 https://doi.org/10.7733/jnfcwt.2019.17.2.139

The Status and Prospect of Decommissioning Technology Development at KAERI

한국원자력연구원의 해체기술 개발 현황 및 향후 전망

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(Received June 3, 2019 / Revised June 17, 2019 / Approved June 21, 2019)

The current status and prospect of decommissioning technology development at KAERI are reviewed here. Specifically, this review focuses on four key technologies: decontamination, remote dismantling, decommissioning waste treatments, and site remediation. The decontamination technologies described are component decontamination and system decontamination. A cutting method and a remote handling method together with a decommissioning simulation are described as remote dismantling technologies. Although there are various types of radioactive waste generated by decommissioning activities, this review focuses on the major types of waste, such as metal waste, concrete waste, and soil waste together with certain special types, such as high-level and high-salt liquid waste, organic mixed waste, and uranium complex waste, which are known to be difficult to treat. Finally, in a site remediation technology review, a measurement and safety evaluation related to site reuse and a site remediation technique are described.

Keywords: Nuclear power plant, Decommissioning, Decontamination, Radioactive waste, Site remediation

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한국원자력연구원에서 개발 중인 해체기술 현황 및 전망에 대해 기술하였다. 특히, 해체의 핵심기술인 제염, 원격절단, 해체폐기물처리 및 부지 복원 분야를 중점적으로 다루었다. 제염기술로는 부품제염과 원자력시스템제염 부분을 고찰하였고, 원격절단기술 관련해서는 절단기술, 원격제어 및 해체공정 모사기술이 다루어졌다. 해체 폐기물처리기술 관련해서는, 비록 해체 후 다양한 폐기물이 발생하지만, 주 폐기물인 금속, 가연성폐기물과 난처리성 특수 폐기물인 고염 고방사성 폐액, 유기혼성폐기물 및 우라늄 복합폐기물 처리기술 등을 주로 기술하였다. 마지막으로, 해체부지 복원 분야에서는 방사선 측정, 부지 재이용의 안전성평가 그리고 부지 복원기술 등을 중점적으로 기술하였다.

중심단어: 원자력발전소, 해체, 제염, 원격절단, 방사성폐기물처리, 부지복원

1. Introduction

Nuclear decommissioning, as a type of nuclear cycle technology indispensable for sustainable nuclear energy use, is defined as all of the technical and managerial processes by which a nuclear facility is dismantled to the point that measures for radiation protection are no longer required. After a facility has been completely decommissioned, it is released from regulatory control.

Many nuclear power plants were constructed as the result of the oil shock in the 1970s, and there are approximately 448 operating nuclear power plants (NPPs) worldwide as of 2018 [1]. A nuclear power plant (NPP) is typically designed to be sustainably operated over a lifetime of 30 ~ 40 years. Among currently operating plants, approximately 179 have been operating for more than 30 years. However, the designed operation lifetime can be extended if the reactor is assured for extended operation from the relevant regulatory body. Since the accident at the Fukushima NPP in 2011, however, the decommissioning of both operating plants and of those not currently in operation has become an important issue around the world. Thus, worldwide, the decommissioning of NPPs will reportedly be required at 430 plants by 2050, and the corresponding cost is expected to exceed $265 billion [1].

Before the Fukushima nuclear accident, Korea had

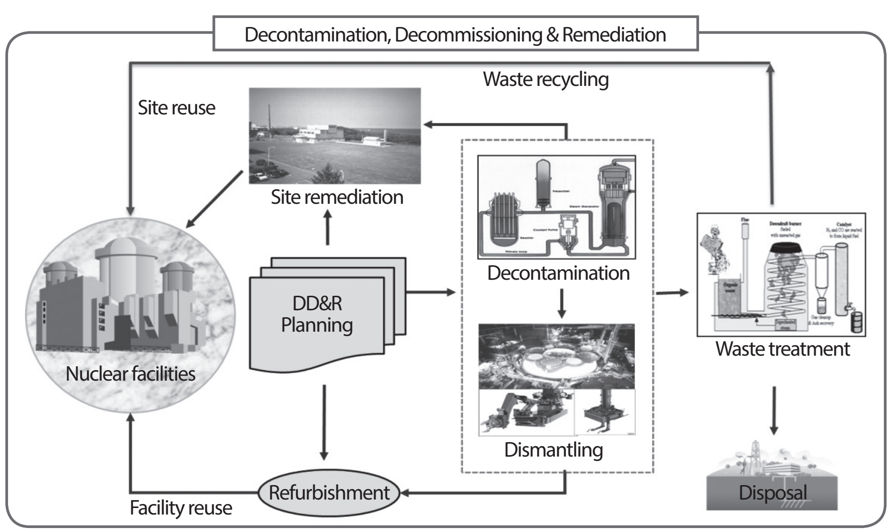


Fig. 1. Decommissioning sequences and required technologies.

been focusing on the safe operation and construction of new plants, whereas relatively little attention had been paid to the closing of aging NPPs. However, the Fukushima nuclear accident seriously affected Korean nuclear energy policies. Although Korean power reactors are relatively recent, the Korean nuclear utility KHNP has decided to decommission the Kori-1 plant and permanently shut down the Wolsung-1 plant, which have been operating since 1978 and 1983, respectively, due to political and social objections.

Thus far, we have secured decommissioning technologies for small research facilities through the experience of the decommissioning of research reactors and a uranium conversion facility in Korea. However, to be prepared for the upcoming decommissioning of domestic NPPs and to enter the worldwide nuclear decommissioning markets, further development is required to secure the proper and practical technologies to carry out safe and economical decommissioning.

For this reason, this paper describes the status of and perspectives on decommissioning technologies in Korea, especially with regard to the four key technologies of decontamination, remote dismantling, decommissioning waste treatment and site remediation. Besides these technologies, the decommissioning of nuclear facilities requires a range of other basic technologies, such as radiological characterizations and cost estimations in the planning stage. These are depicted in Fig. 1.

2. Current Status and Prospects

2.1 Decontamination Technology

Decontamination in the nuclear industry is defined as the removal of contaminated radioactive materials from target objects. A broad definition of decontamination includes the actions taken during the process of the disposal and storage of the removed materials into designated places [2]. Therefore, decontamination affects equipment and systems which have been contaminated by activity build-up over time in relation to maintenance and/or decommissioning. During periodic maintenance activities, the main focus is on reducing occupational exposure. It is also necessary to reduce the level of radioactive waste in preparation for decommissioning. Specifically, NPPs after long-term operation contain deposited radioisotopes which are responsible for most radiation exposure to nuclear power plant workers. The key objectives of decontamination are as follows:

- To reduce radiation exposure
- To reduce the volume of radioactive waste
- To prevent the spreading of contamination

Decontamination technology has been developed in order to achieve designed decontamination factors, as measured by an index of the ratio of the initial activity and residual activity depending on the objects to be decontaminated. Since the 1960s, a number of decontamination methods, such as chemical, electrochemical, mechanical, melting, and thermal erosion, among others, to remove radiological contamination have been developed [3]. The selection of the decontamination process for in-situ application depends on various factors related to the radioactive contaminants as well as the complexity of the system, the types of substrates, accessibility to objects, the required decontamination factor, and time and cost allowances, among other factors [4]. Rough mechanical methods are mainly applied for component decontamination, whereas, chemical decontamination methods are used for system decontamination as well as component decontamination. Pre-evaluation and planning for decontamination activities are also required to select the appropriate methods. It has been shown that both decontamination methods can effectively reduce both occupational exposure and the volume of radioactive waste.

2.1.1 Current Status of Decontamination Technology

There are many criteria by which to classify types of decontamination processes. The purposes of decontamination can be for maintenance and for decommissioning. Decontamination involves both component decontamination and system decontamination depending on the target contaminant. In this section, we compile currently developed decontamination technologies into these two categories. A simplified technical overview of current developments will also be provided. More details about the methods addressed in this paper can also be found in the literature [2, 3, 5, 6].

2.1.1.1 Component Decontamination Technology

Component decontamination is usually applied to the components or subsystems from which radiological contaminants are easily removed using non-chemical or electrochemical methods as well as chemical methods. Non-chemical decontamination methods include the mechanical methods of brushing, abrasive blasting, and the use of a high-pressure water jet containing some abrasives, along with other methods such as electrochemical processes and the use of gel and foam decontamination approaches [3]. The selection of appropriate methods and the qualification of the influential parameters depend on site-specific conditions and requirements. The first principle of component decontamination is to achieve a high decontamination factor given that this process is typically performed in an open system with fewer limitations compared to system decontamination. Component decontamination is often conducted to reduce the radioactivity of decommissioning waste further for free release.

Dry ice (CO_2) blasting is one of the major component decontamination technologies currently in use. This method is used to remove contamination by means of carbon dioxide pellets as a blasting medium [7]. Dry ice blasting has been shown to be effective in tests with many different types of substrates, such as stainless steel, ceramics, and composites, but not soft materials [8]. This process uses the following three mechanisms nearly simultaneously: a contamination removal process with accelerated carbon dioxide pellets, the creation of shear stress on the surfaces of materials due to the thermal shock caused by the cold pellets, and the lift-off of the contamination by the expansion of the CO_2 gas. There are several advantages of CO_2 blasting. First, it generates no secondary residual waste because the CO_2 pellets sublimate from a solid state to a gas when they are applied onto a contaminated surface [9]. Second, the process offers superior decontamination efficiency for loose surface contamination due to its expansion effect and unique flushing action. The use of CO_2 blasting in a radioactive environment requires a highly pressurized pellet delivery system composed of an air compressor, an air dryer, as well as a temperature control system to prevent system blockages caused by the frozen CO_2, and an off-gas treatment system equipped with a containment hut to collect the off-gas, with filtered ventilation to separate radioactive particles from it.

