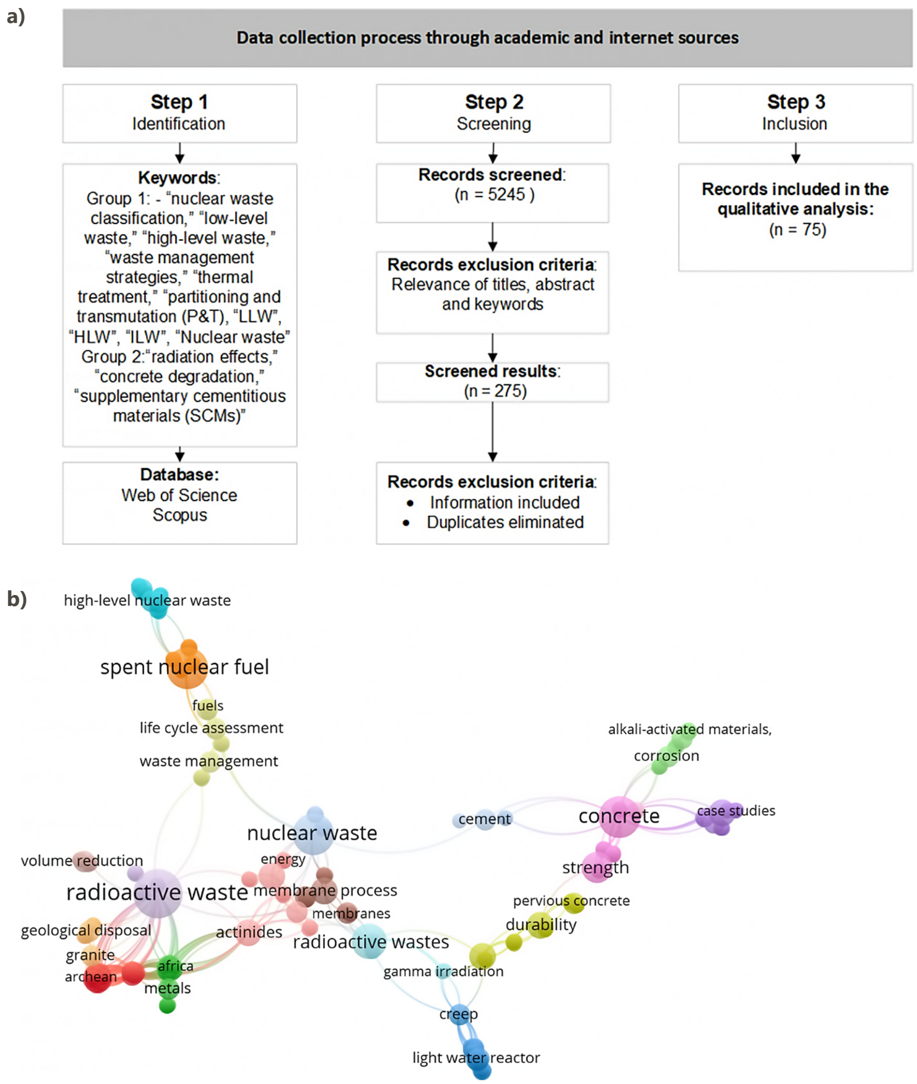

Figure 1. Data collection and analysis: a – approach; b – co-occurrence network of keywords

the UK, Finland, Japan, China, India etc. employ a three-tier classification system based on radioactivity levels comprising HLW, ILW and LLW (French National Radioactive Waste Management Agency, 2022; Nuclear Decommissioning Authority, 2023; Nuclear Science Research Institute, 2014; The People's Republic of China, 2017; Bhabha Atomic Research Centre, 2023; Díaz Gámez, 2020; Kumpula et al., 2022). However, classification systems can vary to address country-specific regulatory and operational needs. For instance, Germany differentiates waste according to the heat generated during radioactive decay, categorizing it into heat-generating waste and waste with negligible heat generation (Federal Office for the Safety of Nuclear Waste Management, 2022).

To foster international consistency, the IAEA has established a common framework for nuclear waste management. Several countries, including Australia (Australian Radioactive Waste Agency, 2022), have adopted this framework, which further refines NPP waste into six categories (Australian Radiation Protection and Nuclear Safety Agency, 2020; IAEA, 2009a):

1. Exempt waste (EW): it falls within the radioactivity levels deemed non-hazardous to human health and the environment. This includes materials such as concrete, plaster, and bricks resulting from the decommissioning or dismantling activities of NPP, with radioactivity levels ranging from 0.1 Bq/g to 104 Bq/g (Ojovan et al., 2019a).
2. Very short-lived waste (VSLW): it contains radionuclides with half-lives lasting only a few years following a designated waiting period and can be safely disposed of as regular waste.
3. Very low-level waste (VLLW): it's generated during nuclear facility maintenance and decommissioning, characterized by a concentration of radionuclides slightly above VSLW levels but not requiring intensive containment, rendering them suitable for disposal in landfill-type facilities (IAEA, 2009a).
4. Low level waste (LLW): LLW includes a variety of materials such as paper, rags, tools, clothing, injections, filters, laboratory animal carcasses and tissues, reactor water treatment residues, and other substanc-

es that exhibit minimal short-lived radioactivity and low concentration of long-lived radionuclides (IAEA, 2009a). Typical activity levels are about 4 GBq of alpha and 12 GBq of beta/gamma radiation per metric ton, with an overall activity per kilogram not exceeding 3.7×108 Bq (WNA, 2020a). Notably, IAEA does not prescribe a specific boundary between LLW and ILW, as the acceptable limit for activity concentration varies between individual radionuclides and groups of radionuclides (IAEA, 2009a).

5. Intermediate level waste (ILW): ILWs are characterized by relatively long-lived radionuclides, possessing radioactivity levels ranging from 3.7×108 to 3.7×1011 Bq/kg (Sandri et al., 2020). Unlike HLW, ILW exhibits lower radioactivity and does not emit heat exceeding 2 kW/m^3. Consequently, ILW typically necessitates shielding but not active cooling. Examples of ILW components encompass nuclear fuel cladding metal, end pieces, resins, chemical sludge, cleanup liquid from reactor coolant, and various contaminated materials, spare parts, as well as graphite resulting from reactor maintenance and decommissioning (IAEA, 2009a).
6. High-Level Waste (HLW): high-level waste is the most radioactive and poses the greatest challenge in terms of management and disposal. HLW primarily consists of spent nuclear fuel from reactors. The long-lived isotopes in HLW, such as plutonium and uranium, require deep geological disposal to prevent contamination of the environment and exposure to humans.

3.2. Waste management strategy

Nuclear waste management, as put forth, is a global challenge that demands diverse strategies based on waste classification, form, and availability. The significance of nuclear waste management strategies lies in ensuring the safe and effective handling of radioactive waste generated by nuclear energy. This approach includes the collection of waste, appropriate treatment processes, and a comprehensive long-term management strategy, which may involve storage, disposal, or conversion to a non-hazardous form. The primary objective is to secure waste in a manner that prioritises the safety of human health and the environment, now and in the future, without imposing an excessive burden on future generations (Ojovan et al., 2019b; IAEA, 2009b).

Examining the typical nuclear waste management cycle, as depicted in Figure 2, the ultimate preferred endpoint of all nuclear waste is disposal. Certain waste categories, such as EW, VSLW, and VLW, are often directly disposed of in selected sites based on activity levels and radionuclide concentration without prior processing (IAEA, 2009a). As per Cuccia et al.'s (2011) study, waste disposal sites for these kinds of wastes are scattered around the world. However, HLW, ILW, and LLW undergo pre-disposal processes involving collection, segregation, and chemical adjustment. Subsequently, these wastes are treated through processes like incineration, solidification, and volume reduction, depending on different forms and nuclide levels (Fernández-Arias et al., 2023).

The state of the waste, whether gaseous, liquid or solid, dictates the treatment approach. The release of liquid or gaseous radioactive waste into the environment must adhere to strict standards, ensuring that levels of radioactive materials and other impurities meet the criteria established by national and international regulations. The waste must undergo treatment to minimise both its volume and the concentration of radioactive and toxic substances (Ambashta & Sillanpää, 2012). Hence, the gaseous radioactive wastes undergo filtration using an air filtering device until they meet the radionuclide emission limit specified by standard regulations before being released into the atmosphere. Simultaneously, treatment methods such as chemical precipitation (Rahman et al., 2011), ion exchange (Avramenko et al., 2017), thermal evaporation (Fuks et al., 2022), biological methods (Son et al., 2019), membrane purification (Pabby et al., 2022) and electrodialysis (Miśkiewicz et al., 2021) are employed to manage to reduce radioactive compounds and other toxic solutes in the effluent (Jiménez-Reyes et al., 2021). Pabby et al.'s (2022) study highlights that the pressure-driven membrane purification processes, including reverse osmo-

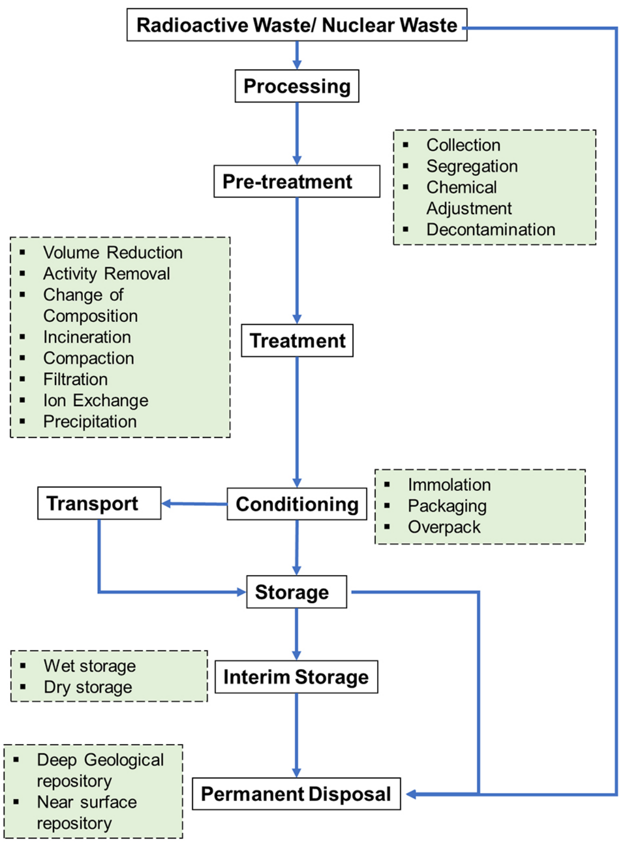

Figure 2. Waste management process

sis, nanofiltration, ultrafiltration and microfiltration, are capable of producing high-quality treated effluents with an acceptably low level of residual radioactivity for discharge.

The subsequent phase, as depicted in Figure 2, the nuclear waste cycle, conditioning involves changing the waste into a form suitable for subsequent management, including transportation, storage, and disposal, ensuring topmost safety. Conditioning stabilizes the waste into a form that will not react or degrade over time (Ojovan et al., 2019c). Prior to selecting an optimal conditioning method, it is imperative to define and understand the function of the conditioned waste form within the comprehensive safety framework of the waste management system. For example, within a near-surface repository, the waste package is required to contain the waste, thereby preventing the migration of radionuclides and providing structural support for a repository cap or cover. Conversely, in a deep geological repository or borehole, the primary function of the waste package is generally isolation and containment rather than structural support. Table 1 provides an overview of the main treatment and conditioning options typically applied to various types of radioactive waste. It is important to acknowledge the absence of a "universal" treatment or conditioning method. The selection of specific techniques is decided on a case-by-case basis, taking into consideration the physical, chemical, and

Table 1. Treatment, conditioning and disposal options for radioactive waste

Waste category	Phase	Treatment methods	Conditioning procedure		Clearance method	References
			Immobilisation	Packaging		
VLLW	Liquid	Decay storage, Ion exchanges, Radionuclide removal, Evaporation,	Cementation, Polymer sorption	Industrial packaging	Surface trench, near surface disposal	Cuccia et al. (2011), M. H. Sanders and C. E. Sanders (2019), Yim (2022),
	Solid	Decay storage	–	Simple packaging if required	Surface trench, near surface disposal	Cuccia et al. (2011), M. H. Sanders and C. E. Sanders (2019), Yim (2022)
LLW	Liquid	Chemical treatment, Evaporation, radionuclide removal, Membrane method, Ion exchange	Cementation, Bituminisation, Polymer sorption, Geopolymer solidification, Vitrification	Metal or concrete containers, High integrity containers	Near surface disposal	M. H. Sanders and C. E. Sanders (2019), Yim (2022), Thakur et al. (2021), Zakrzewska-Trznadel (2013)
	Solid	Sorting, Volume Reduction, Compaction, Incineration, Melting	Encapsulation, Grouting	Industrial packaging, Metal or concrete containers, High-integrity containers	Near surface disposal	M. H. Sanders and C. E. Sanders (2019), Yim (2022), Lim et al. (2021), Chon et al. (2016)
ILW	Liquid	Chemical treatment, Evaporation, Radionuclide removal, Membrane methods, Ion exchange	Cementation, Bituminisation, Polymer sorption, Geopolymer solidification, Vitrification	Metal or concrete containers, High integrity containers	Intermediate depth disposal, Deep geological disposal	M. H. Sanders and C. E. Sanders (2019), Yim (2022), Zakrzewska-Trznadel (2013)
	Solid	Sorting, Volume reduction, Compaction	Encapsulation, Grouting	Metal or concrete containers, High integrity containers	Intermediate depth disposal, Deep borehole disposal, Deep geological disposal	Yim (2022), Lim et al. (2021), Paraskevoulakos et al. (2019), Mallants et al., 2021)
HLW	Liquid	Evaporation in conjunction with Immobilisation	Vitrification, Ceramic Immobilisation	Stainless steel containers	Deep geological disposal	M. H. Sanders and C. E. Sanders (2019), Yim (2022), Kononenko et al. (2021), Tan et al. (2023), Zhou et al. (2021), Patra et al. (2022), Engelhardt et al. (2023)
	Solid	Reprocessing (SNF)	–	Metallic (e.g., copper) container	Deep geological disposal	M. H. Sanders and C. E. Sanders (2019), Yim (2022), Engelhardt et al. (2023), Spykman (2018), Bevelacqua (2023)

radiological properties of the waste, along with the accepted criteria (Ojovan et al., 2019d).

