

The Next Generation of Nuclear Decommissioning Technologies

Authors: Cao, Ping, Prof. Chao Xie, Liu, Prof. Yi-Lin, Zhang, Yanqing, Jinsen, Dr. XIE, Wang, Dr. ling, Li, Jialei, Prof. Jiangxiang Wang, Dr. Qingyi Zeng, Yu, Tao, Dr. Qingyi Zeng

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Abstract

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Full Text

The Next Generation of Nuclear Decommissioning Technologies

Ping Cao¹, **Chao Xie**^{2, 3}, **Yi-Lin Liu**¹, **Qingyan Zhang**², **Jinsen Xie**^{3, 4}, **Ling Wang**⁵, **Jialei Li**¹, **Xiangjiang Wang**¹, **Qingyi Zeng**², **Tao Yu**^{3, 4},

¹ School of Resources & Environment and Safety Engineering, University of South China, Hengyang 421001, China

² Key Lab of Advanced Nuclear Energy Design and Safety, Ministry of Education, University of South China, Hengyang 421000, China

³ School of Nuclear Science and Technology, University of South China, Hengyang 421001, China

⁴ School of Materials Science and Engineering, Hunan University of Technology, Zhuzhou 412007, China

¹ P. Cao and C. Xie contributed equally to this work.

Corresponding authors: liuyilin@usc.edu.cn (Dr. Yi-Lin Liu); wangxiangjinag72@163.com (Prof. Xiangjiang Wang); qingyizeng@usc.edu.cn (Prof. Dr. Qingyi Zeng); yutao29@sina.com (Prof. Yu Tao)

Abstract

The sustained development of global nuclear energy underscores the critical importance of nuclear decommissioning for environmental and public safety. This article systematically reviews recent advances in remediation technologies for nuclear facilities. Significant progress has been made in surface decontamination techniques, including mechanical, chemical, laser, and electrochemical methods, as well as novel stripping materials, with approaches such as laser ablation achieving removal rates exceeding 99%. The integration of intelligent systems, such as robotic operations and AI-driven monitoring, has substantially improved operational safety and efficiency. The study also summarizes relevant regulations pertaining to safety management, radioactive waste management, and nuclear protection. While current remediation technologies show a clear trend toward integrated multi-method solutions, challenges remain in areas such as decontamination of complex structures and immobilization of long-lived radionuclides. Future developments are directed toward smarter, more sustainable approaches, where international cooperation will be crucial in advancing nuclear decommissioning and protection capabilities.

Keywords: Nuclear decommissioning · Remediation technologies · Intelligent systems · Safety management

1. Introduction

The rapid growth of the global nuclear energy sector has brought increasing attention to the decommissioning of nuclear facilities. By 2025, mainland China alone will possess 58 nuclear power reactors holding operating licenses, 31 reactors under construction with building permits, and 13 approved reactors awaiting construction, boasting a total installed capacity of approximately 113 million kilowatts—the largest such capacity worldwide [1]. Upon reaching the end of their operational lifespan, these facilities will face large-scale decommissioning challenges, where the core safety imperative is effective radioactive decontamination. Nuclear facility decontamination involves the technical removal, either partial or complete, of radioactive substances from contaminated equipment surfaces. Its primary objectives include reducing radiation levels to ensure worker

doses remain within controllable limits; enabling either restricted or unrestricted reuse of materials; lowering the waste category to minimize long-term disposal difficulty and cost; and preventing the spread of contamination and secondary pollution [3].

Following the Fukushima nuclear accident, global focus on nuclear decontamination technologies intensified significantly. The accident generated approximately 14 million cubic meters of radioactively contaminated soil within Fukushima Prefecture. Demonstrating the efficacy of advanced decontamination processes, portions of this soil underwent multi-phase purification and were subsequently repurposed in landscaping at the Tokyo Prime Minister's official residence. This reuse initiative served both to validate remediation results and rebuild public trust, while highlighting the crucial role of efficient decontamination technologies in managing nuclear pollution. Furthermore, it underscores the necessity of concurrently addressing societal acceptance and process transparency throughout technology deployment to ensure technical viability while bolstering public confidence.

Nuclear decontamination methodologies are fundamentally categorized by operational mechanisms and application contexts, with primary classification encompassing three principal domains: mechanical-physical interventions based on kinetic energy transfer mechanisms employing high-pressure aqueous jetting, dry ice ablation, or ultrasonic oscillation for surface contaminant displacement; chemical remediation approaches employing redox reactions, chelating agents, or solvent extraction for molecular-level contaminant dissociation; and biological treatment platforms leveraging microbial metabolic pathways or phytoremediation processes for contaminant mineralization, as detailed in Figure 1 [Figure 1: see original paper] [4]. These approaches are particularly suitable for tackling interface-deposited contamination on metal pipelines, reactor vessels, and structural components.

