Technical Paper

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Assessing the Feasibility of Diver Access During Dismantling of Reactor Vessel Internals

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In 2017, a decision was made to permanently shut down Kori Unit 1, and preparations began to be made for its decontamination and decommissioning. The dismantling of the biological shields concrete, reactor vessel (RV), and reactor vessel internals (RVI) is crucial to the nuclear decommissioning process. These components were radiologically activated by the neutron activation reaction occurring in the reactor during its operational period. Because of the radioactivity of the RV and RVI of Kori Unit 1, remotely controlled systems were developed for cutting within the cavity to reduce radiation exposure. Specialized equipment was developed for underwater cutting operations. This paper focuses on modeling related to RVI operations using the MAVRIC code and the dose calculation for a diver entering the cavity. The upper and lower parts of the RVI are classified as low-level radioactive waste, while the sides that came into contact with the fuel are classified as intermediate-level radioactive waste. Therefore, the modeling presented in this paper only considers the RVI sides because the upper and lower parts have a minimal impact on the radiation exposure. These research findings are anticipated to contribute to enhancing the efficiency and safety of nuclear reactor decommissioning operations.

Keywords: MAVRIC, RVI, Diver, Kori 1, Dose, Radiation exposure

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1. Introduction

Kori Unit 1, South Korea's first commercial nuclear reactor, underwent 40 years of operation and was permanently shut down on June 18, 2017. According to an announcement by the Ministry of Trade, Industry, and Energy, plans have been unveiled for the decommissioning process, which includes the demolition of the turbine building and the construction of waste treatment facilities. During the dismantling process, significant large-scale radioactive waste is generated, necessitating meticulous consideration. In the nuclear decommissioning process, the dismantling of radiologically contaminated equipment and concrete structures such as reactor vessel (RV), reactor vessel internals (RVI), and the biological shields concrete is of utmost importance. These components became radiologically contaminated due to nuclear fission reactions occurring in the reactor during its operational period. The degree of radiation contamination in RV/RVI and biological shields concrete varies depending on factors such as the reactor's operational history, the facility's internal condition, and the isotopic composition of materials [1, 2].

The decommissioning process encompasses various complex procedures, including decontamination, dismantling, waste management, and restoration. The division of radiologically contaminated structures poses one of the particularly challenging tasks. Research has also been conducted on cutting methods for the reactor vessel (RV) and reactor vessel internals (RVI). In the case of RVI, which tends to have higher levels of radiation contamination, it is anticipated that remote control systems will be used for underwater cutting. Numerous devices have been developed for underwater cutting operations. However, remote control systems face difficulties in responding to unexpected on-site contingencies [1, 2].

In this paper, an analysis using the MAVRIC code to assess whether divers can access the worksite during reactor vessel internals (RVI) dismantling is presented.

2. Background

2.1 Components of Reactor Vessel Internal

The components of the RVI come in various shapes, including cylindrical barrel, thick circular plate, and hollow tube. The upper interior protects the control rods and fuel assembly simultaneously. It consists of upper core plates, upper support plates, guide tubes, and support columns. The lower interior is fastened to the upper core plates and upper support plates using lock-cup-type locking bolts. Each of these separable components can be detached using bolt removal tools. The lower interior supports fuel both horizontally and vertically and serves as a guide for cooling water. It is composed of lower core plates, barrels, thermal shields, lower support structures, and baffle assemblies. Core support forgings, core barrels, core flanges, and other components are welded together to provide structural support. In the Westinghouse-type reactor like Kori Unit 1, many lower subcomponents are joined using locking bolts. Disassembly can be easily accomplished using disassembly tools, which can help shorten cutting lengths and project durations [2].

2.2 Overseas Experience of Dismantling RVI

Due to its relatively high level of radioactivity, the RVI is primarily dismantled underwater in a cavity filled with water to minimize radiation exposure. At Spain's Jose Cabrera Nuclear Power Plant, RVI was divided into approximately 430 pieces using mechanical bandsaws and disk saws, and this operation took place over a period of 16 months. In the case of Germany's Stade Nuclear Power Plant, the RVI was divided into approximately 170 pieces using mechanical circular saws, with the dismantling process spanning 30 months. Germany's Wurgassen Nuclear Power Plant employed a combination of mechanical saws and waterjets to segment the RVI into approximately 1,200 pieces, and this extensive operation lasted for 61 months [3, 4, 5].

3. Dose Estimation for Diver

The RVI consists of various components, including the baffle plate, former, core barrel, thermal shield, and upper/ lower internal parts. These components are located close to the fuel assembly and are inevitably irradiated due to the neutrons generated during the operation of the nuclear power plant. In particular, some parts like the Baffle Plate, Former, Core Barrel, and Thermal Shield may be relatively more irradiated than other components due to higher neutron flux [6].

