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Radiological analysis of transport and storage container for very low-level liquid radioactive waste

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A B S T R A C T

As NPPs continue to operate, liquid waste continues to be generated, and containers are needed to store and transport them at low cost and high capacity. To transport and store liquid phase very low-level radioactive waste (VLLW), a container is designed by considering related regulations. The design was constructed based on the existing container design, which easily transports and stores liquid waste. The radiation shielding calculation was performed according to the composition change of barium sulfate ($BaSO_4$) using the Monte Carlo N-Particle (MCNP) code. High-density polyethylene (HDPE) without mixing the additional $BaSO_4$, represented the maximum dose of 1.03 mSv/hr (<2 mSv/hr) and 0.048 mSv/hr (<0.1 mSv/hr) at the surface of the inner container and at 2 m away from the surface, respectively, for a 10 Bq/g of ^{60}Co source. It was confirmed that the dose from the inner container with the VLLW content satisfied the domestic dose standard both on the surface of the container and 2 m from the surface. Although it satisfies the dose standard without adding $BaSO_4$, a shielding material, the inner container was designed with $BaSO_4$ added to increase radiation safety.

1. Introduction

Radioactive wastes, including various types of radioactive materials, are generated from the decommissioning and operation of nuclear power plants (NPPs), where they have the forms of solid, liquid, and gaseous states contaminated by radioactive nuclides from fission-product and neutron activation. These wastes should be safely transported in the premise of the NPP site or to a radioactive waste disposal facility, which is subject to criteria of the transport regulations of the Enforcement Decree of the Nuclear Safety Act, for the safety of workers, the public, and the environment. In particular, radioactive material transport containers require a comprehensive and detailed assessment of radioactive material contents. The development of transport containers for radioactive wastes that can satisfy the technical standards under the relevant laws should consider workability and safety.

Domestically, a total of 12 NPPs that would be permanently shut down by 2030, starting with the dismantling of the NPP Kori unit-1 in 2022 is expected to generate a vast amount of radioactive wastes, where the generation of the radioactive waste of 13,800 drums is predicted from the dismantling of the NPP Kori unit-1 [1]. At this point, it is expected that very low-level radioactive waste (VLLW) would account for more than half of the total waste from the dismantling of Kori-1, where VLLWs are mainly generated in the form of solid and liquid radioactive waste [2]. Therefore, the containers used for transportation and storage of radioactive wastes are essential for managing them in radiation protection. Transport containers that meet the technical standards set by the regulations and the classification standards of radioactive waste are needed for their storage, on-site transportation at the NPP dismantling site, and their transportation to the radioactive waste disposal facility.

The large amount of VLLWs generated during NPP operation and dismantling are, approximately 8.38×10^5 m^3 of liquid waste per quarter at the Korea NPP sites. Therefore, containers are needed to transport and store large amounts of liquid VLLW at a low cost. For liquid waste treatment and reduction, a container for transport and storage used exclusively at the operation and dismantling site is required.

There are L, industrial package (IP), A, B, C type, and fissile material transport containers for radioactive waste prescribed by

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domestic laws and regulations, and an IP-type container was selected to design containers that transport and store liquid VLLW. Unlike the IP-1 type, the IP-2 type container is safer for storing liquid waste because it satisfies the free-fall and stacking tests. The container was designed with structural safety and reinforced radiation shielding such that it can also be used as a storage container.

In this study, to ensure the safety of temporary storage and transportation of liquid VLLW generated at the NPP decommissioning and operation site, a container was designed according to the IP-2 type technical standard, and radiological shielding and safety assessment were performed.

2. Materials and methods

The fundamental factors in determining the loading capacity and size of containers for transport and storage are the type and volume of radioactive waste. For on-site transport of the container, the radiation dose rate on the outer surface of the container with radioactive waste should not exceed 2 mSv/hr, and that at 2 m from the outer surface should not exceed 0.1 mSv/hr. The Monte Carlo N-Particle (MCNP) transport code was used to demonstrate whether the dose rate criteria of the container were satisfied. The thickness of the container to be designed was set to a constant of 5 mm, and the composition of the material was changed. Thereafter, the radiation shielding analysis was performed. The composition of the container was selected and mixed with high-density polyethylene (HDPE), a material used in the existing container, and barium sulfate ($BaSO_4$) is known to be effective for radiation shielding, especially gamma-rays.

