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Original Article

Analysis of dismantling process and disposal cost of waste RVCH

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ABSTRACT

During the operation of a nuclear power plant (NPP), the waste reactor vessel closure head (RVCH) that is replaced owing to design or manufacturing defects is buried in a designated area or temporarily stored in a radiation shielding facility within the NPP. In such cases, storing it for extended periods proves a challenge owing to space constraints in the power plant and a safety risk associated with radiation exposure; therefore, dismantling it quickly and safely is crucial. However, not much research has been done on the dismantling of the RVCH in an operational power plant.

This study proposes a dismantling process based on the radioactive contamination level measured for the Kori #1 RVCH, which is currently being discarded and stored, and examines the decontamination and cutting according to this process. In addition, the amount of secondary waste and dismantling cost are evaluated, and the dismantling effect of the reactor closure head is analyzed.

1. Introduction

The reactor pressure vessel is a key component of a nuclear power plant (NPP) and a primary system pressure-resistant structure that produces energy through nuclear fission via embedded nuclear fuel. In a pressurized light water reactor (PWR), a hemispherical lower head and cylindrical body are welded, the hemispherical reactor vessel closure head (RVCH) is fastened with bolts to enable nuclear fuel replacement. Because the reactor vessel cannot be replaced during the design lifetime, it must be able to withstand stress induced by high temperatures and pressures. Therefore, the reactor vessel is typically manufactured using ASME SA508 forging material, which have excellent resistance to fracture toughness deterioration resulting from neutron irradiation and corrosion is prevented by cladding the surface with a stainless material inside the reactor [1]. Moreover, Several through-pipes are attached to the RVCH to install control rods, head exhaust ports, and thermocouples. However, replacement of the RVCH becomes necessary in some case because of design or manufacturing defects. In particular, primary water stress corrosion cracking (PWSCC) defects occur in the welds on the Alloy 600 nozzle and the RVCH containing Alloy 82/182 weld [2].

The replaced waste RVCH is contaminated with radiation due to long-term use, so it must be treated separately. The waste RVCHs are treated in the following ways.

(1) Landfill: After shielding the exterior, the RVCH is disposed by burying it in its original state without any decontamination treatment. In the Davis-Basse power plant, a 906 MW PWR with an outside diameter of 200 inches, a height of 96 inches, and a weight of 163,300 pounds, the total surface contamination level of the RVCH at final disposal was 9.2 $\mu Ci/cm^2$. Each package of the class 7 (radioactive) material was shielded according to transport standards and subsequently disposed of via a train in the Envirocare of Utah (EOU) [3] [4].
(2) Landfill after dismantling: This method primarily used when decommissioning an NPP. The RVCH is cut into pieces in the reactor tank and stored in a shielding container to be buried. In the Jose Cabrera reactor in Spain, which is a 160 MW PWR with an outside diameter of 3.6 m, height of 1.5 m, and weight of 19 tons, the RVCH was cut into 26 pieces using a band saw in a water tank, stored in a CE-2a container, and disposed of in a landfill[5] [6].
(3) Radiation shielding building storage: It is a temporary storage of the power plant before dismantling the head. For this purpose, the storage building must be shielded from radiation.

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Currently, the RVCHs of Kori #1,#2 and Hanbit #3,#4 have been replaced, and another four RVCHs are scheduled to be replaced in the future. The replaced RVCHs are in a state of radioactive contamination, so they are temporarily stored in a radiation-shielding building such as a hot machine shop within the NPP. Table 1 shows the history of head replacement and future plans.

In Korea, based on RS-G1.7, the IAEA safety guideline, the current standards for deregulation of radioactive waste which is the concentration or dose of nuclides are stipulated. Table 2 shows the classification and treatment methods of radioactive waste in Korea. Self-disposal is a form of incineration, burial, and recycling where radioactive waste falls below the allowable concentration and is treated as general waste. This can reduce the cost of disposal of radioactive waste. However, the storage period is too long for radioactive waste to naturally fall below the permissible level, there is insufficient storage space in the power plant, and there is a risk of radiation leakage. Table 3 shows the repository of low-intermediate level radioactive waste in Korea. In addition, in order to dismantle the radioactively contaminated waste RVCH, it should be conducted to minimize radioactive exposure and minimize radioactive waste. The researches on the dismantling of the waste RVCH studied so far are reviewed in a way that they are dismantled in the same way as a reactor vessel in a cavity when decommissioning a nuclear power plant, so it is difficult to apply to the dismantling of a head stored in an operating power plant [8].