According to research conducted so far, the upper and lower parts of the RVI have been classified as low-level radioactive waste, while the baffle plate, former, core barrel, and thermal shield have been classified as intermediate-level radioactive waste. Additionally, the RVI dismantling plan involves separate disassembly of the upper, lower, and side parts, followed by cutting operations. In the analysis of overseas cases, no instances were identified where divers directly entered the cavity for work. However, upon reviewing the work period, it was observed that, although the type of RVI was not same, dismantling process were carried out over periods ranging from 16 to 61 months. The examination of these cases indicates that assessing the feasibility of divers directly entering the cavity holds the potential to decrease the overall work period. Therefore, this paper aims to analyse whether divers can access the RVI during the cutting of the highly irradiated RVI sides using the MAVRIC code [3, 4, 5, 6].

3.1 Methodology

The computational code SCALE-MAVRIC, known as Monaco, developed and maintained by Oak Ridge National Laboratory for dose calculations, is utilized in this study. The MAVRIC sequence involves conducting adjoint calculations with the 3D deterministic code TORT and Monaco. To streamline this process, importance maps and biased sources for the weight window are automatically derived from the adjoint flux using the Consistent Adjoint Driven Importance Sampling (CADIS) methodology. MAVRIC is automated with user input, encompassing the creation of cross-sections (both forward and adjacent), calculation of the first collision source using GRTUNCL3-D, determination of the adjacent flux using TORT, generation of importance maps and bias sources, and the execution of Monaco.

Monaco offers a wide range of tally options, including calculating fluxes by group at specific spatial points, over defined geometrical regions, or across user-defined three-dimensional grids. Additionally, these tallies can integrate fluxes using standard response functions from the cross-section library or user-defined response functions, and all of these tally options are available within the MAVRIC sequence.

This method offers significant advantages by reducing calculation time while ensuring accurate results. Additionally, it simplifies modelling to enhance computational efficiency and enables the active adjustment of various field variables. The study calculates the expected dose for each work position at point detectors No. 1 to 3 based on RVI's height [7].

3.2 Geometric Modeling for RVI

To confirm the radiation assessment using the MAVRIC code, geometric modeling of the inside of the reactor vessel is required. As shown in Table 1, the outermost thermal shield has a diameter of approximately 3,100 mm and

Table 1. Each components specification

Components	Size (mm)	
	Radius [Length]	Height
Core barrel	1,429.30	2,518.80
Thermal shield	1,553	2,518.80
Lower core plate	1,374.80	38
Baffle plate	1,378	2,189.08
Baffle former	[1,150]	2,189.08

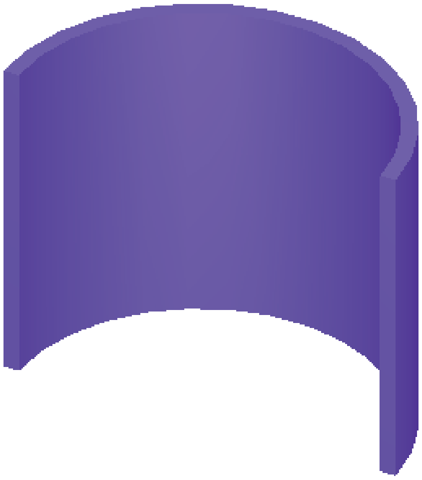

Fig. 1. Thermal shield.

Fig. 2. Core barrel.

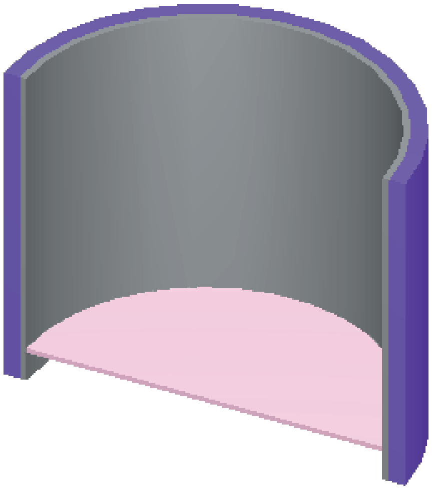

Fig. 3. Lower core plate.

Fig. 4. Baffle plate.