Chemical methods employ processes such as acid-base cleaning, redox reactions, or complexometric dissolution to dissolve or transform radionuclides, enabling thorough decontamination of substrates like metals and concrete [5,6]. Biological approaches utilize specific microorganisms or enzymatic agents to degrade, chelate, or adsorb organic contaminants and certain radionuclides, often applied in the treatment of organic-laden wastewater [7]. When categorized by application scenario, these technologies can be further divided into surface decontamination and bulk contamination treatment. Surface decontamination targets interface pollution on equipment and structures, emphasizing precision, efficiency, and substrate compatibility, while bulk contamination treatment addresses dispersed pollution in media such as soil and groundwater, focusing on large-scale remediation capacity [8].

In practical engineering applications, modern decontamination projects often adopt integrated multi-technology strategies. For example, at the Idaho National Laboratory in the United States, a combined approach involving mechanical separation, chemical washing, and solidification techniques was employed to

treat contaminated soil and debris [9]. This effort successfully concentrated pollutants from an area of 890 square miles into a single managed zone, significantly mitigating the risk of groundwater contamination.

A comprehensive evaluation of nuclear facility decontamination technologies should be conducted based on three key dimensions: technical performance, economic cost, and environmental safety [10]. The decontamination factor (DF), defined as the ratio of radioactive activity before and after treatment, serves as a critical technical indicator, with $DF \geq 10$ considered effective and $DF \geq 100$ classified as high-efficiency decontamination [11]. The amount of secondary waste generated (kg/m^2) directly influences subsequent costs related to waste solidification, storage, and disposal. Substrate compatibility is assessed through metrics such as corrosion depth (m) and changes in surface roughness (ΔRa) to evaluate potential damage to the base material. Economic indicators, including direct unit-area processing cost ($\text{¥}/\text{m}^2$) and equipment payback period (years), are essential for evaluating the feasibility of large-scale application [12].

China's national radiation monitoring network integrates 1835 strategically deployed stations covering critical zones including prefecture-level cities, border ports, and nuclear facility peripheries, establishing a scientific foundation for radioactive decontamination assessment. Longitudinal monitoring data reveal stable environmental radiation levels near nuclear installations compared with 1980s baseline surveys, validating enhanced regulatory frameworks and standardized remediation protocols. This infrastructure demonstrates sustained technical efficacy through integrated radiation management while confirming operational safety parameters of modern decontamination technologies [13].

2.1 Mechanical and Physical Decontamination Methods

Mechanical-physical decontamination technologies remove radioactive contaminants through the application of physical energy, primarily including high-pressure water jetting, dry ice blasting, and ultrasonic techniques (Figure 2 [Figure 2: see original paper]).

High-pressure liquid jetting deploys aqueous or cryogenic fluids accelerated through optimized nozzles at 10-100 MPa, inducing surface modification via synchronized mechanical processes including plastic deformation, microfracture initiation, and particulate removal. Systematic studies by Nedyalkova et al. demonstrate that oblique 45° jet impingement outperforms 90° application on austenitic steels through enhanced shear stress distribution and prolonged interfacial contact, effectively disrupting passivation layers. While offering operational adaptability and high decontamination efficacy, the process generates radioisotope-contaminated effluents necessitating sealed collection systems integrated with coagulation-ion exchange-adsorption treatment trains for secondary pollution control [14].

Dry ice blasting utilizes solid CO_2 pellets accelerated by compressed air propul-

sion systems, producing impact energies capable of microfracture generation on contaminated substrates. The mechanism involves successive phases: pellet penetration into surface capillaries followed by rapid sublimation at -78.5°C (STP), creating volumetric expansion forces exceeding 800:1 that dislodge radioactive particulates through controlled substrate delamination. This non-abrasive technique eliminates secondary waste generation, demonstrating particular efficacy in confined spaces and geometrically complex systems, as evidenced by Japanese PWR maintenance operations [15]. Operational validation in steam generator channel head decontamination achieved DF values >20 during 168-hour cycles, with profilometric analysis confirming <5 μm surface alteration depths.

Ultrasonic decontamination technology operates through high-frequency oscillatory excitation (20–400 kHz) that induces transient cavitation phenomena within liquid media [16], where the asymmetrical collapse of vacuum bubble clusters generates localized hyperbaric conditions exceeding 750 MPa accompanied by transient plasma formation with temperatures surpassing 5000 K. This unique energy transfer mechanism enables contaminant displacement through combined mechanochemical interactions at material interfaces, as demonstrated in pressurized water reactor secondary circuit components. Application optimization studies confirm that coupling ultrasound with a 0.5 vol% anionic surfactant formulation achieves decontamination factors up to 15.3 under 90-minute exposure periods—a 287% efficacy enhancement compared to aqueous-only implementations.

2.2 Chemical Decontamination Methods

Chemical decontamination technology utilizes chemical reactions to dissolve or transform radioactive pollutants [17]. Based on the form of chemical agents used, it can be classified into foam-based, gel-based, and solution immersion methods (Figure 3 [Figure 3: see original paper]).