The final stage of waste management is disposal, where, if required, waste is transported safely and stored in interim storage sites before eventual disposal. In the case of managing LLW and short-lived ILW, as listed in Table 1, the near-surface disposal method is preferred and internationally recommended by IAEA (2009b). This method encompasses both ground-level and subterranean cavern installations fortified with natural and engineered barriers Near-surface disposal sites involve excavation for ground-level disposal, with several meters of soil covering or caverns positioned tens of meters below ground level. These sites, typically maintained for a minimum of 30 years, consider environmental impact, climate change, and safety concerns (WNA, 2020b).

In the case of spent nuclear fuel (SNF), due to its high radioactivity and temperature compared to all the other HLW, immediately after discharge from the reactor, it is subjected to interim storage either at onsite NPPs or at offsite consolidated interim storage facilities until its decay heat is sufficiently lower for final disposal or reprocessing. Currently, the two primary alternatives for SNF interim storage are wet (pool) storage and dry (cask) storage (IAEA, 2012). Wet storage involves underwater storage for initial shielding and cooling, while dry storage relies on heavy concrete or metal casks and/or structures for shielding and provides cooling by natural convection or forced air circulation. Once the SNF is cooled off in wet storage, dry storage is chosen as an interim storage method until final disposal in many countries including Canada, Germany, Switzerland, and the U.S (Wolff et al., 2019).

Nevertheless, HLW is unsuitable for long-term storage in near-surface facilities since it generates a significant amount of heat or contains particularly long-lived radionuclides that are required to be buried in deep underground repositories positioned at depths ranging from 200 to 1000 meters underground (WNA, 2020b) within specifically chosen stable geological formations where the environment will remain largely unchanged over the 100,000 to 1 million years required to allow the waste to safely radioactively decay, isolated from the biosphere (Corkhill & Hyatt, 2018). In the past decade, many studies have been focused on the design, construction and implementation of Deep Geological Repository (DGR) for HLW. For instance, Bennett and Gens (2008) reviewed existing repositories and designs of engineered barrier systems for HLW and SNF disposal in several European nations. The study places particular focus on critical metallic waste containers and their corrosion processes. Further discussion on the global implementation of DGR is provided in Section 3.3.

3.3. Comparative analysis of global waste management strategies

Effective nuclear waste management requires balancing economic feasibility, long-term safety, and environmental sustainability. Table 2 presents a comparative analysis of key waste management strategies discussed in Section 3.2, highlighting their cost implications, safety measures, and challenges.

Near-surface disposal remains the most cost-effective method due to its low initial and operational costs (Bashir, 2007). However, its suitability is limited to LLW and short-lived ILW, making it an inadequate solution for HLW (Nazeeh & Sivakumar Babu, 2018). Countries like the United States, Japan, France, Spain, and the United Kingdom have established near-surface disposal facilities at ground level. In contrast, Sweden and Finland have opted for selected caverns as disposal sites, positioned at depths ranging from 50 to 100 meters below ground level (The Geological Society, 2020). Although widely adopted, near-surface disposal poses risks of potential leakage and groundwater contamination if not properly designed and maintained (Geetha Manjari & Sivakumar Babu, 2018; Zhang et al., 2022).

Interim storage methods, such as wet and dry storage, are commonly used as transitional solutions but present varying degrees of feasibility and risk. Wet storage, which involves submerging spent nuclear fuel in water, is widely utilized in the USA and Canada (Liu, 2015; Nicholson et al., 2013). However, its reliance on active cooling systems increases operational costs and introduces risks of leakage and contamination, making it unsuitable for long-term waste management (Liu et al., 2020; Jäckel et al., 2020; Rothwell, 2021). Dry storage, which relies on casks and natural convection for cooling, offers a safer and more cost-effective alternative for medium-term storage (Rothwell, 2021). While it reduces environmental risks compared to wet storage, it is not a permanent solution, and eventual disposal or reprocessing remains necessary (El-Samrah et al., 2021).

Reprocessing and recycling strategies aim to reduce HLW volume by recovering fissile materials for reuse in nuclear reactors (Terranova & Tavares, 2024). Countries such as France and Russia have invested heavily in reprocessing programs, which minimise waste storage requirements while providing economic benefits through the reuse of valuable materials (Grygie & Romary, 2015). However, this method requires advanced infrastructure and raises concerns about nuclear proliferation due to the extraction of plutonium (Paulillo et al., 2020). Transmutation technology, though still in the experimental stage, presents a potential breakthrough in waste management by drastically reducing the radiotoxicity and longevity of nuclear waste (Wallenius, 2019). Research efforts in Japan, France, and the USA indicate promising results, but the high energy demands and technological complexity currently limit its feasibility for large-scale implementation.

Deep geological repositories, on the other hand, provide the highest level of safety by isolating HLW for over 100,000 years within geologically stable formations (Jang et al., 2024). While a universally permanent solution remains elusive, DGR persists as the preferred long-term disposal method for many countries, each with its selected sites and implementation concepts (WNA, 2020b; Ragoussi & Costa, 2019). Despite its effectiveness in long-term containment, this approach requires substantial initial invest-

Table 2. Comparative analysis of nuclear waste management strategies based on economic feasibility and long-term safety

Strategy	Economic feasibility	Long-term safety	Environmental impact	Global implementation and challenges	References
Near surface disposal	High (Low cost)	Moderate	Moderate (potential leaching and groundwater contamination)	Widely implemented (USA, France, Japan), but limited to LLW & short-lived ILW Risk of leakage in improperly designed facilities	Bashir (2007), Nazeeh and Sivakumar Babu (2018), Geetha Manjari and Sivakumar Babu (2018), Zhang et al. (2022)
Interim wet storage	Low (High maintenance and operational costs)	Low (Risk of leakage, requires active monitoring)	Moderate (Risk of contamination if not managed properly)	Commonly used in the USA and Canada. Requires transition to dry storage or disposal due to long-term instability Risk of leakage and high cooling cost	IAEA (2012), Liu (2015), Nicholson et al. (2013), Liu et al. (2020), Jäckel et al. (2020), Rothwell (2021)
Interim dry storage	Moderate (Lower maintenance than wet storage)	Moderate (Safe for medium term but not permanent)	Low (Reduces environmental risk compared to wet storage)	Widely used in the USA, Germany, and Switzerland Effective for temporary storage, but long-term disposal solution required	Wolff et al. (2019), Rothwell (2021), El-Samrah et al. (2021)
Reprocessing & recycling	High (reduces HLW volume)	High (Minimizes waste storage requirements)	Low (less waste to manage in the long run)	France and Russia lead in reprocessing High initial cost Proliferation risks (e.g., plutonium extraction)	Terranova and Tavares (2024), Grygie and Romary (2015)
Transmutation technology	Very high (still experimental and costly)	Very high (potential to drastically reduce waste toxicity)	Technological and regulatory barriers	Limited to research in Japan, France, USA Technological and regulatory barriers High energy requirements	Wallenius (2019)
Deep geological repository	Moderate (High initial cost, low maintenance)	High (Isolates HLW for 100,000+ years)	Low (Geological stability ensures containment)	Finland and Sweden are pioneers with Onkalo DGR (Finland) operational Long-term development timelines (20-50 years) Site selection Public perception and acceptance barriers	Solomon (2021), Holt and Jalonen (2024), Svensk Kärnbränsförhantering (2024)

ment and prolonged development timelines, often spanning multiple decades. Table 3 provides a summary of the advancements made by countries in regard to the implementation of DGRs.

Finland's Onkalo repository, currently operational, began excavation in 2018 following the approval of a construction license in 2012, with trial operations commencing in 2024 (Holt & Jalonen, 2024). This 12-year timeline from initial approval to trial operation highlights the long and complex process of implementing DGRs, a challenge faced globally. Meanwhile, Sweden has recently obtained an environmental permit for the construction and operation of a similar repository (Svensk Kärnbränsförhantering, 2024). In contrast, Russia has opted for a different disposal approach at the Yeniseisky site in the Krasnoyarsk region of Siberia. Although the geological and hydrological properties of this site are comparable to those at Forsmark (Sweden) and Olkiluoto (Finland), Russia plans to dispose of HLW as aluminophosphate glass rather than utilizing the KBS-3 system (Laverov et al., 2016), encapsulating SNF within boron steel canisters enclosed in copper capsules, which are then housed in repository holes and backfilled with bentonite clay to ensure long-term stability and retrievability (Posiva, 2023).

Wang et al. (2005) examined the progress in geological disposal efforts for HLW in China from 1985 to 2004. China aims to establish an HLW repository by the mid-21st century to handle vitrified waste, transuranic waste, and limited SNF. McEvoy et al. (2016) discussed challenges in developing a deep geological disposal program in the UK, noting the natural processes that could impact repository site selection and design.

In contrast to developed nations, developing and underdeveloped nations face unique challenges in nuclear waste management due to limited financial resources, regulatory frameworks, and technological capabilities (Thomas et al., 1989). Brazil, India, and Malaysia struggle with inadequate disposal practices for LLW, leading to environmental contamination (Paschoa & Tranjan Filho, 1995). India's closed fuel cycle, emphasising reprocessing and vitrification, has helped reduce waste volume, though its scalability remains a challenge (Raj et al., 2006). Indonesia, as an archipelagic nation, faces infrastructure difficulties in waste transportation and storage (Wisnubroto et al., 2021). Addressing these disparities requires international cooperation, financial support, and technology transfer to ensure safe nuclear waste management globally.

Table 3. Global status of HLW disposal projects

Country	Project	Location	Status		Ref
Finland	Onkalo repository	Olkiluoto, Finland	Trial run in progress	First DGR for SNF.	Solomon (2021), Holt and Jalonen (2024)
Sweden	Forsmark repository	Forsmark, Sweden	Environmental permit received for construction and operation	Similar design to Finland's Onkalo repository	Svensk Kärnbränsförhantering, (2024)
USA	Waste isolation pilot plant (WIPP)	Carlsbad, New Mexico	Operational since 1999	Only stores transuranic wastes from nuclear weapon production	Bowen et al. (2024)
Germany	Konrad Mine	Salzgitter	Under construction	Designed to store low and intermediate-level radioactive waste	Noseck et al. (2023)
France	Cigéo	–	Planning and design	Aims to construct DGR for HLW by 2035	Stavropoulou et al. (2020)
Canada	Nuclear waste management organization (NWMO)	–	Site selection process underway	Plans for a deep geological repository for spent nuclear fuel.	Braden and Macfarlane (2023)
Switzerland	Nagra (National cooperative for the disposal of radioactive waste)	–	Site selection in progress	Evaluating potential sites for long-term storage	Zbinden et al. (2023)
China	Research and pilot projects	–	–	Developing technologies and identifying potential sites for deep geological repositories.	Wang et al. (2018), Liu et al. (2019)
Russia	NORWM	Krasnoyarsk region, Siberia	Planning in progress	–	Laverov et al. (2016), Neuvazhaev et al. (2020),
Japan	NUMO (Nuclear waste management Organization of Japan)	–	Site selection process and research	Focus on public engagement and geological studies.	Nuclear Waste Management Organization of Japan [NUMO] (2021)

Economic considerations play a crucial role in evaluating these strategies. While near-surface disposal remains the most financially accessible option, its application is restricted to specific waste types. Deep geological repositories, despite their high initial costs, provide the most secure long-term solution for HLW. Reprocessing, although economically advantageous in terms of material recovery, requires significant infrastructure investment and regulatory oversight. Transmutation, if further developed, could offer an effective long-term strategy, but its current costs and technological barriers prevent widespread adoption.

From a safety perspective, DGR stands out as the most reliable containment method for HLW. At the same time, interim wet storage presents the highest risk due to its dependence on active monitoring and the potential for environmental hazards. Dry storage mitigates some of these risks but does not serve as a permanent disposal solution. Meanwhile, reprocessing reduces the amount of waste requiring disposal but introduces additional complexities related to security and international regulations. Environmental impact remains a key consideration, with geological disposal minimising long-term risks, while near-surface disposal and interim storage methods require careful site selection and continuous monitoring to prevent contamination.

Given the global push for sustainable energy, nuclear waste management policies must balance feasibility, safety, and environmental responsibility. While deep geological repositories remain the preferred long-term solution, advancements in reprocessing and transmutation technologies may provide complementary approaches to enhance the overall effectiveness of nuclear waste management. Future research and international collaboration will be essential in optimising these strategies to ensure the responsible handling of radioactive waste for generations to come.

4. Technological advancements in nuclear waste management

The management of nuclear waste, especially HLW, has experienced substantial technological progress over recent decades, driven by the need to address the long-term environmental, safety, and health risks associated with stored radioactive materials. Key advancements in the pre-disposal of nuclear waste management include the development of methodologies for handling various waste types, the application of thermal treatment techniques (Nieminen et al., 2020), the implementation of partitioning and transmutation technologies (Kooyman, 2021), and the use of advanced digital tools and sensors for monitoring (Finocchiaro, 2020; Manzano et al., 2021, Egorov et al., 2012). The Pre-disposal management of radioactive waste (PREDIS) project, for instance, addresses these innovations in the treatment of metallic materials, liquid organic waste and solid organic waste, which result from nuclear power plant operations and other industrial processes (Holt et al., 2022). The PREDIS project, a combined effort started in 2020, which includes 47 partners from 17 countries and an additional 25 companies as End User Group members, also addresses digitalisation solutions for improved safety and efficiency in handling and assessing cemented-waste packages in extended interim surface storage (Holt et al., 2022).

On the other hand, the thermal treatment for radioactive waste minimisation and hazard reduction (THERAMIN) project, a collaborative European Commission (EC) initiative co-funded by the Horizon 2020 Euratom research and innovation program along with European nuclear waste management and research organizations, has made significant progress in demonstrating the feasibility of various thermal treatment methods. These techniques are aimed at reducing the volume and immobilizing various streams of low- and intermediate-level radioactive waste prior to disposal (Nieminen et al., 2020; Holt et al., 2022). Here, six different thermal treatment techniques were demonstrated, treated products were characterized, and the impact of treatment on disposability was evaluated. It was found that thermal treatment can result in significant volume and hazard reduction, both of which are beneficial for the safe storage and disposal of nuclear waste (Nieminen et al., 2020). Thermal treatment has also been proven to remove organic material, which can form complex agents and make radionuclides more mobile in a repository (Nieminen et al., 2020).

