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A Study on Segmentation Process of the K1 Reactor Vessel and Internals

K1 원자로 및 내부구조물 절단해체 공정에 대한 연구

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After the permanent shutdown of K1 in 2017, decommissioning processes have attracted great attention. According to the current decommissioning roadmap, the dismantling of the activated components of K1 may start in 2026, following the removal of its spent fuel. Since the reactor vessel (RV) and reactor vessel internal (RVI) of K1 contain massive components and are relatively highly activated, their decommissioning process should be conducted carefully in terms of radiological and industrial safety. For achieving maximum efficiency of nuclear waste management processes for K1, we present activation analysis of the segmentation process and waste classification of the RV and RVI components of K1. For RVI, the active fuel regions and some parts of the upper and lower active regions are classified as intermediate-level waste (ILW), while other components are classified as low-level waste (LLW). Due to the RVI's complex structure and high activation, we suggest various underwater segmentation techniques which are expected to reduce radiation exposure and generate approximately nine ILW and nineteen very low level waste (VLLW)/LLW packages. For RV, the active fuel region and other components are classified as LLW, VLLW, and clearance waste (CW). In this case, we suggest in-situ remote segmentation in air, which is expected to generate approximately forty-two VLLW/LLW packages.

Keywords: K1, Waste management, Decommissioning, Segmentation, Reactor vessel, Internal

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고리1호기의 영구정지 이후 해체공정에 대해 관심이 집중되고 있다. 방사선관리구역 내부 방사화구조물의 해체는 2026년 이후 본격적으로 진행될 예정이다. 원자로와 내부구조물은 원자력발전소의 구조물 중 가장 높은 수준의 방사능을 갖고 있으며 1차측의 대표적인 중량물로, 절단해체 과정에서 방사선학적 측면과 산업안전 측면에서 주의가 요구된다. 효율적인 해체 폐기물 관리를 달성하기 위해 원자로와 내부구조물의 절단해체공정에 대한 연구가 수행되었다. 방사화 평가결과 내부구조물의 노심 측면부와 상/하부의 일부는 중준위 폐기물로 평가되었고 이외의 구성품은 저준위로 평가되었다. 상대적으로 방사화가 많이 되고 복잡한 형상을 갖는 내부구조물의 경우 작업자의 피폭을 저감하기 위해 수중에서 다양한 절단방법을 통해 원격절단하는 방안이 제안되었고, 절단물은 약 19개의 극저준위/저준위 포장용기와 9개의 중준위 포장용기에 적재될 것으로 예상되었다. 방사화 평가결과 원자로의 노심 측면부는 저준위 폐기물로 평가되었고 이외의 부분은 극저준위 또는 자체처분 수준의 폐기물로 확인되었다. 상대적으로 방사화가 적게 된 원자로의 경우 열적절단 방법을 사용해 현재위치에서 인양하며 공기중에서 원격절단하는 방안이 제안되었고, 절단물은 약 42개의 극저준위/저준위 포장용기에 적재될 것으로 예상되었다.

중심단어: K1, 폐기물 관리, 절단해체, 원자로, 내부구조물

1. Introduction

After the permanent shutdown of the K1 in 2017, the decommissioning processes have attracted great attention. Various and complex processes will be implemented during the decommissioning process, including decontamination, dismantling, waste management, and remediation [1, 2]. In particular, the segmentation of activated structures is one of the most challenging and complex processes [3, 4].

The segmentation of activated components in the primary circuit is essential to implement the K1 decommissioning. The reactor vessel (RV) and the reactor vessel internal (RVI), as shown in Fig. 1, are one of the most highly activated components in nuclear power plants (NPPs). Since they are directly irradiated to neutrons and contact the coolant of the primary circuit, they are both activated and surface contaminated [5, 6]. In addition, the massive components require significant attention in terms of industrial safety.

It is generally understood that the radiological inventory of the RV and RVI in NPPs is more than 90% [7]. The RVI, including the baffle, former, barrel, and thermal shield, has relatively highly activated components. The Monte-Carlo based computer codes are generally used to perform the activation analysis. The accurate input data of the nuclear design report, geometry of components, and material information are important for accurate calculations [8].