2.1. Liquid waste container

The types of radioactive material transport containers are classified into L, IP, A, B, C type, and fissile material transport containers [3,4]. Among these containers, the IP type is used for the storage of low specific activity (LSA) materials or surface contaminated objects (SCOs). IP type transport containers are classified as IP-1, IP-2, and IP-3 [4].

The criteria for an IP-2 type transport/storage container are applied to the design of the container for the transportation and storage of the liquid VLLW in this research. The design criteria for IP-2 type transport containers should satisfy those for IP-1-type transport containers and tests such as free-fall and stacking tests. The design criteria for IP-1 type transport containers should satisfy the generic standard of transport containers and should also be less than 3 mSv/hr at 3 m from either LSA or SCO materials without radiation shielding. Radiological safety and structural integrity were demonstrated by assessing the loss and distribution of radioactive substances in the container and the shielding loss that can cause the increased radiation dose rate by more than 20% at the container's external surface through the free-fall and stacking test [4].

Intermediate Bulk Container (IBC) is a United Nations-certified container based on the International Maritime Dangerous Goods code, 31H1, which can store containers in a piled state and has a volume lesser than 3000 L [5]. IBC has a capacity between the tank and drum, and the combined pallet enables it to be transported by a forklift. The external support structure makes the IBC stacked. Among various IBC containers, a rigid IBC made of rigid plastic and an external support structure made of steel, as shown in Fig. 1, was determined as the basic container design for liquid waste.

2.2. Basic design of liquid waste container

The transport/storage container structure consists of a top cover, inner container, screw cap, drain valve, cage, and bottom pallet, as shown in Fig. 2. The top cover was designed to be fastened to the cage with bolts in a flat plate shape without protrusions to enable top loading. The inner container was designed as a radiation shielding container with a volume of 1000 L and a 5 mm thick layer, a complex structure mixed with $BaSO_4$ powder and the corrosion and chemical-resistant HDPE material as shown in Fig. 3. It is intended to be able to fill and discharge contents through the screw cap and drain valve. The cage was designed as a steel frame with reinforced structural safety by applying a truss structure to allow stacking. The bottom pallet is designed in a four-way insertion-type structure for easy transport and loading by a forklift, and it is fastened to the cage with bolts and designed with steel or reinforced plastic to withstand a strong impact and load. A rubber guard is installed on the inside edge of the cage to obtain a buffer effect to absorb a direct impact on the internal container in the event of a collision in a free-fall situation. Detailed specifications of the transport/storage container components are listed in Table 1.

2.3. Radiation shielding material of inner container

The container for transporting radioactive waste should shield the radiation from the liquid radioactive waste, including various radioactive nuclides. The dose rate from the surface or outside the inner container depends on the radioactivity concentration, geometry and material of the container. Commonly considered shielding materials include lead and tungsten. Lead has excellent shielding efficiency owing to its high atomic number ($Z = 82$), but has the disadvantage of being a heavy metal material that is harmful to the human body and the environment. Tungsten has approximately 1.5 times higher shielding performance than lead because of its higher density, but it is less economical because of the high cost. $BaSO_4$ is a proven substance that is not harmful to the human body and increases the radiation shielding rate. Accordingly, $BaSO_4$ powder was applied as an alternative shielding material mixed with HDPE, where barium has an atomic number of $Z = 56$ and is chemically stable in water [5]. The radioactivity concentration of VLLW is equal to or higher than that of the clearance level and less than 100 times that of the clearance level [6]. Considering such a low radioactivity concentration level, the inner container, which has a composite shielding material with mixed HDPE and $BaSO_4$, was designed.

