Development of Prototype Code for Material Balance Evaluation in Uranium Fuel Fabrication Facility

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Abstract

Material Balance Evaluation (MBE) is an essential safeguards measure in bulk handling facility dealing with nuclear material. The goal of MBE is to determine whether a diversion is occurred based on quantitative statistical factors such as Material Unaccounted For (MUF) and sigma MUF. Since a uranium fuel fabrication facility is a typical bulk handling type, MBE is essentially required.

In this study, the prototype code has been developed to evaluate material balance in uranium fuel fabrication facility. The main feature is that the code was designed to be used in actual facilities. So, the code has Graphical User Interface (GUI) for easy use by an end-user who may be inspection agency or facility operator. It can be controlled without professional programming knowledge to the end-user. MUF and sigma MUF are calculated based on real nuclear material accountancy data provided by facility operator. Especially, sigma MUF is calculated by IAEA's method based on error propagation technique, and some functions for sigma MUF calculation have been additionally considered for application in actual facilities. Nuclear material accountancy approaches can be set for each key measurement point or each stratum. In addition, such information required for MBE can be set in advance and reloaded according to facility characteristics. Even it is possible to set measurement approaches according to individual items. So, the code can respond appropriately to temporary changes in facility's nuclear material accountancy system. Detailed uncertainty analysis functions have been also introduced. A user can use it to review which measurement or which error type (random or systematic error) has higher contribution to overall sigma MUF.

Since the current version is a prototype, performance improvement will be performed continuously. It is expected that the final version of this code can be utilized to evaluate material balance to check whether a diversion is occurred and to derive approach to improve nuclear material accountancy system in Pressurized Water Reactor (PWR) and Pressurized Heavy Water Reactor (PHWR) fuel fabrication facilities of South Korea.

1. Introduction

Material Balance Evaluation (MBE) represents a crucial measure for the International Atomic Energy Agency (IAEA) to implement safeguards effectively. Material balance is calculated based on nuclear material measurements, and it serves as a criterion for detecting whether or not nuclear materials have been diverted using quantitative statistical techniques. As part of international inspections, the IAEA periodically conducts MBE and examines bulk handling facilities for abnormalities.

South Korea possesses a bulk handling facility with a throughput of 950 MTU/yr, producing fuel assemblies for Pressurized Water Reactor (PWR, 550 MTU/yr) and Pressurized Heavy Water Reactor (PHWR, 400 MTU/yr), supplying all the necessary nuclear fuel assemblies for Korea and the United Arab Emirates. The IAEA conducts MBE for the uranium fuel fabrication facility in Korea every year. Although the Korea Institute of Nuclear Nonproliferation and Control (KINAC), a domestic inspection agency, is responsible for implementing safeguards and supporting the IAEA, a comprehensive MBE by a domestic inspection agency has not yet been conducted.

It is necessary to conduct MBE for the domestic bulk handling facility by domestic inspection agency in order to enhance international reliability and secure and apply safeguards technology. Therefore, the development of a code capable of conducting MBE for the domestic facility is being carried out, and a prototype code was developed in this study.

2. Material Balance Evaluation Fundament

As previously mentioned, the main objective of MBE is to verify whether nuclear material has been diverted, using quantitative statistical method. To perform a quantitative assessment of nuclear material loss, it is necessary to calculate the Material Unaccounted For (MUF) within the Material Balance Area (MBA) for a designated time period called the Material Balance Period (MBP). MUF can be simply calculated using the equation (1), and each value is obtained through nuclear material measurement. Since the MBE is generally conducted once a year in bulk handling facility, m_{input} and m_{output} represent the nuclear material quantities entering and leaving the MBA, respectively, during the one-year period. The term m_{BI} indicates nuclear material amount of inventories present in MBA at PIV time in the previous year, and m_{EI} indicates nuclear material amount of inventories at PIV time in the current year.