In the management of HLW, partitioning and transmutation (P&T) technology, which includes the separation and transmutation of minor actinides that are responsible for most of the long-term decay heat and radiotoxicity available and in development due to its ability to significantly reduce the size and storage requirements of waste management facilities by decreasing the heat load and volume of high-level radioactive waste (Wallenius, 2019). A recent study by Kooyman (2021) has highlighted the current state of P&T technology around the world, which focuses mainly on the experimental results and theoretical developments on minor actinides P&T obtained in the last decade.

Significant advancements in the treatment of nuclear waste have been achieved through the development of innovative cementitious materials, which have greatly enhanced the solidification and stabilization processes. Historically, Portland cement (PC) was predominantly used for the immobilisation of LLW and ILW. However, recent decades have seen a shift towards the use of supplementary cementitious materials (SCM) and chemical additives (Juenger et al., 2019). The introduction of alternative cementitious materials such as calcium aluminate, calcium sulfoaluminate, phosphate, magnesium silicate, and alkali-activated cement has been pivotal. These materials offer higher encapsulation capacities and superior performance in the containment of nuclear waste, addressing some of the longstanding challenges faced in nuclear waste management systems (Rakhimova, 2022).

Furthermore, the advent of thermal plasma technology (TPT) has revolutionized the treatment of various radioactive waste streams. TPT significantly reduces the volume and hazard of waste, ensuring that it meets the stringent criteria for safe storage and disposal (IAEA, 2006). According to the IAEA, the faster processing capabilities of TPT compared to conventional methods are a critical facilitator in the management of radioactive waste (IAEA, 2006). A study by Ghiloufi (2009) indicates that thermal plasma systems efficiently incinerate combustible waste components, reducing their volume, while vitrifying non-combustible counterparts into glassy slags with very low leaching rates.

The integration of digital tools and sensors into nuclear waste management has also seen a significant advancement towards improving safety and operational monitoring prior to disposal. Innovations such as muon imaging (Yang et al., 2019), wireless sensors (Chierici et al., 2024), and remote fiber optic sensors are increasingly deployed to monitor the integrity of cemented waste packages and spent fuel casks over the long term (Holt et al., 2022). Moreover, the application of machine learning techniques is proving beneficial in predicting the future behavior of waste packages, which enhances the decision-making processes regarding waste handling and storage (Lillington et al., 2020).

Additionally, the application of data-driven machine learning for the disposal of the HLW has been of emerging interest in recent years (Hu & Pfingsten, 2023). Currently, there are several supervised and unsupervised Machine Learning algorithms, such as linear regression (LR), principal component analysis (PCA), artificial neural network (ANN), genetic algorithm (GA), etc., that are adopted for the disposal of HLW (Hu & Pfingsten, 2023). PCA has the capability to reduce noisy and redundant variables, thereby helping to identify patterns or leak indications through gamma-ray spectra and streamline hazard detection (Selvam et al., 2025). An ANN and GA are alternatives to the Monte Carlo simulations, which are computationally intensive, used to develop a rapid surrogate model to predict decay heat (DH) and the neutron multiplication factor (Solans et al., 2021).

5. Impact of nuclear waste on infrastructure

Nuclear waste contains varying levels of radioactivity, as discussed. Therefore, the management and storage, particularly of HLW/SNF, pose significant challenges due to their potential impact on the environment, humans, and surrounding and confining infrastructure (Hélie, 2012). To understand this impact on the surrounding environment and infrastructure, it is necessary to understand the composition of HLW. The environment surrounding these waste materials is complex, characterized by numerous variable factors and components. This section explores the composition of HLW and SNF, focusing on how radiation affects structural materials, especially concrete and steel, the primary materials used in both infrastructure construction and nuclear waste containment facilities. Additionally, the current practices that are employed to overcome the possible effects are analyzed.

5.1. HLW/SNF composition

When a nuclear fuel rod is removed from a commercial reactor, it becomes SNF. This SNF is a highly complex material, both in terms of its chemical composition and physical properties and falls under the HLW category. Following its extraction from the reactor, the SNF undergoes significant beta decay within the initial 300 years, primarily triggered by the beta decay of Cs^{137} into Ba^{137m}, Sr^{90} into Zr^{90}, and Pu^{241} into Am^{241} (Carbol et al., 2012). It requires several millennia for the SNF to achieve radioactivity levels equal to those of natural uranium ore, surpassing the entire known human history.

Although various types of SNF are in existence, the majority of the SNF that is presently stored for final disposal comprises UO_2 fuel (Wagner, 2016), with 95% being unused Uranium (Wagner, 2016; Bruno & Ewing, 2006). The remaining 5% includes fission products, transuranic elements, and activation products (Wagner, 2016; Bruno & Ewing, 2006; Buck et al., 2004; Bruno et al., 2020). The irradiation of nuclear fuel within the reactor leads to the continuous generation of fission products (FPs), which can precipitate in different forms like gaseous, metals, and oxides. These fission products consist of isotopes of noble gases such as Xe and Kr, alongside others like H^3, C^{14}, Se^{79}, Tc^{99}, Pd^{107}, Sn^{125}, I^{129}, Cs^{135}, and Cs^{137} (Metz et al., 2012).

While uranium dominates the composition of SNF, the radionuclides are distributed heterogeneously throughout the fuel, existing in various phases ranging from inert gases to relatively stable oxides, as discussed. SNF is identified as a complex, redox-sensitive, semiconducting, and polycrystalline ceramic material, with its components changing over time due to radioactive decay (Bruno & Ewing, 2006). The concentration of certain elements in spent UO_2 fuel following a particular irradiation period is detailed in Table 4. The table data clearly shows that the uranium concentration remains stable even after a million years due to the extended half-life of U^{238} (4×10^9 years). Plutonium (Pu) originates from neutron capture reactions in U^{238} followed by beta decay. The accumulation of Pu^{239} and Pu^{240} during irradiation results in plutonium having the second-highest concentration in SNF, as shown in Table 4. Elements such as lead (Pb), bismuth (Bi), thorium (Th), protactinium (Pa), and neptunium (Np) exhibit increasing concentrations over time, attributed to their longevity or stability as daughter isotopes in the decay chains of heavier actinides. Helium concentration also rises over time due to its formation through all alpha decay. Americium (Am) experiences a gradual increase in concentration over hundreds of years, primarily driven by the in-growth from the beta-decaying Pu^{241} within the initial 100 years. Subsequently, the concentration decreases slowly, influenced by the decay of Am^{241} (half-life – 433 years).

The majority of these fission products undergo beta emission decay and possess relatively short half-lives, varying from minutes to years. Despite their shorter half-lives in comparison to actinides, certain fission products demonstrate longer half-lives, such as Se^{79} (half-life – 6.5×10^4 years), Zr^{93} (half-life – 1.53×10^6 years), Nb^{94} (half-life – 2.03×10^4 years), Tc^{99} (half-life – 2.13×10^5 years), Pd^{107} (half-life – 6.5×10^6 years), Sn^{126} (half-life – 1×10^5 years), I^{129} (half-life – 1.57×10^7 years), and Cs^{135} (2×10^6 years). The decline in hydrogen concentration over the years is linked to the decay of tritium (H^3) with a half-life of 12.346 years. Similarly, the reduction in strontium concentration is a result of the significant presence of short-lived Sr^{90} (half-life – 28.503 years). Niobium (Nb) consists of only one stable isotope, Nb^{93}, shielded by the long-lived radionuclide Zr^{93} (half-life – 1.5×10^6 years). Consequently, the initial dominance of Nb's short-lived isotope Nb^{95} (half-life –

Table 4. Element composition of actinides and decay daughter elements in a UO_2 fuel rod after discharge with fuel burn up of 40 GWd/tHM (data extracted from Carbol et al., 2012)

Element	Concentration (g/tHM)				
	Discharge from reactor	1 year	100years	10,000 years	1 million years
He	0.722	1.067	7.504	81.835	290.756
Pb	<0.001	<0.001	0.001	0.300	409.039
Bi	<0.001	<0.001	<0.001	0.029	389.572
Ra	<0.001	<0.001	<0.001	0.167	0.539
Th	0.003	0.003	0.089	12.220	239.234
Pa	<0.001	<0.001	0.002	0.098	0.688
U	907083.065	907083.065	907083.065	907083.065	907083.065
Np	604.194	575.440	734.315	1947.205	1453.292
Pu	9732.740	10219.079	8008.099	5421.477	85.925
Am	170.054	239.234	1453.292	39.381	<0.001
Cm	55.402	37.507	2.830	0.688	0.005

35.2 days) leads to a four-order magnitude decline within the first 10 years. However, as Zr^{93} decays, the concentration of Nb^{93} rises, causing an overall increase in niobium concentration. The reduction in cesium concentration and the increase in barium concentration are due to the decay of Cs^{137} (half-life – 30.104 years) into Ba^{137m}, which subsequently decays into stable Ba^{137} within 153 seconds.

Therefore, it can be concluded that minor changes in element concentrations occur in spent UO_2 fuel following an initial period of 1000 years. Nonetheless, these changes typically occur within a narrow concentration spectrum relative to the total uranium mass. Despite this, the radioactivity emitted from the fuel undergoes significant changes over the time scale of the repository. After the standard burn-up in a nuclear reactor, the radioactivity of the nuclear fuel increases significantly, reaching approximately 10^{17} Bq/MT of fuel, mainly attributed to beta and gamma decay (Bonin & Tsilanizara, 2017). The residual activity in SNF from a light water reactor (LWR) primarily characterized by beta and gamma decay, generates a decay heat of 1000 W/t ten years after discharge, transitioning to predominantly alpha decay with a decay heat of roughly 20 W/t after 10,000 years (Carbol et al., 2012).

However, the composition and quantities of the elements presented in Table 4 are intended to provide a representative understanding of the typical composition and concentration changes of the SNF. The final actual composition of SNF will depend on the initial fuel type, initial chemical composition, level of enrichment of U, neutron energy spectrum, and the burnup or amount of fission occurring in the fuel during reactor operation (Buck et al., 2004; Ewing & Weber, 2010).

5.2. Impact on construction materials

The radiation and temperature environment experienced by SNF during storage is substantially different from the operational conditions within nuclear reactors (Hélie, 2012). When surrounding infrastructure is exposed to toxic waste, the properties of construction materials such as concrete and steel generally change in accordance with the amount of exposure. The effects of radioactive waste, especially HLW exposure and irradiation, on the constituents of concrete and cement-like materials or on the composite material itself are still not fully understood, although there have been some systematic studies of the effects of irradiation on concrete and the constituting cement paste and aggregate (Field et al., 2015; Pomaro, 2016; Kontani et al., 2014; Vodák et al., 2011). Thus, this section explores the impacts on these materials due to radiation exposure using the available literature.

5.2.1. Radiation-induced degradation of concrete

Concrete, being a multiscale and multiphase (solid, liquid, and gas) composite material composed of hardened cement paste (HCP) and aggregates, undergoes significant structural and chemical changes under radiation exposure (Kontani et al., 2014). Different types of radiation, including alpha, beta, gamma, neutrons, and recoil nuclei, generate varying defect densities within the material, largely influenced by the energy lost by charged particles or photons per unit distance travelled within the medium (Kontani et al., 2014). The interactions between gamma and neutron irradiation and the constituents of concrete have been studied, with much of the publicly available data on neutron and gamma irradiation effects on concrete dating back to the 1960s and 1970s (Field et al., 2015). Table 5 summarises the radiation test conditions and fast neutron fluences typically used in experimental setups of the reviewed studies. Hilsdorf et al. (1978) conducted one of the most frequently cited studies on the mechanical degradation of irradiated concrete, identifying reductions in compressive strength, increased porosity, and microcracking as key effects.

Table 5. Irradiation parameters considered in experimental setups

Parameter	Typical range
Fast neuron fluence (E > 0.1 MeV)	1×10^{18}–1×10^{20} n/cm^2
Gamma dose	0.1–3 MGy
Irradiation temperature	25–320 °C

Radiation exposure alters concrete properties through both chemical and physical mechanisms. Ionizing radiation breaks chemical bonds within the concrete matrix, leading to the formation of free radicals and subsequent chemical reactions that degrade the material (Vodák et al., 2005; Potts et al., 2021; Jin et al., 2023). Studies by Vodák et al. (2025) and Potts et al. (2021) observed compressive strength reductions of approximately 10% and 8.97%, respectively, following radiation exposure. Additionally, increased porosity has been reported, with (Jin et al., 2023) documenting a 5% rise in total porosity over 42 days of xenon radiation exposure (Figure 3a). The pore structure evolved significantly during this period, shifting peak pore sizes from 1–10 nm before exposure to a secondary peak of approximately 0.1 µm within 7 days, further increasing to 10 µm by 14 days (Figure 3b).

A significant degradation mechanism in irradiated concrete is radiation-induced volumetric expansion (RIVE), which primarily affects aggregates. The Japan Concrete Aging Management Program, in collaboration with Oak Ridge National Laboratory, investigated neutron irradiation effects on various geological aggregate compositions, including felsic sandstones, altered tuff, and limestone (Maruyama et al., 2013, 2017). The findings indicated that radiation-induced and thermally driven volumetric expansion of aggregates contributed substantially to concrete degradation, with silicate-based aggregates experiencing the most evident expansion (Field et al., 2015). The degree of RIVE is influenced by the dimensionality of silicate polymerization and the relative number of Si-O bonds per unit cell, as well as the relative bonding energy of the minerals (Le Pape et al., 2018). This expansion causes internal stresses that are induced in the cement paste, ultimately compromising mechanical integrity (Le Pape et al., 2016).