Electrochemical or electropolishing decontamination is a chemical decontamination process assisted by anodic dissolution. Electrochemical decontamination is conducted by immersing a component into a decontamination bath containing an electrolyte [10]. This method is useful for decontaminating items whose surfaces are not easily accessible by means of blasting methods. Electropolishing also utilizes anodic dissolution to strip a controlled amount of material from the surface of a component. Phosphoric acid, sulfuric acid, nitric acid, neutral salts such as sodium sulfate and sodium nitrate, or certain organic acids are most commonly used as electrolytes [3]. In practical applications for decommissioning purposes, decontamination to background levels, removing most radionuclides from the surface, is possible. This results in decontamination factor (DF) typically exceeding 100. When compared to chemical decontamination, the electrochemical process uses a relatively low volume of liquid and produces less secondary decontamination waste. However, the production of explosive hydrogen gas when using these strong acids is the major problem associated with this process. In addition, the effectiveness of this process is limited when the components have complex surfaces or when a decontamination bath is not feasible to the need to immerse the component to be decontaminated.

Chemical reagents also have been applied for single-step component decontamination. SODP, REDOX, MEDOC, HNO_3/HF, and HBF_4 are acronyms representing the typical processes in this category. The SODP (Strong Ozone Decontamination Process), developed in the late 1980s in Sweden, uses ozone as a strong oxidizing medium and Ce^{4+} ions as a catalyst [11]. This process operates at ambient temperatures but under a strong acidic condition of pH 0.6. It has been tested on contaminated materials ranging from steam generators (SGs) in France, the USA, and Sweden, resulting in residual radioactivity levels of less than 1 $Bq \cdot g^{-1}$ [11]. The treatment of the solutions used after decontamination consists of a reduction of the overrun Ce^{4+} to Ce^{3+} using hydrogen peroxide followed by the precipitation of hydroxides in a basic environment. The REDOX (REDuction-OXidation) process was developed in Japan. This process is similar to the SODP in that it also uses Ce^{4+} in nitric acid, but it operates at temperatures of 60 to 80℃. In fact, the increased temperature accelerates the reaction compared to the SODP, which is applied at an ambient temperature. In Belgium, an improved immersive single-step chemical decontamination process known as MEDOC (MEtal Decontamination by Oxidation with Cerium) works by combining the two existing processes of an accelerated attack rate at an increased temperature and a simple regeneration technique using ozone. This process also uses Ce^{4+} as a strong oxidizing agent, with sulfuric acid as a solvent. After the decontamination of ^{137}Cs using this process, it was found to have achieved a DF greater than 10,000, with the treated materials having residual activity lower than 0.1 $Bq \cdot g^{-1}$, a potential level at which free release becomes possible [8]. The HNO_3/HF mixture is commonly used for the etching of stainless steel in a pulverization solution [12]. The dissolution of the oxide occurs due to penetration by a chemical solution. Strong decontamination with the dissolving of even base metals to a thickness of 20 μm reduces the activity of ^{60}Co from 100-5000 $Bq \cdot g^{-1}$ to 0.3 $Bq \cdot g^{-1}$. However, the process is limited to batch systems due to the continuous consumption of HF [3]. The HBF_4 (fluoroboric acid) process dissolves the oxide layer on a metal surface in a batch system. It was developed in Switzerland in the 1980s under the name of DECOHA (Deco-Hanulik process) [13] and later as a diluted version called the DfD (Decontamination for Decommissioning) process [14]. HBF_4 is known to be effective for the dissolution of BWR oxides but not for Cr-rich PWR deposits.

In Korea, the technologies of carbon dioxide pellet blasting and spray decontamination with PFC (Perflorocarbon) fluid have been developed for the cleaning of loosely adhered contaminants. Moreover, a plasma decontamination technology applicable to fixed contaminants on unexposed surfaces as a dry decontamination process has undergone tentative development. An abrasive blasting technology using silicon carbide or alumina was applied to decontaminate the heat transfer tubes of SGs from the Hanbit NPP site, resulting in a high DF of nearly 15,000 [15]. An electrochemical process using various neutral salt electrolytes was developed to decontaminate metal waste contaminated with the uranium compounds (UO_2) during the dismantling of a uranium conversion facility [16]. Tests showed that the process when using sodium sulfate as an electrolyte was much more preferable compared to the use of sodium nitrate as an electrolyte [17]. Decontamination using a $NaNO_3$/HF mixture solution was tested on both surrogate specimens of 304 stainless steel and Inconel 600 [17], showing very a good decontamination factor of 95.

2.1.1.2 System Decontamination Technology

With the long-term operation of nuclear power plants, there are deposited radioisotopes, mainly cobalt and small amounts of fission products throughout the reactor coolant system. Especially in early operation stage of a plant, ^{58}Co is produced from the (n-p) reaction of ^{58}Ni with fast neutrons, and after approximately ten years operation, ^{60}Co forms as a result of the (n-γ) reaction of ^{59}Co, which acts as an impurity of the base material, with thermal neutrons [18]. These radionuclides cause high radiation levels around the primary coolant system of the NPP; therefore, decontamination is necessary to ensure sufficiently reduced radioactivity during routine maintenance or decommissioning. A chemical decontamination process involving oxidation and reduction reactions is considered as the most effective method for the decontamination of the primary coolant system thus far.

For oxidation decontamination, permanganate processes have been developed to dissolve chromium oxides by an oxidation reaction. As oxidizing solutions, nitric acid and potassium permanganate [19], alkaline permanganate (AP), and acid permanganate (HP) are typically used. During the AP process, potassium permanganate is circulated in the coolant system, oxidizing chromium (Ⅲ) ions to chromium ions [8], which are soluble in an aqueous alkaline solution. The nitric permanganate process [19] uses nitric acid to achieve the required pH of about 2.5 in combination with permanganate, which is particularly advantageous for passivating carbon steel. While the NP process is also known to be more effective when used with stainless steel than the AP process, it was found that the use of AP was better than NP when the target is contaminated by grease and graphite. On the other hand, the HP process developed in Germany in the mid-1980s uses permanganic acid as an oxidizing reagent and differs from AP or NP, which uses potassium permanganate. The oxidation reaction in HP is identical to that of NP but the performance outcomes in terms of decomposition and corrosion are superior to those by NP due to the lack of nitrate ions, which promote corrosion. In current oxidation processes, the use of permanganate ions from NP, AP or HP is most favorable.

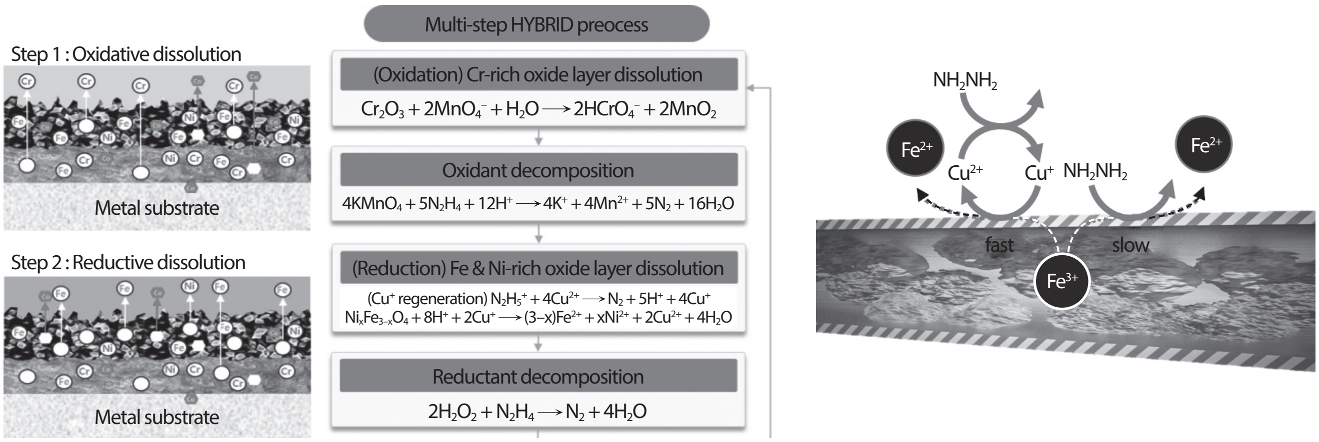
With regard to reductive decontamination processes, the CAN-DEREM, CITROX, LOMI, DfD and CORD processes have commercially eclipsed existing methods. Acidic solutions such as oxalic acid, vanadous picolinate, citric acid, or ethylenediamine tetraacetic acid (EDTA) or a mixture of any of these are commonly used as reducing agents, with a pH range of 2-3 [8]. These reducing agents are known to be very effective for iron oxide dissolution. Initially, the CAN-DEREM (CANadian DEcontamination and REMediation) process arose as a modification of the previous CAN-DECON (CANadian DECONtamination) process in the 1980s, eliminating oxalic acid from the CAN-DECON process [2, 20]. In the evolution of the original CAN-DECON process, it was operated at temperatures between 85-120℃ with a pH of 2.1-2.3 for 24-36 hours. The solution consisted of 0.01wt% EDTA, 0.03wt% citric acid, and 0.03wt% oxalic acid. However, after the observation of types of localized corrosion, such as intergranular attacks (IGA) during the decontamination of the Peach Bottom 2 plant, the AECL undertook numerous corrosion and decontamination experiments to find the mixture of reagents that minimized IGA or other localized attacks of sensitized 304 SS. As a result, the CAN-DEREM process was successfully developed and is now being used by Westinghouse for PWR decontamination.

The CITROX (CITRic and OXalic acids) process was developed in the 1960s and thus early in the decontamination chronologically for the decontamination of PRTRs (Plutonium Recycle Test Reactors) at the Hanford and Shippingport reactors and was later modified for use with BWRs and PWRs as a regenerative process [2]. Unlike the CAN-DECON and CAN-DEREM processes, it used higher reagent concentrations of 2.5wt% oxalic acid and 5wt% dibasic ammonium citrate with a corrosion inhibitor such as 2wt% ferric nitrate or 0.1wt% diethythiourea. Therefore, it required approximately double the amount of anion exchange resin for the waste treatment process. While CITROX does not contain EDTA, which causes further environmental problems during its disposal, this process must maintain a very low concentration of ferric ions through the use of cation resin, as citrate and ferric chelate are less stable than EDTA and ferric chelate.