$$MUF = m_{input} - m_{output} + (m_{BI} - m_{EI}) \tag{1}$$

where m_{input} = Total nuclear material amount measured in input flow for MBP
m_{output} = Total nuclear material amount measured in output flow for MBP
m_{BI} = Total nuclear material amount measured in beginning inventory
m_{EI} = Total nuclear material amount measured in ending inventory

In theory, assuming that there is no unmeasured nuclear material, a zero value of MUF indicates that no nuclear material diversion occurred in MBA. However, due to the presence of measurement errors, MUF is very likely to have a non-zero value even if there is no diversion. So, statistical hypothesis test is required to find diversion case from non-zero MUF value.

A relatively simple hypothesis test is applied in the case of single MBE once a year, and if MUF value exceeds a specific threshold, it is judged that nuclear material diversion is occurred. Degree of MUF uncertainty, called sigma MUF, must be identified to determine this specific threshold, which is a key factor in MBE. As mentioned above, since MUF value contains various errors, it does not represent zero and shows a positive or negative value including errors. Moreover, it is impossible to accurately know the errors occurred during the measurement process. Instead, the MUF distribution can be estimated, and sigma MUF means the standard deviation of this distribution, as illustrated in Figure 1.

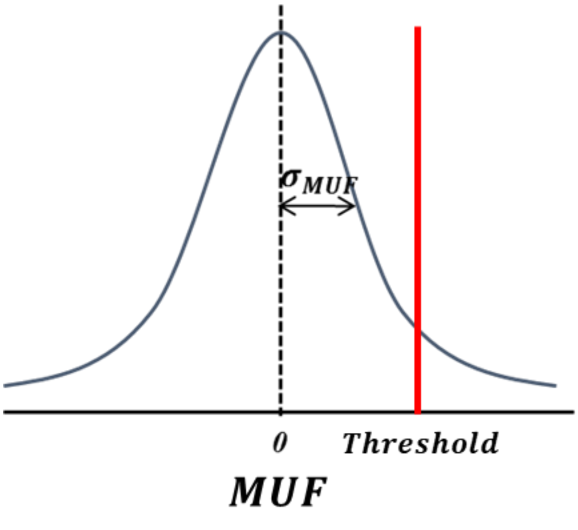


Figure 1. Concept of MUF-based Hypothesis Test

Various factors can influence the scale of sigma MUF, such as the measured nuclear material amounts and measurement uncertainty. As the nuclear material amount measured during the MBP increases, the sigma MUF also increases, and as the measurement uncertainties increase, the sigma MUF tends to increase as well.

To estimate sigma MUF, which is the standard deviation of MUF, the error propagation method [1] is commonly used. The error propagation method depends on the type of measurement uncertainty, which is determined based on whether covariance has occurred between each measurement. The uncertainty types include random, short-term systematic, and long-term systematic, and the code developed in this study currently considers only random and long-term systematic errors.

$$\sigma_{MUF} = \sqrt{\sum_{i=1}^{I} \sigma_{i,r}^2 + \sigma_{i,s}^2} \tag{2}$$

$$\sigma_{i,r}^2 = \sum_{j=1}^{J} \frac{m_j^2 \cdot \delta_{i,r}^2}{n_j} \tag{3}$$

$$\sigma_{i,s}^2 = \left(\sum_{j=1}^{J} \pm m_j \right)^2 \cdot \delta_{i,s}^2 \tag{4}$$