Foam-based decontamination technology utilizes formulated chemical cocktails (acids/oxidizers/surfactants/chelants) pneumatically aerosolized through precision nozzle arrays to generate gas-liquid dispersions exhibiting surface-area-to-volume ratios exceeding $800 \text{ m}^2/\text{m}^3$. These viscoelastic foams demonstrate superior adhesion dynamics on non-planar substrates including vertical planes and geometrically complex protrusions through tunable rheological properties, thereby extending contaminant-removal agent interfacial contact durations beyond 30 minutes—critical for effective dissolution of radioactive species [18]. The remediation mechanism operates through synergistic physiochemical pathways: acid-induced matrix dissolution, oxidative valence state modification, and chelated complex formation with dissolved radionuclides, enabling conversion of surface-bound particulates into aqueous-soluble ionic species for subsequent extraction.

Gel-based decontamination systems provide engineered solutions for vertical and geometrically complex substrates through formulator-controlled rheology.

The methodology employs acid-based redox cocktails (oxalic/nitric acid formulations) compounded with alginate derivatives to establish thixotropic matrices demonstrating controllable adhesion kinetics, enabling sustained chemical attack through redox cycling at the gel-substrate interface during controlled adhesion intervals (1-4 hours). A 2025 advancement in polysaccharide-based peelable nanocomposites [19] combines pectin/gum arabic matrices with chelating complexes that generate flexible interfacial films upon curing, achieving >90% ^{137}Cs extraction efficiency through mechanically induced film delamination. This innovation demonstrates secondary waste reduction (>60% vs. conventional techniques) while exhibiting enhanced biodegradability profile, significantly mitigating environmental remediation risks [19].

Solution immersion decontamination constitutes an industry-standard chemical remediation approach wherein contaminated components undergo full immersion in reagent tanks charged with acidic oxidation matrices or alkaline redox formulations [20], employing thermomechanical activation through thermal regulation and ultrasonic agitation to optimize solid-liquid phase interactions and enhance contaminant dissolution efficacy via controlled reaction kinetics.

A major challenge in chemical decontamination is the treatment of radioactive liquid waste. Traditional inorganic acid pickling generates wastewater volumes of up to 10 L/m², requiring complex neutralization and solidification processes. To address this, the University of South China developed an electrochemical-ultrasonic hybrid system that integrates pulsed electrolysis with 40 kHz ultrasonication, reducing wastewater generation to below 4 L/m². This system also enables electrolyte recycling through ion-exchange resins, significantly improving techno-economic efficiency [21].

2.3 Laser and Electrochemical Technologies

Laser decontamination employs short-pulsed high-energy laser beams to vaporize or ablate contaminated layers, integrated with a multi-stage filtration system for fumes and particulate recovery to prevent dispersion of solid and aerosolized pollutants [22]. As a representative non-contact precision decontamination technology, it has achieved breakthrough progress in recent years. Utilizing an Nd:YAG laser (wavelength 1064 nm) with a pulse width of 10-100 ps and an energy density of 5-20 J/cm², the process leverages selective photothermal effects to instantaneously vaporize surface contaminants, achieving a removal rate exceeding 99% for α -contaminants on stainless steel while generating less than 0.1 kg/m² of secondary waste. In 2024, Japan developed an integrated laser-robotic system deployed inside the containment vessel of Fukushima Daiichi Unit 1, utilizing optical fiber transmission and a six-axis robotic arm for operation in confined spaces, reducing personnel exposure doses by 90% [23].

Electrochemical decontamination submerges contaminated components as anodes in an electrolyte solution, dissolving or depositing radionuclides through electrolysis or electrocoagulation (Figure 4 [Figure 4: see original paper]). This

method demonstrates particular value in internal pipeline decontamination. Using a phosphoric acid-glycerol-sodium nitrate electrolyte (pH=1.5) under a current density of 100 A/m² assisted with 300 W ultrasound (40 kHz), glycerol molecules form complexes with Fe³⁺ via hydroxyl groups, suppressing secondary oxide formation, while ultrasonic cavitation enhances mass transfer, increasing the dissolution efficiency of embedded Fe₃O₄ to 97%. A research team from the University of South China further optimized the electrolyte composition to a system containing phosphoric acid (30 wt%), glycerol (10 wt%), and sodium nitrate (5 wt%), achieving a surface roughness Ra below 0.8 μm and a corrosion rate of less than 0.01 mm/year [24].

The integration of laser and electrochemical methods has led to the development of hybrid laser-electrochemical decontamination, representing a cutting-edge approach for surface decontamination. This technique begins with a 1064 nm laser (15 J/cm²) removing approximately 95% of superficial contaminants, followed by electrochemical treatment of residual pollution, resulting in an overall decontamination factor exceeding 500 and reducing total waste to below 1 kg/m². This technology has been applied in primary circuit maintenance of steam generators at French nuclear power plants, with a unit processing cost of around ¥2500/m². However, the initial equipment investment remains as high as ¥3 million, highlighting an urgent need for cost reduction through domestic production and technological localization.