LOMI (Low Oxidation Metallic Ion) is a chemical process developed by the Central Electricity Generating Board (CEBG) in the U.K. with financial support from EPRI (Electric Power Research Institute in the US) in the early 1980s. This process uses a relatively dilute solution of a strong reducing agent, V^{2+} ions in the form of vanadium tri (picolinate) or simply vanadous picolinate, to reduce ferric ions (Fe^{3+}) in the oxide layer. In an excess picolinic acid, ferric ions in the corrosion products are dissolved as soluble ferrous ions (Fe^{2+}) with the V^{2+} ions being oxidized to V^{3+}. LOMI has the advantage of faster decontamination, though it produces more secondary waste compared to other processes, especially the CORD process. In addition, EPRI developed the LOMI-2 process, which is similar to LOMI but is instead a regenerative process. This adjustment was done to reduce secondary waste during the decontamination process.

The CORD (Chemical Oxidation Reduction Decontamination) process was invented in the mid-1980s by Siemens in Germany but later overtaken by Areva Framatome in France. This process consists of oxidation, reduction, decontamination, and clean-up steps, like most decontamination processes, but is uniquely combined with a UV process that serves as an advanced oxidation process to decompose oxalic acid, resulting in a volume reduction of ion exchange resin. In addition, D(decommissioning)-option, in which the solution becomes more aggressive when exposed to the base metal and where the redox potential is reduced from the initial 100 mV to approximately –275 mV, with thus significantly increased levels of corrosive solutions capable of dissolving up to 10 μm of the base metal, was added to make the CORD process suitable for the decontamination before the decommissioning work. Thus far, this process is considered as the most useful process in terms of decontamination performance and secondary waste generation, generating ion exchange resins of 0.08 to 0.1 m^3 with a 1 m^3 decontamination solution. However, localized corrosion (e.g., IGA and pitting) often observed on some materials after using this process, and oxalate formation during the decontamination step make process purification somewhat difficult [10].

The DfD (Decontamination for Decommissioning) process is a diluted chemical decontamination process for reactor coolant systems and components developed by EPRI with Bradtec in 1996. This process was intended to serve as a new chemical decontamination process for decommissioning with the advantage of typical diluted decontamination processes used at operating plants, such as LOMI, with the high performance of DF coming from the concentrated and aggressive processes involved. This process consists of a diluted solution of fluoroboric acid (~ 0.088%) with sequential additions of an oxidizing agent and a reducing agent. The circulation of this solution results in the progressive removal of a thin layer of the base metal to release radioisotopes trapped in the oxide layers regardless of the type of substrate, i.e., stainless steel or Inconel. Because the final waste form is an ion exchange resin, it generates only a small amount of secondary waste, similar to any diluted decontamination method. This method was successfully applied to the overall process of the full loop decontamination of several retired plants, including the Big Rock Point BWR, Maine Yankee PWR and the Trojan reactor. While all previous methods were focused on radioisotope removal to reduce the radioactivity to an appropriate level for a working environment under numerous limitations, this process made it possible to treat all decontaminated metal as non-radioactive materials to be recycled, thus offering very significant economic and environmental benefits. In Korea, decontamination research started in 1982 with fundamental research and equipment development to apply existing decontamination processes to the SG of the Kori-1 reactor during its maintenance. The first domestic decontamination process based on a diluted solution was invented in 1987 by KAERI. The applicability of this process was confirmed with the demonstrated results of the decontamination for a PZR notch ball (DF 17.7) and a SG u-tube (DF 3.5) [21]. It was applied later to the decontamination of a check valve from the Kori-4 reactor, showing a sufficient DF of 14.5 in 1997. Recently, the decontamination of a reactor coolant pump (RCP) from the Ulzin-3 reactor was carried out, resulting in a DF of 19.46, higher than the initial plan of a DF of 10 [22]. There was intensive research on the regenerative LOMI process, which was used in general successfully for the



(a) (b)

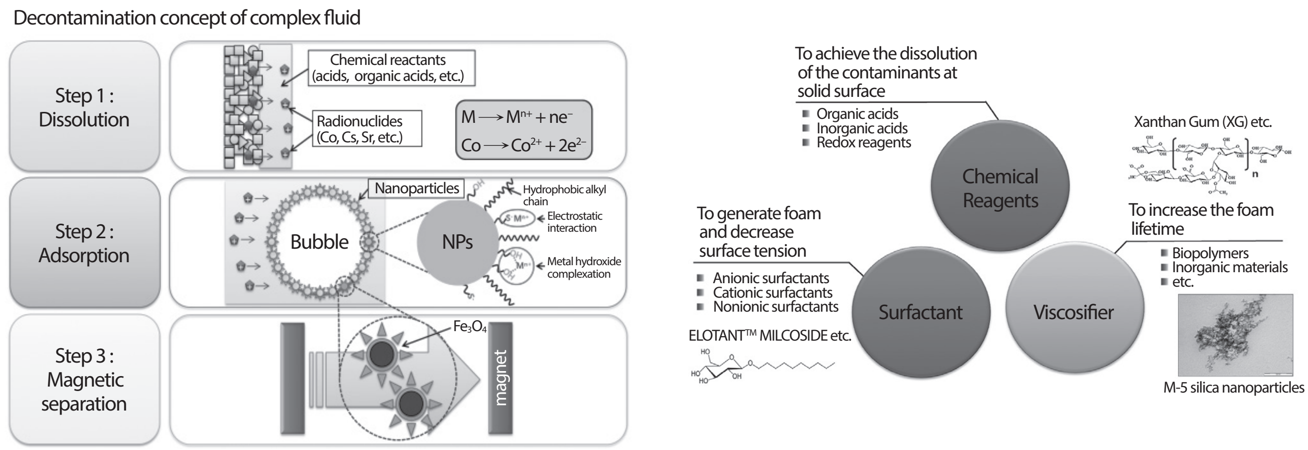
Fig. 2. Schematic diagrams and flowsheet of the HYBRID decontamination process (a) and the mechanism of decontamination facilitation by the Cu(II) catalyst (b).

decontamination of a KSC-4 PWR spent fuel transport cask in the early 1990s. For the decontamination of the KRR-1 and 2 research reactors, a diluted decontamination process using HBF_3 was developed and proved to be effective on the aluminum surface of the primary coolant system of these research reactors.

2.1.2 KAERI Perspective on Decontamination Technology Development

The US, UK, Germany, and France have accumulated in-situ decontamination experience using their proprietary commercial decontamination processes. Decades ago, there was some flexibility with regard to the development of decontamination technologies due to less strict standards of safety and environmental effects. As these standards become stringent and public acceptance of nuclear and radiation safety became more important, the commercial processes described above are by no means generally in a state of technological completeness. For example, the DfD (Decontamination for Decommissioning) process developed by EPRI uses a highly corrosive solution and is associated with the safety issue of producing explosive hydrogen gas during the decontamination process, while the CORD process is not appropriate for decontamination during NPP maintenance due to localized corrosion which affects the substrate integrity. Furthermore, organic chelates used in most commercial decontamination processes for preventing the precipitation of dissolved metal ions through metal-organic acid chelation and even increased decontamination efficiency can represent an environmental pollutant because they become toxic after losing one acidic group, especially at repository sites [23]. Hence, spent oxalate is decomposed and the resulting metal ions including radionuclides are removed using an organic resin, resulting in increased levels of organic secondary waster requiring disposal. Therefore, certain complementary technologies to resolve these current limitations are crucial in the near future to meet the upcoming worldwide demand for decommissioning.

Along this line, a new concept in system decontamination was sought, and KAERI in Korea has accomplished the development of a chemical decontamination process without organic chelating reagents to decontaminate reactor coolant systems. The preliminary results have proven the effectiveness of this process for in-situ system decontamination [24, 25]. This process, termed HYBRID (Hydrazine-Based Reductive Metal Ion Decontamination), is capable of dissolving metal oxides by protonation, surface complexation, or reduction. A solution containing



(a) (b)

Fig. 3. Schematic diagrams of the complex fluid decontamination process (a) and its basic functional classification (b).

hydrazine and an organic acid such as sulfuric acid or nitric acid provides hydrogen to break the bonds between Fe and oxygen by protonation, providing electrons for the reduction of insoluble Fe(Ⅲ) to soluble Fe(Ⅱ) in an acidic solution at a pH or around 3. When combined with the SP oxidation process, HYBRID can serve as a multi-step process, as shown in Fig. 2(a). Moreover, it uses Cu ions as a catalyst to maximize the dissolution rate, based on considerable research to determine the effects of transitional metal ions. In fact, the bridged bond between the Cu(Ⅰ) ion and hydrazine can facilitate the transfer of an electron from the Cu(Ⅰ) ion to the Fe(Ⅲ) of magnetite. Moreover, the reduction of Cu(Ⅱ) ions, oxidized by the reaction with Fe(Ⅲ) to Cu(Ⅰ), has been found to be effective for the further oxidation of hydrazine, as shown in Fig. 2(b). During the cycle of Cu(Ⅰ) ions to Cu(Ⅱ) ions, the released electron promotes the reduction of Fe(Ⅲ), and Cu(Ⅱ) ions return to Cu(Ⅰ) ions due to the oxidation of hydrazine [26]. Currently, the HYBRID process is being prepared to demonstrate its decontamination performance and applicability to actual radioactive components retired from an operating RCS. Eventually this process will be ready for in-situ system decontamination application, after 2021.