In this study, the dismantling process was established through radioactive review of the waste RVCH of Kori # 1, which is currently stored in the power plant, and the amount of radioactive wastes was calculated through decontamination and cutting analysis, and the decommissioning cost was calculated for them.

2. Dismantling of the RVCH of Kori #1

2.1. Specifications of the RVCH

The 587 MW PWR 2-loop type Kori #1, designed by Westinghouse and manufactured by B&W, started commercial operation in 1978, reached 30 years of design life in 2008, and after receiving approval for life extension, was operated until 2017 before being permanently shutdown. The original RVCH was manufactured with Alloy 600 using pipes and alloy 182/82 welding material, while the new RVCH in 2013 was replaced with Alloy 690. The waste RVCH is divided into four parts: a body and flange clad with SA309 from SA508 forging, control rod drive mechanism (CRDM) penetration nozzles welded to the body made of Alloy 600, and thermal sleeves to guide the control rods were made for stainless steel. Fig. 1 and Table 4 present the structure and specifications of the RVCH, respectively.

Assuming 10 years of cooling after 40 years of operation for the RVCH of the Kori #1 reactor, the activation evaluation results show that it is sufficiently away from the source term; Therefore, it is considered exempt waste based on Co-60 standard 6.03 E-04Bq/g [14]. However, measurements of radioactive contamination of the RVCH after actual replacement indicated that the surface contamination level and space dose value were high. Table 5 shows radioactive contaminations of Kori #1 RVCH. In addition, the contamination due to each nuclide was measured to be approximately 1.58×10^{8}Bq for Co-60, which was higher than the simulation value. In particular, there was a large difference between the measured values of the internal and external surfaces of the RVCH, and the CRDM penetration nozzles had similar internal and external surface differences. Therefore, it can be assumed that only the internal surface of the RVCH is contaminated by system water during operation, and the CRDM penetration nozzles and thermal sleeves are irradiated because of their thickness, resulting in volumetric contamination [15,16]. If stored in its current state, it will take approximately 31 years to exempt waste at 0.07Bq/g, which is less than the standard value [16]. Table 6 shows major nuclide half-life and exempt waste level.

Table 1
Schedule of RVCH replacement in Korea [7].

NPP	Head type	Replacement time	Storage
Kori #1	W/H 2Loop	2013.9	NPP Hot machine shop
Kori #2	W/H 2Loop	2018.6	
Hanbit #3	OPR1000	2015.3	
Hanbit #4	OPR1000	2015.12	
Hanbit#5	OPR1000	2024	Undetermined
Hanbit#6	OPR1000	2024	
Hanul#3	OPR1000	2024	
Hanul#4	OPR1000	2024	

2.2. Method of decontamination and dismantling

The decontamination of radioactively contaminated structures is important when maintaining or dismantling the primary side of an NPP. In particular, radioactive decontamination and dismantling methods for large structures have been developed to safely decommissioning an NPP that has been shutdown at the end of its design life [17] [18].

(1) Decontamination conditions: To effectively decontaminate the RVCH, decontamination is performed on the inside and outside of the RVCH whole, and the depth of decontamination is over 100 μm [19] [20]. In addition, because the dismantling site is narrow, the size of the decontamination device must be small, the amount of secondary waste and the radiation exposure must be minimized. Accordingly, decontamination is performed by applying the laser cleaning method, which has fast decontamination speed, effective decontamination and can be operated remotely.
(2) Cutting conditions: Because The waste RVCH is not reused after it was cut and discarded, It does not consider the condition of the cut surface. To minimize the cutting time and reduce the radiation exposure of workers, cut a lot at once and it must be possible to work remotely. In addition, cutting it into complex shapes, installing it in a narrow place, and generating less secondary waste are essential requirements. Accordingly, the cutting operation is remotely performed using a manipulator. The penetration nozzle is cut by plasma cutting, and the remaining parts are cut by oxygen cutting. The gas generated after cutting is collected and processed using a dust collector at the end of the manipulator [5] [21]. Table 7 shows he characteristics of cutting methods.