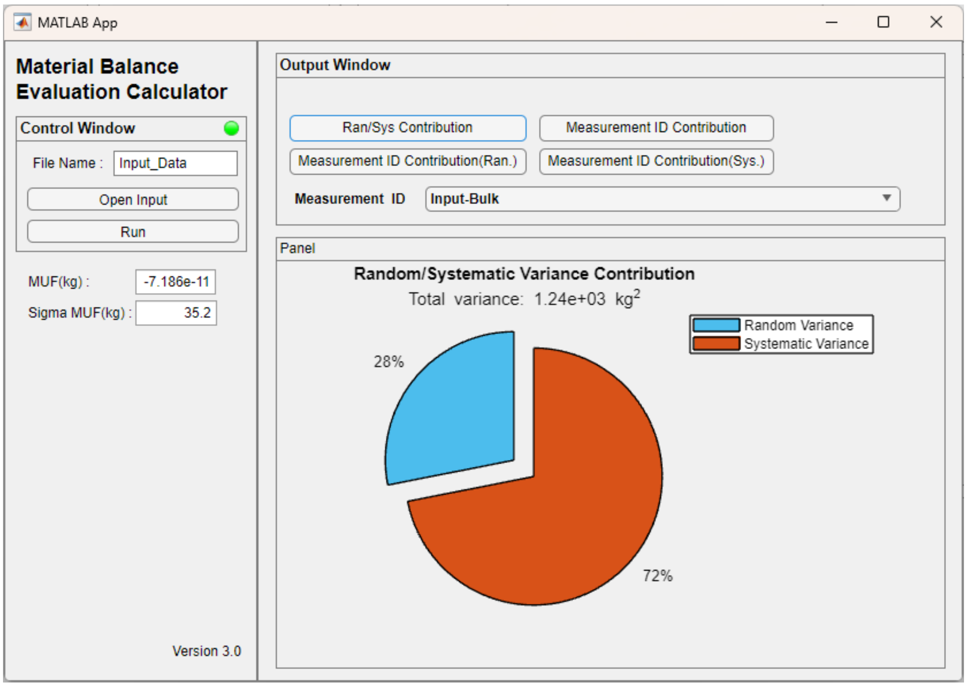
where σ_{MUF} = sigma MUF, standard deviation of MUF
$\sigma_{i,r}$ = total uncertainty occurred by random error in measurement (i)
$\sigma_{i,s}$ = total uncertainty occurred by systematic error in measurement (i)
$\delta_{i,r}$ = relative standard deviation of random uncertainty in measurement (i)
$\delta_{i,s}$ = relative standard deviation of systematic uncertainty in measurement (i)
n_j = number of measurement (i) for item or batch (j)
m_j = nuclear material mass in item or batch (j) measured by measurement (i)

Equations (2) to (4) describe the error propagation method. Equation (3) shows that when there is random uncertainty, error propagation is performed in units of measurement since there is no covariance between individual measurements. In the case of random error, the uncertainty decreases as the number of measurements increases.

In contrast, for long-term systematic uncertainty, all nuclear material quantities related to the measurement are first added up, and then multiplied by the measurement uncertainty. This is because covariance (bias) occurs in all measurements. If the measured nuclear material is the input or beginning inventory, it has a plus sign, and if it is the output or ending inventory, it has a minus sign. Moreover, systematic uncertainty does not decrease as the number of measurements increases.

3. Development of MBE Code

In this study, a prototype code for MBE was developed, which includes the main function of calculating MUF and sigma MUF based on the actual inventory list in a domestic uranium fuel fabrication facility. To facilitate ease of use for end-users such as inspection agencies or facility operators, a Graphical User Interface (GUI) was introduced, as depicted in Figure 2. The GUI provides various analysis tools accessible through the main screen.



