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Research on Secondary Waste Minimization Technology in Nuclear Waste Treatment

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Abstract. Nuclear energy development faces many challenges in secondary waste treatment. Its high radioactivity, complex composition, and diverse morphology increase the difficulty of treatment. This paper introduces the key technologies for minimizing secondary waste from the perspective of nuclear power plant operation, fuel reprocessing, and facility decommissioning. The source reduces the amount of production by optimizing the process, utilizing corrosion-resistant materials, and implementing classified management. Compression, incineration, and melting, as well as other volume reduction technologies, reduce the volume and improve stability. Resource-based approaches extract nuclides, prepare shielding materials, and produce industrial products for recycling. New technologies also show potential in efficient volume reduction and stable solidification. Currently, related technologies are still limited by several issues, including high costs and the immaturity of certain technologies. In the future, we should strengthen the research and development of low-cost technologies, improve regulatory supervision and international cooperation, and promote the sustainable development of nuclear waste management.

Keywords: nuclear waste treatment, secondary waste, minimization technology

1. Introduction

In the global energy landscape, nuclear energy is assuming an increasingly pivotal role. Against the backdrop of depleting traditional fossil fuels and mounting concerns over environmental protection, nuclear energy—hailed as a clean and highly efficient energy source—is gradually emerging as an indispensable cornerstone of many nations' energy strategies. In recent years, the global tally of nuclear power plants has maintained steady growth, while the share of nuclear power in total electricity generation has continued its upward trajectory [1].

A concomitant challenge in the advancement of nuclear energy is the inevitable generation of nuclear waste. The pathways through which nuclear waste arises are intricate and multifaceted: they encompass spent fuel produced when nuclear fuel undergoes fission within reactor cores during nuclear power plant operations; various waste streams generated during chemical separation and associated processing of spent fuel at the reprocessing stage; and contaminated equipment, construction materials, and debris resulting from the decommissioning of nuclear facilities. These nuclear wastes contain substantial quantities of radioactive substances, and any mishandling poses

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grave and far-reaching threats to both the environment and human health. Presently, conventional nuclear waste treatment technologies in common use include solidification, transmutation, reprocessing, geological disposal, and free-electron laser applications [2]. Nevertheless, these traditional methods often fall short in effectively addressing secondary waste, necessitating the adoption of specialized secondary waste minimization technologies.

This paper provides an overview of the sources, composition, and minimization technologies of secondary waste, with the objective of enhancing the safety and sustainability of nuclear waste management practices.

2. Overview of secondary waste

2.1. Definition and characteristics of secondary waste

Secondary waste refers to new waste streams generated through the application of various treatment technologies and methods during the processing of nuclear waste. The radioactive levels of secondary waste vary depending on the specific treatment technologies employed and the nature of the original waste. Some secondary wastes may even exhibit relatively high radioactivity, thereby necessitating the implementation of stringent protective measures. In terms of composition, secondary waste is notably complex, encompassing radioactive nuclides, chemical reagents, additives, reaction by-products, and other substances. It also exists in diverse physical forms, which may be solid, liquid, or gaseous.

2.2. Sources of secondary waste

Table 1 outlines the sources of secondary waste generated by different types of nuclear activities. As indicated in Table 1, while the sources of secondary waste from various nuclear activities possess distinct characteristics, they all share the common traits of radioactivity and compositional complexity. These shared attributes present varying degrees of challenges for subsequent treatment processes.

Table 1. Secondary waste generated by different nuclear activities

Nuclear Activity	Specific Sources of Secondary Waste
Nuclear power plant operation	Ion exchange resins, filter cores, etc., generated during reactor coolant purification; contaminated metal parts and tools from equipment maintenance and replacement; activated carbon and filters from radioactive gas treatment; sludge and evaporation residues from radioactive wastewater treatment, etc.
Nuclear fuel reprocessing	A large amount of organic solvents is used in chemical separation processes, which become radioactive-contaminated waste solvents after extraction, back-extraction, etc.; waste residue formed after reactions of chemical reagents used for precipitation and separation of radioactive nuclides; discarded filters and ion exchange resins containing radioactive substances generated during treatment, etc.
Nuclear facility decommissioning	Contaminated building materials such as concrete and steel generated during demolition; radioactive coatings, oil stains, and other pollutants on the surface of decommissioned equipment; sludge and residues from wastewater treatment after cleaning decommissioned equipment and sites.