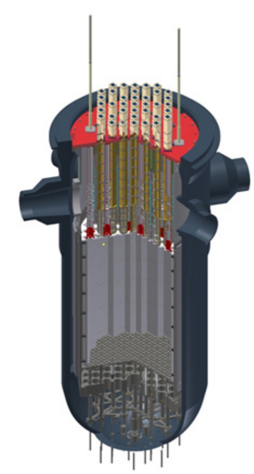
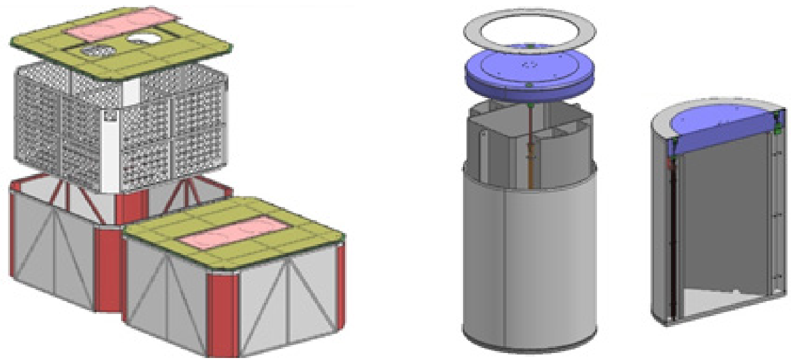


Fig. 1. Image of RV and RVI of K1.

The activation analysis indicates that the average neutron fluxes at the baffle and the RV were about 7×10^{13} and about 2×10^{11} #/cm^2·s, respectively [9]. It has been clearly demonstrated that the neutron flux decreases as the distance from the fuel assembly increases. It has also been discovered that the neutron flux affects the activation of the materials and waste classification. The high concentrations



(a) (b)

Fig. 2. Image of packages for (a) VLLW/LLW and (b) ILW [10].

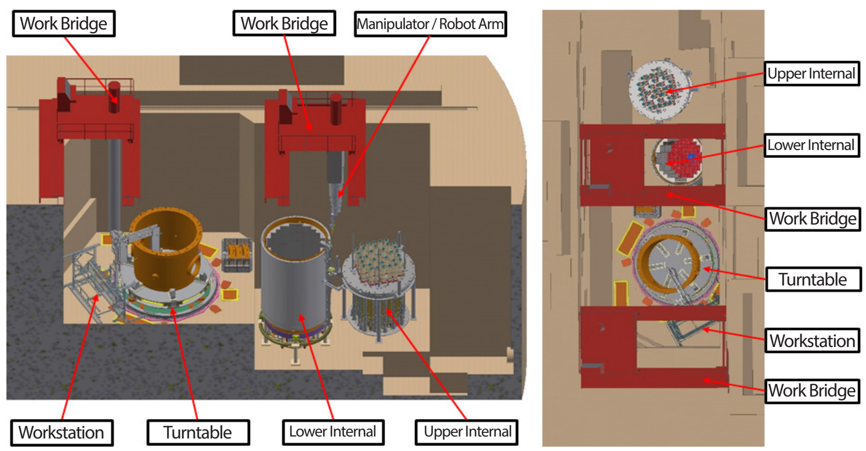


Fig. 3. Schematic diagram of K1 RVI segmentation.

of ^{55}Fe, ^{63}Ni, and ^{60}Co have also been observed in the RV, which mainly consists of carbon steel. Similarly, high concentrations of ^{63}Ni, ^{55}Fe, and ^{60}Co have also been observed in the RVI, which mainly consists of stainless steel.

The segmentation process of the RV and RVI are studied in this paper. The RVI, which is relatively highly activated, was segmented underwater using a remote-controlled system to reduce the radiation exposure. After the segmentation of the RVI and the drainage of the cavity water, the RV in-situ segmentation follows. The RV, which is relatively less activated, is segmented using a thermal cutting method to reduce the process duration. Various cutting methods, including thermal cutting, mechanical cutting, and electrical cutting, are widely considered to develop the segmentation process effectively. The package plan of the segments is designed using two types of packages, as shown in Fig. 2 [10]. The width, length, and height of the package for LLW and VLLW are ~1.5 m, ~1.5 m, and ~0.9 m, respectively. The diameter and height of the package for ILW are ~1.6 m and 2.4 m, respectively.