File Name : Input_Data

MUF(kg) : -7.186e-11

Sigma MUF(kg) : 35.2

Measurement ID Input-Bulk

Total variance: 1.24e+03 kg^2

Figure 2. Main Screen of Material Balance Evaluation Calculator Code

The MBE code requires input data in the form of an Excel file that includes three sheets: “Inventory_List”, “Facility_Configuration_MA”, and “Facility_Configuration_StratumID”. The contents and structure of these sheets are shown in Figure 3. The first sheet, "Inventory_List", contains the item list of inputs, outputs, beginning inventories, and ending inventories. MUF and sigma MUF are calculated based on the stratum ID and nuclear material mass recorded in this sheet. The second sheet, "Facility_Configuration_StratumID, shows the measurement method applied to each stratum ID, which allows for identification of the nuclear material accountancy method used for each item and whether each item is input, output, beginning, or ending inventory. The last sheet, ""Facility_Configuration_MA", contains information related to the random and systematic uncertainties considered for each nuclear material accountancy method, which represent the relative standard deviation of error. In addition, in this code, even one measurement method can be further subdivided and set according to various factors, enabling more detailed uncertainty contribution analysis as shown in Figure 3. By considering all measurement methods for each item from the input Excel file having three sheets, the MBE code can evaluate MUF and sigma MUF. To make it easy to use for end-users, the code features GUI as shown in Figure 2, providing various analysis tools through the main screen.

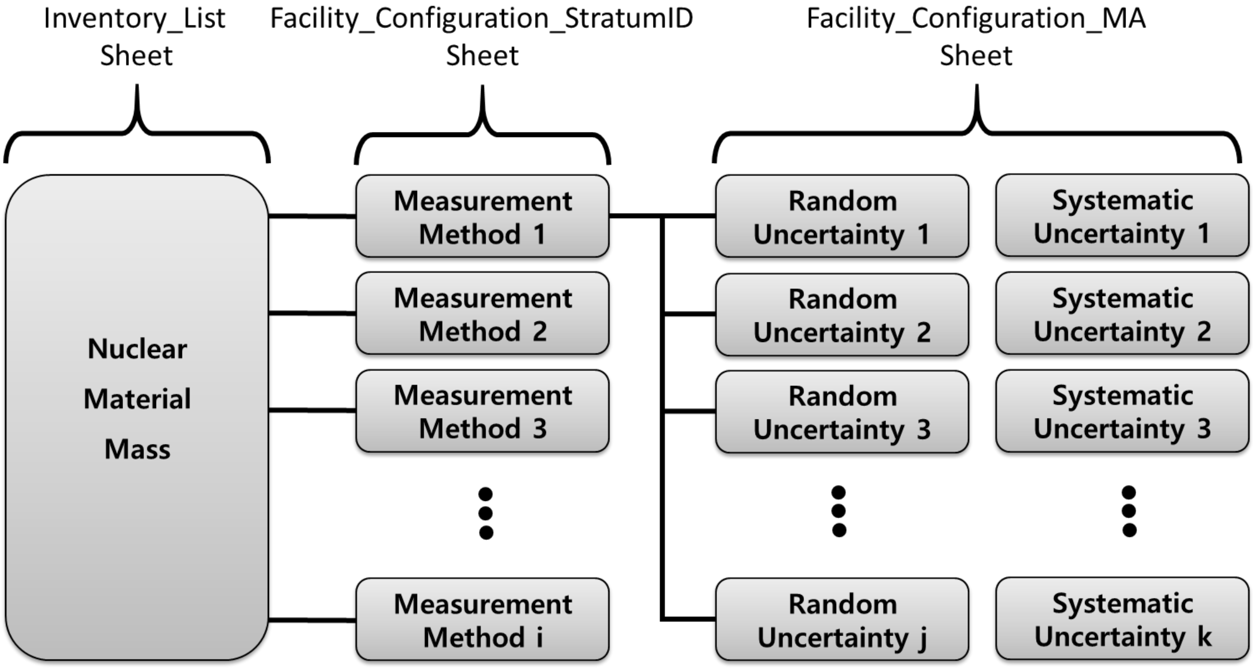
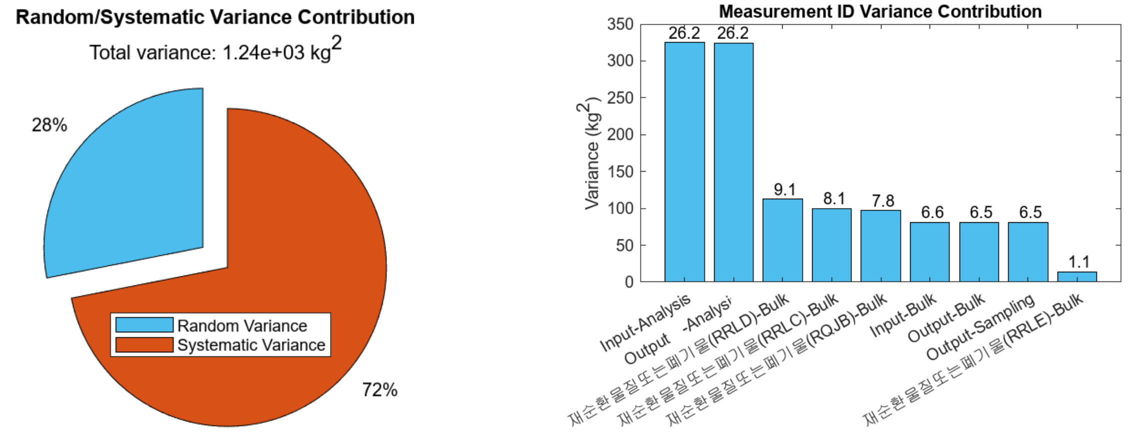