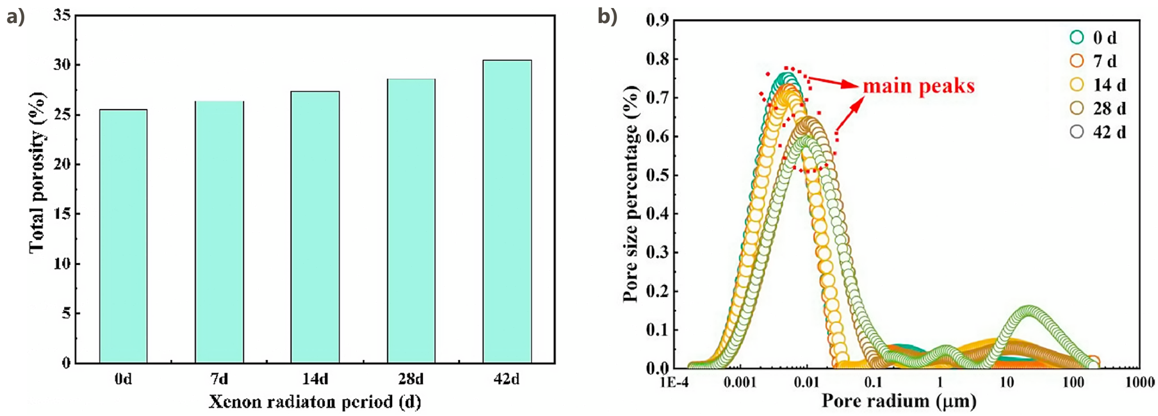

Figure 3. The pore structure of cement paste before and after different periods of xenon radiation: a – pore size distribution; b – total porosity (Jin et al., 2023).

Despite extensive reactor-based experimental studies, there remains a critical gap in understanding the effects of radiation on concrete structures near nuclear waste repositories. Field et al. (2015) revisited historical irradiation data and compiled 307 data points on compressive strength, 62 on tensile strength, 138 on elastic modulus, and 114 on linear expansion. The analysis of the findings indicated that the mechanical properties of concrete began to degrade beyond neutron fluences of approximately 1×10^{19} n/cm^2, although this threshold varies depending on composition and exposure conditions. However, as most experimental data were derived from reactor environments, neutron fluence exposure in radioactive waste storage-related infrastructure may yield different outcomes.

Fast neutrons (>0.1 MeV) induce atomic displacements within aggregate minerals, particularly affecting crystalline structures such as quartz. Neutron irradiation disrupts Si-O bonds, leading to metamictization and aggregate swelling (Maruyama et al., 2017). Studies (Sasano et al., 2020; Rasheed et al., 2022) have shown that quartz can undergo volumetric expansion of 15–20% under high neutron fluences, contributing to a network of microcracks along aggregate-cement interfaces (Sasano et al., 2020). The mechanical implications of this damage are significant, with some studies reporting compressive strength reductions of up to 50% (Field et al., 2015) and Young's modulus reductions of 70% at about 1.0×10^{20} n/cm^2 neutron fluences neutron fluences (Maruyama et al., 2021).

Gamma radiation, unlike neutrons, primarily interacts with concrete through ionization and heating rather than direct atomic displacements. A key effect of gamma exposure is the radiolysis of pore water, where high-energy photons break down water molecules into hydrogen, oxygen, and peroxide, effectively dehydrating the cement paste (Rasheed et al., 2022). This dehydration leads to microstructural shrinkage and alters hydration products. Moderate gamma exposure can initially increase compressive strength due to the drying effect, but higher doses result in embrittlement and microcracking. Historically, gamma doses exceeding 10^8 Gray (Gy) were considered necessary to impair concrete properties (Rasheed et al., 2022; Dąbrowski et al., 2023) significantly. However, recent studies have identified measurable strength losses at low doses, particularly in young or moisture-rich concrete (Dąbrowski et al., 2023). For instance, Robira et al. (2018) observed that cement paste samples exposed to a total gamma dose of 85.7 kGy exhibited compressive strength reductions of approximately 3.6% for uncarbonated specimens and up to 13% for carbonated specimens. Similarly, Soo and Milian (2001) reported that Portland cement mortars experienced a compressive strength decline of around 15% when the total gamma dose exceeded approximately 0.14 MGy compared to control specimens.

In environments where both neutron and gamma radiation are present, these mechanisms interact, intensifying concrete degradation. While neutrons induce aggregate expansion, gamma rays cause cement paste shrinkage, leading to a deleterious internal volume mismatch (Sasano et al., 2020). This disparity results in internal stresses that propagate cracks along the aggregate-mortar interface, further reducing load transfer capacity and structural cohesion. Experimental evidence suggests that concrete specimens submerged in water experienced reduced gamma-induced shrinkage, mitigating some microcracking compared to dry conditions (Dąbrowski et al., 2023). However, this does not eliminate the fundamental incompatibility between neutron-driven expansion and gamma-induced contraction, which remains a dominant degradation mechanism in irradiated concrete.

Historical research on radiation-induced concrete degradation, such as Hilsdorf et al. (1978), established practical guidelines suggesting that neutron fluences below 10^{19} n/cm^2 and gamma doses below 10^8 Gy would not significantly damage structural concrete. However, re-examination of these datasets by Kontani et al. (2014) revealed inconsistencies, particularly concerning concrete mix compositions and irradiation conditions that were not representative of real-world structures. In response to these uncertainties, renewed efforts have been undertaken in Japan, the United States, and Europe to update reference thresholds and assess modern concrete materials in realistic nuclear environments (Maruyama et al., 2017; Remec et al., 2017).

These studies emphasize the necessity of evaluating radiation impacts within the specific conditions expected in nuclear waste storage settings, rather than relying on data derived from reactor-based experiments alone.

Recent experimental and modeling studies have significantly advanced the understanding of radiation effects on concrete. Maruyama et al. (2017) confirmed neutron-induced metamictization of aggregates as a primary degradation mechanism, particularly affecting α-quartz. The findings underscored the vulnerability of siliceous aggregates to neutron radiation and provided evidence that gamma radiation primarily induces thermal drying effects rather than direct chemical degradation (Maruyama et al., 2017). Computational modeling efforts by Sasano et al. (2020) simulated heterogeneous aggregate expansion and its influence on mechanical properties, demonstrating that elastic modulus reduction often precedes compressive strength loss. Further studies by Dąbrowski et al. (2023) linked gamma irradiation effects to accelerated carbonation, which can undermine the alkaline environment necessary for steel reinforcement protection.

Despite these advancements, significant gaps remain in understanding the long-term performance of concrete exposed to nuclear waste radiation. Unlike nuclear reactors, HLW repositories present distinct radiation fields, exposure durations, and environmental conditions that significantly influence degradation processes. As such, there is a critical need to establish reference levels specific to infrastructure exposed to radioactive waste. These findings underscore the importance of ongoing experimental validation and the refinement of computational models to improve predictive assessments of radiation-induced concrete degradation over extended periods.

5.2.2. Radiation-induced degradation of steel

Radiation-induced steel degradation, particularly in nuclear reactor environments, is a critical area of study due to its implications for the longevity and safety of reactor components. This synthesis examines the various mechanisms and effects of radiation on different types of steel, including stainless steel and reactor pressure vessel (RPV) steel (Murty, 1984). Steels exposed to nuclear radiation fields undergo displacement damage when energetic particles (primarily neutrons) collide with lattice atoms. Each collision can produce a cascade of atomic displacements, leaving behind Frenkel defects (vacancies and self-interstitials) that aggregate into clusters. Vacancies coalesce into voids or vacancy-rich regions, while interstitials form dislocation loops (e.g., Frank loops in austenitic steel) (Kuleshova et al., 2020; Kenik & Busby, 2012). Prolonged irradiation thus generates a high density of lattice defects from nanometer-scale "black spot" damage (small defect clusters) to larger voids and loop structures distributed throughout the steel matrix (Kenik & Busby, 2012). These defects are not static; they act as sinks for migrating point defects and facilitate radiation-induced segregation (RIS) of alloying elements. RIS is a non-equilibrium redistribution of elements driven by fluxes of vacancies and interstitials to sinks like grain boundaries, dislocation loops, and void surfaces (Kuleshova et al., 2020). For instance, grain boundary regions in long-term irradiated stainless steels showed pronounced Ni and Si enrichment accompanied by Fe and Cr depletion (over a 3 to 5 nm zone), a clear manifestation of RIS (Kuleshova et al., 2020). Simultaneously, irradiation can induce nanoscale precipitates or clusters; in austenitic steel internals irradiated over decades, a high number density of Ni–Si-rich clusters (precursors to G-phase precipitates) was observed (Kuleshova et al., 2020). Notably, void swelling (macroscopic volumetric growth from voids) tends to be limited at moderate temperatures and doses of light-water reactor or storage conditions. In Kulshova et al.'s (2020) study, negligible swelling was found up to 43 displacements per atom (dpa) at 300 °C, but higher temperatures or extreme doses can trigger appreciable void formation. Finally, transmutation reactions from neutron exposure can produce insoluble gases (primarily helium and also hydrogen) within the steel. These gases readily diffuse into vacant lattice sites or voids, inflating them and promoting cavity formation (Slugeň et al., 2020). In conclusion, it can be stated that the radiation environment drives significant microstructural evolution in steels, creating vacancy and interstitial clusters, solute segregations, and sometimes gas-filled cavities. These changes collectively degrade the microscopic properties of steel. The accumulation of radiation defects at a micro level directly impacts the mechanical behavior of steel.

It is well established that neutron-irradiated metals exhibit a combination of increased yield strength and decreased ductility, often quantified as an upward shift in the ductile-to-brittle transition temperature in ferritic steels (Murty, 1984). The underlying mechanisms of radiation embrittlement consist of two primary modes. First, the high density of defects (e.g. loops and clusters) impedes dislocation glide and alters flow behavior, leading to elevated flow stress and strain localization (Murty, 1984). Second, radiation can induce chemical and phase changes that embrittle internal interfaces: for instance, nanoscale precipitation of Cu-rich phases in reactor pressure vessel steels or segregation of impurity elements (P, Sb, etc.) to grain boundaries. In particular, radiation-induced segregation of embrittling species to grain boundaries, along with precipitation of transmutation-produced helium in these regions, creates weakened interfaces that serve as potential fracture initiation locations (Murty, 1984). These microstructural processes collectively cause a loss of fracture toughness.

Beyond microstructural damage, radiation in a nuclear waste environment can also alter the chemical composition of steel surfaces, which can accelerate corrosion and cracking (Kenik & Busby, 2012; Smart et al., 2008). Ionizing radiation (particularly γ-rays from radioactive decay) causes radiolysis of water and other repository media, generating aggressive species such as H_2O_2, O_2, and radicals that can attack metals (Kenik & Busby, 2012). Study by Smart et al. (2008), simulating geological disposal conditions, has shown that even in anoxic (oxygen-free) groundwater, the presence of a γ-radiation field markedly increases the corrosion rate of carbon steel. Under irradiation, steel corrosion products tend to include the usual magnetite (Fe_3O_4) and higher-oxide phases, indicating a more oxidizing local chemistry at the metal surface (Smart et al., 2008). The higher the radiation dose rate, the greater the corrosion acceleration observed.

In parallel, if tensile stresses are present, irradiation can concurrently induce irradiation-assisted stress corrosion cracking (IASCC), especially in austenitic stainless steels used in reactor or storage environments. IASCC is a form of intergranular cracking resulting from the combined action of radiation, corrosive environment, and stress. Radiation contributes by modifying the material and the environment simultaneously (Kenik & Busby, 2012). On the material side, radiation-induced segregation causes chromium depletion at grain boundaries, similar to degradation, along with hardening that promotes localized stress and strain accumulation (Kenik & Busby, 2012; Simonen & Bruemmer, 1998). On the environmental side, radiolysis elevates the electrochemical corrosion potential via oxidizing species, exacerbating intergranular attack (Kenik & Busby, 2012). Notably, chromium depletion due to RIS is identified as a primary factor for IASCC susceptibility in stainless steels (Simonen & Bruemmer, 1998). Empirical evidence shows a threshold radiation dose on the order of 0.8–1 dpa, beyond which IASCC becomes observable (Kenik & Busby, 2012; Simonen & Bruemmer, 1998). Above this threshold, grain boundaries significantly depleted in Cr (and enriched in Ni/Si or P) lose their passivity and are prone to corrosive attack and cracking under stress. Cracks initiate and propagate along these embrittled boundaries, mirroring the intergranular stress corrosion cracking seen in thermally affected materials. IASCC has been documented in reactor core internals after sufficient neutron irradiation, and it remains a concern for any long-term steel component in a high-radiation, aqueous environment (Kenik & Busby, 2012; Simonen & Bruemmer, 1998).

Over the extended timescales of nuclear waste storage, the degradation processes can cumulatively weaken steel structures and barriers. Radiation-induced embrittlement means that storage canister materials (often carbon or low-alloy steels encased in corrosion-resistant shells) may lose ductility and fracture toughness over decades of low-dose exposure, raising the risk of brittle failure under thermal or external loads. Likewise, any radiation-enhanced corrosion can thin steel walls or crack welds over time, potentially compromising the containment of radioactive waste. These issues are central to safety assessments for repositories, as the structural integrity of waste packages must be maintained for many years. Lessons learned from reactor pressure vessels and internals, where fast neutron embrittlement and irradiation-assisted cracking have been extensively studied, are being applied to predict long-term performance in waste storage scenarios. It is recognized that radiation degradation phenomena ultimately limit the service lifetime or at least reduce the safety margins of nuclear structural materials (Slugeň et al., 2020). Ongoing research and surveillance programs continue to monitor how steel ages next to stored waste, looking for signs of embrittlement, microstructural changes, or accelerated corrosion. In conclusion, understanding radiation-induced degradation in steel is crucial for ensuring the long-term containment of nuclear waste. By accounting for mechanisms like defect accumulation, embrittlement, RIS, and radiolytic corrosion, nuclear waste storage facilities can be designed and managed to maintain their structural integrity and safety over the required lifespan (Slugeň et al., 2020).

Several researchers agree that the technical information necessary for determining an appropriate threshold value of nuclear radiation in assessing the soundness of structures under irradiation conditions is poor, especially with regard to concrete durability evaluation. Consequently, further experimental tests are needed. On the other hand, from the first studies, some advancements in the interaction between concrete and neutrons or gamma-rays have been made, which would now need implementation in predictive models of concrete deterioration and validation against representative laboratory tests to evaluate the related rate effects. The inherent difficulty with evaluating the compiled literature is the number of variables inherent in an irradiation experiment; these variables include the different materials used (cement and aggregate); mix proportions, curing and environmental conditions (temperature and relative humidity) during irradiation; internal moisture content; and testing conditions (neutron fluxes and spectra, in particular).