2.4. Radiation shielding assessment

In the inner container design in terms of radiation shielding from VLLW, which is subject to criteria such as the radiation dose rate according to the distance from the surface of the IP-2 type transport container, the allowable radiation dose rate on the outside of the transport container should be considered. The radioactivity limit of the liquid radioactive waste, which is stored and transported in the IP-2 type transport container, is less than 10^{-5} A_2/g where A_2 is the value of the radioactivity for basic radionuclides [4]. When considering high-energy gamma-ray emitting nuclides such as ^{60}Co and ^{137}Cs in radioactive waste generated during NPP decommissioning, they can be transported up to a concentration of 4×10^6 Bq/g and 6×10^6 Bq/g, respectively, as the IP-2 type package. Meanwhile, in terms of VLLW, whose radioactivity concentration ranges from the concentration of clearance to 100 times less than that of clearance, radioactive waste, including radionuclides such as ^{55}Fe, ^{57}Co, ^{60}Co, and ^{137}Cs with a radioactivity concentration of up to 100,000 Bq/g, 100 Bq/g, 10 Bq/g, and 10 Bq/g could be handled as VLLW, for instance. These radionuclides are assumed to be contained in the VLLW. In the case of on-site transport, the standard for the exclusive transport dose rate

Fig. 1. Example of rigid plastic intermediate bulk container design.

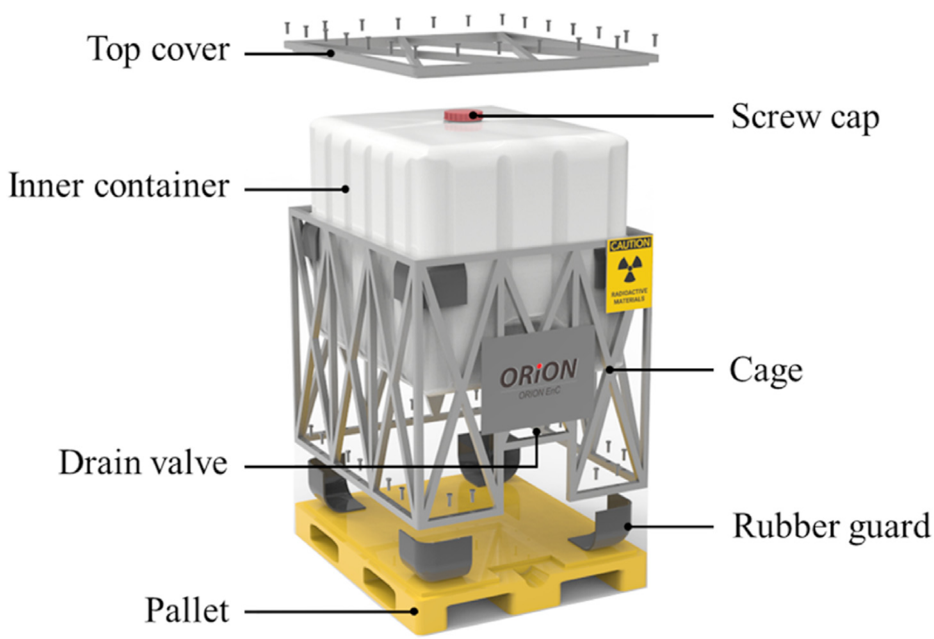

Fig. 2. Structure of transport and storage container for very low-level liquid waste.

should be considered, but the standard for non-exclusive transport was applied for the conservative assessment. The radiation dose rate on the outer surface of the container loaded with the maximum amount of liquid waste should not exceed 2 mSv/hr at the surface and 0.1 mSv/hr at a location of 2 m from the outer surface of the inner container [4].

Using the MCNP computational simulation code, the radiation shielding performance of the inner container was calculated [7]. Radiation shielding calculations were performed at the surface and at a distance of 2 m from the surface of the container with a thickness of 5 mm with the change in the composition ratio of $BaSO_4$, considering that the maximum radioactivity of liquid VLLW was assumed to be homogeneously distributed in the container, as shown in Fig. 4.

3. Results and discussion

The MCNP radiation shielding calculation results according to the inner container's composition change are presented in Tables 2 and 3. Table 2 summarizes the maximum dose calculation results at the surface of the inner container according to the change in the rate of $BaSO_4$ for each nuclide. The maximum dose rate of ^{55}Fe at the surface tended to decrease, but the results of 0%, 10% and 20% of the $BaSO_4$ content surface dose exhibited negligible values. ^{57}Co exhibited a tendency to decrease to an average dose reduction rate of 22.5% as the $BaSO_4$ content increased, but ^{60}Co and ^{137}Cs exhibited an average dose reduction rate of 2.1% and 3.7%, respectively. In addition, the doses decreased linearly as the $BaSO_4$ content increased. Table 3 lists the maximum dose rate at a distance of