2. RVI segmentation

The RVI, which consists of an upper internal and a lower internal, is a massive component with a weight of 122 tons and offers fuel support and protection for the RV by absorbing excess radiation. The schematic diagram of the K1 RVI segmentation is shown in Fig. 3. Since the RVI is relatively highly activated, underwater segmentation is favored for the RVI segmentation in the cavity region filled with water to reduce the radiation exposure [11, 12]. The RVI of the Jose Cabrera NPP in Spain was segmented into ~430 pieces using mechanical band and disc saw for 16 months [12]. The RVI of the Stade NPP in Germany was segmented into ~170 pieces using mechanical band saw for 30 months [13]. The RVI of the Wurgassen NPP in Germany was segmented into ~1,200 pieces using mechanical saw and abrasive waterjet for 61 months [14].

The sub-components of RVI have various shapes, including a cylindrical barrel, thick circular plate, and hollow tube. Various cutting techniques have been used for the RVI segmentation, which corresponds to the shapes. In addition, the disassembling is used to unfasten the locking structure and separate the sub-components, such as baffle plates and formers.

2.1 RVI sub-component

The upper internal arranges the control rod and fuel, as well as protects the control rod assembly. The upper internal also consists of an upper core plate, an upper support plate, a guide tube, and a support column. The sub-components are fastened to the upper core plate and upper support plate by using locking cup type locking bolts. The separation of each item can be achieved using a bolt unfastening tool.

The lower internal offers horizontal and vertical support to the fuel and guides the coolant. The lower internal consists of a lower core plate, a barrel, a thermal shield, a lower support structure, and a baffle former assembly. The core support forging, core barrel, and core flange are welded and designed to support the structure. The secondary core support column and the baffle plate are fastened using locking cup type locking bolts. The separation of each item can be achieved by using a bolt unfastening tool.

2.2 RVI segmentation process

The K1 is a Westinghouse type reactor. Many sub-components are combined using locking bolts. They can be easily separated by using a disassembling tool.

The disassembling process reduces the cutting length and project duration. The RVI is usually cut into many pieces, which are suitable to be loaded into packages. The disassembling process reduces the cutting length, area, and process duration. It is estimated that applying the disassembling process reduces about 30~40% of the cutting length.

The disassembling process has advantages in terms of designing the handling and cutting process. It reduces the volume and mass of the sub-components and allows for the easier handing of them. The easier transportation, rotation, and lifting reduce the technical difficulties for massive components. The disassembling of the sub-components enables the accurate classification and management of waste.

The dual segmentation strategy that uses the lower and upper cavities simultaneously improves the process efficiency. The mechanical disassembling, coarse cutting, and loading/packaging of segments are designed for the lower cavity. The fine cut using the workstation and interim storage of sub-components and segments are implemented in the upper cavity. It is expected that the parallel segmentation process reduces the project duration by about 30% and the radiation exposure to workers.

Two types of packages, the rectangular type package for VLLW/LLW and the cylindrical type package for ILW, as shown in Fig. 2, were suggested for the packaging of the RVI segments [10, 11]. The physical dimension of the segments, the specific activity of the package, the surface dose rate, the shielding property, and structural integrity were carefully considered when designing the packages [10,11]. The segments are loaded under the water and dried in a cage (VLLW/LLW) or package with inserts (ILW). The dried cage is loaded in the package and grouted using cementation.