5.3. Remedies to control the impacts and improve infrastructure

5.3.1. Concrete

Different types of concrete exhibit varying levels of vulnerabilities, as discussed above, such as gamma and neutron radiation, depending on their constituent materials. Thus, concrete strength, durability and sustainability are compromised at different levels. Nevertheless, measures can be taken to improve these aspects of concrete at an early stage. Numerous studies have been conducted to identify the most effective solutions for enhancing concrete's durability (Hooton & Bickley, 2014), strength (Panesar et al., 2021) and sustainability (Makul, 2020), such that concrete used in nuclear waste management related and surrounding infrastructure can withstand these impacts.

The integration of SCMs such as fly ash, ground granulated blast furnace, silica fume and metakaolin along with limestone filler (LF) has been identified as an effective strategy for enhancing concrete's compressive strength, reducing porosity, and boosting long-term durability as well as increasing radiation shielding properties (Hooton & Bickley, 2014; Panesar et al., 2021). Adil et al. (2020) studied the influence of Silica Fume on the properties of pervious concrete and concluded that up to 5% replacement of cement with Silica Fume resulted in ease of compaction and improvement in strength and durability in harsh environments (Adil et al., 2020). Moreover, Siddique and Kaur (2012) studied the mechanical properties of concrete made with ground granulated blast furnace slag subjected to temperatures up to 350 °C and discovered that reduction in the values of compressive strength, splitting tensile strength, and modulus of elasticity remained lower than 40% of the initial value even after a temperature of 350 °C was applied to prove concrete containing granulated blast furnace slag could possibly be used in applications involving elevated temperatures (Siddique & Kaur, 2012).

Further advancements have been made through the incorporation of steel fibres, which significantly enhance the mechanical properties and durability of concrete (Panesar et al., 2021; Makul, 2020). Steel fibres, ranging from 1 to 1.5% by volume, have improved fracture toughness, control shrinkage, and enhance ductility (Banthia & Sappakittipakorn, 2007). A comparative study by Panesar et al. (2021) proved that steel fibres improve compressive strength, freeze-thaw resistance, sulfate resistance, alkali-silica reaction (ASR) expansion reduction/elimination, and carbonation resistance. Data from existing studies on steel fiber-reinforced concrete show that, at optimal dosages, steel fibers can enhance material properties significantly. For example, an optimal dose of 1% hooked-end fibers increased compressive strength by up to 13.5%, while a 1.5% dose of shear and waveform fibers improved the durability factor by 17%. Furthermore, porosity was reduced by approximately 30% with 2% of 10 mm microfibers, sulfate expansion decreased by 63% with 1% hooked-end fibers, carbonation depth was reduced by 39% at 1.5% hooked-end, and ASR expansions lowered by 42% with 1.3% hooked-end fibers (Panesar et al., 2021). Although these improvements depend on fiber types, they collectively highlight the enhanced performance of fiber-reinforced concrete compared to conventional concrete (Panesar et al., 2021).

Additionally, the development of nano-engineered concrete represents a significant leap forward in concrete technology. Nano-engineering allows for the optimization of both physio-mechanical and chemical properties at the molecular level, resulting in concrete that exhibits superior flexural and compressive strengths, enhanced thermo-mechanical properties, and drastically reduced water absorption rates (Makul, 2020). El-Sayed et al. (2022) investigated and predicted the effects of adding different nano additives such as nano alumina (NA), carbon nanotubes (CNT), and a hybrid mix of both materials within normal strength concrete and found that all nano additives at all replacement ratios showed remarkable positive effects while the hybrid mix of 1.5% NA along with 0.1 CNT showed the optimum enhancement for both the mechanical and radiation shielding properties. This nano-scale improvement presents a promising avenue for further enhancing the radiation shielding properties, durability, and sustainability of concrete structures in nuclear waste management.

The radiation created damage or microcracks in the mineral of the aggregates, which reduced the concrete's strength and radiation shielding efficiency of the concrete (Akkurt et al., 2007; Lee et al., 2013). The use of heavy natural aggregates, such as magnetite or barite, can improve the physical and radiation shielding properties of concrete (Abdullah et al., 2022). To maintain the mechanical stability and improve the leach resistance of the waste matrix, bidirectional ion-exchange resin is commonly used (Frizon & Cau-dit-Coumes, 2006; Duffó et al., 2010, 2012). However, some resins that contain sulphate ions can impair the stability of binders and concrete, reducing the structural integrity of the concrete (Frizon & Cau-dit-Coumes, 2006). This impact can be reduced by using resin that contains encapsulating material such as Amberlite (IRN77) (Frizon & Cau-dit-Coumes, 2006).

Overall, the radiation shielding efficiency, compressive strength retention and durability under thermal stress of these advanced methodologies are summarized qualitatively in Table 6. It can be said that these advanced methodologies not only fulfil the stringent requirements of nuclear waste management infrastructure but also contribute

Table 6. Comparative analysis of concrete under radiation exposure

Material	Radiation shielding efficiency	Compressive strength retention	Durability under thermal stress	Primary advantage	References
Conventional concrete	Low	Moderate	Poor	Cost-effective but weak under prolonged radiation exposure	Masoud et al. (2020)
SCM-based concrete	High (due to heavy metal oxides)	High	Moderate	Enhances shielding durability	Hooton and Bickley (2014), Panesar et al. (2021)
Fibre reinforced concrete with barite	High for 0.2MeV	High	High	Effective at lower energy photon attenuation	Li et al. (2017)
Fibre reinforced concrete with granulated ferrous waste	High for 0.662 MeV and 1.25MeV photons	High	High	Enhanced shielding for high-energy radiation	Li et al. (2017)
Nano engineered concrete	Very high	Very high	Very high	Superior shielding, strength and durability	Makul (2020), El-Sayed et al. (2022)

to the broader goals of environmental sustainability and resource efficiency. However, there is a need for more research in assessing the impact of irradiation on the mechanical performance and properties of advanced infrastructure subjected to prolonged exposure to radiation, as current research predominantly focuses on comparing the effectiveness of additives in enhancing radiation shielding properties.

5.3.2. Steel

Prolonged exposure to neutron and gamma radiation leads to embrittlement, swelling, and corrosion, ultimately compromising the strength, durability, and sustainability of steel-based infrastructure. However, various remedies can be implemented to mitigate these effects at an early stage. Numerous studies (Zinkle et al., 2017; Shang et al., 2023; Kan et al., 2020; Benedito et al., 2024) have explored advanced materials and surface treatments to enhance the durability, mechanical performance, and radiation resistance of steel.

The development of advanced steel alloys presents one of the most effective approaches to improving radiation resistance. Reduced Activation Ferritic/Martensitic (RAFM) steels have been optimized using computational thermodynamics and modified thermomechanical treatments to enhance their mechanical properties and reduce neutron radiation damage (Zinkle et al., 2017). These steels incorporate low-activation elements, ensuring long-term stability while limiting radioactive waste accumulation. Furthermore, Oxide Dispersion Strengthened (ODS) steels are produced through powder metallurgy by embedding a high density of nanometer-sized oxide particles in the steel matrix that act as potent sinks for radiation-induced point defects, promoting the recombination of vacancies and interstitials and thereby controlling radiation damage accumulation (Zinkle et al., 2017). As a result, ODS alloys demonstrate superior resistance to radiation-induced swelling and embrittlement compared to conventional steels. For instance, Zinkle et al. (2017) found that void swelling in ODS ferritic/martensitic steel is negligible (<5% volume change) even after 500 dpa of irradiation, whereas standard ferritic/martensitic steels began to swell appreciably at lower doses. Moreover, the oxide nanoclusters in ODS steel have been reported to remain stable under high-temperature irradiation (300–750 °C) up to at least 50–100 dpa, ensuring durability (Zinkle et al., 2017).

Further advancements have been made through the introduction of nanostructured steels, which exhibit significantly improved yield strength and tensile ductility due to their unique grain structure. Gradient nanostructured ferritic steel, for instance, demonstrates an increase in yield strength by 36% and uniform elongation by 50% compared to conventionally structured steel (Shang et al., 2023). Shang et al. (2023) observed that the nanolaminate grains in gradient-structured steel facilitate deformation accommodation, reducing embrittlement while simultaneously improving mechanical performance. The study also documented an increase in yield strength by 36% and uniform elongation by 50% compared to conventionally structured steel. These findings highlight the role of nanostructured steel in enhancing the durability and service life of steel-based infrastructure subjected to high radiation exposure.

In addition to material improvements, surface treatments and protective coatings provide an effective means of mitigating corrosion and wear in radiation-exposed steel components. The application of biobased ion exchangers in corrosion protection coatings has been identified as a sustainable strategy for enhancing adhesion, moisture resistance, and corrosion protection (Soroushian et al., 2022). Soroushian et al. (2022) demonstrated that incorporating biobased ion exchangers at 1–2% by weight in polymer-based protective coatings effectively removes corrosive ions from diffusing solutions, thereby reducing steel degradation. Additionally, novel surface treatment techniques utilizing waste materials have been developed to enhance corrosion resistance (Kan et al., 2020). Kan et al. (2020) introduced a cost-effective approach using raw materials obtained from automotive waste, leading to the formation of a thin ceramic layer on the steel surface. This treatment significantly reduces decarburization and improves abrasion and corrosion resistance, extending the lifespan of steel components in harsh environments (Kan et al., 2020).

By integrating these strategies, steel can be significantly strengthened against radiation-induced degradation. These improvements collectively enhance the durability, strength, and sustainability of steel infrastructure, ensuring that nuclear waste containment systems and surrounding structures maintain their integrity over extended operational lifetimes.

6. Conclusions

In the evolving field of nuclear waste management, the advancements and challenges can be summarized with key takeaways that capture the essence of the discussion. These points reflect the ongoing efforts to handle nuclear waste responsibly, keeping human and environmental safety as top priorities.

- In terms of nuclear waste classification, in general, nuclear waste is classified into three primary categories based on radioactivity levels. However, classification approaches vary based on different countries, and notable differences exist among these classification approaches. Since the establishment of a standardised international classification system is vital for the legitimate regulation of nuclear waste, the IAEA has put forward a six-category classification system, and this system is being adopted in the context of nuclear waste management in Australia.
- Managing nuclear waste requires customized strategies depending on its classification, which ranges from low-level to high-level. Each type of waste undergoes different processes, with high-level waste requiring extensive pre-disposal treatments to mitigate risks associated with long-term storage.

- Significant advancements in nuclear waste management, especially for HLW, include cutting-edge technologies, including thermal treatment and P&T. These innovations reduce waste volume and radiotoxicity, contributing to safer, more efficient waste handling.
- Initiatives such as the PREDIS and THERAMIN projects under the Horizon 2020 Euratom program illustrate the international collaboration driving advancements in nuclear waste management. These efforts focus on minimising hazards and improving waste processing efficiency, aided by digital tools and material innovations.
- In the context of impacts on infrastructure, one major concern is the effect of radiation on storage materials such as concrete. Neutron and gamma radiation degrade concrete over time, posing a threat to the structural integrity of waste containment. Research suggests that enhanced materials, such as SCMs and steel fibres, can improve concrete's resilience against radiation damage. Furthermore, studies have shown that a 10% drop in compressive strength can be observed in concrete due to radiation, accompanied by an increase in total porosity. Moreover, radiation hardening and embrittlement were identified as the main concerns when considering steel structures.
- Provided the emergence of advanced technologies in infrastructure, such as digital fabrication and Design for Manufacturing and Assembly (DfMA) for 3D printing, further research is required to assess their potential influence on nuclear waste management. Additionally, the social impacts associated with these technological advancements, including international trade policies, sister-city investments, and tariff policies, should be explored. A comprehensive future study integrating technical and socio-economic factors is recommended to provide a holistic perspective on the evolving landscape of nuclear waste management.

These conclusions underscore the importance of continued innovation, collaboration, and research to address the global challenge of nuclear waste management and ensure that future generations are protected from the dangers of radioactive waste. While progress has been made, gaps remain between historical data and current conditions in nuclear waste disposal. Ongoing research is crucial, particularly in developing predictive models and improving containment materials, to ensure the long-term durability of nuclear waste management infrastructures.

Acknowledgements

The authors acknowledge Swinburne University of Technology and Federation University for their support in terms of technical, financial and other research facilities.

Conflicts of interest

The authors declare there are no conflicts of interest in this research.

References

Abdullah, M. A. H., Rashid, R. S. M., Amran, M., Hejazii, F., Azreen, N. M., Fediuk, R., Voo, Y. L., Vatin, N. I., & Idris, M. I. (2022). Recent trends in advanced radiation shielding concrete for construction of facilities: Materials and properties. *Polymers*, *14*(14), Article 2830. https://doi.org/10.3390/polym14142830

Adil, G., Kevern, J., & Mann, D. (2020). Influence of silica fume on mechanical and durability of pervious concrete. *Construction and Building Materials*, *247*, Article 118453. https://doi.org/10.1016/j.conbuildmat.2020.118453

Akkurt, I., Altindag, R., Onargan, T., Basyigit, C., Kılıncarslan, S., Kun, M., Mavi, B., & Güney, A. (2007). The properties of various igneous rocks for γ-ray shielding. *Construction and Building Materials*, *21*(12), 2078–2082. https://doi.org/10.1016/j.conbuildmat.2006.05.059

Alwaeli, M., & Mannheim, V. (2022). Investigation into the current state of nuclear energy and nuclear waste management—a state-of-the-art review. *Energies*, *15*(12), Article 4275. https://doi.org/10.3390/en15124275

Ambashta, R. D., & Sillanpää, M. E. (2012). Membrane purification in radioactive waste management: A short review. *Journal of Environmental Radioactivity*, *105*, 76–84. https://doi.org/10.1016/j.jenvrad.2011.12.002

Australian Radiation Protection and Nuclear Safety Agency. (2020). *Joint convention on the safety of spent fuel management and on the safety of radioactive waste management*: *Australian National Report of the Commonwealth of Australia 2020 to the Joint Convention Seventh Review Meeting October 2020*.