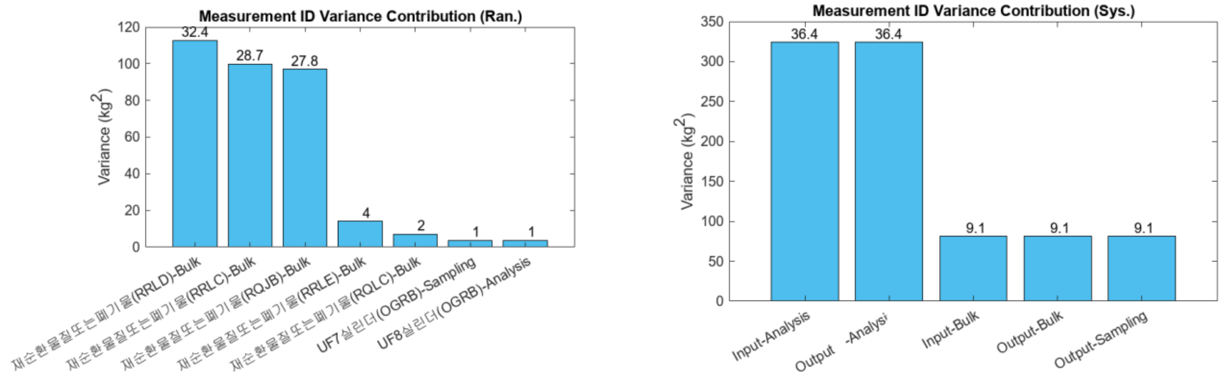
Figure 3. Input Structure of the Code for Calculating MUF and Sigma MUF

As previously mentioned, the MBE code offers several analysis functions related to sigma MUF, as demonstrated in Figure 4 and 5. These functions mainly focus on identifying the factors that contribute to the overall generation of sigma MUF. Figure 4 (a) illustrates the uncertainty contribution caused by random and systematic errors to the total uncertainty, which is the variance of MUF. Figures 4 (b) to (d) show the uncertainty contribution caused by each nuclear material accountancy approach to the total variance, total variance by random errors, and total variance by systematic errors. By utilizing these analysis functions, users can scrutinize the factors that have a significant impact on the overall uncertainty in detail.



(a) Random/Systematic Variance Contribution

(b) Measurement Method Variance Contribution



(c) Measurement Method Variance Contribution (Ran.)

(d) Measurement Method Variance Contribution (Sys.)