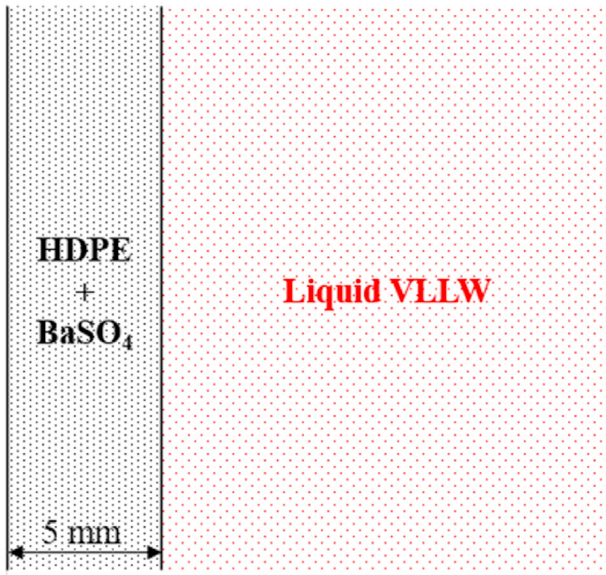

Fig. 3. Schematic view of inner container, HDPE and $BaSO_4$ mixture and liquid VLLW.

Table 1
Specification of transport and storage container for VLLW.

Component	Specification	
	Size (mm)	Weight (kg)
Top cover	1282 (L) × 1082 (W) × 45 (H)[a]	90
Inner container	1180 × 980 × 993	18
Screw cap	144[b]	
Drain valve	56	
Cage	1282 × 1082 × 1080	313
Pallet	1300 × 1100 × 145	170

[a] L: length, W: width, H: height.
[b] Diameter size of screw cap and drain valve.

2 m from the surface of the inner container according to the change in the rate of $BaSO_4$ for each nuclide. The average dose rates were 16.3%, 1.4% and 2.8% for ^{57}Co, ^{60}Co and ^{137}Cs, respectively. The average shielding rates were analogous to the maximum surface dose. As described in Table 4, ^{55}Fe and ^{57}Co are nuclides that emit low-energy gamma rays and achieve a fine shielding performance with increasing $BaSO_4$, whereas ^{60}Co and ^{137}Cs, which mainly emit high-energy gamma rays and beta-rays as decay, achieve a relatively deficient shielding performance. The container with the liquid VLLW content should satisfy the dose rate criteria, 2 mSv/hr at the surface, and 0.1 mSv/hr at a distance of 2 m from the surface. The maximum dose rate results from the HDPE without mixing additional shielding material achieved 1.7096 mSv/hr and 0.08 mSv/hr, which satisfied the dose rate criteria. In addition, the inner container, which comprised HDPE and $BaSO_4$, exhibited a linear decreased in the total maximum dose rate and satisfied the dose rate criteria. Although each radionuclide has various shielding rates, it was verified that the dose rate criteria of the VLLW container were sufficiently satisfied.

Only HDPE, without $BaSO_4$, the maximum dose at 2 m from the inner container surface, and the maximum dose due to each nuclide was found to be below 0.1 mSv/hr. This indicates that the inner container material HDPE without $BaSO_4$ could satisfy the radiological criteria in terms of the standard dose rate for the IP-2 type transport/storage container. Even though the radiation dose criteria were satisfied without $BaSO_4$, to reinforce the radiation safety from liquid VLLW, a reasonable ratio of $BaSO_4$ will be added to HDPE. To determine the reasonable ratio of $BaSO_4$, additional analysis of the physical properties and structural safety of the inner container should be conducted, which is an HDPE and $BaSO_4$ mixture material.