Australian Radioactive Waste Agency. (2022). *Australia's national inventory of radioactive waste 2021*.

Avramenko, V., Egorin, A., Papynov, E., Sokol'nitskaya, T., Tananaev, I., & Sergienko, V. (2017). Processes for treatment of liquid radioactive waste containing seawater. *Radiochemistry*, *59*, 407–413. https://doi.org/10.1134/S1066362217040142

Banthia, N., & Sappakittipakorn, M. (2007). Toughness enhancement in steel fiber reinforced concrete through fiber hybridization. *Cement and Concrete Research*, *37*(9), 1366–1372. https://doi.org/10.1016/j.cemconres.2007.05.005

Bashir, S. (2007). Performance assessment of near-surface facilities for disposal of low-level radioactive waste. *Medical Physics*, *34*(3), Article 1131. https://doi.org/10.1118/1.2567992

Benedito, A. V., Benedetty Torres, C. A., Silva, R. M. de C., Krahl, P. A., Cardoso, D. C. T., Silva, F. de A., & Martins, C. H. (2024). Effects of niobium addition on the mechanical properties and corrosion resistance of microalloyed steels: A review. *Buildings*, *14*(5), Article 1462. https://doi.org/10.3390/buildings14051462

Bennett, D., & Gens, R. (2008). Overview of European concepts for high-level waste and spent fuel disposal with special reference waste container corrosion. *Journal of Nuclear Materials*, *379*(1–3), 1–8. https://doi.org/10.1016/j.jnucmat.2008.06.001

Bevelacqua, J. (2023). *Speculative high-level nuclear waste processing methods*. Qeios. https://doi.org/10.32388/ERXS1B

Bhabha Atomic Research Centre. (2023). *Radioactive waste management*: *Indian scenario*. Department of Atomic Energy, Government of India.

Bonin, A., & Tsilanizara, A. (2017). A method to improve dose assessment by reconstruction of the complete isotopes inventory. *Radiation Protection Dosimetry*, *175*(1), 46–57. https://doi.org/10.1093/rpd/ncw266

Bowen, M., Ponangi, R. T., & Khan, H. (2024). *The waste isolation pilot plant completes 25 years of operation*. Nuclear Energy, Center on Global Energy Policy, Columbia University.

Braden, Z., & Macfarlane, A. (2023). The final countdown to site selection for Canada's nuclear waste geologic repository. *Bulletin of the Atomic Scientists*, *79*(1), 22–27. https://doi.org/10.1080/00963402.2022.2155007

Bruno, J., & Ewing, R. C. (2006). Spent nuclear fuel. *Elements*, *2*(6), 343–349. https://doi.org/10.2113/gselements.2.6.343

Bruno, J., Duro, L., & Diaz-Maurin, F. (2020). Spent nuclear fuel and disposal. In *Advances in nuclear fuel chemistry* (pp. 527–553). Elsevier. https://doi.org/10.1016/B978-0-08-102571-0.00014-8

Buck, E. C., Hanson, B. D., & McNamara, B. K. (2004). The geochemical behaviour of Tc, Np and Pu in spent nuclear fuel in an oxidizing environment. *Geological Society*, *London*, *Special Publications*, *236*(1), 65–88. https://doi.org/10.1144/GSL.SP.2004.236.01.05

Carbol, P., Wegen, D., Wiss, T., & Fors, P. (2012). Spent nuclear fuel as waste material. In R. Konings (Ed.), *Comprehensive nuclear materials* (pp. 389–420). Elsevier. https://doi.org/10.1016/B978-0-08-056033-5.00106-3

Chierici, A., Cancemi, S. A., Niederleithinger, E., & Frano, R. L. (2024). Enhanced radioactive waste drum monitoring: A sensorized LoRa-based network for identification and integrity assessment. *Nuclear Engineering and Design*, *424*, Article 113231. https://doi.org/10.1016/j.nucengdes.2024.113231

Choi, J.-H., Lee, B., Lee, K.-R., Kang, H. W., Eom, H. J., Shin, S.-S., Kim, G.-Y., & Park, H.-S. (2022). Characterization of waste generated from nuclide management process in waste burden minimization technology for spent nuclear fuel. *Science and Technology of Nuclear Installations*, *2022*, Article 4764825. https://doi.org/10.1155/2022/4764825

Chon, J. K., Beaudoin, V., & Pitcher, C. S. (2016). Conceptual design of volume reduction system for ITER low level radioactive waste. *Fusion Engineering and Design*, *109*, 1001–1004. https://doi.org/10.1016/j.fusengdes.2016.01.035

Corkhill, C., & Hyatt, N. (2018). *Nuclear waste management*. IOP Publishing. https://doi.org/10.1088/978-0-7503-1638-5

Cuccia, V., Uemura, G., Ferreira, V. V. M., Tello, C. C. O. de, & Malta, R. S. V. (2011). An updated overview of low and intermediate level waste disposal facilities around the world. In *2011 International Nuclear Atlantic Conference* (*INAC 2011*), Belo Horizonte, MG, Brazil.

Dąbrowski, M., Kuziak, J., Dziedzic, K., & Glinicki, M. A. (2023). Influence of environmental conditions on steel corrosion in concrete exposed to gamma radiation. *Materials Proceedings*, *13*(1), Article 44. https://doi.org/10.3390/materproc2023013044

Darda, S. A., Gabbar, H. A., Damideh, V., Aboughaly, M., & Hassen, I. (2021). A comprehensive review on radioactive waste cycle from generation to disposal. *Journal of Radioanalytical and Nuclear Chemistry*, *329*(1), 15–31. https://doi.org/10.1007/s10967-021-07764-2

Díaz Gámez, A. (2020). *A comparative legal study of radioactive waste disposal in France and Spain* [Thesis]. Universitat Autònoma de Barcelona.

Duffó, G. S., Farina, S. B., Schulz, F. M., & Marotta, F. (2010). Corrosion susceptibility of steel drums containing cemented intermediate level nuclear wastes. *Journal of Nuclear Materials*, *405*(3), 274–279. https://doi.org/10.1016/j.jnucmat.2010.08.016

Duffó, G. S., Farina, S. B., & Schulz, F. M. (2012). Corrosion of steel drums containing cemented ion-exchange resins as intermediate level nuclear waste. *MRS Online Proceedings Library*, *1475*(1), 501–506. https://doi.org/10.1557/opl.2012.623

Egorov, O. B., O'Hara, M. J., & Grate, J. W. (2012). Automated radioanalytical system incorporating microwave-assisted sample preparation, chemical separation, and online radiometric detection for the monitoring of total 99Tc in nuclear waste processing streams. *Analytical Chemistry*, *84*(7), 3090–3098. https://doi.org/10.1021/ac300418b

Ekidin, A. A., & Antonov, K. L. (2020). Application of the specific indicator for estimating the volume of radioactive waste generation during normal operation of Russian NPPs. *Radioactive Waste*, *2*(11), 66–74. https://doi.org/10.25283/2587-9707-2020-2-66-74

El-Samrah, M. G., Tawfic, A., & Chidiac, S. E. (2021). Spent nuclear fuel interim dry storage: Design requirements, most common methods, and evolution—A review. *Annals of Nuclear Energy*, *160*, Article 108408. https://doi.org/10.1016/j.anucene.2021.108408

El-Sayed, A. A., Fathy, I. N., Tayeh, B. A., & Almeshal, I. (2022). Using artificial neural networks for predicting mechanical and radiation shielding properties of different nano-concretes exposed to elevated temperature. *Construction and Building Materials*, *324*, Article 126663. https://doi.org/10.1016/j.conbuildmat.2022.126663

Engelhardt, H.-J., Fischer, T., Haverkamp, B., Wanne, T., & Wunderlich, A. (2023). Deep borehole disposal as a potential solution for high-level waste (HLW) and spent nuclear fuel (SNF) in Norway: Current status and a first generic safety assessment. *Safety of Nuclear Waste Disposal*, *2*, 31–30. https://doi.org/10.5194/sand-2-31-2023

Ewing, R., & Weber, W. (2010). Actinide waste forms and radiation effects. In L. R. Morss, N. M. Edelstein, & J. Fuger (Eds.), *The chemistry of the actinide and transactinide elements* (pp. 3813–3887). Springer, Dordrecht. https://doi.org/10.1007/978-94-007-0211-0_35

Fazzo, L., Minichilli, F., Santoro, M., Ceccarini, A., Della Seta, M., Bianchi, F., Comba, P., & Martuzzi, M. (2017). Hazardous waste and health impact: A systematic review of the scientific literature. *Environmental Health*, *16*, Article 107. https://doi.org/10.1186/s12940-017-0311-8

Federal Office for the Safety of Nuclear Waste Management. (2022). *Waste types*. BASE.

Fernández-Arias, P., Vergara, D., & Antón-Sancho, Á. (2023). Global review of international nuclear waste management. *Energies*, *16*(17), Article 6215. https://doi.org/10.3390/en16176215

Field, K. G., Remec, I., & Le Pape, Y. (2015). Radiation effects in concrete for nuclear power plants – Part I: Quantification of radiation exposure and radiation effects. *Nuclear Engineering and Design*, *282*, 126–143. https://doi.org/10.1016/j.nucengdes.2014.10.003

Finocchiaro, P. (2020). From nuclear physics to applications: Detectors for beam handling, medical diagnostics and radioactive waste monitoring. *The European Physical Journal Plus*, *135*(4), Article 345. https://doi.org/10.1140/epjp/s13360-020-00352-5

French National Radioactive Waste Management Agency. (2022). *Waste classification*. Andra.

Frizon, F., & Cau-dit-Coumes, C. (2006). Cementation of ILW ion exchange resins: Impact of sulfate ions released by radiolysis on hydrated matrix. *Journal of Nuclear Materials*, *359*(3), 162–173. https://doi.org/10.1016/j.jnucmat.2006.08.024

Fuks, L., Herdzik-Koniecko, I., Kiegiel, K., Miskiewicz, A., & Zakrzewska-Koltuniewicz, G. (2022). Methods of thermal treatment of radioactive waste. *Energies*, *15*(1), Article 375. https://doi.org/10.3390/en15010375

Gee, G. W., Meyer, P. D., & Ward, A. L. (2005). *Nuclear waste disposal*. Pacific Northwest National Laboratory. https://doi.org/10.1016/B0-12-348530-4/00524-5

Geetha Manjari, K., & Sivakumar Babu, G. (2018). Probabilistic analysis of groundwater and radionuclide transport model from near-surface disposal facilities. *Georisk*: *Assessment and Management of Risk for Engineered Systems and Geohazards*, *12*(1), 60–73. https://doi.org/10.1080/17499518.2017.1329538

Ghiloufi, I. (2009). Simulation of radioelement volatility during the vitrification of radioactive wastes by arc plasma. *Journal of Hazardous Materials*, *163*(1), 136–142. https://doi.org/10.1016/j.jhazmat.2008.06.110

Grygie, J.-M., & Romary, J.-M. (2015). *Radioactive waste management in France*: *Taking-up present and future challenges-15120*. WM Symposia, Inc.

Hélie, M. (2012). Corrosion issues in radioactive waste interim storage facilities. In *Nuclear corrosion science and engineering* (pp. 988–1014). Elsevier. https://doi.org/10.1533/9780857095343.988

Hilsdorf, H., Kropp, J., & Koch, H. (1978). The effects of nuclear radiation on the mechanical properties of concrete. *ACI Symposium*, *55*, 223–254.

Holt, E., & Jalonen, T. (2024). Recent advances from Finland's R&D, supporting final operation of the deep geological repository. In *WM2024 Conference*, Phoenix, Arizona, USA.

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. *Nuclear Sciences* & *Technologies*, *8*, Article 40. https://doi.org/10.1051/epjn/2022036

Hooton, R. D., & Bickley, J. A. (2014). Design for durability: The key to improving concrete sustainability. *Construction and Building Materials*, *67*, 422–430. https://doi.org/10.1016/j.conbuildmat.2013.12.016

Hu, G., & Pfingsten, W. (2023). Data-driven machine learning for disposal of high-level nuclear waste: A review. *Annals of Nuclear Energy*, *180*, Article 109452. https://doi.org/10.1016/j.anucene.2022.109452

International Atomic Energy Agency. (2006). *Application of thermal technologies for processing of radioactive waste*.

International Atomic Energy Agency. (2012). *Storage of spent nuclear fuel*.

International Atomic Energy Agency. (2009a). *Classification of radioactive waste*.

International Atomic Energy Agency. (2009b). *Policies and strategies for radioactive waste management*.