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2.3. Analysis of secondary waste composition

The composition of secondary waste is highly complex and diverse. Inorganic substances constitute a significant component, typically including metal oxides, salts, and other compounds. During the operation and decommissioning of nuclear facilities, metal components undergo radiation and chemical corrosion, leading to the formation of metal oxides. Meanwhile, chemical agents added during wastewater treatment processes react to produce various salt-based substances, which also contribute to the inorganic fraction of secondary waste.

Organic substances also form an integral part of secondary waste. Organic solvents employed in the nuclear fuel reprocessing stage, such as tributyl phosphate, become part of secondary waste after fulfilling their extraction functions. Additionally, certain organic materials used for equipment lubrication and protection, once contaminated by radioactivity, are classified as secondary waste.

Radioactive nuclides represent a critical component of secondary waste. These include long-lived actinides like plutonium and americium, as well as fission products such as cesium-137 and strontium-90. Due to their varying half-lives and distinct radiation characteristics, these nuclides increase both the complexity and risk associated with the treatment and disposal of secondary waste. The coexistence of multiple components necessitates comprehensive consideration of numerous factors and the development of targeted treatment technologies for effective secondary waste processing.

2.4. Challenges posed by secondary waste

Secondary waste presents numerous challenges throughout the treatment process. Traditional treatment methods often fail to meet required standards, necessitating the development of specialized technologies tailored to secondary waste—a requirement that inevitably increases both treatment costs and technical complexity. Storing secondary waste is equally challenging, as it demands the construction of highly protective storage facilities to prevent radioactive leakage over extended periods. Suitable storage sites are difficult to identify, and the maintenance and management of such facilities incur substantial costs.

The potential threats posed by secondary waste to the environment and human health cannot be overlooked. In the event of a leakage accident, radioactive substances would spread rapidly, contaminating soil, water sources, and air, and inflicting devastating harm on ecosystems. Human exposure to contaminated environments may trigger various diseases, including cancer and gene mutations, thereby severely impacting human survival and development.

3. Analysis of secondary waste minimization technologies

The secondary waste generated in the current nuclear waste treatment process faces many problems, such as low efficiency of chemical treatment, where nuclides like technetium-99 and iodine-129 are difficult to separate effectively; deficiencies in solidification technologies, as glass/ceramic solidification has high energy consumption and its long-term stability is questionable, while cement solidification is prone to cracking; risks of secondary pollution, as incineration may release gaseous radioactive nuclides; and waste volume expansion and short material lifespan. These limitations can be improved by adopting corresponding technologies to build a more efficient, low-carbon, and safe nuclear waste treatment system.

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3.1. Source reduction strategies

Optimizing process flows is an extremely critical measure in source reduction. Carefully sorting out and improving the nuclear waste treatment process can effectively eliminate unnecessary intermediate links, thereby reducing the generation of secondary waste. For example, in a nuclear power plant, advanced ion exchange technology was applied in the reactor coolant purification process, and the resin regeneration process was optimized, which extended the service life of ion exchange resins and reduced the secondary waste generated due to frequent resin replacement [3].

The use of corrosion-resistant materials can effectively reduce the corrosion rate of equipment, thereby reducing secondary waste generated from equipment maintenance or replacement. During the construction of nuclear facilities, selecting new corrosion-resistant alloy materials to manufacture key equipment, such as reactor pressure vessels, can not only increase the service life of the equipment but also reduce the amount of secondary waste generated from the accumulation of corrosion products [4].

Strengthening waste classification can help accurately treat nuclear waste, preventing the mixing of different types of waste from increasing treatment difficulty and secondary waste generation. In nuclear fuel reprocessing plants, strict classified collection of waste with different radioactive levels and compositions is implemented, and specialized treatment methods are selected according to different types of waste, significantly reducing the generation of secondary waste in subsequent treatment links. The implementation of these source reduction measures cuts down the generation of secondary waste at the source, alleviating the pressure on subsequent treatment.