Besides primary coolant system decontamination technologies, various decontamination technologies have been developed and applied to complete nuclear decommissioning. Among them, some decontamination methods for large-size equipment and facilities with large surface areas have been reviewed as important technologies for successful decommissioning. For this reason, a complex fluid decontamination process composed of functional silica nanoparticles and chemical decontaminants is now being developed in Korea [27]. With the well-known foam decontamination processes, a new technological concept involving the addition of functional nanoparticles has been implemented to enhance the stability of the foam for longer stationary times on contaminated surface, hopefully contributing to more functional reactions for the efficient removal of radioactive isotopes (see Fig. 3) [27]. Functionally activated nanoparticles induce the complex of a metal or nuclide (^{60}Co) by electrostatic interaction to enhance the decontamination efficiency despite the reduced contact with decontaminants and metal oxides. A significantly reduced volume of the chemical solution used in this process would be advantageous for the decontamination of large-size equipment (e.g., steam generators) or large-area facilities (e.g., spent fuel pools).

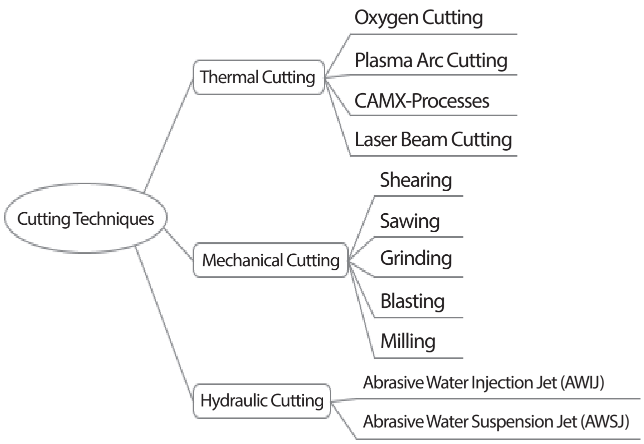


Fig. 4. Classification of cutting technologies for the dismantling of nuclear facilities.

2.2 Dismantling Technology

Dismantling technology covers cutting, remote handling and simulation technologies, targeting an enhancement of worker safety and greater economic results during decommissioning. Cutting technology mainly refers to the removal of the metal and concrete structures of nuclear facilities. Remote handling indicates remote control of equipment for cutting, packaging and transporting the dismantled components to minimize the exposure dose to workers during the decommissioning of a nuclear facility. Simulation technology is a very powerful tool to realize an effective work process, as this technology can minimize unforeseen problems using virtual environments that display physical and logical schema and the behaviors which arise during actual decommissioning work. This method can reduce time and cost amounts, can reduce risk when making subsequent changes, and can facilitate the development of various decommissioning scenarios.

Because decommissioning activities are performed under highly radioactive environments of nuclear facilities and considering that the systems or components to be dismantled are mostly heavy or complex, remote dismantling technologies should meet the following requirements:

- High reliability in a highly radioactive environment
- Easy handling for dismantling objects
- Guarantee of worker safety

To meet the above requirements, many countries, including the USA, UK, France, and Japan, have focused on developing advanced remote dismantling technologies. These countries have already experienced the decommissioning of nuclear facilities and have been securing a foundation upon which to develop technologies based on their experiences. In particular, to dismantle the highly radioactive systems and structures of nuclear facilities, they have developed their own specialized technologies for cutting large structures, for remote handling and for evaluations of the dismantling processes. In this section we describe briefly the development status of dismantling technologies.

2.2.1 Current Status of the Dismantling Technology

2.2.1.1 Cutting Technologies

For the dismantling of the highly radioactive structures of nuclear facilities, cutting methods with much higher reliability and robustness are required compared to the dismantling of non-nuclear facilities. For this reason, various types of cutting equipment have been applied depending on the size and shape of the objects to be cut. In addition, minimizing secondary waste should be considered during the development of cutting technology. Cutting technologies for nuclear facilities can be mainly divided into three types: thermal, mechanical and hydraulic, as shown in Fig. 4.

Thermal cutting refers to methods which separate materials by applying heat without direct contact. There are three typical thermal cutting technologies according to the type of energy source used to generate the heat: chemical (e.g., oxygen cutting), electrical (e.g., plasma arc cutting, contact arc metal processes), and laser beam cutting.

Oxygen cutting uses a flowing mixture of a fuel gas and oxygen ignited at the orifice of a torch. The fuel gas can be acetylene, methylacetylene, polypropylene, propane, or hydrogen. This technology is generally applicable to ferrous metals, including steel products such as sheets, plates, bars, piping, forgings, castings, and wrought iron products. This technology, although easily adaptable to an automated process, is normally hand-held and can be performed in air or under water.

Plasma arc cutting and CAMC (Contact Arc Metal Cutting) were used to dismantle a reactor pressure vessel (RPV) at KGR and a thermal shield at MZFR in Germany, respectively [28].

On the other hand, laser cutting technology has been considered a next-generation tool for the decommissioning of nuclear power plants. It has many advantages compared to other cutting methods such as mechanical cutting, abrasive water jet cutting, and plasma arc cutting [28-30]. For the decommissioning of main components such as a reactor pressure vessel (RPV) and its internals (RPVI) and the reactor coolant pumps (RCP) and steam generators (SG) of nuclear power plants, remote cutting is essential because human workers cannot approach a highly radioactive working environment. Remote cutting is much easier when using a laser, as the laser beam is delivered by a fiber up to several tens or hundreds of meters, and only the small cutting head is used at the work place, without any other mechanical or electrical equipment. Furthermore, the cutting head is easily controlled by, for instance, a robot arm, as laser cutting is a noncontact process and because there is no repulsive force. In addition, the amount of secondary waste is very low due to the narrow kerf widths of the laser cutting. Currently available continuous wave lasers such as CO_2, YAG (Yttrium Aluminum Garnet), and fiber lasers are widely used. The cutting mechanisms of all lasers used to machine the materials involve the blow-off or burn-out of melted materials by the feeding of an assisting gas, typically a highly pressurized inert gas, and an oxidation gas such as N_2 or O_2 [29].

Regardless of which cutting method is selected, water clarity and water filtration are extremely important issues. Water clarity and water filtration may be the most troublesome aspects of underwater cutting.

Mechanical cutting is used to separate materials by direct contact between the cutter and the objects to be dismantled, unlike thermal cutting. Typical mechanical cutting technologies include shearing, sawing, grinding, blasting, and milling. Mechanical cutting methods are generally slower than plasma arc or abrasive water jet cutting. It has been reported that specially designed circular and band saws have been developed to cut the large and thick metal structures of nuclear facilities for underwater cutting [30]. One disadvantage of mechanical cutting is the high cost of equipment maintenance, as the cutting blades should be replaced frequently. Mechanical cutting technologies are generally stable but are also applied in a limited manner to, for instance, the end effectors of manipulators with high degrees of freedom due to the tool sizes involved.

Hydraulic cutting generally refers to methods which use fluid power without direct contact. A high-pressure fluid is sprayed onto the cut object in a narrow zone. It is easily applicable to a manipulator for precise cutting. An abrasive water injection jet (AWIJ) and an abrasive water suspension jet (AWSJ), which use abrasive materials with high-pressure water, have been applied successfully to the dismantling of nuclear facilities. For example, AWIJ technology was applied to dismantle a biological shield at JPDR in Japan, and AWSJ technology was applied to dismantle a core shroud and a thermal shield and RPV at VAK in Kahl, Germany, respectively [28, 30]. One drawback of an abrasive water jet is the generation of large amounts of debris due to the abrasive grit material.

As mentioned above, each of the cutting techniques has some advantages and drawbacks as well. These must be weighed and evaluated prior to determining which is most appropriate. The most suitable technology among the three categories above can be selected considering the factors of the cutting efficiency, the degree of economic feasibility, and the cutting environment. Others we should take into account are generally ALARA concerns, debris management, and the reliability and projected maintenance

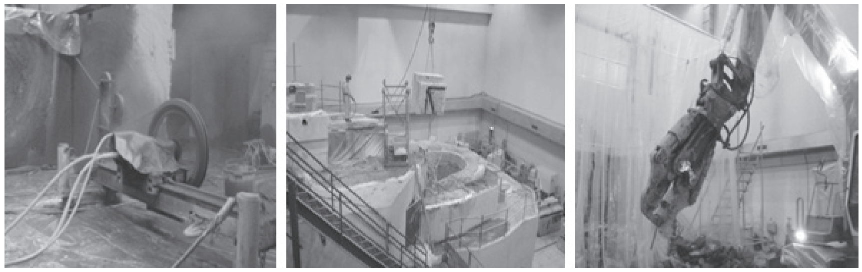


Fig. 5. Examples of dismantling the reactor shielding concrete of KRR-2.

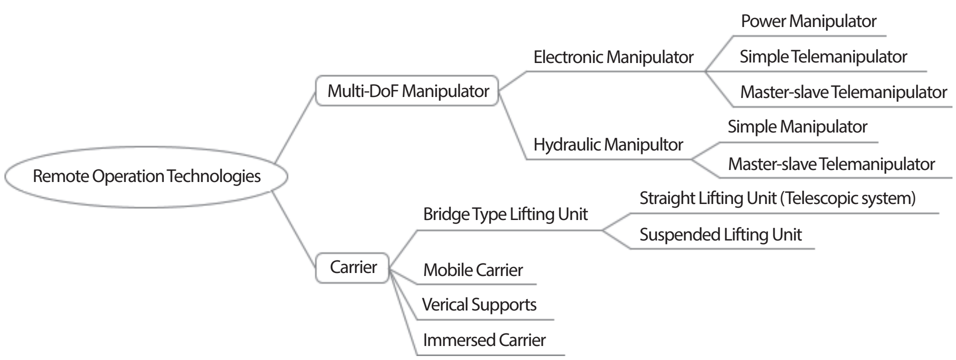


Fig. 6. Classification of remote handling technologies for the decommissioning of nuclear facilities.

of the equipment.

