

R&D Status and Advanced Strategies for Nuclear Power Plant Decommissioning Decontamination Technologies

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1. Introduction

Nuclear Power Plant (NPP) decommissioning is a comprehensive engineering process aimed at safely closing permanently shut-down nuclear facilities, reducing residual radioactivity below regulatory standards, and restoring the site for unrestricted or restricted reuse. The decommissioning process typically comprises five sequential phases: preparation prior to permanent shutdown, spent fuel removal and cooling, decontamination/dismantling, radioactive waste management/disposal, and site restoration, requiring approximately 11 to 15+ years.

Decontamination is a critical preliminary phase designed to lower radiation dose rates via chemical, physical, or electrical mechanisms prior to dismantling. The key performance metric, the Decontamination Factor (DF), is defined as the ratio of initial radioactivity (A_0) to final residual radioactivity (A_f).

Achieving a high DF minimizes occupational radiation exposure to satisfy the ALARA (As Low As Reasonably Achievable) principle. Furthermore, it reclassifies intermediate-level waste into low-/very-low-level waste or clearance levels, significantly reducing radioactive waste disposal costs.

2. Classification & Mechanism of Decontamination Technologies

Decontamination technologies are categorized according to target items, radionuclides, penetration depth, and secondary waste volume.

- Chemical Decontamination: Employs acids, alkalis, and redox agents to dissolve surface oxide layers on metals, extracting trapped radionuclides (^{60}Co , ^{137}Cs , etc.) into aqueous solution. It includes Full System Decontamination and component immersion decontamination. While it offers high DFs, it generates secondary liquid waste.
- Physical/Mechanical Decontamination: Utilizes shockwaves, abrasive impacts, ultrasonics, high-pressure water jets, or blasting to mechanically remove surface layers. It features high processing

speeds without chemical corrosion risks, but produces large volumes of solid secondary waste and airborne dust.

- Special & Advanced Decontamination: Combines hybrid chemical and physical mechanisms, such as hydrogel coatings, nanocomposite fluids, foams/gels, and laser ablation. It minimizes agent usage, drastically reducing secondary waste generation via dry or ultra-low-volume wet operations.

3. R&D and Field Demonstration Status

3.1 International Trends

Repeated By 2050, over 588 NPPs worldwide are projected to reach permanent shutdown, representing a cumulative market size exceeding 500 trillion KRW.

- United States: Has completed the decommissioning of 16 reactors (including 8 commercial units). Holds extensive experience in strong acid-based chemical decontamination, such as the EPRI-DfD process.
- Germany: Commercialized the HP/CORD-UV process over 18 full-system applications. By utilizing UV photochemical reactors, it completely decomposes organic acids (oxalic acid) into H_2O and CO_2 , minimizing liquid waste generation.
- France & Japan: France leads in foam/gel decontamination via CEA/EDF, while Japan focuses on remote robotic decontamination leveraging JAEA JPDR decommissioning experience post-Fukushima.

3.2 Domestic Status & Field Applications

Korea's overall technology level stands at approximately 82% compared to top-tier nations, but complete technological self-reliance (100%) for 96 essential decommissioning technologies has been achieved through collaboration between KHNP (58 commercialization technologies) and KAERI (38 core foundational technologies).

- Kori Unit 1 (PWR) Full-System Decontamination: Successfully performed full-system decontamination on primary systems (RCS, CVCS, RHR) using a low-concentration organic acid process (CRI_RWDecom) and mobile system equipment (CIDF). System dose rates were reduced by over 30-fold, and a 4-legged autonomous robot was deployed for real-time radiation monitoring to enforce ALARA principles. This milestone contributed to securing Nuclear Safety and Security Commission (NSSC) approval for the Final Decommissioning Plan.
- Wolsong Unit 1 CANDU Decontamination: R&D is underway for inorganic acid-based processes and demonstration equipment tailored to heavy water reactor carbon steel piping (Fe_3O_4 thick oxide layers, ^3H retention).
- Next-Generation Core Technologies: KAERI developed a 'hydrogel-based surface coating' that selectively adsorbs ^{137}Cs and separates adsorbents via water washing, as well as 'nanocomposite fluid decontamination technology' (transferred to SunKwang T&S; tested at Hanul Unit 1), which reduces liquid waste by 90%.

4. Advanced Strategies for Decontamination Technologies

4.1 Secondary Waste Minimization & Non-Chelating Eco-Friendly Agents

Transition from organic chelating agents (which risk radionuclide mobility in geological repositories) toward inorganic acid-based processes. Combine magnetic/nano-adsorbents to selectively capture dissolved high-activity radionuclides, establishing a zero-liquid-discharge recirculation system.

4.2 AI, Robotics & Digital Twin-Based Smart Autonomous Operations

Integrate Physical AI into robots and multi-DOF (Degree of Freedom) manipulators for autonomous decontamination in high-radiation zones. Utilize IoT sensor networks to feed realtime environmental data (dose rates, flow, temperature) into digital twin platforms for dynamic process optimization.

4.3 Infrastructure Integration & International KEPIC Standardization

By utilizing domestic demonstration infrastructure (e.g., KRID), we verify the performance and secure field applicability of technologies and equipment developed in underwater and high-radiation virtual environments.

5. Conclusions

Korean NPP decommissioning decontamination technology has transitioned into the commercial execution phase following the successful full-system decontamination of Kori Unit 1. To secure leadership in the emerging 500 trillion KRW global market and accommodate diverse reactor types (e.g., PHWRs), ongoing R&D in eco-friendly nonchelating agents, AI-driven robotics, digital twin controls, and KEPIC international standardization will be essential to establishing complete technological self-sufficiency across the entire nuclear fuel cycle.

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