The segmentation process of the RVI consists of preparation, installation of primary and secondary segmentation

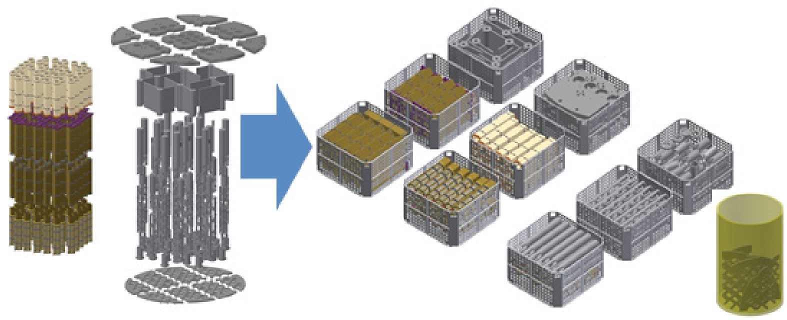


Fig. 4. Packaging plan of K1 upper RVI segments.

tools, upper/lower RVI disassemble/segmentation, removal of installed segmentation tools, movement of packages, and cavity cleaning and inspection. The segments are loaded and packaged immediately to prevent any confusion and mixing.

2.2.1 Upper internal segmentation

Various cutting techniques such as band saw, disc saw, plasma cutting, and disassembling tool are applied to segment the upper internal. The segmentation of the upper internal starts with disassembling the guide tube. The segmentation and separation start from the upper region and move to the lower region. In the upper cavity region, the coarse cutting, disassembling, and interim storage of the upper RVI take place. In the lower cavity region, the fine cutting and loading/packaging of the segments take place. It is generally accepted that the segmentation process starts from a less activated region and moves to a highly activated region to prevent any proliferation of contamination [12]. Most of the upper RVI sub-components are classified as VLLW and LLW [9]. Only the upper core plate, which is the lowest part in the upper internal, is classified as ILW. Since the segmentation of the upper core plate can increase the possibility of the contaminants proliferation, it is stored in the upper cavity region and will be segmented after the LLW region is segmented in the lower RVI. It is estimated that 9 VLLW/LLW packages and 1 ILW package are generated from the upper RVI segmentation process. The brief packaging plan of the K1 upper RVI segments is shown in Fig. 4.

2.2.2 Lower internal segmentation

Various cutting techniques such as the band saw, disc saw, plasma cutting, contact arc metal cutting, and disassembling tool are applied to segment the lower internal. The RVI is classified as ILW and LLW [9]. The upper and lower active fuel regions, including the flange, support column, and core support forging are classified as LLW. The LLW components are segmented after segmentation of the upper RVI, which is classified as LLW. The LLW region is segmented, transported, loaded, and dried using the VLLW/LLW package in the lower cavity region. The coarse cutting in upper cavity region is achieved by using various cutting tools, such as the contact arc metal cutting (CAMC) and plasma cutting, while the disassembling process is implemented in the lower cavity. In the upper cavity, the fine cutting and interim storage of the segments take place. After the LLW region segmentation, the segmentation of the ILW, including the upper core plate from the lower internal, the baffle plate, baffle former, barrel, thermal shield, and lower core plate, takes place. The baffle plate is one of the most highly activated components. The primary nuclides in baffle, over the specific activity limit of LLW, are ^{60}Co, ^{59}Ni, and ^{63}Ni. The calculated specific activity of ^{60}Co, ^{59}Ni, ^{63}Ni, and ^{94}Nb are around 4×10^{8}, 5×10^{6}, 1×10^{9}, and 3×10^{2} Bg/g, respectively. It is estimated that 10 VLLW/LLW

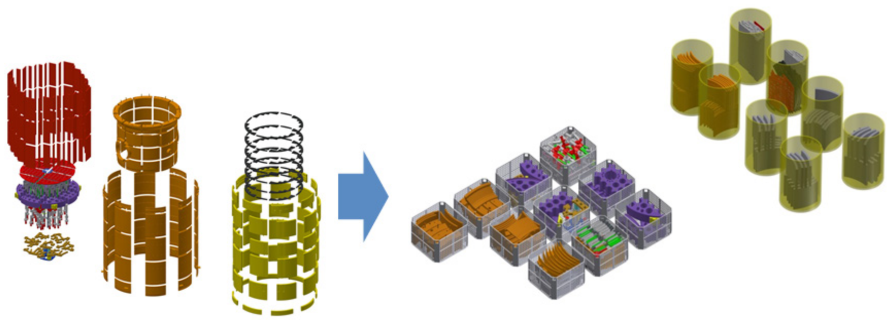


Fig. 5. Packaging plan of K1 lower RVI segments.

packages and 8 ILW packages are generated from the lower RVI segmentation process. The brief packaging plan of the K1 lower RVI segments is shown in Fig. 5.