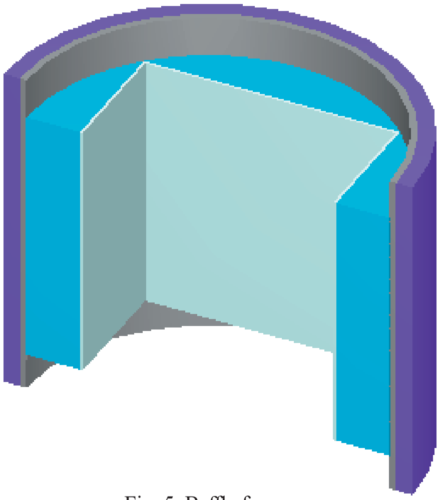

Fig. 5. Baffle former.

Table 2. Radioactivity characteristics

	Decay mode	Product	Decay energy (MeV)
^{63}Ni	Electron capture	^{63}Cu	0.017
^{55}Fe	Electron capture	^{55}Mn	0.00519
^{60}Co	β	^{60}Ni	0.317
	γ		1.1732, 1.3325
^{59}Ni	β	^{59}Co	0.0046
	γ		0.0024
^{54}Mn	γ	^{54}Cr	0.8213
^{3}H	β−	^{3}He	0.018591
^{14}C	β−	^{14}N	0.156476
^{93m}Nb	γ	^{93}Nb	0.03377
^{154}Eu	β−	^{154}Gd	1.96884
	ε	^{154}Sm	0.71722
^{93}Mo	ε	^{93}Nb	0.40478

a height of 2,500 mm. The baffle former, located closest to the fuel, is a 30 mm-thick polygon. Additionally, the baffle plate consists of four thin plates with a thickness of 59 mm each. While ideal modeling was possible using the MAVRIC code, it was not feasible to define the radiation properties of the baffle plate and baffle former accurately. As a result, it would be proceeded to model using practical methods. The baffle plate was modeled as a single cylinder, and the baffle former was modeled as a cuboid with a length of 1,150 mm.

Figs. 1 to 5 show the models for each component:

3.3 Radiation Modeling for RVI

To evaluate the radiation exposure for divers, it is necessary to have information about the radiation activity inside the reactor vessel. The main source terms within the reactor vessel are ^{63}Ni, ^{55}Fe, ^{60}Co, ^{59}Ni, ^{54}Mn, ^{3}H, ^{14}C, ^{93m}Nb, ^{154}Eu, and ^{93}Mo. Among these source terms, those emitting alpha and beta particles were excluded, assuming that they would be shielded by water when divers approach the RVI, except for gamma radiation. The values can be found in Table 2. The total decay energy of these components is 2.18997 MeV. Radioactivity characterization evaluation inside the reactor vessel is essential for calculating the radiation exposure of divers. The specific activity ($Bq \cdot g^{-1}$) of each component, including the 40-year operation history of Kori Unit 1, are as follows Table 3 [6]. In order to calculate the radiation dose received by a diver underwater, it is necessary to determine the total activity for Major Nuclides on Each Position. To calculate the total activity for major nuclides on each position, it needs to know the specific activity and the mass of each component. It would refer to Tables 3 and 4 for relevant information and use those values to calculate total activity on each material and each position. The calculated values should match those in Table 5. The total activity of the baffle plate adjacent to the nuclear fuel is evaluated as 3.81×10^{11} Bq, which was rated as the highest. Next, the Core Barrel was evaluated at 1.25×10^{10} Bq. Among the components, the Lower Core Plate, which is the furthest from the nuclear fuel, has an activity of 2.13×10^{8} Bq.

Table 3. Radioactivity characterization evaluation [6]

	Baffle former	Baffle plate	Core barrel	Thermal shield	Lower core plate
^{63}Ni	1.01×10^{8}	1.49×10^{9}	1.63×10^{8}	2.57×10^{7}	2.10×10^{7}
^{55}Fe	7.87×10^{7}	1.82×10^{9}	1.28×10^{8}	2.07×10^{7}	1.90×10^{7}
^{60}Co	5.72×10^{6}	9.91×10^{8}	1.04×10^{7}	1.34×10^{6}	1.22×10^{6}
^{59}Ni	9.62×10^{5}	5.93×10^{6}	1.51×10^{6}	2.57×10^{5}	2.08×10^{5}
^{54}Mn	4.21×10^{4}	1.03×10^{6}	6.80×10^{4}	1.18×10^{4}	1.08×10^{4}
^{3}H	4.87×10^{3}	2.91×10^{4}	7.04×10^{3}	1.25×10^{3}	1.05×10^{3}
^{14}C	1.77×10^{3}	3.83×10^{4}	2.91×10^{3}	4.45×10^{2}	3.60×10^{2}
^{93m}Nb	6.71×10^{2}	1.40×10^{4}	1.10×10^{3}	1.70×10^{2}	1.45×10^{2}
^{154}Eu	1.29×10^{2}	6.19×10^{0}	1.42×10^{2}	3.86×10^{1}	3.33×10^{1}
^{93}Mo	1.16×10^{2}	2.17×10^{3}	1.89×10^{2}	2.93×10^{1}	2.38×10^{1}