In Korea, the decommissioning project for Korean research reactors ((KRR)-1&2 (reactor types of TRIGA Mark Ⅱ and Ⅲ respectively)) was launched in 1997. All affected systems and facilities have been dismantled, using several cutting methods. The core structure of KRR-2 was cut into small pieces by hydraulic scissors and packed into a shielded waste cask in the water pool. The rotary specimen rack of KRR-1, a highly irradiated component, was dismantled with a specially developed tool. The highly radioactive parts of the pipes were dismantled underwater and the less active parts were pulled out of the water and cut into small pieces in a temporary shielding apparatus. For dismantling of the shielding concrete, all of the facilities embedded in the concrete, such as the thermal columns and beam port tubes, were dismantled before the main concrete dismantlement. Moreover, because the graphite blocks located in the thermal column near the core were highly activated, they were pulled out using a specially designed and remotely operated gripping tool. The aluminum casing for graphite was cut using a long-reach plasma arc. A boring machine was used to remove the beam port and concrete around the ports simultaneously. Finally, the reactor shielding concrete of KRR-2 was cut using a diamond wire saw and packed into waste containers. These dismantling examples of the shielding concrete of the KRR-2 are shown in Fig. 5. The domestic cutting technologies applied to cut the core parts of KRR-1&2 were a hydraulic shear cutter and a plasma cutter. A hydraulic wheel saw was used to cut the core liners, a diamond wire saw served to cut the concrete structures, a band saw cut the beam ports.

2.2.1.2 Remote Handling Technologies

Remote handling technology is indispensable for the decommissioning of nuclear facilities due to the very high radioactive environments inside these facilities. In the course of decommissioning, remotely operated machines have been used to perform a wide variety of tasks. These applications have ranged from the dismantling of radioactive structures to underwater decontamination tasks. Remote devices have also been used to perform radiological surveys and for the packing of highly radioactive waste. Remote handling technologies can be a crucial solution to improve radiation safety during the decommissioning of highly radioactive nuclear facilities. Thus far, adequate remote handling technologies have been selected according to the shape, size, materials and radiation level of the nuclear facilities involved.

Figure 6 presents the classification of remote handling technologies applied to the decommissioning of nuclear facilities. These are largely classified into multi-DoF (Degree-of-Freedom) manipulators for remote operations and carriers which can transport various materials or equipment adequately [30].

Multi-DoF (Degree of Freedom) manipulator technology is affiliated with robot system technologies to replace manual operations by workers through control of a robot arm which consists of links and joints. There are two types: electric manipulators and hydraulic manipulators depending on the power source. Electric manipulators can also be classified into power manipulators, simple telemanipulators and master-slave manipulators depending on the number of degrees of freedom, the payload capacity and the level of control accuracy. Among hydraulic manipulators, there are simple manipulators and master-slave manipulators. The multi-DoF manipulator for the decommissioning of nuclear facilities requires radiation hardening technology to guarantee precise control of the manipulator in highly radioactive areas. Various manipulators have been developed for use during the dismantling of nuclear facilities. MAESTRO by CEA in France and the DAWP (Dual Arm Work Platform) by ANL in the United States are representative manipulators used for the dismantling of nuclear facilities [31].

In fact, this type of dismantling system has not been applied in Korea. Currently, research and development activities are underway with the aim of securing high-payload, high-precision manipulator technology capable of dismantling very large and heavy radioactive facilities of nuclear power plants by 2021.

2.2.1.3 Simulation Technology to Optimize a Dismantling Process

The dismantling of nuclear facilities is still a costly and possibly hazardous task. Moreover, its processes are highly diverse and complex. Therefore, it is necessary to establish an optimized dismantling process in terms of cost and safety before the undertaking of actual decommissioning tasks. Thus, simulation technology can serve to verify the performance capabilities during the application or operation of specialized equipment for the dismantling of nuclear facilities beforehand. In the past, cutting or dismantling processes were demonstrated using real-scale physical mock-up systems to verify and optimize the processes. However, this strategy required long times and high costs until the physical mock-up system was established. Moreover its fatal drawback was that it could not be applied to various decommissioning scenarios related to the dismantling of objects.

Currently, digital simulations are being developed as a very effective tool instead of conventional physical mock-up systems due to technological advances in computer graphics. Hence, various dismantling scenarios can be simulated in a 3D virtual space by building a full-size decommissioning environment. The advantages of this simulation approach are the simple evaluations of specific advantages and disadvantages of processes by applying a variety of scenarios to the objects involved. In addition, during the decommissioning process, any interference or even collisions with the object can be checked, unforeseen problems can be identified, and possible errors can also be prevented at the design stage so that the cost can be reduced to a considerable extent. These advantages can also help us design, chose, and apply the process more effectively in actual decommissioning situations. Recently, these tools have provided an easy way to obtain various computing, simulation, and analysis data based on information technologies, as opposed to the conventional method based on text. In particular, attempts to customize and specialize various digital modeling and simulation technologies using 3D CAD/CAE and virtual reality have been made to support more effective process planning and decision-making by providing greater user intuitiveness [32-35]. Typical cases include VRDose by the Japan Nuclear Cycle Institute (JNC), which can support evaluations of radiation exposure during decommissioning work, and NARVEOS by CEA to produce optimal dismantling and maintenance processes in a virtual environment [36, 37].

A dismantling DMU (Digital Mock-Up) system was developed to show the dismantling process through animation for the decommissioning of KRR-1 & KRR-2. It could visualize any procedure to evaluate process parameters through an animation prior to the in-situ dismantling task [38]. This DMU system consisted of several modules, including those that handled 3D CAD modeling, visualization and assessment of the radioactivity inventory, animation, simulation, and analysis and evaluation. The system could also visualize the radioactivity distribution of objects through 3D contour mapping, which helps us determine the best scenario for the dismantling process.

2.2.2 KAERI Perspective on the Development of Dismantling Technology

The global decommissioning market is expected to increase remarkably in the near future. As technical competition becomes more intense, technology protection barriers will also increase. Therefore, it is essential to develop core technologies to overcome technology barriers in the area of remote handling for nuclear decommissioning. With regard to this connection, we have been focusing on the development of competitive-edge key technologies applicable to the remote dismantling of nuclear facilities in high-radiation environments.

For the effective decommissioning of NPPs, a cutting technology with which thick steel more than 100 mm thick can be cut is required. One of the most challenging tasks is the removal of the main components of an RPV, its internals, and the reactor coolant pipes. Thus far, certain cutting methods have been used relatively successfully for these components. However, improvements are still necessary, and the performance capabilities of cutting technologies in terms of the cutting speed, amount of secondary waste generated and adaptability to remote handling systems must be assessed. Laser cutting is considered as one of the most promising cutting technologies.

KAERI has developed the technology to cut 100-mm-thick carbon steel and stainless steel in the air using a 6 kW fiber laser to overcome functional limits such as remote operability and to reduce the amounts of secondary waste generated during the process of the cutting of nuclear facilities. Hence, we are currently developing underwater laser cutting technology for the remote dismantling of the highly radioactive core components of reactors, such as the RVI.

For the remote dismantling of the heavy components of NPPs, such as the RPV and the steam generator, we started the development of an advanced modular type of hydraulic manipulator for high loads (> 250 kg) and high accuracy (±1 mm), designed for easy replacement and maintenance in case of failure. As a result, a hydraulic-driven 6-DOF high-load handling manipulator prototype and precision control technology for remote dismantling were developed. Based on this prototype, we are currently developing a lightweight modular underwater remote dismantling manipulator capable of heavy loads.

We also developed an integrated dismantling process evaluation system to evaluate various scenarios at a low cost and with high efficiency in digital environments. This enables the selection of the best scenario for optimizing the dismantling schedule, minimizing worker exposure, and reducing the decommissioning cost. This system consists of several modules, including those for a real-time

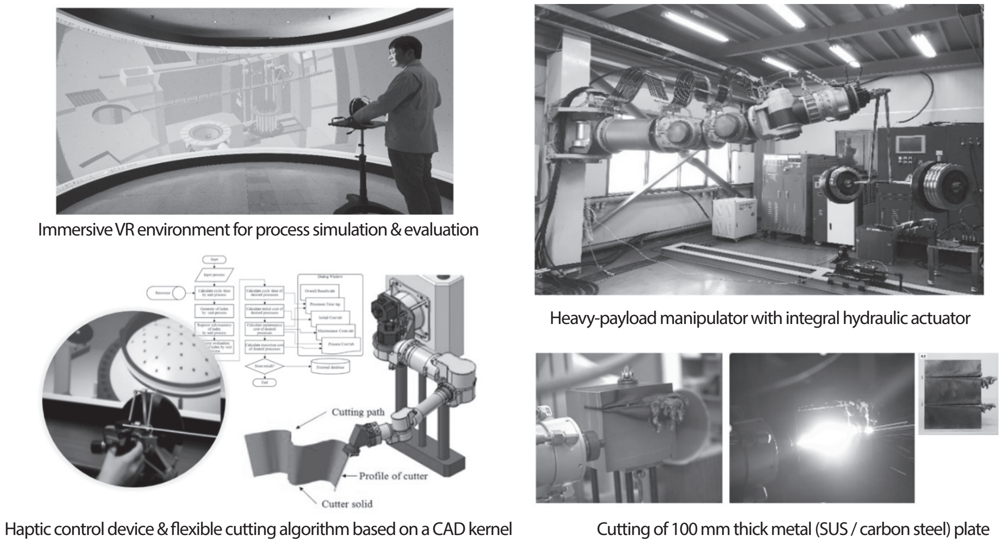


Fig. 7. Representative remote dismantling technologies developed by KAERI.

cutting simulation, kinematics simulation, visual assessments of the radioactivity inventory, and economic and safety evaluations of the dismantling processes. In addition, immersive virtual reality visualization technology and haptic-based control technology were applied to this system as part of the user interface. This system can also be used for planning and training by displaying the possible impacts of steps on the overall decommissioning process.