Iqbal, J., Howari, F. M., Mohamed, A.-M. O., & Paleologos, E. K. (2021). Assessment of radiation pollution from nuclear power plants. In *Pollution assessment for sustainable practices in applied sciences and engineering* (Chapter 20, pp. 1027–1053). Elsevier. https://doi.org/10.1016/B978-0-12-809582-9.00020-7

Jäckel, B. S., Steiner, P., & Klügel, J.-U. (2020). Loss-of-cooling accident calculations for the wet storage pool of NPP Gösgen/Däniken. *Nuclear Engineering and Design*, *370*, Article 110839. https://doi.org/10.1016/j.nucengdes.2020.110839

Jain, S., Onuaguluchi, O., Banthia, N., & Troczynski, T. (2025). Advancements in immobilization of cesium and strontium radionuclides in cementitious wasteforms—A review. *Journal of the American Ceramic Society*, *108*(1), Article e20131. https://doi.org/10.1111/jace.20131

Jang, J., Jeong, M.-S., Yoon, H., Lee, J.-H., Jung, H., Cho, C.-H., Lim, Y., Kim, B., & Lee, D. S. (2024). Radiological safety assessment for deep geological disposal of high-level radioactive waste. *International Journal of Energy Research*, *2024*, Article 6663859. https://doi.org/10.1155/2024/6663859

Jiménez-Reyes, M., Almazán-Sánchez, P., & Solache-Rios, M. (2021). Radioactive waste treatments by using zeolites: A short review. *Journal of Environmental Radioactivity*, *233*, Article 106610. https://doi.org/10.1016/j.jenvrad.2021.106610

Jin, M., Li, W., Yang, H., Li, X., Huang, M., Zeng, H., Ma, Y., & Tao, Z. (2023). Investigation on the compositional and performance evolution of cement paste subjected to xenon radiation. *Developments in the Built Environment*, *16*, Article 100291. https://doi.org/10.1016/j.dibe.2023.100291

Juenger, M. C., Snellings, R., & Bernal, S. A. (2019). Supplementary cementitious materials: New sources, characterization, and performance insights. *Cement and Concrete Research*, *122*, 257–273. https://doi.org/10.1016/j.cemconres.2019.05.008

Kan, W. H., Huang, S., Man, Z., Handoko, W., Chang, L., Pahlevani, F., Rasmussen, K., & Sahajwalla, V. (2020). Utilization of waste materials for the manufacturing of better-quality wear and corrosion-resistant steels. *Metallurgical and Materials Transactions A*, *51*, 2404–2410. https://doi.org/10.1007/s11661-020-05686-4

Kenik, E. A., & Busby, J. T. (2012). Radiation-induced degradation of stainless steel light water reactor internals. *Materials Science and Engineering*: *R*: *Reports*, *73*(7), 67–83. https://doi.org/10.1016/j.mser.2012.05.002

Kononenko, O. A., Milyutin, V. V., Makarenkov, V. I., & Kozlitin, E. A. (2021). Immobilization of NPP evaporator bottom high salt-bearing liquid radioactive waste into struvite-based phosphate matrices. *Journal of Hazardous Materials*, *416*, Article 125902. https://doi.org/10.1016/j.jhazmat.2021.125902

Kontani, O., Ichikawa, Y., Ishizawa, A., Takizawa, M., & Sato, O. (2014). Irradiation effects on concrete structures. In *Infrastructure systems for nuclear energy* (Chapter 27, pp. 459–473). Wiley. https://doi.org/10.1002/9781118536254.ch27

Kooyman, T. (2021). Current state of partitioning and transmutation studies for advanced nuclear fuel cycles. *Annals of Nuclear Energy*, *157*, Article 108239. https://doi.org/10.1016/j.anucene.2021.108239

Kuleshova, E. A., Fedotova, S. V., Gurovich, B. A., Frolov, A. S., Maltsev, D. A., Stepanov, N. V., Margolin, B. Z., Minkin, A. J., & Sorokin, A. A. (2020). Microstructure degradation of austenitic stainless steels after 45 years of operation as VVER-440 reactor internals. *Journal of Nuclear Materials*, *533*, Article 152124. https://doi.org/10.1016/j.jnucmat.2020.152124

Kumpula, L., Huhtanen, I., Palander, S., Ylä-Mella, M., & Kuhmonen, V. (2022). *Management of spent nuclear fuel and radioactive waste in Finland*: *Second national programme under Article 12 of Directive 2011/70/EURATOM of the Council of the European Union*. Ministry of Economic Affairs and Employment of Finland Helsinki.

Laverov, N. P., Yudintsev, S. V., Kochkin, B. T., & Malkovsky, V. I. (2016). The Russian strategy of using crystalline rock as a repository for nuclear waste. *Elements*, *12*(4), 253–256. https://doi.org/10.2113/gselements.12.4.253

Le Pape, Y., Giorla, A., & Sanahuja, J. (2016). Combined effects of temperature and irradiation on concrete damage. *Journal of Advanced Concrete Technology*, *14*(3), 70–86. https://doi.org/10.3151/jact.14.70

Le Pape, Y., Alsaid, M. H., & Giorla, A. B. (2018). Rock-forming minerals radiation-induced volumetric expansion: Revisiting literature data. *Journal of Advanced Concrete Technology*, *16*(5), 191–209. https://doi.org/10.3151/jact.16.191

Lee, S. Y., Daugherty, A. M., & Broton, D. J. (2013). Assessing aggregates for radiation-shielding concrete. *Concrete International*, *35*(5), 31–38.

Li, S. (2022). Estimation of decommissioning radioactive wastes quantity for nuclear power plant. In *Proceedings of the International Conference on Nuclear Engineering* (Vol. 9, Article ICONE29-91672). American Society of Mechanical Engineers. https://doi.org/10.1115/ICONE29-91672

Li, X. L., Bao, Y., Wu, L., Yan, Q., Ma, H., Chen, G., & Zhang, H. (2017). Thermal and mechanical properties of high-performance fiber-reinforced cementitious composites after exposure to high temperatures. *Construction and Building Materials*, *157*, 829–838. https://doi.org/10.1016/j.conbuildmat.2017.09.125

Lillington, J. N., Goût, T. L., Harrison, M. T., & Farnan, I. (2020). Predicting radioactive waste glass dissolution with machine learning. *Journal of Non-Crystalline Solids*, *533*, Article 119852. https://doi.org/10.1016/j.jnoncrysol.2019.119852

Lim, S.-H., Kim, S.-I., Song, J.-S., & Kim, K.-H. (2021). A study on the pelletizing condition for roll compaction of powdered radioactive wastes. *Powder Technology*, *384*, 554–563. https://doi.org/10.1016/j.powtec.2021.01.068

Liu, Y. (2015). Wet storage of spent nuclear fuel. In *Safe and secure transport and storage of radioactive materials* (Chapter 18, pp. 299–310). Elsevier. https://doi.org/10.1016/B978-1-78242-309-6.00018-6

Liu, J., & Dai, W. (2019). Overview of nuclear waste treatment and management. *E3S Web of Conferences*, *118*, Article 04037. https://doi.org/10.1051/e3sconf/201911804037

Liu, X., Liu, P., Dai, C., Liu, S., Deng, J., Zhang, W., & Yu, Z. (2019). Site screening of clay formations in NW China as host rocks for a high-level radioactive waste disposal repository. *Geological Society*, *London*, *Special Publications*, *482*(1), 93–99. https://doi.org/10.1144/SP482.17

Liu, R.-F., Chen, C.-K., & Yang, P.-Y. (2020). Safety aspects of spent fuel management in nuclear power plants during transition to decommissioning. *Annals of Nuclear Energy*, *144*, Article 107469. https://doi.org/10.1016/j.anucene.2020.107469

Makul, N. (2020). Modern sustainable cement and concrete composites: Review of current status, challenges and guidelines. *Sustainable Materials and Technologies*, *25*, Article e00155. https://doi.org/10.1016/j.susmat.2020.e00155

Mallants, D., Phalen, J., & Griffiths, H. (2021). Deep borehole disposal of intermediate-level waste. *Safety of Nuclear Waste Disposal*, *1*, 263–264. https://doi.org/10.5194/sand-1-263-2021

Manzano, L. G., Boukabache, H., Danzeca, S., Heracleous, N., Murtas, F., Perrin, D., Pirc, V., Alfaro, A. R., Zimmaro, A., & Silari, M. (2021). An IoT LoRaWAN network for environmental radiation monitoring. *IEEE Transactions on Instrumentation and Measurement*, *70*, Article 6008512. https://doi.org/10.1109/TIM.2021.3089776

Maruyama, I., Kontani, O., Sawada, S., Sato, O., Igarashi, G., & Takizawa, M. (2013). Evaluation of irradiation effects on concrete structure: Background and preparation of neutron irradiation test. In *ASME Power Conference* (Vol. 2, Article POWER2013-98114). American Society of Mechanical Engineers. https://doi.org/10.1115/POWER2013-98114

Maruyama, I., Kontani, O., Takizawa, M., Sawada, S., Ishikawao, S., Yasukouchi, J., Sato, O., Etoh, J., & Igari, T. (2017). Development of soundness assessment procedure for concrete members affected by neutron and gamma-ray irradiation. *Journal of Advanced Concrete Technology*, *15*(9), 440–523. https://doi.org/10.3151/jact.15.440

Maruyama, I., Takizawa, M., Sato, O., Etoh, J., Kontani, O., Sawada, S., & Ishikawa, S. (2021). Post-Japanese NRA research project on soundness evaluation criteria for radiation-induced concrete degradation. In *Nuclear Power Plant Life Management*: *Proceedings of an International Conference*. IAEA.

Masoud, M., Kansouh, W., Shahien, M., Sakr, K., Rashad, A. M., & Zayed, A. (2020). An experimental investigation on the effects of barite/hematite on the radiation shielding properties of serpentine concretes. *Progress in Nuclear Energy*, *120*, Article 103220. https://doi.org/10.1016/j.pnucene.2019.103220

McEvoy, F., Schofield, D., Shaw, R., & Norris, S. (2016). Tectonic and climatic considerations for deep geological disposal of radioactive waste: A UK perspective. *Science of the Total Environment*, *571*, 507–521. https://doi.org/10.1016/j.scitotenv.2016.07.018

Metz, V., Geckeis, H., Gonzalez-Robles, E., Loida, A., Bube, C., & Kienzler, B. (2012). Radionuclide behaviour in the near-field of a geological repository for spent nuclear fuel. *Radiochimica Acta*, *100*(8–9), 699–713. https://doi.org/10.1524/ract.2012.1967

Miśkiewicz, A., Nowak, A., Pałka, J., & Zakrzewska-Kołtuniewicz, G. (2021). Liquid low-level radioactive waste treatment using an electrodialysis process. *Membranes*, *11*(5), Article 324. https://doi.org/10.3390/membranes11050324

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L. A., & PRISMA-P Group. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews*, *4*, Article 1. https://doi.org/10.1186/2046-4053-4-1

Murty, K. L. (1984). Is neutron radiation exposure always detrimental to metals (steels)?. *Nature*, *308*, 51–52. https://doi.org/10.1038/308051a0

Nazeeh, K., & Sivakumar Babu, G. (2018). Reliability analysis of near-surface disposal facility using subset simulation. *Environmental Geotechnics*, *6*(4), 242–249. https://doi.org/10.1680/jenge.17.00004

Neuvazhaev, G., Rastorguev, A., Morozov, O., Kapyrin, I., & Grigorev, F. (2020). 3D hydrogeological modeling of deep geological disposal in the Nizhnekansky rock massif. In *EGU General Assembly* (Article 21509). https://doi.org/10.5194/egusphere-egu2020-21509

Nicholson, K., McDonald, J., Draper, S., Ikeda, B. M., & Pioro, I. (2013). Centralization of Canada's spent nuclear fuel. In *International Conference on Nuclear Engineering* (Vol. 6, Article ICONE21-16511). American Society of Mechanical Engineers. https://doi.org/10.1115/ICONE21-16511

Nieminen, M., Olin, M., Laatikainen-Luntama, J., Wickham, S. M., Doudou, S., Fuller, A. J., Kent, J., Fournier, M., Clarke, S., & Scales, C. (2020). Thermal treatment for radioactive waste minimisation. *EPJ Nuclear Sciences & Technologies*, *6*, Article 25. https://doi.org/10.1051/epjn/2019040

Noseck, U., Wellmann, P., Rübel, A., Kindlein, J., Panning, D., & Wolf, J. (2023). Selection of essential records from a repository program to inform future generations: Insights from a study for the Konrad repository. *Safety of Nuclear Waste Disposal*, *2*, 229–238. https://doi.org/10.5194/sand-2-229-2023

Nuclear Decommissioning Authority. (2023). *UK Radioactive Waste Inventory 2022*. Department for Business, Energy & Industrial Strategy.

Nuclear Energy Agency, & Organisation for Economic Co-operation and Development. (2006). *Waste generation processes and waste characteristics*.

Nuclear Energy Agency, & Organisation for Economic Co-operation and Development. (2008). *Radioactive waste management and decommissioning*.

Nuclear Science Research Institute. (2014). *Generation and classification of radioactive waste*. Japan Atomic Energy Agency.

Nuclear Waste Management Organization of Japan. (2021). *The NUMO pre-siting SDM-based safety case*.

Nuttall, W. J. (2022). *Nuclear renaissance*: *Technologies and policies for the future of nuclear power*. CRC Press. https://doi.org/10.1201/9781003038733

Ojovan, M., & Lee, W. (2014). *An introduction to nuclear waste immobilisation*. International Atomic Energy Agency. https://doi.org/10.1016/B978-0-08-099392-8.00020-6

Ojovan, M., Lee, W., & Kalmykov, S. (2019a). Principles of nuclear waste management. In M. I. Ojovan, W. E. Lee, & S. N. Kalmykov (Eds.), *An introduction to nuclear waste immobilisation* (Chapter 9, pp. 107–118). Elsevier. https://doi.org/10.1016/B978-0-08-102702-8.00009-1

Ojovan, M., Lee, W., & Kalmykov, S. (2019b). Nuclear waste types and sources. In M. I. Ojovan, W. E. Lee, & S. N. Kalmykov (Eds.), *An introduction to nuclear waste immobilisation* (Chapter 10, pp. 119–143). Elsevier. https://doi.org/10.1016/B978-0-08-102702-8.00010-8

Ojovan, M., Lee, W., & Kalmykov, S. (2019c). Immobilisation of radioactive wastes in glass. In M. I. Ojovan, W. E. Lee, & S. N. Kalmykov (Eds.), *An introduction to nuclear waste immobilisation* (Chapter 19, pp. 319–368). Elsevier. https://doi.org/10.1016/B978-0-08-102702-8.00019-4

Ojovan, M., Lee, W., & Kalmykov, S. (2019d). Nuclear waste regulations. In *An introduction to nuclear waste immobilisation* (Chapter 8, pp. 81–106). Elsevier. https://doi.org/10.1016/B978-0-08-102702-8.00008-X

Pabby, A., Swain, B., Sonar, N., Mittal, V., Valsala, T., Ramsubramanian, S., Sathe, D., Bhatt, R., & Pradhan, S. (2022). Radioactive waste processing using membranes: State of the art technology, challenges and perspectives. *Separation & Purification Reviews*, *51*(2), 143–173. https://doi.org/10.1080/15422119.2021.1878221

Panesar, D. K., Zhang, R., & Narneni, S. R. (2021). Chemical and physical approaches to improve the properties of concrete for application to nuclear related structures. *Nuclear Engineering and Design*, *374*, Article 111041. https://doi.org/10.1016/j.nucengdes.2020.111041

Paraskevoulakos, C., Stitt, C., Hallam, K., Banos, A., Olloqui, M. L., Jones, C., Griffiths, G., Adamska, A., Jowsey, J., & Scott, T. (2019). Monitoring the degradation of nuclear waste packages induced by interior metallic corrosion using synchrotron X-ray tomography. *Construction and Building Materials*, *215*, 90–103. https://doi.org/10.1016/j.conbuildmat.2019.04.178

Paschoa, A., & Tranjan Filho, A. (1995). Radioactive waste management in developing and newly industrialized countries. *Applied Radiation and Isotopes*, *46*(6–7), 707–715. https://doi.org/10.1016/0969-8043(95)00136-0

Patra, K., Sengupta, A., Mittal, V. K., Bera, S., Sahu, A. K., & Valsala, T. P. (2022). Understanding the mechanism of Cs accumulation on stainless steel suspended in nuclear high-level liquid waste. *ACS Omega*, *7*(38), 34190–34199. https://doi.org/10.1021/acsomega.2c03535

Paulillo, A., Dodds, J. M., Milliken, A., Palethorpe, S. J., & Lettieri, P. (2020). The environmental impacts of reprocessing used nuclear fuels: A UK case study. *Sustainable Materials and Technologies*, *25*, Article e00186. https://doi.org/10.1016/j.susmat.2020.e00186

Pomaro, B. (2016). A review on radiation damage in concrete for nuclear facilities: From experiments to modeling. *Modelling and Simulation in Engineering*, *2016*, Article 4165746. https://doi.org/10.1155/2016/4165746

Posiva. (2023). *Annual report*.