2.4 Novel Peeling Materials

Novel strippable coatings combine chemical adsorption and mechanical peeling, utilizing water-based or solvent-borne polymers that form a contaminant-adsorbing film when brushed or sprayed onto surfaces. After drying and curing, the film can be peeled off entirely, enabling decontamination without generating dust or liquid waste. Due to their operational simplicity and minimal waste production, these coatings have attracted significant research interest [25]. As shown in Table 1, various materials exhibit distinct characteristics in substrate compatibility, target contaminants, and decontamination performance. For example, pectin gel on stainless steel demonstrates a decontamination factor of 58.2 for ¹³⁷Cs and ⁶⁰Co, along with low secondary waste and favorable cost efficiency.

A seminal 2025 *Applied Clay Science* investigation demonstrated that graphene oxide (GO)-modified geopolymer matrices significantly enhance organic radioactive waste encapsulation through GO's colloidal stabilization mechanism, forming nanoconfined barrier architectures at oil-water interfaces that triple emulsion stability during alkali activator-oil dispersion processes [26]. The composite exhibited progressive mechanical resilience with 28-day compressive strength reaching 65.5 MPa (attributed to 65.5% cross-linking density enhancement), concurrently maintaining <0.12% total organic carbon leaching through controlled Si-O-Al network polycondensation. Parallel studies on polysaccharide remedia-

tion systems reveal that pectin-based hydrogels develop chelating coordination networks via α -1,4-linked galacturonic acid carboxylate moieties, effectively immobilizing $\text{Cs}^+/\text{Sr}^{2+}$ contaminants through ion-exchange saturation thresholds. Practical validation on Zircaloy substrates achieved 98.3% radionuclide removal efficiency using 1 mm-thick viscoelastic films via cohesive film delamination, outperforming synthetic analogues in both decontamination factor and interfacial adhesion energy. Crucially, natural polysaccharides demonstrate inherent advantages including enzymatic biodegradability (COD reduction $>80\%$ in 60 days), non-bioaccumulative properties, and carbon-neutral sourcing pathways—operational parameters strategically aligned with IAEA’s sustainable nuclear cycle initiatives.

3.1 Robot Operating System

Advanced nuclear decommissioning robotics address high-dose radiation environment challenges through integrated systems combining γ -emitter isotopic composition analysis, radiation-hardened manipulator assemblies, and adaptive shielding configurations. Contemporary platforms employ tripartite modular architecture comprising wide-spectrum Cherenkov imaging detectors, six-degree-of-freedom hydraulic actuation systems, and probabilistic radiation exposure management algorithms capable of sustaining 1000 Gy/h operational thresholds while achieving personnel exposure minimization. Mitsubishi’s RACCOON series implementation at Fukushima exemplifies this paradigm, where LiDAR topographic reconstruction enables millimeter-level containment vessel mapping coupled with autonomous adaptive path generation using stochastic gradient descent optimization for surface ablation trajectory planning [27].

Nuclear decontamination robotics employ multi-tool kinematic chains integrating hydraulic shearing modules, impact percussion systems, and HEPA-filtered vacuum sequestration units that demonstrate fivefold efficiency enhancement compared to manual remediation protocols. The German-engineered Brokk platform implements modular architecture through interchangeable end-effector interfaces (hydraulic breaker heads, rotary waterjet lances, or electro-hydraulic grapples) deployable within 8-minute operational cycles, coupled with gamma-ray scintillation detectors enabling real-time isotope localization that maintains occupational dose rates below 0.02 mSv/h. UK Sellafield deployments demonstrated operational cycle extension from 2 to 8 hours during high-activity waste tank remediation alongside contaminant removal efficiency improvement from 65% to 98% through synchronized abrasive blasting and particulate capture cycles. Orano Group’s technological advancement incorporates full-scope digital twin ecosystems synthesizing Monte Carlo radiation transport modeling with equipment degradation algorithms, enabling multivariate scenario simulation (radiation intensity, kinematic constraints, tool wear) prior to physical implementation while optimizing ablation velocity and manipulator trajectory parameters [28]. Practical applications have shown that this platform reduces decontamination planning time by an average of 40%, decreases operational in-

interruptions and rework by approximately 30%, and curbs overall project cost overruns to below 5%.

3.2 Multi-Technology Integrated Process

For complex scenarios involving diverse materials and contamination characteristics, a single decontamination method often fails to meet both efficiency and economic requirements [29]. The Idaho National Laboratory (INL) engineered a sequential remediation workflow integrating diamond wire cutting, multi-stage chemical leaching, and high-tonnage isostatic compression for prototype land-based naval reactor decommissioning (Figure 5 [Figure 5: see original paper]). Initial component segmentation employing 12 mm-diameter diamond-impregnated cables achieves geometrically controlled sectioning, followed by six-cycle oxidative-etchant treatment using HF/HNO₃ formulations at 60°C that consistently delivers 50±5% decontamination factor through stoichiometric dissolution of activation products. Terminal phase processing applies 2000-metric-ton triaxial compaction forces to produce geometrically stable fragments (<200 mm major axis) within engineered containment chambers, realizing 8:1 mass-volume reduction coefficients. This entire technological sequence operates within INL's CERCLA-certified radiologically controlled area featuring multiple confinement barriers and negative pressure zoning [30]. Since its expansion in 2024, the facility's annual treatment capacity has reached 530,000 cubic meters, sufficient to meet decommissioning demands for the next 25 years.