Figure 7 shows typical examples of the developed technologies described above. We aim to secure the core technologies of an advanced remote dismantling system capable of effectively dismantling core facilities in the highly radioactive environment of a nuclear power plant by 2021. For this purpose, we are currently developing an underwater manipulator and laser cutting technologies for flexible and effective dismantling, and radiation-resistant technologies for robustness and reliability of remote devices in a highly radioactive environment. We are also undertaking the research and development of human-machine interface technologies based on environmental information feedback to maximize the on-site interworking performance of the remote dismantling system. The technologies to be developed will be actively promoted to practical use through engineering verification and cooperation with related companies, and they are expected to contribute to the efficiency and safety of the nuclear decommissioning industry.

2.3 Waste Treatment Technology

The amount of decommissioning waste from a 1,100-megawatt electric pressurized water reactor (PWR) is estimated to approach 500,000 tons. Radioactive waste in Korea has been classified into five categories: high-level waste (HLW), intermediate-level waste (ILW), low-level waste (LLW), very-low-level waste (VLLW) and exempt waste [7]. EW is waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection and can be handled and reused equally to typical industrial waste. Unless the waste arising from decommissioning activities is managed systematically, it is difficult to distinguish between radioactive waste and exempt waste. This makes it impossible to trace the sources of waste, and the amounts of radioactive waste can thus increase. The actual amount of radioactive waste generated from decommissioning is less than 5% overall.

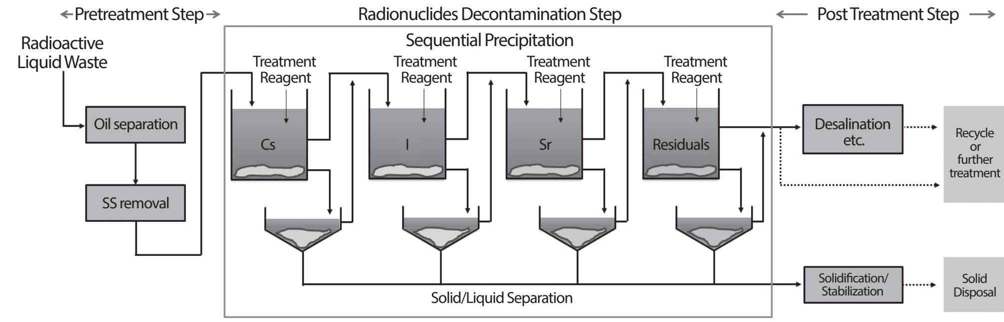


Fig. 8. Conceptual diagram of precipitation/adsorption processes for large volumes of high radioactivity level/highly salt-laden radioactive liquid waste.

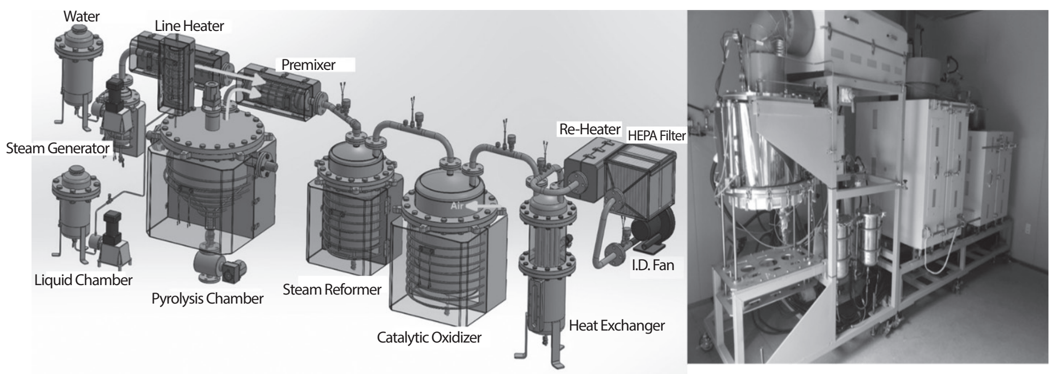


Fig. 9. Schematics and a picture of the bench-scale steam reforming process and system installed at KAERI.

If their radioactivity levels are lowered below the level of free release by decontamination, the disposal cost could be reduced and the efficiency of decommissioning could be enhanced. The principal purpose of a decommissioning waste treatment is to reduce the volume of radioactive waste to be disposed of by applying appropriate treatment technologies or to treat radioactive waste for safe disposal.

2.3.1 Current Status of Waste Treatment Technology

Technologies for the treatment of radioactive metal and concrete waste generated from the decommissioning of a commercial nuclear power plant have been developed in Korea, and they have reached the stage of practical application, except for those related to large and highly irradiated waste products, such as reactor pressure vessels. Radioactive metal waste treatment technology consists of various unit technologies, such as measurements of residual radioactivity levels, safety evaluations for reuse or recycling, decontamination, cutting, and melting. KAERI has developed a melting decontamination technology for the volume reduction and recycling of the large amounts of metal waste arising from the decommissioning of nuclear research facilities (research reactors, uranium conversion plants, and nuclear fuel cycle facilities). Some basic technologies for the management of large metal components such as steam generators have also been developed [39].

Concrete waste generated from the decommissioning of nuclear power plants accounts for more than 70% of all such waste. In-depth research on decontamination and volume reduction for such large amounts of concrete waste is already underway in France, Japan, and the UK. France is at the level of commercialization through experimental research, and many European countries, including the UK and Spain, are developing technologies to minimize the volume of radioactive concrete waste to be disposed of through the recycling of generated waste.

KAERI has carried out research on reducing the volume of decommissioning concrete waste by a thermal/mechanical crushing method to separate self-releasable aggregate and radioactive cement powder. Further studies of volume reduction methods for the cement phase separated by a chemical treatment and then stabilizing to a solidified matrix have also been carried out [40].

In fact, different types of radioactive wastes are generated during the decommissioning of nuclear facilities. An incineration facility and a metal melting facility were constructed and have been operated to reduce the volume of radioactive combustible and metal waste from the decommissioning of a uranium conversion plant which had been operated until 1992. In addition, certain treatment technologies for mixed organic waste containing alpha-emitters such as TBP/n-dodecane with uranium, used in a uranium conversion plant, were also developed.

KAERI has also undertaken the development of a rapid treatment technology for high-level radioactive liquid waste with a high salt content of the type that can arise during abnormal disasters, such as also Fukushima nuclear accident.

2.3.1.1 Treatment Technology of High-Level Radioactive Liquid Waste with a High Salt Content

Large volumes of seawater were injected into the reactors for a cooling of the reactor core and the spent nuclear fuel due to the loss of the cooling system caused by the accident at the Fukushima Daiichi nuclear power plant in Japan in March of 2011. The accident caused the generation of a huge amount of highly radioactive liquid waste under high-salt conditions. In such an emergency case, the rapid treatment of the massive amounts of contaminated water is clearly very important. For this reason, we designed simpler processes based on batch-wise precipitation incorporated with adsorption instead of the column operation actually applied to a treatment of a large amount of liquid waste after the Fukushima accident [41, 42].

Many experimental data have been secured by KAERI for the establishment of research directions since 2012. Along this line, the adsorption/precipitation properties and removal mechanisms of each group of high-level radionuclides, specifically Cs, Sr, I and multiple residual nuclides, were evaluated. As a result, we designed a sequential precipitation process for large volumes of radioactive liquid waste with high radioactivity and salt levels, as shown in Fig. 8.

2.3.1.2 Organic Waste Treatment Technology

The decommissioning of a nuclear facility generates organic mixed waste such as uranium-bearing spent TBP (tributyl phosphate) and ‘carbowaste' such as irradiated graphite, both of which are burnable. One effective treatment option is to incinerate these burnable types of waste to gas and ash. However, one criticism of high-temperature incineration is the concern over possible emissions of radioactive elements into the environment. Certain radionuclides such as cesium form vapors at temperatures reached in the flame zone of the incinerator [43]. When the vapors cool, they condense to form submicron particles which are relatively difficult to capture in ventilation systems. In addition, it is no surprise that incinerators are not readily installed due to public objections regarding dioxin emissions. For this reason, various alternative oxidation technologies have been evaluated and developed over the last few decades. Steam reforming has been considered as one of the most promising alternatives to incineration. Steam reforming processes for the treatment of mixed organic waste have been developed in several countries which use nuclear power, such as the USA and Japan [44-46].

KAERI also has been developing an advanced thermal treatment technology that is capable of effectively reducing the volumes of uranium-bearing spent TBP. The thermal decomposition characteristics of uranium bearing spent TBP and the phosphate behavior were initially investigated to aid in the selection of a proper thermal treatment system [47]. KAERI selected an integrated steam reforming process that mainly consists of pyrolysis, steam reforming and catalytic oxidation units. The bench-scale steam reforming process is shown in Fig. 9. A relatively low-temperature pyrolysis chamber decomposes thermally uranium-bearing spent TBP in the absence of oxygen without releasing gaseous phosphorus oxides, P_4O_{10}(g), while the organics and nitrates are decomposed into various unburned hydrocarbons (UHCs) and nitrogen oxides, respectively. This process guarantees no problems associated with the condensation of corrosive phosphoric acid in the off-gas system. The steam reforming units decompose partially UHCs into hydrocarbons with lower masses, such as ethylene and propylene, which are substantially oxidized in the subsequent catalytic oxidation unit. Hot demonstration tests for this bench-scale process using uranium-bearing spent TBP were completed in 2014. This bench steam reforming process will commercially be scaled-up later to treat various types of liquid organic waste, such as spent lubricates and scintillation fluids, as well as uranium-bearing spent TBP.