3. RV segmentation

The RV, where thermal energy is generated via a nuclear reaction, consists of a shell and upper head. Recently, the in-situ remote controlled thermal segmentation of the RV, which is relatively simple and less activated compared to the RVI, has attracted great attention [15, 16]. The RV of the Humbolt Bay NPP in the USA was segmented into ~20 pieces using various mechanical saws [17]. The RV of the Stade NPP in Spain was segmented into ~170 pieces using oxy-propane torch for 4 months [15]. The RV of the ZION NPP in the USA was segmented into 17 pieces using oxy-propane torch for 16 months [16].

3.1 RV structure

The RV is a massive component and offers coolant and RVI support, as well as arrangement of the in-core instruments. The RV includes the shell, cladding, primary coolant pipe, and ICI nozzle. The exterior of the RV is covered with several layers of crumpled STS304 foil. Without the upper head, the height, outer diameter, and mass of the RV are about 9.7 m, 3.5 m, and 187 tons, respectively. The surface of the RV inner region is covered with stainless steel cladding. The maximum thickness of the RV is a flange region, about 448 mm thick.

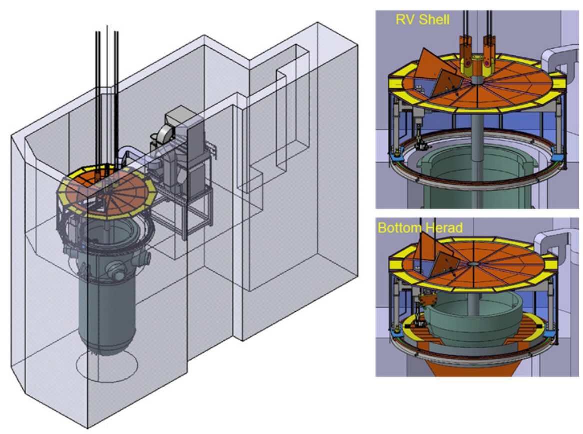


Fig. 6. Schematic diagram of K1 RV segmentation.

3.2 RV segmentation process

The RV is segmented in an ambient surrounding with in-situ remote controllable tools. The additional ventilation system and packages are placed in the lower cavity region. The rigging tool, which lifts the RV via a lug, enables the efficient thermal cutting and withdrawal of segments near the upper cavity region. The cut-off pieces are loaded to the package just after the segmentation. The schematic diagram of the K1 RV segmentation is shown in Fig. 6.

3.2.1 Preparation work

To realize the in-situ RV segmentation, some preparation is needed, including a permanent sealing edge removal, cover removal, and bio-shield concrete partial removal. The RV is located in the upper cavity, which is a concrete structure covered with a stainless-steel plate. Since the cavity is filled with water during the overhaul, the permanent sealing covers the gap between the RV and bio-shield concrete to prevent the water leakage. The distance between the RV and bio-shield concrete is about 270~280 mm. The permanent sealing is welded to the RV and stainless-steel liner plate. It means that removing the permanent sealing cover for further cutting process and bio-shield concrete for the installation and operation of an oxy-propane torch and guide rail system is needed.

3.2.2 Pre-cut of flange

The primary purpose of pre-cut process is to remove the STS cladding, which covers the inner surface of the RV, for the application of the thermal cutting method. The STS cladding covers the inner surface and flange of the RV to prevent the corrosion of the RV from the coolant. The oxy-propane torch offers high thermal energy to melt the steel surface [15]. The blown high-pressure oxygen gas moves the melts to make the cutting process proceed. However, the Cr based oxidized layer’s higher melting temperature of the STS prevents the melting and application of the oxy-propane based cutting method. The pre-cut, which removes the STS cladding on the flange using a mechanical method, enables the application of the method. Considering the torch flame, the required pre-cut depth for cladding is ~10 mm.