3. RVCH dismantling scenario

The dismantling sequence of the RVCH is as follows.

3.1. Installation of RVCH

A 6-axis manipulator is installed at the end of the Z-axis of the gantry structure, which can move along the X-, Y–, and Z-axes to work with the entire RVCH. A work tools and dust collector are attached to the end of the manipulator, and the cutting parts are supported by an auxiliary crane. Before dismantling, the interference and work behavior are verified via simulation. This work is performed remotely. The fumes generated during cutting and decontamination is collected in a dust collector, after work is completed the filters are treated as radioactive waste.

Table 2
Classifications of radioactive waste and methods of disposal in Korea [9], [10].

Classification	Waste level	Disposal
HLW(SNF)	>4,000Bq/g (α-emitter, half-life>20 years) Heat generation >2 kW/m^3	Deep geological disposal
ILW	>LLW concentration criteria	Disposal at depth of between a few tens to100 M
LLW	LLW~100 × CLconcentration criteria	Disposal at depth from the surface down to 30 M
VLLW	1 × CL ~ 100 × CL	Disposal in engineered surface landfill-type facilities
EW	Below clearance level	Clearance (reuse)/Self-disposal

Table 3
Current status of low-intermediate level radioactive waste repository in Korea [11].

Classification	Area	Usage (drum)	Capacity (drum)	Rate (%)
NPP	Kori	41,755	60,200	69.3
	Hanbit	21,420	23,300	91.9
	Hanul	16,478	17,400	94.7
	Wolseong	15,596	19,000	82
	Saeul	429	10,000	4
Radioactive waste disposal plant	WLDC	29,795	100,000	29.8

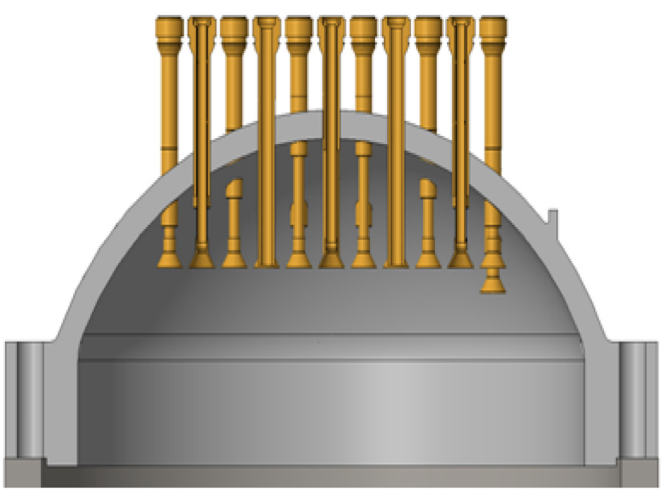


Fig. 1. Kori #1 RVCH

Table 5
Radioactive contamination of Kori #1 RVCH [13].

Classification	Surface contamination (Bq/cm$_2$)	Dose rate (mSv/h)
RVCH body	6.48 ~ 123.93	20
CRDM penetration	89.3 ~111.6	0.5 ~ 2.0
Flange (Stud bolt)	0.45 ~ 3.95	0.003

Table 6
Major nuclide half-life and exempt waste level [10] [14].

Nuclide	Half-life (day)	Exempt waste Level (Bq/g)
Mn-54	312.7	0.1
Co-57	270.9	1
Co-60	1923.92	0.1
Zn-65	244.4	0.1
Ce-144	284.3	10

3.2. Penetration nozzles and thermal sleeves cutting

Because the CRDM penetration nozzles are radioactively contaminated, cutting is performed without decontamination. The cutting parts of the penetration nozzles consisted of an upper nozzle attached to the external surface of the RVCH and a bottom nozzle attached to the internal surface of the RVCH and thermal sleeves.

(1) External nozzle cutting

Because the penetration nozzles were made of stainless steel, cutting is performed horizontally using a plasma cutting torch. The cutting sequence is performed from the outside to the inside. When the external nozzle is cut, it is supported by an auxiliary crane. During cutting, the thermal sleeves installed inside are also cut and can drop on the floor. Therefore, it need to install anti-shock pads on the floor. Table 8 lists specifications of external nozzle cutting, including the length, weight, and quantity of nozzle cut. Fig. 2 depicts the cutting procedure of external nozzles from the RVCH.