Figure 4. Variance Contribution Analysis Functions of MBE Calculator Code

This code also includes an analysis function to check the main factors according to the measurement method used. Figure 5 illustrates that for each selected measurement method, the measured nuclear material amount for each input/output, beginning, and ending inventory can be identified. In addition, the contributions of each uncertainty factor considered within the measurement method are provided. This feature allows a user to determine the major sources of uncertainty for a particular measurement method and to take appropriate measures to reduce the overall uncertainty.

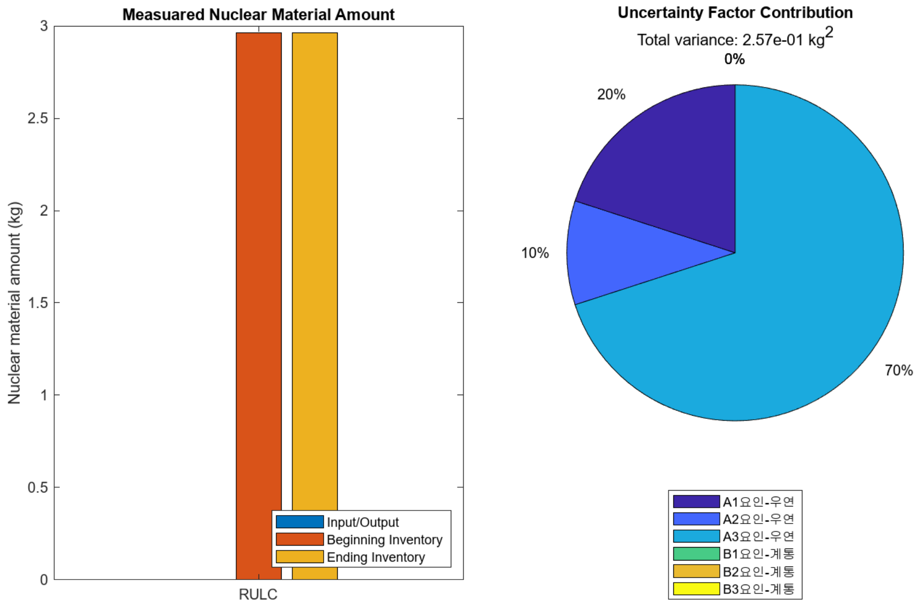
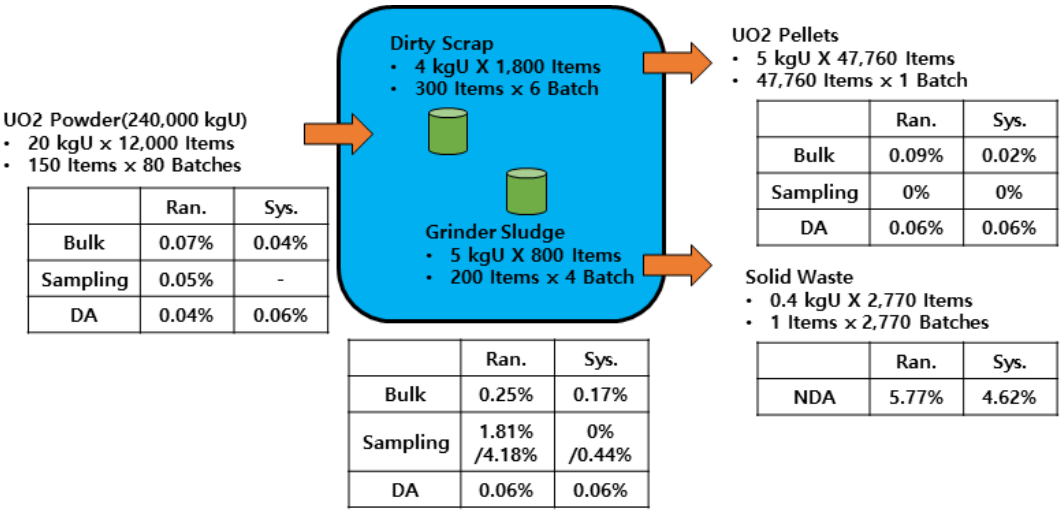


Figure 5. Detailed Analysis Function according to Measurement Method

4. Inter-comparative study

An inter-comparative study was conducted to verify the accuracy of the code developed in this study in calculating MUF and sigma MUF.

