Establishing Conservative Limits through a Statistical Approach for Low-Level Waste (LLW) from Decommissioning

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1. Introduction

At KAERI, the decommissioning of two research reactors, the 250 kW TRIGA® Mark-II and 2 MW TRIGA® Mark-III that have been operating since 1962 and 1972, respectively, is currently taking place. However, the duration of the decommissioning project, which is being conducted for the first time in Korea, is extended due to various reasons such as lack of an international regulation and unfinished construction of a disposal site. As the national policy related to decommissioning also changes frequently, the reclassification of waste had to be conducted again as well. Multiple rounds of reclassification, however, make the waste records more diverse and complex, which may cause difficulty in confirming the radioactive concentration of the decommissioning waste. Currently, 120 tons (343 drums) of concrete radioactive waste generated during the decommissioning is being disposed. Countries that have already performed decommissioning have developed and applied a scaling factor using the correlation between nuclides for reactive waste that have the same generation history in order to find the concentration of radioactive nuclides that are difficult to detect; however, such a method is not applicable to CV stream waste. Applying a detailed analysis or conservative limiting value to such radioactive waste is recommended in IAEA TECDOC-1357. [1]

Destructive analysis using chemicals is commonly performed for the nuclides that are difficult to detect; however, performing a detailed analysis for a large amount of waste such as decommissioning waste is difficult as it requires an extensive amount of time and costs. Therefore, 23 samples were selected among the entire 120 tons (343 drums) of concrete waste for the destructive analysis, and a conservative limiting value was deduced by using a statistical method on the analysis results.

Figure 1. Decommissioning Concrete Waste Drum

2. Methods and Results

2.1 SETTING A STATISTICAL UNIT OF DECOMMISSIONING WASTE

To set the conservative limiting value of radioactive concentration using a statistical method, the decommissioning waste must initially be categorized into proper statistical unit quantities at constant volume and mass. For such a purpose, Cheong suggests three statistical units of waste, which are the evaluation, sample, and measurement units. [2]

The entire waste to be disposed of is included in the evaluation unit or the population, while the samples being made for a nuclide analysis among the entire waste are included in the sample unit. In the measurement unit, the measured samples that are extracted for actual measurements are included. Hence, this indicates that all the generated samples have been measured if the sample and the measurement units are identical.

The concrete waste generated from the decommissioning can be considered the evaluation unit, or the population, of the 343 drums (120 tons) of the decommissioning waste; 343 samples extracted from each drum can be considered the sample unit, while the 23 samples that were actually used in the measurement can be considered the measurement unit.

2.2 SETTING THE CONSERVATIVE LIMITING VALUE USING A STATISTICAL APPROACH

The distribution of the population (the entire waste) was first determined to estimate the conservative limiting value using a statistical method. The concentration of radioactive waste typically follows a normal or log-normal distribution; however, we assumed that the nuclide concentration for disposing of the ultra-low-level waste from the decommissioning follows a normal distribution. To reduce the risk of underestimating the population mean, the cumulative probability density function (CDF) 99.99%, or the maximum value of the normal distribution, was selected as the population mean instead of the two-sigma that is commonly used in statistical estimation. Subsequently, the population distribution was estimated using the deviation of the sample in order to correct the distribution of the estimated mean value. Here, the χ^2 distribution was applied to estimate the population variance, and the confidence interval of the population variance was the upper two-sigma value, which is commonly used. Finally, the conservative limiting value of the concentration of the nuclides that are difficult to extract from the ultra-low-level waste was determined by combining the estimated population variance with the induced population mean.

2.3 Estimation of the Population Mean and Maximum Cumulative Probability Density Function

The probability density function (PDF) was calculated based on the values of the 23 samples that were measured, and the CDF was calculated by integrating the PDF. When the sample distribution follows a normal distribution, the PDF and the CDF can be represented in the following equations. [3]

$$\mathrm{f(x)} = \frac{1}{\sqrt{2\pi}\sigma_x} \cdot \exp\left(-\frac{(x-\mu_x)^2}{2\sigma_x^2}\right) \qquad \text{(Eq.1)}$$

Here, f(x) is the PDF of x where x is the radioactive concentration of the sample [Bq/g], σ_x is the standard deviation of x [Bq/g], and μ_x is the arithmetic mean of x [Bq/g].

$$\mathrm{F(x)} = \frac{1}{2} \cdot \left(1 + erf\left(\frac{x-\mu_x}{\sqrt{2}\sigma_x}\right)\right) \qquad \text{(Eq. 2)}$$

Here, F(x) is the cumulative probability density function of x. Subsequently, the nuclide concentration at CDF 99.99% can be set as the population mean.

