Design Study of High-Efficiency Inspection System for Waste Drums of Nuclear Power Plant Decommissioning

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***Keywords :** nuclear waste drum, 6/3 MeV, LINAC, X-ray 3D-CT, room temperature semiconductor detector, CdZnTe

1. Introduction

The number of radioactive waste drums to be disposed of at Korean nuclear power plants, such as Kori Unit 1 and Wolseong Unit 1, which have been confirmed for decommissioning, is estimated at 14,500 drums per unit (based on 200L drums). The decommissioning radioactive waste is expected to be mostly low-level waste, with metal (70%), miscellaneous materials (16%), and concrete (14%) in that order. It is expected that a large amount of waste will be generated in various forms in a short period of time[1]. Assuming that the 14,500 drums of radioactive waste produced above are processed within 5 years, the number of statutory working days for civil servants under the Labor Standards Act of the Republic of Korea is 247 days, and if the 8-hour work condition is applied and all 7 processes applied during the standard radioactive waste acceptance inspection are included, a processing rate of at least 1.47 drums per hour must be secured. The current radioactive waste drum acceptance inspection facility owned by KORAD is confirmed to take about 3 hours per drum, which is about 30% of the target processing speed[2].

2. Methods and Results

The inspection for radioactive waste drums consists of a total of seven items: weight measurement, visual inspection, surface dose rate, surface contamination, X-ray, nuclide analysis, and compressive strength measurement. In order to secure a drum processing rate higher than the set standard processing rate while performing all the inspections, overlapping parts from existing inspections must be removed and the processing time for each process must be minimized. In this chapter, we present a methodology to reduce the measurement time for the two most time-consuming processes in existing processes[3].

2.1 X-ray Inspection

X-ray inspection is used to confirm the filling rate and liquid ratio in the drum. The existing X-ray equipment owned by KORAD is operated for the purpose of confirming the filling rate of 85% or more, which is the legal standard, and the liquid ratio of 1% or less for high wholesome containers by using both 2D and 3D information during the measurement time of 30 minutes. However, there is an overlapping part because 2D and 3D are measured separately, and the drum is tilted and measured to confirm the liquid ratio.

The method proposed by KAERI is a technology that confirms all the conditions required for X-ray inspection with only measurement by the 3D CT method, and in particular, it is possible to confirm quickly by the organic and inorganic material classification algorithm without having to tilt the drum to confirm the liquid ratio. According to this method, it is possible to secure inspection results with better resolution and material classification information even if all X-ray inspections are completed in 10 minutes[4].

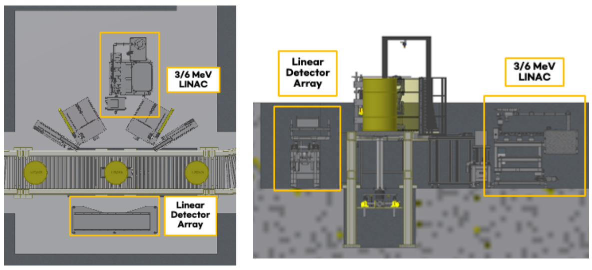

Fig. 1 Appearance of the X-ray inspection equipment proposed by KAERI (left: plan view, right: side view)

Table I: Specifications of the X-ray inspection equipment

Items	KORAD	KAERI
Energy (MeV)	3	6/3
Spatial resolution(mm)	4	0.8
Data acquisition time(min)	30	10
Material discrimination	Impossible	Possible
Raw data sharing	Impossible	Possible

2.2 Nuclide Analysis

The largest portion of the entire radioactive waste drum inspection time is the nuclide analysis. The current inspection process takes from a minimum of 1 hour to a maximum of 2 hours. The nuclide analysis equipment currently in operation at KORAD was developed based on the HPGe detector. The main inspection purpose is to measure the radioactivity of the nuclides in the drum, and the types of images acquired include the radioactivity emission image to check the radioactivity distribution, and the transmission image to check the density distribution (attenuation coefficient) of the waste in the drum. In addition, after acquiring the two pieces of information, the radioactivity is estimated through a complex analysis process. The density method for the medium in the waste drum used for radioactivity estimation applies the TGS (Tomographic Gamma Scanning) mode for low density and the SGS (Segment Gamma Scanning) mode for high density, based on 1 kg/l [5,6].