The cutting conditions for the work type are as follows.

- Size: diameter 101.6 mm, thickness 15.85 mm
- Cutting speed: 60 mm/min
- Cutting time: 1.7 min/piece
- Setup time: 10 min/piece
- Cutting quantity: 40 EA
- Total working time: 7.8 h

(2)Internal nozzle cutting

Table 4
Specifications of waste Kori #1 RVCH [12] [13].

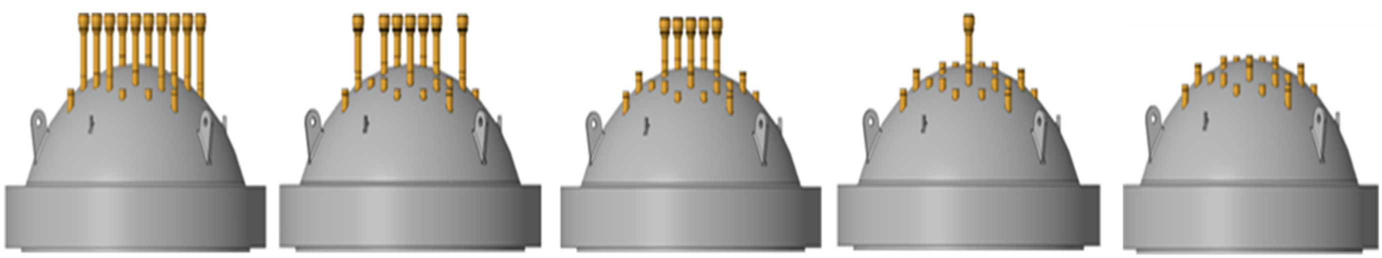
Classification	Material	Size (mm)	Qty	Weight (Kg)
RVCH body	SA508 + SA309clad	Inner Dia.: 3,352, Thickness: 177~196.9	1	12,615
RVCH flange	SA508 + SA309clad	Inner Dia.: 3,352, Outer Dia.: 4,000	1	18,458
CRDM Penetration nozzle	Alloy 600(SB-167)	Outer dia.: 101.6, Inner Dia.: 69.9	40	2,128
Thermal sleeve	SUS 304	Outer dia.:63.5, Inner Dia. 54.5	37	93

Table 7
Comparison of cutting characteristics [22].

Type	Classification	Cutting thickness (mm)	Material	Cutting speed (mm/min)	Cutting shape	Cutting quality	Manipulator	Second waste
Thermal cutting	Oxygen cutting	~800 mm	CS, Alloy	~700	Normal	Poor	Yes	Slag, gas
	Plasma cutting	~160 mm	metal	~500	Normal	Good	Yes	Slag, gas
	Laser cutting	~110 mm	N/A	300 ~ 1000	Complex	Very good	Yes	Gas

Table 8
Specifications of external nozzle cutting.

Penetration nozzle No.	Length (mm)	Weight (kg)	Qty.	Thermal Sleeve + Guide cone No.	Length (mm)	Weight (kg)	Qty.
30 ~ 40	700	45.2	11	30 ~ 40	638	45.2	11
18 ~ 29	595	38.7	12	18 ~ 29	743	38.7	12
10 ~ 17	510	35.1	8	10 ~ 17	828	35.1	8
2 ~ 9	450	32.5	8	2 ~ 9	888	32.5	8
1	438	32	1	1	900	32	1



(a) Nozzle No. 30–40 (b) Nozzle No. 18–29 (c) Nozzle No. 10–17 (d) Nozzle No.2–9 (e) Nozzle No.1

Fig. 2. Cutting procedure of external nozzle.

Because the RVCH body is made of Carbon Steel and the cutting thickness varies depending on the cutting position, an oxygen cutting torch is used to cut the internal nozzle. The internal nozzle cutting procedure is from No. 30~40 to No.1 located on the outermost surface of the RVCH. The cutting shape is circularly cut at a distance of 100 mm from the center of the external nozzle. When the internal nozzle is cut, it is supported by an auxiliary crane. Table 9 lists the length, weight, and quantity of the internal nozzles cut. Fig. 3 depicts the cutting procedure of internal nozzles from the RVCH. Fig. 4 shows the internal nozzles cut from the RVCH. The cutting conditions for the work type are as follows.