2.3.1.3 Treatment Technology of Uranium Waste

Uranium complex waste usually consists of a large portion of other metal oxides besides uranium, along with impurity materials. When they are simply disposed of without any treatment, their volumes to be stabilized and solidified are large, causing a great increase in the disposal cost. Therefore, if the uranium is selectively separated from this type of waste, the radioactive waste volume to be finally disposed of could be decreased.

Most of the volume of uranium catalyst waste generated by the nuclear industry stems from the supporting material of SiO_2. It therefore appears to be an effective method to dissolve and separate the supporting components from the waste and then permit free release after purification, thereby lowering the final volume of the radioactive waste for disposal. For this purpose, KAERI has developed a novel and innovative technology for the treatment of uranium catalyst waste [50-52], in which the supporting component is selectively dissolved using acid-alkali solutions in series followed by sequential precipitation for uranium separation. The purified supporting component is then purified once again, hopefully for free release. In addition, a residual uranium waste treatment and solid waste stabilization technologies have been developed to ensure safe final disposal.

KAERI has developed engineering verification and practical application technologies for the uranium waste catalyst treatment methods also developed by KAERI in cooperation with others in the industry. These are methods for the treatment and demonstration of uranium waste that has occurred in the private sector but has come to national awareness.

2.3.1.4 Treatment Technology for the Decommissioning of Combustible and Metal Waste

Large quantities of contaminated combustible waste are generated during decommissioning projects. In Korea, two decommissioning projects have been carried out owing to the retirement of nuclear research facilities (KRR-1 & KRR-2) and a uranium conversion plant (UCP). The decommissioning of KRR-2 and a uranium conversion plant (UCP) at KAERI were completed in 2011, and the decommissioning activities of KRR-1 are also completed. A large quantity of radioactive waste was generated during the decommissioning of the KRR and UCP facilities. The radioactive waste was packed into 200-liter drums and 4 m^3 containers which were temporarily stored onsite until their final disposal in the national repository facility. Some of the releasable waste was freely released and utilized for non-nuclear industries. For the purposes of volume reduction and clearance of the combustible and metal waste generated from the decommissioning projects, incineration and melting decontamination technologies were selected for the treatment of the combustible and metal waste, respectively.

Contaminated combustible waste presents a considerable storage volume as well as a significant cost, as it must be

Fig. 10. Demonstration melting facility.

maintained and monitored indefinitely in secure storage. The high cost of either disposal or storage requires that the volume of the material be minimized. An incineration facility was built to demonstrate the applicability of this technology to hazardous and low-level radioactive waste from nuclear facilities [53].

Melting decontamination technology is considered as the most effective treatment method for the decommissioning of metal waste. Metal melting technology can be used to achieve three aims: a volume reduction of the waste, segregation or separation of the contaminants, and homogeneity of contaminants within the bulk metal. In addition, cost reductions may be realized because melting will create ingots in a homogeneous waste form, making waste characterization simpler and stabilizing the final waste package. KAERI has been operating a demonstration melting facility since 2013. It was constructed by rebuilding and extending an existing vitrification facility. The induction melting demonstration facility with a capacity of 350 $kg \cdot batch^{-1}$ was allowed to operate by the regulatory body. The demonstration facility consists of four systems: a preparation system, a melting system, an ingot treatment system, and an off-gas treatment system. Figure 10 shows the demonstration melting facility. For the decommissioning of metal waste, demonstration tests were performed using a high-frequency induction furnace with a capacity of 350 $kg \cdot batch^{-1}$.

2.3.2 KAERI Perspective of Waste Treatment Technology Development

As stated earlier, radioactive waste generated from the decommissioning of a nuclear power plant consists mainly of metals, concrete, liquid waste forms such as decontamination waste water, and some combustible waste. Korea has developed most technologies domestically for the treatment of decommissioning metal and concrete waste, except for components related to highly radioactive or large waste forms, such as pressurized vessels, and currently those developed are at the commercialization step. KAERI has also developed technology for the treatment of organic mixed waste, uranium waste generated from the nuclear industry, and highly toxic and radioactive liquid waste arising during abnormal disasters such as the Fukushima nuclear accident. KAERI also developed technology for the treatment of organic mixed waste, based on the steam reforming technique. This technique is expected to be applied for the effective management of radioactive waste lubricants, waste alcohol, and scintillation fluids, as well as for the enhancement of the safety of the treatment process.

Ion-exchange resin/activated carbon waste, which is a pending issue related to nuclear waste, also lacks an optimal treatment option. We are developing a thermochemical treatment technology that can convert such waste into disposable forms. This technology has been evaluated for its applicability to thermochemical nuclide separation, gasification, and stabilization of these waste forms.

The suitability of the disposal of radioactive waste should adhere to very complex requirements, such as those related to radiometry, solidification, and certain physical and chemical properties. Final disposal waste forms, especially in the case of various types of dispersive and fluidic waste generated during the dismantling of nuclear facilities, should be treated appropriately with advanced technologies for safe disposal. Dispersive and fluidic waste, for which appropriate treatment options remain not established include typical actinide-containing waste such as uranium-contaminated soil and sludge, nuclear dry waste, boric acid dry waste, and highly radioactive waste adsorbents. KAERI is developing a target-specific solidification technology for various types of waste by improving a cement solidification medium and developing an inorganic polymer and a ceramic solidification medium.

On the other hand, irradiated graphite waste generated from the decommissioning of the research reactors KRR-1 and KRR-2, which contains an excess of ^{14}C, is classified as a type of waste for which no disposal method applies. Thus far, 250,000 tons of irradiated graphite waste have been generated worldwide, but it is stored temporarily without disposal. Various studies related to its treatment have been conducted in the US and in European countries that use GCRs and HTGRs. The previously mentioned pyrolysis/steam reforming technique now being developed at KAERI, in combination with the ^{14}C separation technique, will eventually be utilized as the unit process to treat carbowaste in the near future.

Henceforth, KAERI will continue to develop innovative technologies for carbowaste treatments and will also focus on the development of certain novel and innovative technologies for the treatment of radionuclides such as tritium and some toxic actinides.

2.4 Environment Remediation

Environmental remediation refers to a reduction of radiation exposure, for example, from contaminated soil, groundwater or surface water. The purpose is more than simply to eliminate radiation sources; it is about protecting people and the environment against the potentially harmful effects of exposure to ionizing radiation. In the past, many nuclear activities were carried out without appropriate consideration of their environmental aspects and impacts. Accordingly, numerous radiological contamination sites were generated by nuclear and radiological accidents.

The development of environmental remediation technologies has been a priority since the Chernobyl disaster in 1986 and has gained even more urgency in the wake of the Fukushima accident in Japan. The Japanese government has estimated a clean-up cost of about $14 billion USD and soil waste at least 100 million cubic meters, enough to fill 80 domed baseball stadiums. Moreover, remediation is estimated to take several decades.

Environmental remediation has usually been considered as the last phase of the nuclear life cycle. All of these activities are intended to remove contaminants from nuclear sites and turn them into “green fields”, i.e., to a condition free from restrictions linked to the presence of radioactivity, making them suitable for any other use. A number of technologies are required to carry out site remediation after the decommissioning of nuclear facilities, such as radiation measurements, dose assessments, and contaminated soil treatments. As every country is different and every site has its own characteristics, possible choices for the best environmental remediation mean balancing risks, costs, benefits and available technologies while also considering public acceptance.

2.4.1 Current Status of Environment Remediation Technologies

2.4.1.1 Measurement and Safety Evaluation Technology for Site Reuse

Characterization of a contaminated site involves gathering and analyzing data to describe the processes controlling the transport of waste from the site. It provides an understanding

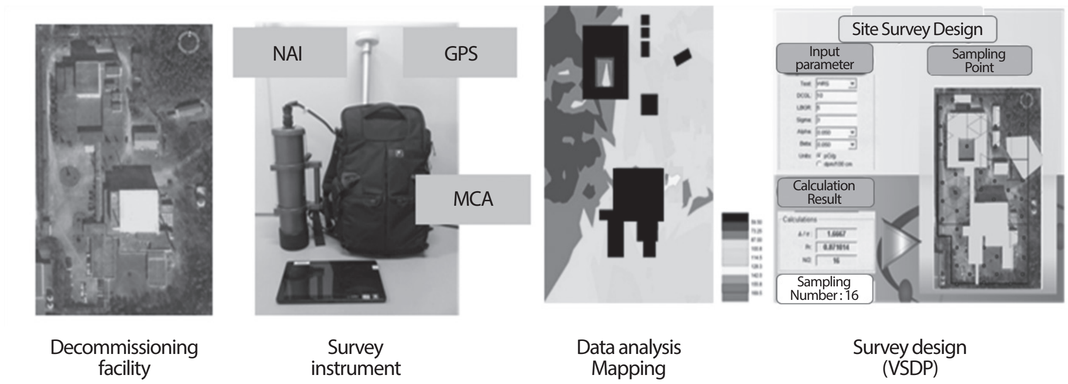


Fig. 11. R&D results for site remediation and the final status survey.

with which to predict the future behavior of the site. It can encompass the characterization of the waste itself as well as that of various transport pathways, such as air, surface water, biota, and ground water. Site characterization establishes the level of concern over the contaminants, the radioactivity levels, and the spatial distributions. This information is used to determine radiation doses using exposure scenarios and dose modeling analyses to assess compliance with site release regulations and to supplement on-site characterizations. Therefore, adequate site characterization techniques are required to assess environmental impacts. Another important issue is the development of detection techniques, particularly the remote detection of surface contamination and the transport of contaminants in subsurface media together with contamination mapping.

Site characterization provides data on the physical, chemical and radiological conditions to assess the status, nature and level of contamination of the facilities. Several radiological characterization techniques have been developed to assist site remediation and release under pertinent environmental regulations. The selection of appropriate survey methods can be a critical factor determining the residual radioactivity of a site for clearance. Moreover, the purpose of the final status survey (FSS) is to demonstrate that the residual radioactivity is lower than the release criteria [48]. To do this, a real-time characterization system using a NaI(Tl) detector and a global positioning system (GPS) was developed for field measurements. The system was applied to the final status survey of the KRR 1&2 decommissioning site. It brought about significant cost savings and a reduction of the measurement time compared to the traditional approaches which rely on hand-held detectors.