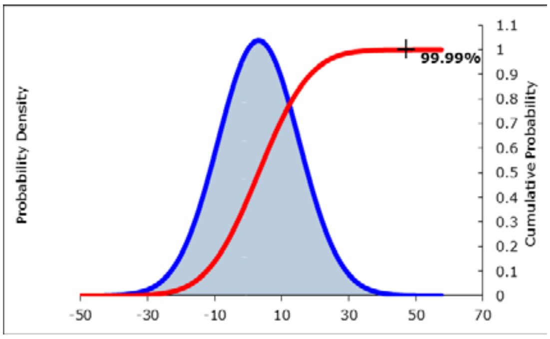

Figure 3. Estimated population mean (CDF 99.99%)

When the same estimation was performed for the nuclide Co-60 for which a total inspection was conducted, the estimated population mean was similar to the maximum value of the population.

TABLE I. Estimated population mean value

(23 samples) Estimated population mean [Bq/g]	(343 drums) Maximum value of the population [Bq/g]
1.15.E+02	1.27.E+02

2.4 Estimation of Population Standard Deviation

The standard deviation of the sample was calculated to estimate the population distribution in order to correct the distribution of the estimated mean value. The chi-squared distribution, which is commonly used for estimating the distribution, was used for the population standard deviation, and the PDF of the χ^2 distribution can be represented in the following equation. [3]

$$\mathrm{f(x,\nu)} = \begin{cases} 0, & x < 0 \\ \frac{1}{2^{\frac{\nu}{2}} \cdot \Gamma\left(\frac{\nu}{2}\right)} \cdot x^{\frac{\nu}{2}-1} \cdot e^{-\frac{x}{2}}, & x \geq 0 \end{cases} \quad \text{(Eq. 3)}$$

Here, $f(x, \nu)$ is the PDF of the chi-squared distribution of x, x is the radioactive concentration of the sample [Bq/g], ν is the number of freedom of x, and Γ is the gamma function.

Subsequently, the two-sigma (2σ) confidence interval was estimated and the upper two-sigma value was set as the estimated population variance. In general, a one-sided confidence interval is used to determine if a specific value has been exceeded while a two-sided confidence interval is used to deduce a specific value. Thus, a one-sided confidence interval was applied as this study focused on whether the conservative limiting value of the nuclide concentration exceeded the legally restricted limit. When the same estimation was performed for the nuclide Co-60, for which a total inspection was conducted, the estimated population variance was more conservative than the actual population variance.

TABLE II. Estimated population variance value

(23 samples) Estimated population variance [Bq/g]	(343 drums) Variance value of the population [Bq/g]
1.66.E+03	1.46.E+02

2.5 Setting the Conservative Limiting Value

Among the 343 drums generated from the decommissioning, the concentration of the nuclides for which a detailed analysis is difficult to conduct was determined by combining the estimated population mean with the population standard deviation calculated by estimating the population variance; when the same approach was applied for the nuclide Co-60 for which a total inspection had been conducted, the set conservative limiting value was similar yet more conservative than the maximum value of the actual population.

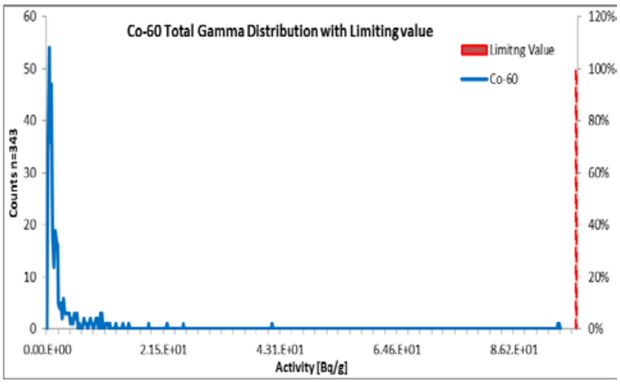

Figure 1. Comparison of the conservative limiting value and the population (Co-60)

TABLE III. Estimated conservative limiting value

(23 samples) Estimated conservative limiting value [Bq/g]	(343 drums) Maximum of the actual population [Bq/g]
1.67.E+02	1.15.E+02

3. Conclusions

In order to determine the conservative limiting value of the CV stream waste generated during the decommissioning, the population mean was estimated using the cumulative probability normal distribution to observe if the radioactive concentration follows a normal distribution, and the population standard deviation was estimated using the chi-squared distribution to correct such a distribution.

Ultimately, the sum of the estimated values was used for setting the conservative limiting value; when the same statistical estimation was performed for the nuclides Co-60 for which a total inspect had been conducted, the estimated conservative limiting value was more conservative than the maximum value of the actual population.

The risk when deducing the conservative limiting value using a statistical method is the overestimation of the radioactive concentration. Therefore, before using the conservative limiting value, a user should compare the cost of conducting a detailed analysis and that generated when the radioactive concentration of the nuclides increases by applying the conservative limiting value in order to make a strategic decision on whether to use the conservative limiting value based on the comparison.

REFERENCES

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