- Cutting speed: 60 mm/min
- Setup time: 10 min/piece
- Cutting quantity: 40 EA

3.3. Decontamination of RVCH

Although, the external surface of the surface of RVCH body is low contamination, it is also decontaminated for effective decontamination. The laser cleaning decontamination coefficient is set to 100 and the decontamination effect is calculated by multiplying the decontamination by 20% during decontamination. The decontamination was performed only once.

- External decontamination area: 26.4 m^2
- Decontamination speed: 4 m^2/hour
- Total decontamination time: 6.7 h

After the completion of the external surface decontamination, the RVCH is turned over, and decontamination is performed on the internal surface with the RVCH facing up.

- Internal decontamination area: 19.4 m^2
- Decontamination speed: 4 m^2/hour
- Total decontamination time: 4.8 h

3.4. Cutting of RVCH body and flange

After the decontamination of RVCH body and flange are completed, they use oxygen cutting method because the cutting thickness is thick. The total cut pieces weighed approximately

Table 9
Specifications of internal nozzle cutting.

Penetration nozzle No.	Length (mm)	Weight (kg)	Qty.	Cutting depth (mm)	Cutting length (mm)	Cutting time (min)
30 ~ 40	466.8	50	11	172	725	12.1
18 ~ 29	345.6	41.3	12	163	675	11.3
10 ~ 17	256	41.2	8	155.6	664	11.1
2 ~ 9	237.4	33.9	8	140.6	632	10.5
1	217.6	32.8	1	140.4	628	10.4

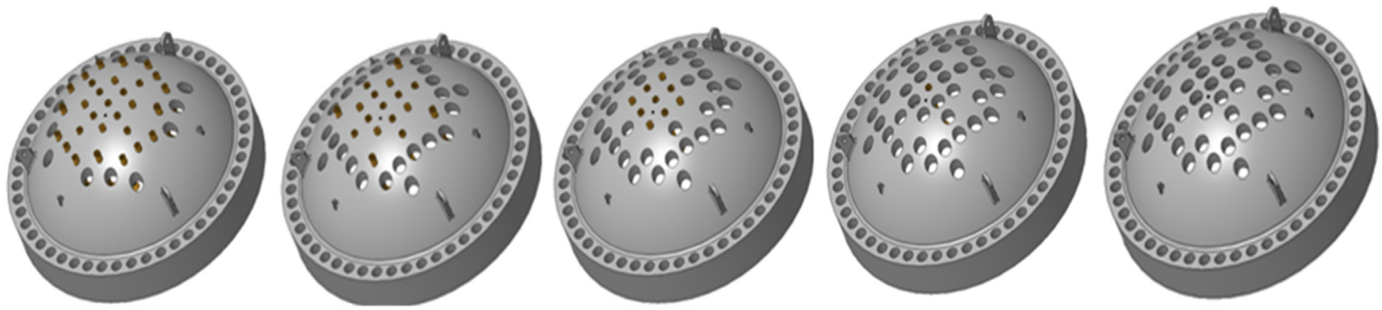


Fig. 3. Cutting procedure of internal nozzle.

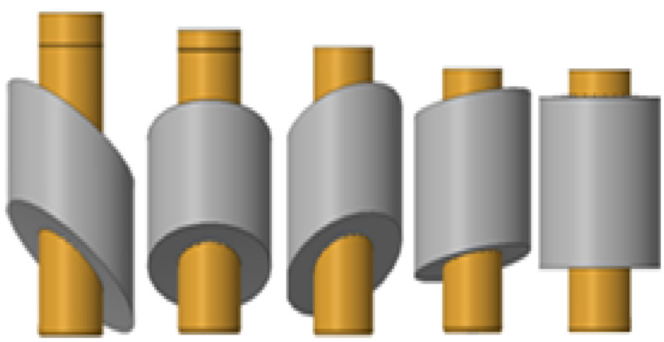


Fig. 4. Internal nozzle cut from the RVCH.