A typical sample evaluation approach using a geostatistical method for the FSS in the UCP was also developed. The relevance of a geostatistical analysis relies on the spatial continuity of the radiological contamination. The phenomenon variability is analyzed using variogram, kriging and simulation processes, which provide good reliability for activity estimations [49]. The evaluation results can reduce about 35% of the required number of representative samples. Furthermore, the Visual Survey Design Program (VSDP) was developed to create efficiently survey designs of the final status survey of the site. Figure 11 shows the integrated survey system, including radiological mapping, data analysis and the survey design program for the final status survey of the decommissioning site.

2.4.1.2 Remediation Technology for Contaminated Sites

The nuclear accident at the Fukushima Daiichi nuclear power plant in 2011 released massive quantities

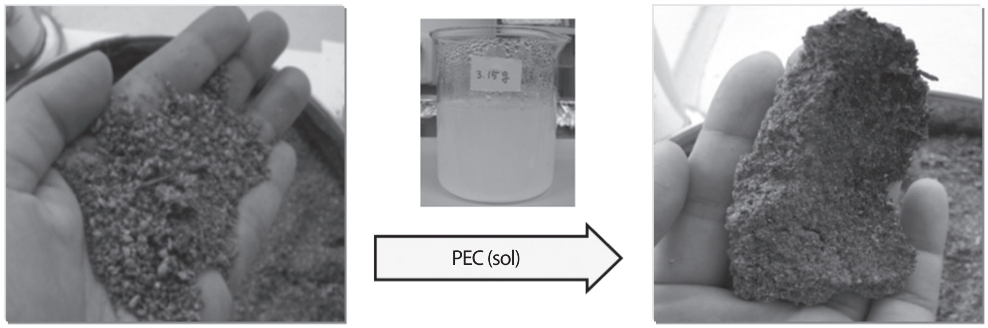


Fig. 12. Fixation of soil using a polyelectrolyte complex solution.

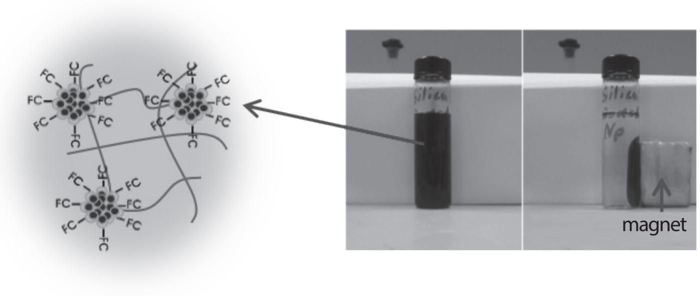


Fig. 13. Copper ferrocyanide functionalized magnetic nanoparticles for the removal of ^{137}Cs.

of radioactive contaminants into the environment. Among these, cesium (^{137}Cs) is the most problematic due to its long half-life (30.2 years), high solubility in water, and high-energy gamma ray (γ-ray) emissions. To reduce radioactive cesium transfer in nature from contaminated soil, it should be treated to immobilize radionuclides in the soil and prevent their uptake by plants.

About 95% of radioactivity is reportedly localized within the topsoil [50]. For this reason, the top layer of the soil surface should be immobilized to prevent the spreading of contamination by wind and water erosion. Many methods have been developed for soil fixation to remove radioactive contaminants from soil and to prevent the diffusion of radioactive materials. One approach is soil fixation using a polyelectrolyte complex. The main idea of this type of fixation is the use of ecologically friendly polymeric binders to facilitate interaction between oppositely charged polyelectrolytes. The polyelectrolyte forms polyelectrolyte complexes (PEC) due to the electrostatic interaction between poly-anions and poly-cations in the aqueous solution. PEC can fix soil particles by flocculation and formation of the crust between the soil and the polymer, as shown in Fig. 12. This method can also prevent the spread of radioactive material by floating on the soil surface. Using this characteristic, the optimized condition to fix radioactive materials in soil using PEC was determined.

Unfortunately, remediation technologies for contaminated soils and groundwater are currently not well developed. A variety of methods, including ion exchange, solvent extraction, and precipitation, have been applied for the remediation of contaminated surfaces [51]. Metal ferrocyanides in particular display high selectivity toward ^{137}Cs [52]. However, very fine powder forms of metal ferrocyanide are difficult to separate from water using filtration techniques. If the size could be increased, it would greatly improve the procedure of eliminating radioactive cesium from contaminated water, as the metal ferrocyanides could then be rapidly removed. Magnetic nano-adsorbents composed of a magnetic core and a functional shell that can adsorb contaminants could help to overcome this obstacle, as they provide magnetic separation [19, 53]. For this purpose, magnetite nanoparticles (MNPs) that provide unique superparamagnetic functionalities were coated with copper ferrocyanide to facilitate the adsorption of radioactive ^{137}Cs. Copper ferrocyanide was grafted onto the magnetic nanoparticle surfaces. These magnetic nano-absorbents could easily be separated from water using an external magnet, as shown in Fig. 13. This method shows high removal efficiency with regard to radioactive cesium [54, 55].

2.4.2 KAERI Perspective on the Development of Environment Remediation Technology

Decommissioning activities involve a number of steps which help lead to the ultimate goal of releasing facilities and sites from regulatory control. Hence, radiological surveys and evaluation technologies are required to secure reliability and feasibility. These technologies must verify that residual contamination levels are met based on the release criteria for unrestricted reuse after decommissioning. Low-level measurement technology to identify surface and subsurface contamination levels has been developed for field surveys. In-situ gamma spectrometry is a useful method for measuring radionuclides in soil. The main shortcoming of in-situ gamma spectrometry has been its inability to determine radionuclide depth distributions. In addition, real-time site characterization and evaluation technologies are under development and will be able effectively to identify residual contamination to assist in site remediation. The objectives of R&D should be extended in relation to site release criteria, in-situ measurement methods, and statistical analyses to optimize the surveys and sampling requirements for surface and subsurface contamination so as to apply for the final status survey and site release.

The use of PEC compounds in the process of soil decontamination should include gathering and the compaction of contaminated soil-PEC crust areas. This can be done via the mechanical separation of the protective crust using available machines. This procedure is not environmentally hazardous because the contamination is present in the structured crust. The key process of decontamination is the separation of the highly contaminated part of collected soil using a well-known technique, such as a classifier. Most of the radionuclides are located in the highly disperse fraction. Concentration and separation of this fraction can be achieved only via effective flocculation. This can be done successfully using the same PEC compounds which were used as binders.

There are of course limited options when dealing with soil and groundwater issues. Essentially, a clear scientific understanding of the interactions between contaminants and environments such as soil and water must be developed before more effective remediation technologies can be realized. Understanding fundamental physical and chemical processes, such as sorption, desorption, chemical reactions, and the chemical bonding of contaminants within the soil are necessary to evaluate and describe the mechanisms by which decontamination and environmental remediation techniques work most efficiently. Nearly all current soil remediation methods are time-consuming and produce significant volumes of secondary waste. Effective in-situ and ex-situ remediation technologies should be developed to minimize the volumes of generated waste.

3. Concluding Remarks

Korea has secured decommissioning technologies for small research reactors. However, to be prepared for the upcoming decommissioning of large and high-radiation facilities such as nuclear plants and spent fuel treatment facilities, it was confirmed that the further R&D on DD&R key technologies must be conducted.

Chemical decontamination of a reactor coolant system in the phases of maintenance, periodic safety assessments, and the decommissioning of NPPs is quite important to mitigate occupational exposure and improve worker safety. As reviewed above, there have been developed worldwide several remarkable decontamination processes, such as CANDEREM, CORD, and DfD, for the decommissioning of NPPs, while only partial chemical decontamination technology using organic acid-based reagents applicable to RCPs has been secured in Korea. Recently, the unique HyBRID decontamination process has been developed to complement or improve the performance, environmental friendliness, and process safety of the existing commercial processes. It promises to lead to an increased decontamination share in the worldwide market and to aid in the decommissioning of domestic NPPs.

One of the most challenging tasks during the dismantling of a NPP is the removal of the main components, especially the reactor pressure vessel (RPV), its internals (RPVI) and the reactor coolant pipes. Thus far, several cutting methods have been applied more or less successfully for those components. However, it is still necessary to improve the performance capabilities of cutting technologies until they can cut steel more than 100 mm thick with low secondary waste generation and adaptability to a remote handling system. Moreover, to ensure worker safety against radiation exposure, it is necessary to develop a fine remote control technology for an advanced remote handling system. In this regard, KAERI has been developing an integrated remote dismantling system which requires the lowest level of worker intervention during dismantling, and it will be completed by the end of 2021.

Regarding radioactive waste treatments, Korea has developed most of its own technologies for the decommissioning of metal and concrete waste, which are of main components of decommissioning waste. However, it remains necessary to develop new and advanced technologies to reduce waste volumes and to ensure the safe disposal of special types of waste, such as organic mixed waste and irradiated graphite waste containing ^{14}C. Henceforth, our R&D will focus on certain noble and innovative technologies for the treatment of radionuclides such as tritium and certain toxic actinides.

Finally, with regard to environmental remediation, it was confirmed that in-situ and real-time measurement technologies should be developed to improve the efficiency of the processes discussed here. Moreover, several novel site remediation technologies should be secured as a means of preparedness for a severe nuclear accident.

Acknowledgment

This work was supported financially by the MSIT (Ministry of Science and ICT) under the Mid-and Long-term Nuclear R&D Project (No. 2017M2A8A5015144). The authors would like to express their gratitude for this support.

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