Potts, A., Butcher, E., Cann, G., & Leay, L. (2021). Long-term effects of gamma irradiation on in-service concrete structures. *Journal of Nuclear Materials*, *548*, Article 152868. https://doi.org/10.1016/j.jnucmat.2021.152868

Ragoussi, M.-E., & Costa, D. (2019). Fundamentals of the NEA thermochemical database and its influence over national nuclear programs on the performance assessment of deep geological repositories. *Journal of Environmental Radioactivity*, *196*, 225–231. https://doi.org/10.1016/j.jenvrad.2017.02.019

Rahman, R. A., Ibrahium, H., & Hung, Y.-T. (2011). Liquid radioactive wastes treatment: A review. *Water*, *3*(2), 551–565. https://doi.org/10.3390/w3020551

Raj, K., Prasad, K., & Bansal, N. (2006). Radioactive waste management practices in India. *Nuclear Engineering and Design*, *236*(7–8), 914–930. https://doi.org/10.1016/j.nucengdes.2005.09.036

Rakhimova, N. (2022). Recent advances in alternative cementitious materials for nuclear waste immobilization: A review. *Sustainability*, *15*(1), Article 689. https://doi.org/10.3390/su15010689

Rasheed, P. A., Nayar, S. K., Barsoum, I., & Alfantazi, A. (2022). Degradation of concrete structures in nuclear power plants: A review of the major causes and possible preventive measures. *Energies*, *15*(21), Article 8011. https://doi.org/10.3390/en15218011

Remec, I., Rosseel, T. M., Field, K. G., & Le Pape, Y. (2017). Characterization of radiation fields for assessing concrete degradation in biological shields of NPPs. *EPJ Web of Conferences*, *153*, Article 05009. https://doi.org/10.1051/epjconf/201715305009

Robira, M., Hilloulin, B., Loukili, A., Potin, G., Bourbon, X., & Abdelouas, A. (2018). Multi-scale investigation of the effect of γ irradiations on the mechanical properties of cementitious materials. *Construction and Building Materials*, *186*, 484–494. https://doi.org/10.1016/j.conbuildmat.2018.07.038

Rosenfeld, P. E., & Feng, L. (2011). *Risks of hazardous wastes*. William Andrew. https://doi.org/10.1016/B978-1-4377-7842-7.00013-1

Rothwell, G. (2021). Spent nuclear fuel storage: What are the relationships between size and cost of the alternatives? *Energy Policy*, *150*, Article 112126. https://doi.org/10.1016/j.enpol.2020.112126

Sanders, M. H., & Sanders, C. E. (2019). *Nuclear waste management strategies*: *An international perspective*. Academic Press. https://doi.org/10.1016/B978-0-12-813738-3.00003-0

Sandri, S., Contessa, G. M., D'Arienzo, M., Guardati, M., Guarracino, M., Poggi, C., & Villari, R. (2020). A review of radioactive wastes production and potential environmental releases at experimental nuclear fusion facilities. *Environments*, *7*(1), Article 6. https://doi.org/10.3390/environments7010006

Sasano, H., Maruyama, I., Sawada, S., Ohkubo, T., Murakami, K., & Suzuki, K. (2020). Meso-scale modelling of the mechanical properties of concrete affected by radiation-induced aggregate expansion. *Journal of Advanced Concrete Technology*, *18*(10), 648–677. https://doi.org/10.3151/jact.18.648

Selvam, D. C., Devarajan, Y., & Raja, T. (2025). Exploring the potential of artificial intelligence in nuclear waste management: Applications, challenges, and future directions. *Nuclear Engineering and Design*, *431*, Article 113719. https://doi.org/10.1016/j.nucengdes.2024.113719

Shang, Z., Sun, T., Ding, J., Richter, N. A., Heckman, N. M., White, B. C., Boyce, B. L., Hattar, K., Wang, H., & Zhang, X. (2023). Gradient nanostructured steel with superior tensile plasticity. *Science Advances*, *9*(22), Article eadd9780. https://doi.org/10.1126/sciadv.add9780

Siddique, R., & Kaur, D. (2012). Properties of concrete containing ground granulated blast furnace slag (GGBFS) at elevated temperatures. *Journal of Advanced Research*, *3*(1), 45–51. https://doi.org/10.1016/j.jare.2011.03.004

Simonen, E., & Bruemmer, S. (1998). Radiation effects on environmental cracking of stainless steels. *JOM*, *50*, 52–55. https://doi.org/10.1007/s11837-998-0309-3

Slugeň, V., Sojak, S., Egger, W., Krsjak, V., Simeg Veternikova, J., & Petriska, M. (2020). Radiation damage of reactor pressure vessel steels studied by positron annihilation spectroscopy—A review. *Metals*, *10*(10), Article 1378. https://doi.org/10.3390/met10101378

Smart, N., Rance, A., & Werme, L. (2008). The effect of radiation on the anaerobic corrosion of steel. *Journal of Nuclear Materials*, *379*(1–3), 97–104. https://doi.org/10.1016/j.jnucmat.2008.06.007

Solans, V., Rochman, D., Brazell, C., Vasiliev, A., Ferroukhi, H., & Pautz, A. (2021). Optimisation of used nuclear fuel canister loading using a neural network and genetic algorithm. *Neural Computing and Applications*, *33*(23), 16627–16639. https://doi.org/10.1007/s00521-021-06258-2

Solomon, B. D. (2021). Solving a wicked problem in deep time: Nuclear waste disposal. *Science and Engineering Ethics*, *27*, Article 21. https://doi.org/10.1007/s11948-021-00299-5

Son, Y., Lee, S. Y., Jung, J., & Kim, C.-L. (2019). Development of chemical and biological decontamination technology for radioactive liquid wastes and feasibility study for application to liquid waste management system in APR1400. *Journal of Nuclear Fuel Cycle and Waste Technology*, *17*(1), 59–73. https://doi.org/10.7733/jnfcwt.2019.17.1.59

Soo, P., & Milian, L. (2001). The effect of gamma radiation on the strength of Portland cement mortars. *Journal of Materials Science Letters*, *20*(14), 1345–1348. https://doi.org/10.1023/A:1010971122496

Soroushian, P., Balachandra, A., Weerasiri, R., Darsanasiri, N., & Abdol, N. (2022). A sustainable approach to improvement of corrosion protection coatings for steel structures. *Civil Engineering Journal*, *31*(1), Article 1. https://doi.org/10.14311/CEJ.2022.01.0001

Spent Fuel and Radioactive Waste Information System. (2022). *Radioactive waste summary*. International Atomic Energy Agency (IAEA).

Spykman, G. (2018). Dry storage of spent nuclear fuel and high active waste in Germany—Current situation and technical aspects on inventories integrity for a prolonged storage time. *Nuclear Engineering and Technology*, *50*(2), 313–317. https://doi.org/10.1016/j.net.2018.01.009

Stavropoulou, E., Briffaut, M., Dufour, F., & Camps, G. (2020). Time-dependent behaviour of the Callovo-Oxfordian claystone-concrete interface. *Journal of Rock Mechanics and Geotechnical Engineering*, *12*(1), 89–101. https://doi.org/10.1016/j.jrmge.2019.09.001

Svensk Kärnbränsförhantering. (2024). *Environmental judgement means construction can start on SKB's spent fuel repository*. Swedish Nuclear Fuel Management.

Tan, S., Chang, J., Liu, X., Sun, S., Xian, L., & Zhang, S. (2023). Influence of radioactive sludge content on vitrification of high-level liquid waste. *Sustainability*, *15*(6), Article 4937. https://doi.org/10.3390/su15064937

Thakur, D., Sonar, N., Pabby, A. K., Valsala, T., Sathe, D., & Bhatt, R. (2021). Separation of 99 Tc from low level radioactive liquid waste using hollow fiber supported liquid membrane: Optimisation and performance evaluation. *Journal of Radioanalytical and Nuclear Chemistry*, *330*, 811–820. https://doi.org/10.1007/s10967-021-07983-7

Terranova, M. L., & Tavares, O. A. (2024). Trends and perspectives on nuclear waste management: Recovering, recycling, and reusing. *Journal of Nuclear Engineering*, *5*(3), 299–317. https://doi.org/10.3390/jne5030020

The Geological Society. (2020). *Geological disposal of radioactive waste*. London.

The People's Republic of China. (2017). *Fourth national report for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*. Beijing, China.

Thomas, K., Baehr, W., & Plumb, G. (1989). Radioactive waste management in developing countries. *IAEA Bulletin*, *31*(4), 32–36.

Vodák, F., Trtík, K., Sopko, V., Kapičková, O., & Demo, P. (2005). Effect of γ-irradiation on strength of concrete for nuclear-safety structures. *Cement and Concrete Research*, *35*(7), 1447–1451. https://doi.org/10.1016/j.cemconres.2004.10.016

Vodák, F., Vydra, V., Trtík, K., & Kapičková, O. (2011). Effect of gamma irradiation on properties of hardened cement paste. *Materials and Structures*, *44*, 101–107. https://doi.org/10.1617/s11527-010-9612-x

Wagner, J. C. (2016). *Spent nuclear fuel disposition*. Idaho National Lab. (INL), Idaho Falls, ID, United States.

Wallenius, J. (2019). Maximum efficiency nuclear waste transmutation. *Annals of Nuclear Energy*, *125*, 74–79. https://doi.org/10.1016/j.anucene.2018.10.034

Wang, J., Xu, G., Zheng, H., Fan, X., Wang, C., & Fan, Z. (2005). Geological disposal of high level radioactive waste in China: Progress during 1985–2004. *World Nuclear Geoscience*, *22*(1), 5–15.

Wang, J., Chen, L., Su, R., & Zhao, X. (2018). The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: Planning, site selection, site characterization and in situ tests. *Journal of Rock Mechanics and Geotechnical Engineering*, *10*(3), 411–435. https://doi.org/10.1016/j.jrmge.2018.03.002

Wisnubroto, D., Zamroni, H., Sumarbagiono, R., & Nurliati, G. (2021). Challenges of implementing the policy and strategy for management of radioactive waste and nuclear spent fuel in Indonesia. *Nuclear Engineering and Technology*, *53*(2), 549–561. https://doi.org/10.1016/j.net.2020.07.005

Wolff, D., Bevilacqua, A., Carlsen, B., Chiguer, M., González-Espartero, A., Grahn, P., Saegusa, T., Sampson, M., Seelev, I., & Wasinger, K. (2019). *Storing spent fuel until transport to reprocessing or disposal* (IAEA Nuclear Energy Series No. NF-T-3.3, pp. 1–54). IAEA Publishing Section.

World Nuclear Association. (2020a). *Radioactive waste management*. London.

World Nuclear Association. (2020b). *Storage and disposal options for radioactive waste*. London.

World Nuclear Association. (2023). *Radioactive waste repository* & *store for Australia*. London.

Yang, G., Clarkson, T., Gardner, S., Ireland, D., Kaiser, R., Mahon, D., Jebali, R. A., Shearer, C., & Ryan, M. (2019). Novel muon imaging techniques. *Philosophical Transactions of the Royal Society A*, *377*, Article 20180062. https://doi.org/10.1098/rsta.2018.0062

Yim, M.-S. (2022). *Nuclear waste management*. Springer. https://doi.org/10.1007/978-94-024-2106-4

Zakrzewska-Trznadel, G. (2013). Advances in membrane technologies for the treatment of liquid radioactive waste. *Desalination*, *321*, 119–130. https://doi.org/10.1016/j.desal.2013.02.022

Zbinden, D., Lengler, U., Luu, K., Shabani, B., Li, C., & Papafotiou, A. (2023). Multiphase flow modeling at the component level for the Swiss deep geological repository. *Safety of Nuclear Waste Disposal*, *2*, 131–130. https://doi.org/10.5194/sand-2-131-2023

Zhang, H., Zhang, Q., Chen, Y., Shao, J., Cui, Y., Wan, W., & Han, S. (2022). Groundwater flow modeling of a near-surface disposal repository for low- and intermediate-level radioactive waste in Southwest China. *Frontiers in Environmental Science*, *10*, Article 917416. https://doi.org/10.3389/fenvs.2022.917416

Zhou, L., Li, F., Liu, J.-X., Sun, S.-K., Liang, Y., & Zhang, G.-J. (2021). High-entropy A2B2O7-type oxide ceramics: A potential immobilising matrix for high-level radioactive waste. *Journal of Hazardous Materials*, *415*, Article 125596. https://doi.org/10.1016/j.jhazmat.2021.125596

Zinkle, S., Boutard, J., Hoelzer, D., Kimura, A., Lindau, R., Odette, G., Rieth, M., Tan, L., & Tanigawa, H. (2017). Development of next generation tempered and ODS reduced activation ferritic/martensitic steels for fusion energy applications. *Nuclear Fusion*, *57*(9), Article 092005. https://doi.org/10.1088/1741-4326/57/9/092005