3.2.3 Nozzle cut

The inlet and outlet nozzles support the massive RV and guide the coolant. Before implementing the in-situ RV remote controlled segmentation, liberation of the RV is prerequisite. The nozzle cutting and partial segmentation of neighboring bio-shield concrete offer liberation to the RV and sufficient space for the oxy-propane torch installation, which is a primary method for the RV segmentation process.

3.2.4 RV shell cutting using an in-situ remote segmentation system

The oxy-propane torch, which is a non-contact type segmentation method, is a suitable method for the RV segmentation. Since the method is remote controllable and cuts the materials with high speed, it offers radiation exposure and process duration reduction. The thermal energy from the torch melts the metal. The gas from the torch blows the melted metal. Since the method does not require contact between the cutting nozzle and material, there is almost no reaction force and secondary contamination, while the mechanical cutting system requires contact and usually becomes secondary waste.

The oxy-propane torch moves through the installed guide rail and cuts the shell region with a remote controllable system. After removing the bio-shield around the flange, a multi- rigging tool is installed. The rigging tool supports and lifts the RV to enable the segmentation. After fixation of the RV with rigging tool, the liberation of the RV takes place via segmentation of the inlet and outlet nozzles. The in-situ remote segmentation system, which includes a guide rail for torch movements, gantry manipulator, robot arm, turnable shielding table, and local ventilation system, is installed near the flange region. The primary segmentation process takes place near the flange region through the guide rail. The gantry manipulator and robot arm offer remote handling and operation beneath the system. The turnable shielding table, which has a gate for withdrawing segments, provides a working floor for workers and reduces the radiation exposure. The local ventilation system collects the gaseous wastes, including fume and aerosols. The most concerning aspect of thermal segmentation is the generation of radioactive aerosol. The local ventilation system offers the negative pressure and prevents the proliferation of contaminants. The RV segments are classified as VLLW and LLW [9]. The segments are moved to the package, which is

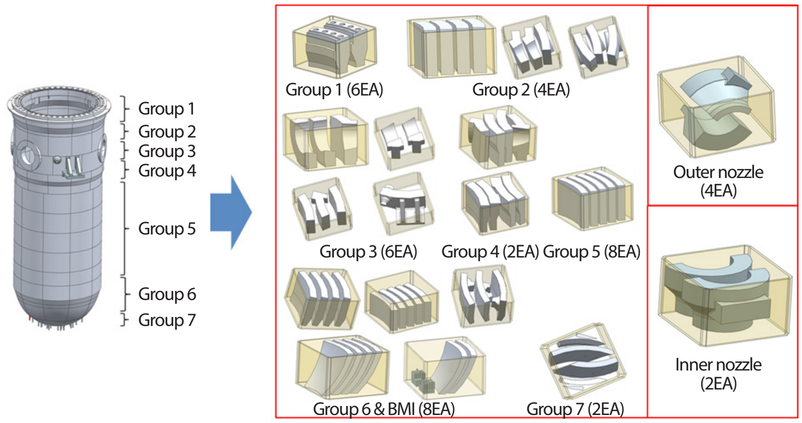


Fig. 7. Packaging plan of K1 RV segments.

prepared in the lower cavity region, just after the segmentation of each piece. It is estimated that 42 VLLW/LLW packages are generated from the RV segmentation process. The brief packaging plan of K1 RV segments is shown in Fig. 7.

4. Conclusion

The segmentation process of the RV and RVI are thoroughly studied to achieve efficient decommissioning waste management. The RVI, which consists of ILW and LLW, is segmented underwater by using a remote-controlled system to reduce the radiation exposure. It is assumed that about 9 ILW and 19 VLLW/LLW packages will be generated from the process. The RV, which consists of LLW, VLLW, and CW, is segmented using in-situ remote controllable equipment in the air. It is expected that about 42 VLLW/LLW packages will be generated from the process.

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