The example model used for the study is a virtual uranium fuel fabrication facility, which was provided in the IAEA technical report on statistical techniques [1]. The Figure 6 displays the information required for MBE in the example model, including the nuclear material amount per item, the number of items and batches, and relative random/systematic uncertainties at each stratum.



	Ran.	Sys.
Bulk	0.07%	0.04%
Sampling	0.05%	-
DA	0.04%	0.06%

	Ran.	Sys.
Bulk	0.25%	0.17%
Sampling	1.81% /4.18%	0% /0.44%
DA	0.06%	0.06%

	Ran.	Sys.
Bulk	0.09%	0.02%
Sampling	0%	0%
DA	0.06%	0.06%

	Ran.	Sys.
NDA	5.77%	4.62%

Figure 6. IAEA’s Example Model

This model produces UO_2 pellets from UO_2 powder, with 240,000 kg U as the total amount of uranium at the input point. The powder is divided into 80 batches based on enrichment, with 150 items per batch, resulting in 20 kg of uranium per item. At the output point, 238,800 kg U of UO2 pellets leave the MBA after final processing, with only one batch and 47,760 pellets (items), amounting to 5 kg U per pellet. Solid waste is the other output point, with 1,200 kg U of total uranium, 2,770 batches, and 1 item per batch, which translates to 0.43 kg U per item. The dirty scrap inventory at the beginning and ending times has the same amount of nuclear material, with 7,200 kg U, 6 batches, and 300 items per batch, resulting in 4 kg U per item. The grinder sludge has 4,000 kg U of total uranium, 4 batches, and 200 items per batch, amounting to 5 kg U per item. This inventory point also has the same amount of nuclear material at the beginning and ending times.

For MBE of this facility, the chemical analysis method, including bulk measurement, sampling, and Destructive Analysis (DA, analytical method), is used at each major measurement point except for solid waste. Therefore, random uncertainty and long-term systematic uncertainty of the three measurement methods need to be considered when evaluating facility uncertainty using error propagation. Non-Destructive Analysis (NDA) is used for nuclear material measurement in the solid waste, and in this case, the measurement uncertainty due to bulk and sampling is not considered because the amount of nuclear material can be measured only with the analytical method.

MBE (MUF and sigma MUF) was performed with the code developed in this study based on the example model. In the IAEA report, the mass balance evaluation results showed that the MUF was zero kg U, and the sigma MUF was 212 kg U. The MUF calculated through the code developed in this study is -1.3×10^{-11} kg U, and the MUF uncertainty is 212.2 kg U, which are almost consistent with the results derived from the IAEA report.

5. Conclusions

A code has been developed in this study, which is capable of calculating MUF and sigma MUF based on the actual inventory list. The code uses nuclear materials present in inputs, outputs, and inventories to calculate the MUF value, and applies the error propagation technique mentioned in the IAEA technical report to calculate sigma MUF. It also offers various analysis functions to enable users to perform detailed analyses on sigma MUF. MBE was carried out for the virtual example facility model provided by the IAEA report using the code, and the result obtained was consistent with the result derived by IAEA.

However, the current version of the code is a prototype and not yet ready for a complete performance of MBE based on the actual inventory list in Korea. The code also requires updates to enable it to determine whether nuclear material is diverted or not using statistical hypothesis test. Therefore, it will be continuously updated to allow for a comprehensive material balance evaluation of domestic bulk handling facilities.

The final code developed in this study will be utilized for domestic material balance evaluation, thereby supporting IAEA inspection and domestic inspection activities. The application of this code is expected to enhance international reliability and safeguard technology.

Acknowledgements

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Reference

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