3.2. Volume reduction methods

Compression, as a commonly used volume reduction method, works by compacting loose solid secondary waste through mechanical pressure to reduce its occupied volume. The specific operation process usually involves placing the waste into specially designed compression equipment and applying pressure through hydraulic or mechanical devices to arrange waste particles closely. After compression treatment, the volume of solid secondary waste is significantly reduced, which undoubtedly facilitates subsequent storage and transportation. For example, compressing the discarded filter cores generated by nuclear power plants can reduce their volume to a fraction of the original [5].

Incineration is a method that decomposes organic substances in secondary waste through high-temperature oxidation to achieve volume reduction. During the incineration process, secondary waste is fed into a high-temperature incinerator, where organic substances are decomposed into harmless gases such as carbon dioxide and water under sufficient oxygen conditions, while the remaining inorganic substances eventually form ash. Incineration can not only significantly reduce the volume of secondary waste but also effectively reduce its radioactive level. However, the incineration process must strictly control temperature and gas emissions to avoid secondary pollution.

Vitrification involves melting secondary waste at high temperatures to form dense glass or ceramic bodies. This method can firmly fix radioactive nuclides in stable lattice structures, thereby reducing their mobility [6]. In the specific operation process, secondary waste is mixed with specific additives and then placed into a melting furnace, heated to a high temperature until completely melted, and then cooled to form a certain shape. The product after vitrification treatment has a significantly reduced volume compared to before and possesses excellent chemical stability and mechanical strength, which is extremely beneficial for long-term storage and subsequent disposal.

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3.3. Resource utilization approaches

Extracting useful nuclides is a key approach to resource utilization of secondary waste. Secondary waste contains some valuable nuclides such as plutonium and americium. With advanced chemical separation technologies, these useful nuclides can be extracted from secondary waste and reused in nuclear fuel production or other related fields. For example, in the secondary recovery of specific volcanic rock-type uranium tailings, a process flow of nitric acid stirring, leaching-anion exchange-precipitation of yellow cake is adopted. Uranium concentrates with a uranium mass fraction of 65% to 75% can be obtained, and the uranium recovery rate can exceed 90% under optimal process conditions. In addition, the uranium mass fraction in the leaching residue can be effectively controlled within the range of (20 to 30) × 10-6 [7].

Preparing radiation shielding materials is also an effective way to achieve resource utilization. By utilizing certain specific components in secondary waste, such as heavy metal-containing substances, high-performance radiation shielding materials can be produced through special processing operations. These materials can be used in various fields such as nuclear facilities and medical equipment, providing strong support for radiation protection. For instance, lead-based materials in secondary waste are processed and modified to produce radiation shielding plates, which have been widely used in protection projects in nuclear power plants [8].

Producing industrial products is an innovative direction for secondary waste resource utilization. After appropriate treatment and processing of secondary waste, it can be converted into industrial products with certain use value. For example, treated secondary waste is mixed with other materials to produce construction bricks, which are then used in various construction projects around nuclear facilities. This approach not only achieves the goal of resource utilization of secondary waste but also reduces treatment costs, thus having good economic and environmental benefits.

4. Future prospects of secondary waste minimization technologies

4.1. Exploration of new and efficient volume reduction technologies

Supercritical water oxidation technology, as an emerging volume reduction method, is making significant research progress. Supercritical water technology is a technology that utilizes the special physical and chemical properties of water in the supercritical state (temperature higher than 374°C, pressure higher than 22.1MPa) for reactions and treatment. Supercritical water has unique solubility and reaction activity, enabling rapid oxidation and decomposition of organic substances in it. Currently, efficient treatment of various organic secondary wastes has been successfully achieved at the laboratory stage, significantly reducing waste volume and radioactive levels. Some pilot projects are also advancing steadily, verifying the feasibility of this technology in continuous and large-scale treatment. In the future, it is expected to be applied on a large scale in nuclear waste treatment plants to achieve efficient volume reduction of organic secondary waste [9]. However, this technology faces key bottlenecks such as reactor corrosion, salt deposition and blockage, difficulty in controlling nuclide migration, high operating costs, and by-product management, which need to be overcome through material improvement and process optimization to break application limitations.