27,659.1 kg and the cutting direction is from the top to the bottom. Table 10 lists the cutting specifications and cutting time, and Fig. 5 shows the cutting shape for each RVCH part.

- Cutting speed: 60 mm/min
- Cutting width: 20 mm

4. Dismantled RVCH treatment

4.1. Nozzle penetrations and thermal sleeves

The penetration nozzles and thermal sleeves are radioactively contaminated, they should be placed in a disposal container and buried. Currently, there is no standard for disposal container about large-sized waste, so they are stored and processed in the existing 200 L drum type disposal container. The container drum is an internal diameter of 617 mm and a height of 887 mm, with a loading capacity of 500 kg. The number of drums need to store the cutting nozzles and thermal sleeves are listed in Table 11. Fig. 6 shows the arrangements of the 200 L container drum according to the shape of the nozzle.

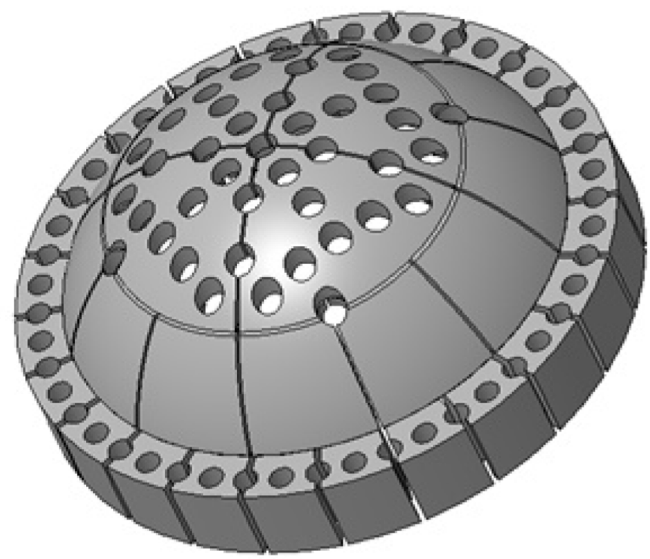


Fig. 5. RVCH body and flange cutting shape.

4.2. RVCH body and flange parts

For self-disposal of the dismantled RVCH body and flange parts, the permissible concentration for each nuclide must be 0.1Bq/g or less. The radioactive contamination values for the RVCH body and flange before and after decontamination are calculated based on values listed in Table 12. Because the Co-60 accounts for 34.28% of all nuclides [15], the radioactive contamination values for the RVCH body and flange before and after decontamination are able to calculate [23]. Table 13 shows decontamination results for RVCH.

As a result of decontamination, the level of radioactive contamination is below the allowable value for self-disposal, the RVCH body and flange cutting parts are self-disposable.

Table 10
Specifications of RVCH body and flange.

Cutting location	Cutting length (mm)	Cutting time (min)	Weight (kg)	Piece Qty.
Top	12,468	207.8	3,034.4	4
Middle	19,176	319.6	7,452.8	12
Flange	12,096	201.6	17,171.9	24

Table 11
Arrangement on drum according to nozzle and TS.

Parts	Nozzle number/drum	Drum qty. (EA).
External nozzle	(1–9), (10–17), (18–25), (26–34), (35–40)	5
Internal nozzle	(2–9), (10–17), (18–25), (26–34), (35–40,1)	5
Thermal sleeve	(1–10), (11–20), (21–30), (31–40)	4

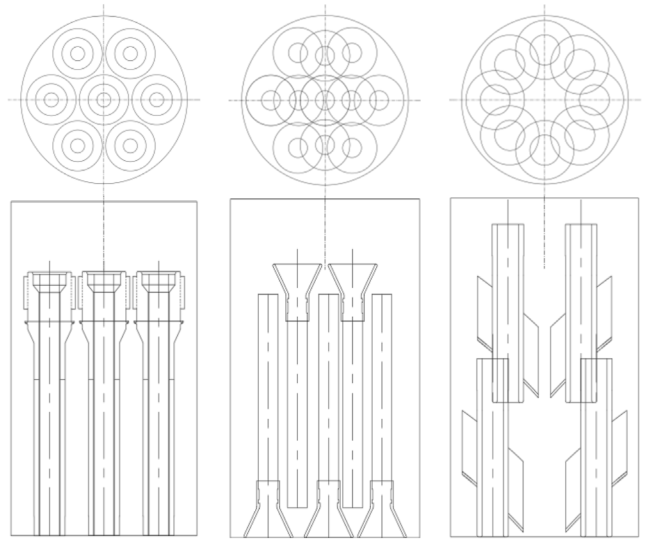

(a) External nozzles (b) Internal nozzles (c) Thermal sleeves

Fig. 6. Arrangement on cutting nozzles in container drum.