The biggest reason for the long measurement time in the current inspection process is that the density measurement is performed using a radioisotope. Even though there is already transmission data obtained from the X-ray inspection, the two types of equipment are not compatible with each other, so a low-efficiency transmission image must be separately obtained to perform density analysis on the drum. If the method proposed by KAERI can obtain density information by utilizing the transmission image information obtained from the X-ray inspection process and proceed directly to the radioactivity distribution and nuclide analysis without a separate density measurement, the measurement time in the nuclide analysis process can be drastically reduced.

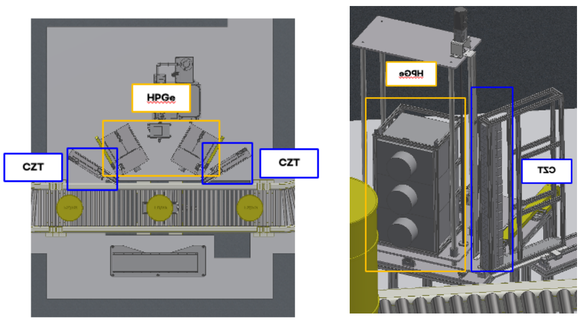

Fig. 2 Appearance of the nuclide inspection equipment proposed by KAERI (left: plan view, right: side view)

Table 2: Specifications of the nuclide inspection system

Items	KORAD	KAERI
Energy resolution(%)	0.2	0.8
Material	HPGe	CdZnTe
Pre-cooling (min)	40	Not Required
	(Superconducting cooling method)	(Room temperature)
Nuclide 3D distribution imaging	Impossible	Possible
Time for MDA <0.01 of Cs-137 (min)	> 40 min	< 5 min

The nuclide analysis equipment proposed by KAERI is designed to be equipped with a CZT-based room-temperature semiconductor detector, and the minimum detectable activity (MDA) for each radionuclide, which is one of the key performance indicators, must be able to detect radioactivity equivalent to 1/10 of the self-disposal allowable concentration for most nuclides except for difficult-to-detect nuclides, as specified in the regulations. As a result of conducting a comparative experiment through MCNP, it was confirmed that the MDA performance of the KAERI proposed equipment was about 10 times higher than that of the KORAD equipment, and as a result, it was confirmed that the time in the nuclide analysis process could be reduced to about 10 minutes, which is 1/6 of the existing maximum of 2 hours.

2.3 MCNP Simulation of MDA

Minimum detectable activity (MDA) is the minimum amount that can be used to determine the presence or absence of radioactive material. A lower MDA means that a smaller amount of material can be measured. MDA can be calculated using eq.1, where N_B is the number of background radiation counts, is the emission rate per decay, ε is the detection efficiency, and T is the measurement time (seconds). The background radiation generated inside a building is mainly gamma rays and X-rays from the U series, Th series, and K-40 emitted from concrete. In this study, the photons emitted from the concrete in the building and drum, which are 10 x 10 x 5 m and 0.2 m in size and thickness, respectively, were considered as background radiation, and the counts per second were calculated using the following eq.2. A is the radioactivity (Bq), ε is the detection efficiency, and y is the emission rate per decay. The ratio of each series, specific activity (Bq/kg), and release rate per decay were applied by referring to NNDC data. The detection efficiency is a value that can be calculated through MCNP, and the computer simulation conditions are as shown in Figure 3.