Table 4. The mass and volume of each component [8]

	Mass (kg)	Volume (m^3)
Baffle former	2,716	0.64
Baffle plate	9,408	1.19
Core barrel	15,137	1.91
Thermal shield	37,447	4.72
Lower core plate	1,896	1.87

Table 5. Total activity on each component

Component	Baffle former	Baffle plate	Core barrel	Thermal shield	Lower core plate
Bq	1.38×10^{9}	3.81×10^{11}	1.25×10^{10}	4.88×10^{9}	2.13×10^{8}

3.4 Dose Estimation

The divers' radiation exposure is calculated by entering the geometric modeling and radiation modeling into the MAVRIC code. The diver is assumed to be 100 mm away on the x-axis (horizontal) from the RVI, and measurements were taken at 800, 1,600, and 2,400 mm on the z-axis (height). Since the diver's work location could not be determined, the height of the RVI was assumed 2,400 mm instead of the actual 2,500 mm, and the measurement points were evenly divided into three equal parts. Given that actual underwater work is not feasible at the seabed (0 mm), the starting point was chosen at a height exceeding the knee level, specifically at 800 mm from the floor. The MAVRIC sequence produces the result of the adjoint calculation of the 3D deterministic code TORT with Monaco. Both importance maps and biased sources for the weight window are automatically generated from the adjoint flux using the Consistent Adjoint Driven Importance Sampling (CADIS) methodology. The MAVRIC is automated with simple user input, creating cross-section (forward and adjacent), calculating the first collision source using GRTUN-CL3-D, calculating adjacent flux using TORT, generating importance maps and bias sources, and running Monaco.

Table 6. Result of radiation dose

Diver position	x	z	x	z	x	z
	100 (mm)	800 (mm)	100 (mm)	1,600 (mm)	100 (mm)	2,400 (mm)
Photon flux	1.52×10^{3}		2.15×10^{3}		$1.18E\times10^{3}$	
Radiation dose ($Sv\cdot h^{-1}$)	1.24×10^{-4}		1.54×10^{-4}		1.02×10^{-4}	
Maximum radiation dose (Sv)	2					
Maximum work time (hours)	161.50		129.59		195.32	
Maximum work time (days)	7		5		8	

This calculation method is advantageous because it can reduce the calculation time and produce necessary calculations accurately. In addition, the modeling is simplified as much as possible to increase computational efficiency and actively adjust many possible variables in the field. The expected dose at each Point Detector No. 1 to 3 by height is calculated for each work position [7].

The value calculated by the SCALE-MAVRIC code represents the radiation dose ($Sv\cdot h^{-1}$). The maximum radiation dose (Sv) denotes the permissible radiation exposure for nuclear power plant workers within a year. The maximum work time (hours) is obtained by dividing the maximum radiation dose (Sv) by the radiation dose rate ($Sv\cdot h^{-1}$). The maximum work time (days) is then determined by dividing the maximum work time (hours) by 24. Using these methods, at a Z-axis position of 800 mm, the working time is 161 hours, approximately 7 days of work. At a Z-axis position of 1,600 mm, the working time is 125 hours, approximately 5 days of work. However, at the upper location of 2,400 mm on the Z-axis, it is evaluated that there are fewer RVI components, as confirmed even by the geometric data. This results in a longer working time of 195 hours, approximately 8 days of work. The values are as shown in Table 6.

4. Conclusion

To ensure the safety of workers and the stability of the operation for RVI dismantling, it is determined that the cutting work of RVI will be carried out underwater. Various remote-controlled cutting equipment has been developed for the operation. When performing cutting work using a remote-control system, immediate response during the operation is challenging. While the main operation is conducted remotely, evaluating the dose exposure of the diving work is important in case workers need to access the cavity. To perform precise calculations using the MAVRIC code, geometric modeling and radiation modeling were conducted. The dose rates at heights of 800, 1,600, and 2,400 mm were evaluated, considering the height of the reactor vessel. The maximum allowable work time is evaluated to be approximately 8 days based on a limit of maximum dose expose 0.02 Sv (2 rem). However, it should be noted that the results obtained using the MAVRIC code are not absolute, and cross-comparing with other radiation calculation programs would provide a more reliable basis for conducting the work safely.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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