Plasma vitrification technology has also attracted much attention. Through high-temperature plasma, secondary waste can be instantly melted and solidified. Research has solved some key technical problems, such as the stability of plasma torches and energy utilization efficiency. This technology can handle secondary waste with complex compositions, and the formed glass or

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ceramic bodies have extremely high stability, which can effectively fix radioactive nuclides. It is expected to play an important role in the field of nuclear waste treatment in the future.

4.2. Directions for improving management systems

The formulation of regulatory standards is the cornerstone of improving the secondary waste management system. It is necessary to further refine the standard specifications for secondary waste treatment, storage, transportation, and other links based on technological development and actual treatment experience. Clarify treatment requirements for different types of secondary waste, emission limits for radioactive substances, etc., to ensure that all treatment activities are carried out in accordance with laws and regulations. At the same time, regulations and standards should be revised and updated in a timely manner according to newly emerging problems and technological breakthroughs to maintain their scientificity and adaptability.

Strengthening supervision is extremely critical. Efforts should be made to establish a professional and efficient supervision team, equipped with advanced monitoring equipment and corresponding technical means, to carry out comprehensive and regular supervision of nuclear waste treatment enterprises and their related activities. On the one hand, it is necessary to carefully check the actual operation status of treatment facilities to see if the waste treatment process complies with regulations; on the other hand, it is necessary to strictly track and record the entire process of secondary waste from generation to transfer and disposal. Only by further strengthening supervision measures can we ensure the correct application of secondary waste minimization technologies, thereby effectively safeguarding environmental safety and public health.

4.3. In-depth development of resource utilization

To improve the efficiency of useful nuclide extraction, emphasis should be placed on developing more advanced and efficient separation technologies. In-depth research on new extractants and adsorption materials should be conducted to improve their selectivity and adsorption capacity for specific useful nuclides. At the same time, the separation process flow should be optimized, and various separation methods should be comprehensively applied to achieve continuous and efficient nuclide extraction. Through these efforts, extraction costs can be reduced and resource recovery rates can be improved.

The development of high-value-added resource-based products requires strengthening interdisciplinary cooperation. Combine innovative achievements in fields such as materials science and engineering technology to explore the application possibilities of secondary waste in cutting-edge fields such as new energy and high-end materials. For example, special components contained in secondary waste can be used to prepare high-performance battery materials and new catalysts. By continuously expanding its application fields, the economic value of secondary waste resource-based products can be improved, thereby providing a stronger economic driving force for the promotion and application of secondary waste minimization technologies.

5. Conclusion

Secondary waste minimization technologies have achieved remarkable results in the field of nuclear waste treatment. In terms of source reduction strategies, they have effectively reduced the generation of secondary waste at the source, and measures such as optimizing process flows, selecting corrosion-resistant materials, and strengthening waste classification have effectively alleviated the

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pressure on subsequent treatment. Volume reduction methods, through compression, incineration, vitrification, etc., have significantly reduced the volume of secondary waste, facilitating storage and transportation operations. Resource utilization approaches have achieved the goal of resource recycling, creating economic and environmental benefits.

However, these technologies are not without shortcomings. Some technologies have high treatment costs, which restrict their large-scale promotion. Some new technologies are currently only in the research stage and are not fully mature, so there is still a certain gap from actual application. Overall, secondary waste minimization technologies are of great significance for nuclear waste management. On the one hand, they reduce the environmental risks posed by nuclear waste; on the other hand, they provide strong support for the sustainable development of the nuclear industry.

To promote the development of secondary waste minimization technologies, first, increase investment in scientific research. Both the government and enterprises must attach importance to research in this field, set up special scientific research funds, encourage universities and research institutions to conduct technical research, and focus on developing low-cost and efficient treatment technologies and equipment. Strengthening international cooperation is also important. After all, nuclear waste treatment is a global issue, and countries must share technical experience and research results. Through international cooperation projects, it works together to overcome technical difficulties and accelerate the research, development, and application of new technologies. At the same time, attention should be paid to talent cultivation, offering relevant professional courses in universities to train professional talents; enterprises should provide training and practical opportunities to improve the technical level and innovation ability of practitioners. With multi-party collaboration, strong impetus will be injected into the development of secondary waste minimization technologies.

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