4. Conclusion

The shielding performance of the IBC for storing and transporting liquid VLLW was analyzed using MCNP. The IBC for storage and transport of VLLW designed the external supporting structure, and the inner container differs from the commercialized IBC. The external support structure is designed in a truss structure to satisfy the IP-2 type free-fall and stacking criteria and to increase structural safety. The inner container was intended to increase radiation safety by homogeneously mixing $BaSO_4$ in HDPE to improve the radiation shielding performance. The source term was established by assuming that the ^{55}Fe, ^{57}Co, ^{60}Co, and ^{137}Cs nuclides, which are expected to be mainly present in liquid waste, are the maximum radioactive concentration based on the VLLW criteria. The MCNP results were lower than the dose criteria of the transport container of 2 mSv/hr from the surface and 0.1 mSv/hr at a distance of 2 m

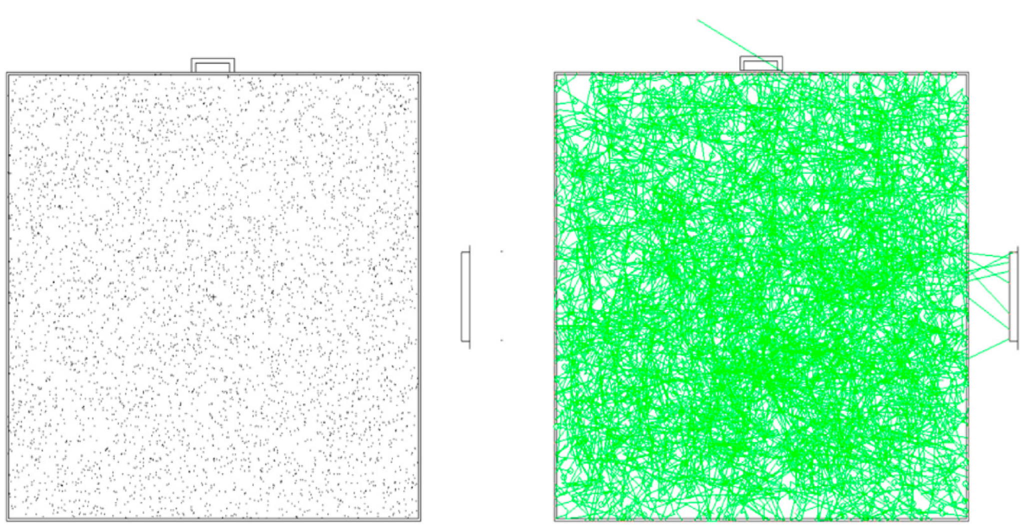

Fig. 4. Inner container radiation shielding performance calculation using MCNP.

Table 2
Calculation results of maximum dose from very low-level liquid waste inner container surface.

	Radioactivity concentration (Bq/g)	Max. Dose at inner container surface (mSv/hr)		
		$BaSO_4$ (0%)	$BaSO_4$ (10%)	$BaSO_4$ (20%)
^{55}Fe	100,000	4.77×10^{-5}	–	–
^{57}Co	100	0.4395	0.3515	0.2631
^{60}Co	10	1.0307	1.0094	0.9876
^{137}Cs	10	0.2367	0.2283	0.2195
Total		1.7069	1.5892	1.4702

Table 3
Calculation results of maximum dose from very low-level liquid waste inner container surface.

	Radioactivity concentration (Bq/g)	Max. Dose at 2 m from the inner container surface (mSv/hr)		
		$BaSO_4$ (0%)	$BaSO_4$ (10%)	$BaSO_4$ (20%)
^{55}Fe	100,000	–	–	–
^{57}Co	100	0.0210	0.0181	0.0147
^{60}Co	10	0.0480	0.0474	0.0467
^{137}Cs	10	0.0110	0.0107	0.0104
Total		0.0800	0.0762	0.0718

Table 4
Average decay energy of electromagnetic radiation (ER) and beta-ray from radionuclides [8].

	^{55}Fe	^{57}Co	^{60}Co	^{137}Cs
ER (keV)	1.642	125.142	2503.843	597.255
Beta (keV)	4.201	18.662	96.769	243.589

with a thickness of 5 mm of the inner container. As the composition ratio of $BaSO_4$ increased, the maximum dose of all nuclides tended to decrease linearly, and ^{55}Fe was completely shielded by an inner container made of HDPE and $BaSO_4$ mixture. The shielding rate according to the increase in the composition of $BaSO_4$ in the inner container achieved evident results for ^{55}Fe and ^{57}Co, which are low-energy gamma-ray sources, but ^{137}Cs and ^{60}Co, which have a high ratio of beta and high-energy gamma-rays, exhibited a relatively low shielding rate. Physical analysis of the newly designed inner container and external supporting structure of IBC is required for conserving liquid VLLW.

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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