Waste minimization and resource recovery constitute pivotal considerations in nuclear process engineering, exemplified by Studsvik UK's pyrometallurgical resource recovery platform featuring sequential thermal dissociation (480°C) under oxygen-free argon curtain conditions for organics removal and subsequent metallurgical refining through alloy phase separation that generates certified metal ingots (99.6×10³ metric tons annually). Operational validation across UK nuclear facilities demonstrates effective radiation containment through multi-barrier confinement systems during continuous metal reclamation cycles [31]. China's Daya Bay Nuclear Power Plant employs a multi-stage purification train for primary coolant remediation, commencing with depth filtration (5 μm nominal pore size) for colloidal Fe₃O₄ particulate removal, followed by selective adsorption using sulfonic acid-functionalized cation exchange matrices (50% DVB crosslink density) achieving 98% Co-60 uptake through ionic radius selectivity. The tertiary phase incorporates spiral-wound semipermeable polyamide membranes exhibiting >99% ionic rejection efficiency via solution-diffusion mechanisms to concentrate non-radioactive TDS below 500 ppm. This integrated configuration achieves DF=100 operational benchmarks at 10 m³/h throughput rates, enabling annual 1500 m³ wastewater volumetric reduction with >90% effluent reuse capability across secondary circuit applications, demonstrating concurrent compliance with Chinese nuclear effluent NRC-7000 regulations.

3.3 Digitalization and AI Monitoring

The integrated digital monitoring architecture employs multimodal sensor networks and automated analytics pipelines to synchronize radiation characterization, waste logistics, and environmental surveillance throughout decontamination operations. China National Nuclear Corporation's (CNNC) Nuclear Clear Cloud platform implements tripartite architecture comprising: vehicle-mounted high-purity germanium detectors with 5-second temporal resolution generating gamma-specific isodose contour maps through Compton scattering correction algorithms; ultra-high-frequency RFID tracking matrices encoding waste packaging parameters (mass, nuclide inventory, dose rate) for cradle-to-grave material stewardship across treatment-facility-disposal pathways; and multi-parametric risk modeling subsystems synthesizing 10-meter-resolution meteorological data with hydrogeological stratigraphy profiles to simulate radionuclide transport mechanisms, achieving 85% predictive accuracy in contamination plume trajectory forecasts through convolutional neural network pattern recognition [32].

Artificial intelligence algorithms demonstrate significant potential in process optimization. Tsinghua University has developed a deep reinforcement learning model named DRL-Decon, which uses substrate properties, radionuclide types, and dose constraints as inputs to automatically recommend optimal decontamination process combinations [11]. The Qinshan Nuclear Power Plant field validation demonstrated that AI-optimized workflow allocation achieved 23% process efficacy enhancement through reinforcement learning algorithms, simultaneously reducing chemical flux demand by 35% and ancillary waste streams by 28% via solvent recovery pathway prioritization. Parallel blockchain integration revolutionizes nuclear material stewardship—Canadian Nuclear Laboratories developed an enterprise-grade Hyperledger Fabric solution with Byzantine Fault Tolerance consensus mechanisms that immutably archives batch processing metadata (radiation profiles, quality assurance certificates, shipment manifests) across decentralized nodes, enforcing International Atomic Energy Agency safeguards compliance through smart contract-executed custody transfers and automated regulatory reporting frameworks [28]. The system has already managed over 5000 waste drums, shortened audit time from two weeks to two days, and reduced compliance costs by 40%.

4.1 International Security Standards Framework

Decontamination activities at nuclear facilities must strictly comply with the safety standards established by the International Atomic Energy Agency (IAEA) [33]. The IAEA SSR-6 regulatory framework stratifies radioactive waste through quadruple classification criteria: *Category I—unrestricted release materials* ($\leq 0.01\text{Bq/g total activity}$); *Category II—decay storage — managed VSLW*; *Category III—engineered near-surface disposal LILW* ($\leq \$4,000\text{ Bq/g } \beta/\gamma \text{ activity under ICRP 141 guidance}$); and *Category IV—deep geological*