$$MDA = \frac{4.65\sqrt{N_B}+2.71}{f\varepsilon T} \text{ -- eq.1}$$

$$Count\ Rate = A \times \varepsilon \times y \text{ -- eq.2}$$

Table. 3: MCNP simulation-based MDA calculation results

Detector	Detection time	Source	Energy (MeV)	Background counts	Source detection efficiency	MDA (Bq/g)
CZT	4.5 min	Point	0.662	185.32	(Point) 1.60E-09 (Volume) 4.66E-06	**171.39**
		Volume				**0.059**
	40 min	Point		1647.29		**55.92**
		Volume				**0.019**
HPGe	4.5 min	Point	0.662	31.48	(Point) 4.00E-10 (Volume) 4.16E-07	**150.56**
		Volume				**0.29**
	40 min	Point		279.79		**47.34**
		Volume				**0.09**

The detection efficiency of the source can be calculated using MCNP in the same way as the background radiation. The detection efficiency for the Cs-137 point source located at the center of the drum and the volume source uniformly distributed in the concrete inside the drum were calculated, and the simulation conditions are as shown in Figure 4. The expected MDA of the Cs-137 source measured for 4.5 minutes and 40 minutes using eq.1 are as shown in Table 3. When the threshold (30 keV) is exceeded, the MDA of the CZT detector for the region of interest (662 keV energy region) is 171.39 Bq/g and 55.92 Bq/g for 4.5 and 40 minutes for the point source, respectively, and 0.059 Bq/g and 0.019 Bq/g for 4.5 and 40 minutes for the volume source, respectively.

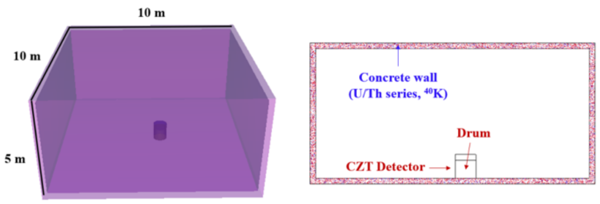

Fig. 3. Concrete wall computer simulation conditions for calculating the background radiation count .

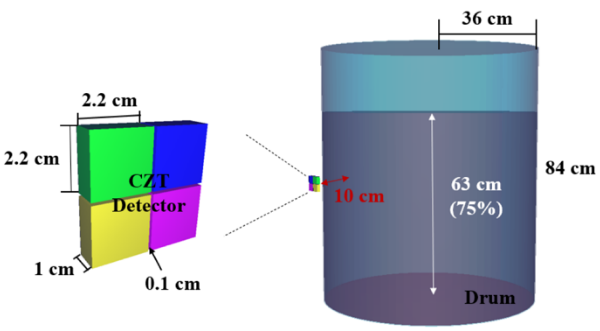

Fig. 4. Conditions for computer simulation of MDA using a CdZnTe detector.

The computer simulation results were conducted using a CdZnTe detector corresponding to one module, and unlike HPGe, CZT, which does not require a separate cooling device, can be stacked without spatial restrictions. In other words, as the number of detector modules increases, the MDA value decreases inversely, so the target MDA value can be obtained when approximately 16 modules or more are used. In addition, it can be said to be a great advantage that the three-dimensional position distribution of radioactive isotopes can be obtained.

3. Conclusions

In this study, it is proposed to two key technologies that can drastically reduce the inspection time of radioactive waste drums. One is an X-ray inspection method using a 6/3 MeV dual-energy linear high-frequency electron accelerator, and the other is a nuclide analysis method using a CdZnTe-based room-temperature semiconductor detector. The two existing inspection methods had the disadvantage of taking a long time because separate data was acquired from each device and drum inspection was conducted, but the inspection method proposed in this study is expected to greatly reduce the time because the transmission information acquired from the X-ray inspection is used for nuclide analysis. If the inspection method using the new technique proposed in this paper is applied to the field, it is expected that radioactive waste drums will be processed within the time targeted by the government.

ACKNOWLEDGEMENTS

This study was conducted with the support of the Cultural Technology Research and Development (R&D) of the Korea Creative Content Agency funded by the Ministry of Culture, Sports and Tourism (Project Number: RS-2023-00227749).

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