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Research on Recycling and Reutilization of Radioactive Waste Generated in the Front-end Processes of Nuclear Fuel Cycle

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Abstract: The front-end processes of the nuclear fuel cycle mainly serve the fuel demand of nuclear power plants. Inevitably, a large quantity of radioactive waste is produced during these processes, which will pose severe threats to the ecological environment and human health if improperly disposed of. This paper elaborates on the properties, classification, and hazards of radioactive waste, and analyzes the limitations of current treatment technologies for such waste. A series of innovative recycling and reutilization solutions combining physical, chemical, and biological treatment methods are proposed to realize the reduction, resource recovery, and harmless treatment of radioactive waste. These solutions can not only cut down the discharge of radioactive waste, but also achieve efficient utilization of resources. They provide strong support for the sustainable development of the nuclear fuel cycle and are of great significance for promoting low-emission and sustainable development of the whole nuclear fuel cycle.

Keywords: Nuclear fuel cycle; Radioactive waste; Recycling; Reutilization

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1. Introduction

Converting natural uranium ore into nuclear fuel for reactors involves multiple sophisticated procedures, including uranium extraction, purification and conversion, which is an indispensable link in the industrial chain of nuclear power generation. Apart from nuclear fuel, a great deal of nitric acid-containing waste liquid, tail gas, and wastewater are generated in the production process [1]. Though categorized as waste, these materials contain abundant recyclable resources, especially nitric acid, recoverable gases, and purified reusable wastewater [2].

At present, the disposal of radioactive waste from nuclear fuel production mainly focuses on safe storage and solidification, especially for waste arising from the back-end processes of the nuclear fuel cycle, so as to prevent harm to the environment and human health [3]. However, such conventional methods ignore the potential resource value of waste and fail to maximize resource utilization. With the rising global awareness of environmental protection and the vigorous development of the nuclear industry, efficient and safe recovery and reutilization of valuable components in such waste has become a new research hotspot in the field of the nuclear fuel cycle [4–6]. The recycling of nitric acid, reuse of recoverable gases in tail gas, and reutilization of purified wastewater in the front-end processes of nuclear fuel production can effectively reduce production costs and environmental pollution, thus achieving a win-win situation for economic benefits and environmental protection [7].

2. Properties and classification of radioactive waste

Radioactive waste refers to waste containing radionuclides generated throughout the nuclear fuel cycle. Based on physical forms and radioactivity levels, it is divided into three major categories: solid waste, liquid waste, and gaseous waste [8].

Solid waste: It mainly includes tailings, residues, and spent filter media. Tailings are residual wastes after uranium extraction from ore, which contain high levels of radionuclides and harmful substances [9]. Residues are produced during chemical reactions and physical treatments such as extraction, precipitation, and filtration in uranium purification and conversion processes. Spent filter media used for filtering radioactive liquid waste also carry radionuclides.

Liquid waste: It primarily consists of waste liquor and wastewater. Waste liquor derives from uranium dissolution, extraction, and precipitation processes, containing radionuclides and various chemical substances [10]. Wastewater mainly comes from equipment washing and process tail gas scrubbing, with relatively low concentrations of radionuclides and hazardous substances [11].

Gaseous waste: It covers radioactive exhaust gas and other harmful gases, mostly discharged from chemical reaction units and ventilation systems, including nitrogen oxides, ammonia, fluorine-containing gases, and other radioactive hazardous gases.

3. Current treatment methods and their limitations for radioactive waste

For radioactive waste produced in nuclear fuel processing, mainstream treatment ideas are to convert gaseous waste into liquid and liquid waste into solid to minimize the volume of radioactive waste. Another core objective is to render gaseous and liquid waste harmless so that they can meet emission standards and be discharged directly.

Currently, radioactive exhaust gas, waste liquor and wastewater from uranium purification and conversion are mostly treated by separation technologies [12]: gas is disposed of via scrubbing, absorption and adsorption; liquid waste and wastewater are treated through extraction, adsorption, precipitation, membrane separation and evaporation. Solid radioactive waste such as combustible cotton fabrics, metal scraps and alkaline residues is generally disposed of by incineration, smelting or storage. Nevertheless, these conventional treatment methods have obvious limitations:

(1) Storage of radioactive waste: Radioactive liquid and solid waste are temporarily placed in dedicated safety facilities for subsequent disposal. Strict safety and stability control are required to prevent leakage and diffusion of radionuclides [13]. In addition, the construction and maintenance of storage facilities entail high costs, and long-term storage poses potential risks to the environment and public health.