repository-confined HLW requiring $100\text{W}/\text{m}^3$ thermal output compliance. Post-Fukushima remediation protocols established Japan's March 2025 Soil Reutilization Standard implementing multi-tiered reuse pathways: 8,000 Bq/kg contamination threshold for subgrade construction material; 3,000–8,000 Bq/kg geotechnical applications requiring 50 cm geoen지니어ed encapsulation layers; and >8,000 Bq/kg contaminated soils mandating surface dose-restricted ($<0.23\text{ Sv/h}$) monitored retrievable storage under multilayer compacted clay/geomembrane composite barriers [34]. Domestically, China's *Technical Specifications for Decontamination During Nuclear Facility Decommissioning* (GB/T 16143-2023) issued in 2023 specifies quantitative decontamination criteria including a surface contamination limit for metal equipment of $0.4\text{ Bq}/\text{cm}^2$ for alpha emitters and $4\text{ Bq}/\text{cm}^2$ for beta/gamma emitters, and for concrete surfaces limits of $0.8\text{ Bq}/\text{cm}^2$ for alpha and $8\text{ Bq}/\text{cm}^2$ for beta/gamma contamination, with clearance levels requiring a gamma dose rate below 0.25 Sv/h and surface contamination under $0.04\text{ Bq}/\text{cm}^2$ [35]. These international and national standards together establish a comprehensive safety framework covering the entire process from waste classification and technology application to final clearance [20].

4.2 Radiation Protection System

The “As Low As Reasonably Achievable” (ALARA) principle serves as the cornerstone of radiation protection, emphasizing the control of personnel dosage through three fundamental strategies: time limitation, distance maximization, and shielding [36]. For time reduction, promotion of robotic and remote automated systems has limited the proportion of manual operations to less than 20%. Distance-based protection employs long-handled tools exceeding 2 meters or extended robotic arms to reduce incident dose rates to a quarter of the original level. In terms of shielding, the use of 20 mm lead glass or tungsten alloy shielding materials attenuates gamma radiation by at least 90%. During remediation activities at uranium tailings ponds, without protective measures, the annual effective dose for workers can reach 6.0 mSv [37]. Operational engineering controls combining aqueous dust suppression systems, enclosed microenvironment ventilation, and 4-hour dosimetric exposure thresholds demonstrate effective annual effective dose suppression below 1 mSv regulatory limits.

Concurrent personal protection innovations include Orano Group's 2024 hermetic liquid-cooled microenvironment suit integrating zirconium-phosphate composite filtration matrices and countercurrent heat exchangers that sustain 120-minute operational durability in 60°C thermal stress conditions while maintaining ambient dose equivalent rate ($H^*(10)$) attenuation at 0.05 mSv/h through multi-layered Pb/Cu/B₄C nanocomposite shielding architecture [38]. Domestically, the “Dragon Scale” series utilizes nanocomposite tungsten-polyethylene material, which offers a 30% weight reduction compared to traditional shielding and achieves an 85% shielding rate against ¹³⁷Cs gamma radiation [39].

4.3 Waste Regulatory Framework

The management of radioactive waste adheres to the principles of minimization, recycling, and harmless treatment, with full lifecycle supervision implemented at all stages [40]. China's radioactive waste management system implements a three-tier regulatory framework: the Ministry of Ecology and Environment enforces licensing and compliance verification, provincial authorities conduct radiation zoning controls, while operators maintain onsite radiation safety organizations for contamination documentation. All gaseous/liquid effluents require pretreatment to meet GB 14500 discharge limits with real-time online monitoring systems transmitting data to provincial platforms. Solid waste must undergo classification and centralized treatment within 180 days, explicitly prohibiting indefinite interim storage, while high-level waste mandates deep geological disposal facilities incorporating engineered barrier systems with mandatory 100-year integrity monitoring through distributed sensor networks [41].

The U.S. Department of Energy's Office of Environmental Management (DOE EM) has established an integrated database that tracks each cubic meter of waste from generation through transportation to final disposal. The Idaho CERCLA Disposal Facility (ICDF) employs a Geographic Information System (GIS) to tag the location of waste packages and uses drone-based inspections to enable real-time integrity verification of disposal units. This three-tier regulatory framework, supported by digital tracking systems, provides a solid foundation for the safe management of post-decommissioning waste and ensures societal oversight [42].

5.1 Summary of Current Technical Development Status

Nuclear facility decontamination methodology has transitioned from discrete unit operations to integrated process trains combining surface remediation and bulk matrix treatment. High-peak-power pulsed laser ablation (1064 nm wavelength, 10 J/cm² fluence) achieves >99% uranium surface removal through non-contact photomechanical spallation mechanisms. Electrochemical-ultrasonic hybrid reactors operating at 28 kHz with 0.5 A/dm² current density leverage controlled ultrasonic cavitation fields to enhance passivation layer dissolution, achieving 60% process fluid demand reduction. Topologically adaptive functionalized polymeric formulations (vinyl acetate-ethylene copolymer matrices) demonstrate millimeter-scale defect penetration for geometrically complex component decontamination. Subsurface remediation employs sulfuric acid-hydrogen peroxide leaching cocktails achieving 0.7 g U/kg residual soil contamination, while phytoremediation strategies utilizing *Brassica juncea* cultivars amplify ¹³⁷Cs phytoextraction coefficients to 9.8 via rhizosphere acidification. Geopolymer encapsulation matrices maintain ⁹⁰Sr effective diffusion coefficients below 1×10⁻¹¹ m²/s through zeolitic cage structure immobilization. Complementary digital twin platforms employ discrete

element modeling accelerate project lifecycles by 40%, while Hyperledger-based immutable custodial chains provide multistakeholder waste tracking with 256-bit SHA-3 cryptographic verification across disposal value chains.