5. Analysis of dismantling cost of the Kori #1 RVCH

The cost of dismantling the RVCH was divided into the facility investment cost for dismantling and the cost of disposal of radioactive waste generated during dismantling. Table 14 shows dismantling facility investment and disposal cost for dismantling the waste RVCH of Kori #1. Currently, the disposal cost per 200 L container drum is approximately $12,700 based on calculation by the Wolseong Low and Intermediate Level Radioactive Waste Disposal Center [24]. If the Kori #1 waste RVCH is cut into 200 L drum size without decontamination treatment, at least 74 drums are required based on 450 kg per drum and disposal cost is approximately $ 939,800.

Dismantling the RVCH via cutting after decontamination results in the reduction of radioactive waste from 74 to 19 compared to the existing RVCH before decontamination. In addition, for self-disposal of the cut pieces of RVCH head body and flange after decontamination, a specimen of 1 kg per 200 kg should be collected and a radionuclide concentration test. The cost of the test was approximately $243,760. So the total cost is approximately $485,060, which is approximately 48.3% lower than before The dismantling facility can be used continuously for dismantling not only the Kori #1 RVCH but also of other waste RVCHs or waste

Table 12
Comparison of decontamination results for RVCH.

Location	Internal area (cm^2)	External area (cm^2)	Before decontamination (Bq/g)		After decontamination (Bq/g)	
			Internal	External	Internal	External
Top	5,236	8,976	0.855	0.076	8.55E-03	7.66E-04
Middle	5,219	5,884	1.041	0.061	1.04E-02	6.13E-04
Flange	3,941	4,435	0.682	0.04	6.62E-03	4.01E-04

Table 13
Comparison of decontamination results for RVCH based on Co-60.

Location	Before decontamination (Bq/g)		After decontamination (Bq/g)	
	Internal	External	Internal	External
Top	0.239	0.026	2.93E-03	2.62E-04
Middle	0.357	0.021	3.57E-03	2.10E-04
Flange	0.234	0.013	2.34E-03	1.37E-04

Table 14
Dismantling Facility investment and disposal cost for dismantling the waste RVCH of Kori #1.

classification	Item	Unit price ($)	Quantity	The mount ($)
Dismantling facility	X,Y,Z gantry	96,000	1set	96,000
	6-axis manipulator system	60,000	1set	60,000
	Plasma cutting system	200,000	1set	200,000
	Oxygen cutting system	10,000	1set	10,000
	Laser decontamination system	450,000	1set	450,000
	Dust collector system	40,000	1set	40,000
Radioactive waste disposal	Nozzle disposal	12,700/drum	14drum	177,800
	Second waste disposal	12,700/drum	5durm	63,500
	Inspection cost for self-disposal	8,800/ton	27.1ton	243,760

steam generators. If applied to the four waste RVCHs in storage, the total disposal cost, including the dismantling facility cost of $ 856,000, is $2,796,240. Which represents a 25.6% cost saving compared to landfill disposal; in addition, radioactive waste can be reduced by 69.6%.

6. Conclusion

The waste RVCH must typically be stored for an extended period at a radiation shielding building more than 30 years for the contamination to drop below self-disposal level. To solve the problem, the RVCH contamination was analyzed and the effect was reviewed by establishing the decontamination and cutting process. In addition, the working time and dismantling cost were evaluated based on the dismantling process.

The results indicated that radioactive waste was reduced by approximately 69.6% and disposal costs by approximately 25.6%, compared to those before decontamination. The proposed method can be effectively applied to the currently temporarily stored waste RVCH or to RVCH when the power plant is decommissioned in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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