(2) Incineration of radioactive waste: Combustible radioactive waste is incinerated at high temperatures to decompose organic matter into ash and gas. This process is likely to cause secondary pollution, including atmospheric pollutants and radionuclides remaining in ash residues. Incineration facilities also require huge investment in construction and operation, and the incinerated ash still needs further treatment and disposal [14–16].
(3) Separation of radioactive waste: This technology separates useful components from hazardous substances to realize resource recovery. However, it relies on complex physical, chemical, and biological means, and the separation efficiency and operation cost are affected by multiple factors.

4. Recycling and reutilization solutions for radioactive waste

4.1. Recycling of solid waste

Uranium tailings are the major solid waste in uranium purification. Valuable components such as uranium and radium can be extracted and recovered from tailings by physical, chemical or biological methods. After radionuclides are removed to reach clearance levels, the treated tailings can be mixed with cement, gypsum and other materials to produce building materials for houses, roads and other infrastructure.

Industrial residues also contain plenty of usable resources. Valuable metallic and non-metallic materials can be recovered through crushing, screening, magnetic separation and other processes. Spent filter media can be cleaned and regenerated to restore filtration performance for repeated use in radioactive liquid waste filtration, or further processed to produce adsorbents, catalysts and other products.

4.2. Reutilization of liquid waste

Waste liquor from the front-end nuclear fuel cycle is rich in recyclable substances including nitric acid, sodium nitrate, sodium fluoride and ammonium nitrate. Uranium can be recovered via neutralization, precipitation, ion exchange and extraction technologies. The remaining liquid after uranium recovery can be further treated and reused: ammonium nitrate can be applied to agricultural irrigation, while sodium nitrate and sodium fluoride can be used in industrial production. Advanced wastewater treatment technologies such as biological treatment and membrane separation can thoroughly remove hazardous substances and radionuclides from wastewater, making it reusable.

4.3. Treatment and reutilization of gaseous waste

Radioactive exhaust gas can be purified by adsorption, condensation, and absorption to remove harmful components and radionuclides, and the purified gas can be reused in industrial production or utilized as energy. For instance: nitrogen oxides generated during denitrification can be converted into nitric acid via pressure absorption and returned to the uranium dissolution system for cyclic use; purified gas can be reused as fluidizing gas in production. Hydrogen contained in tail gas from hydrogen reduction is separated and recycled as a reactant to reduce gas consumption. Tail gas from hydrofluorination is treated by condensation and scrubbing, and the obtained hydrofluoric acid is rectified into anhydrous hydrogen fluoride for reuse. Besides, harmful gases such as ammonia can be converted into valuable chemicals or energy through chemical absorption and catalytic oxidation.

5. Technical feasibility and economic analysis of recycling and reutilization solutions

There is still room for improvement in source control for waste minimization and terminal waste treatment in current domestic nuclear fuel production lines. The recycling and reutilization solutions proposed in this paper enjoy high technical feasibility. Adopting advanced physical, chemical, and biological technologies can realize effective separation and recovery of useful components from radioactive waste. Meanwhile, practical application needs to fully take technical costs and environmental risks into consideration.

Economically, these solutions can cut down the expense of radioactive waste treatment and disposal and improve resource utilization efficiency. Recycling valuable components from waste reduces the exploitation and consumption of raw materials, thereby lowering overall production costs. Furthermore, building a circular economy industrial chain through cross-industry collaborative utilization can further improve comprehensive economic benefits. However, the promotion and application of these solutions still face certain challenges and constraints.

6. Conclusion

This paper systematically analyzes the properties, classification, and existing treatment technologies of radioactive waste from the front-end processes of the nuclear fuel cycle, and puts forward targeted recycling and reutilization solutions. These solutions can reduce the discharge of radioactive waste, lower environmental pollution risks, and realize efficient resource utilization, which boosts the sustainable development of the nuclear fuel cycle. With the continuous advancement of science and technology and increasingly stringent environmental regulations, further in-depth research on the recycling and reutilization of radioactive waste is required in the future. Joint efforts should be made to address challenges in the development of global nuclear energy, so as to contribute to a better future for humanity and the protection of the ecological environment.

Disclosure statement

The authors declare no conflict of interest.

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