5.2 Core Challenges and Response Strategies

Nuclear decontamination engineering continues to face unresolved challenges in balancing technical efficacy with operational safety due to multi-component interactions between heterogeneous contamination matrices and dynamic radiation fields. Current limitations persist in portable real-time monitoring systems capable of simultaneous multi-nuclide detection and immediate secondary waste mitigation during active remediation processes. Radiation tolerance thresholds of sensor networks and adaptive machine learning algorithms under high-intensity radiation conditions require substantial optimization. Furthermore, divergent certification protocols between radiation protection standards and industrial equipment specifications create systemic barriers for emerging technology implementation.

However, as shown in Table 2, targeted solutions such as microfoam-gel composite technology have been developed to address specific challenges, with practical validations in cases like heat exchanger tubing cleaning in nuclear power plants. To overcome existing limitations, deeper integration of materials science, nuclear engineering, environmental management, and artificial intelligence must be pursued. Collaborative efforts should focus on key common technologies, enhanced pilot and demonstration platforms, and multi-scenario, multi-scale validation. An integrated system for real-time monitoring and emergency response should be established. Furthermore, aligning international standards with domestic regulations will help form a closed loop encompassing technology, standards, oversight, and business—accelerating the industrial application of new advances.

5.3 Future Development Directions

Driven by technological evolution and policy support, nuclear facility decontamination technology is advancing toward three key trends: greening, intellectualization, and resource recovery (Figure 6 [Figure 6: see original paper]). Greening entails the development of bio-based decontaminants aimed at reducing the carbon footprint by 60%; the establishment of zero-liquid discharge systems to ensure a reuse rate exceeding 95%; and the creation of low-carbon cementitious materials capable of cutting CO₂ emissions to one-sixth of current levels. Intellectualization involves promoting high-fidelity digital twin platforms to increase operational efficiency by 40%; developing nanoscale intelligent robots capable of precision decontamination at the 0.1 mm level; and building AI-powered process optimization systems based on deep learning to enable real-time adaptive adjustment of working conditions. Resource recovery refers to advancing mi-

icrobial enrichment and targeted recovery technology to increase radionuclide enrichment factors beyond 1,000, as well as exploring energy utilization pathways for contaminated soil to raise biomass yield to 12 t/ha.

Overall, nuclear facility decontamination is shifting from a “simple removal” approach to a “cyclic purification” paradigm. Through interdisciplinary innovation integrating materials science, intelligent control, and nuclear technology, next-generation decontamination systems will strive to achieve contamination removal efficiency exceeding 99.9%, near-zero secondary waste generation, and carbon emission reduction throughout the lifecycle, thereby providing solid technical support for the sustainable development of nuclear energy worldwide. It is recommended that research institutions and enterprises strengthen basic research in areas such as electrolyte formulation optimization and laser-material interaction mechanisms, and promote industry-academia collaboration in modular equipment, including mobile laser decontamination units, to secure a leading position in future nuclear environmental protection technology.

6.1 Analysis of Technical Bottlenecks

Although significant breakthroughs have been made in surface and bulk contamination treatment technologies for nuclear facility decontamination, achieving uniform cleaning in complex structural areas remains a challenge. Narrow spaces such as pipeline inner walls and heat exchanger tube bundles hinder efficient fluid circulation, and the decontamination factor (DF) of traditional chemical circulation methods in dead zones like 90° bends is often 50% lower than that in straight pipe sections. To address this, a microbubble-gel composite technology developed by the University of South China utilizes ozone micro-bubbles smaller than 100 μm in diameter. Leveraging surface tension, these micro-bubbles penetrate into narrow gaps, and a temperature-sensitive gel prolongs the reaction residence time, increasing the DF value in bent pipes from 15 to 40 [43].

Furthermore, treating organic radioactive waste such as ion-exchange resins and lubricating oils poses a challenge in balancing efficient pyrolysis with low secondary pollution. The low-temperature plasma oxidation technology introduced by China General Nuclear Power Research Institute in 2025 employs dielectric barrier discharge to generate $\cdot\text{OH}$ radicals under conditions of 200°C and 10 kPa. This process achieves a mineralization rate of 99% for organic components, with residual ash accounting for only 5% of the original volume, allowing direct incorporation into vitrification systems.

For the deep removal of long-lived radionuclides such as ^{129}I and ^{99}Tc , conventional chemical immobilization methods are often inadequate. Novel adsorption materials have shown promising results: Zr-UiO-66 exhibits an iodine adsorption capacity of 1.2 g/g with a selectivity coefficient exceeding 1,000, while functionalized magnetic $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-NH}_2$ demonstrates an adsorption rate constant for TcO_4^- that is eight times higher than that of ion-exchange

resins [44,45]. Although these materials have shown excellent removal performance in small-scale tests, key processes for engineering-scale application and regeneration remain to be further developed.

6.2 Green and Low-Carbon Technologies

Nuclear environmental protection technology is transitioning toward low-carbon solutions to reduce the carbon footprint and environmental impact throughout the decontamination process. In the area of bio-based decontaminants, a sophorolipid surfactant developed by the French Alternative Energies and Atomic Energy Commission (CEA) exhibits an exceptionally low critical micelle concentration of 80 mg/L, achieves a uranium removal rate of 92%, and biodegrades more than 90% within 28 days [46]. Compared to traditional chemical surfactants, it reduces the carbon footprint by approximately 60%.

For zero-liquid discharge systems, the decontamination system supporting China's Hualong One reactor employs a treatment train combining membrane distillation with crystallization. The process begins with ultrafiltration (0.01 m) to remove suspended solids, followed by reverse osmosis (99% desalination rate) to concentrate the stream to a total dissolved solids content exceeding 200 g/L. Mechanical vapor recompression crystallization is then used to recover solid salts, with condensed water reuse rates surpassing 95%. In low-carbon solidification materials, a notable example is the alkali-activated slag cementitious technology from the University of Sheffield in the UK. This material replaces 90% of cement with blast furnace slag, reducing CO₂ emissions to only one-sixth of those from conventional cement. With the addition of 5% nano-SiO₂, the compressive strength reaches 75 MPa, and the 42-day leaching rate of ⁶⁰Co remains below 10⁻⁶ g/(cm² · d), ensuring a combination of safety and mechanical performance [47].

6.3 Smart System Integration

The deep integration of digital twin technology and smart materials is reshaping the management and implementation of decontamination engineering. At the equipment level, sensor networks are deployed to collect real-time parameters such as temperature, pressure, and radiation levels, enabling the development of high-fidelity models of physical fields and chemical reaction kinetics. At the decision-making level, AI-driven algorithms are utilized to optimize process parameters and predict equipment lifespan. The interaction layer employs augmented reality (AR) glasses to facilitate remote expert guidance, improving maintenance efficiency by 40%.

In the domain of smart materials, shape memory alloys (SMA) are used in adaptive sealing systems, where they autonomously expand to fill cracks when temperatures exceed 50°C. Self-healing concrete, enhanced with urea-formaldehyde

resin microcapsules, releases epoxy resin upon crack formation to achieve autonomous repair, restoring permeability coefficients to 10^{-12} m/s. These intelligent approaches not only enhance decontamination efficiency but also significantly improve on-site emergency response capabilities.

6.4 Future Development Trends

Nuclear decontamination technology evolution manifests through five integrated vectors: Firstly, synergistic process configurations combining laser-electrochemical ablation and ultrasonic-biological treatment achieve >99.9% contaminant removal through multi-stage purification processes; secondly, modular systems incorporating containerized laser units enable field deployment within 48-hour operational windows via plug-and-play installation protocols; thirdly, functional materials including pH-responsive hydrogels and magnetic adsorbents implement selective contamination binding mechanisms; fourthly, blockchain-integrated AI platforms establish cryptographic audit trails across waste lifecycle processes using deep neural network pattern recognition; fifthly, IAEA-coordinated standardization initiatives through multinational working groups anticipate 30% cross-border project implementation under harmonized radiation safety protocols.

As indicated in Table 3, near-term efforts (2025-2028) will leverage integrated methods such as laser-electrochemical decontamination. Medium- (2029-2035) and long-term (2036-2050) developments will introduce advanced technologies including nanorobotic decontamination and genetically engineered microbes, accompanied by continuously optimized performance metrics. Overall, the field is transitioning rapidly from “singular removal” to “cyclic purification,” and from “manual operation” to “intelligent autonomy.” With deeper integration of materials science, artificial intelligence, and green chemistry, next-generation decontamination technologies are expected to achieve higher efficiency, enhanced safety, and lower carbon footprints—laying a solid foundation for the sustainable development of nuclear energy worldwide.

This study systematically evaluates technological advancements and critical challenges in nuclear facility decommissioning and decontamination across four critical dimensions: surface contaminant removal, subsurface contamination remediation, intelligent process optimization, and standardization frameworks. Against the backdrop of accelerating global nuclear infrastructure development, advanced decontamination technologies have become paramount for ensuring radiological safety and supporting sustainable environmental governance. Research priorities should concentrate on developing eco-functional materials such as biodegradable chelating agents and low-carbon waste immobilization matrices, while advancing the integration of robotics-assisted operations with digital twin platforms to enable autonomous contamination management. Parallel efforts must strengthen radioactive waste valorization through selective

separation membranes and nuclide transmutation processes to achieve material reuse and energy conversion synergistically. The establishment of multidisciplinary innovation consortia alongside internationally harmonized regulatory protocols will constitute essential drivers for transforming nuclear decommissioning practices into efficient, carbon-constrained, and intelligence-enhanced systems, thereby underpinning the sustainable evolution of nuclear energy within planetary boundaries.

Conflict of Interest: The authors declare no conflict of interest.

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