Investigation of Revised Sampling Method for on-site National Safeguards Inspection

Haneol Lee*, Yewon Kim, Hyun Ju Kim, Jung Yoon Choi, Ju Young Jeon
KINAC, Yuseong-daero 1534, Yuseong-gu, Daejeon, Republic of Korea
**Corresponding author: haneol@kinac.re.kr*

1. Introduction

The Nuclear Safety and Security Council (NSSC) of the ROK made an amendment on to the "notification on the range of national safeguards inspection (NSSC No. 2017-83)", as a result of applying the state level approach (SLA) as the IAEA safeguards [1]. In the notification, sub-paragraph 4 of Article 2 requires an on-site inspection (verification of the location, quantity and composition of each item). However, conventional national inspection adopts the results of the IAEA on-site inspection. Therefore, an independent on-site inspection must be included in the national safeguards inspection process to satisfy the requirement of relevant notification.

The goal of this research is to investigate the sampling method of the on-site inspection for national safeguards inspection. We reviewed IAEA's sampling planning method and identified its limitations, which are mainly derived from the assumptions used to simplify the calculation process. Based on our investigation, we propose a revised sampling method that improves the identified limitations of the previous method for on-site safeguards inspection.

2. IAEA's Sampling Planning Method

The IAEA's sampling planning process consists of the following processes [2]:

1) Stratification of inventory items
2) Identification of defect types (verification methods) for each stratum
3) Calculation of the initial sample size for each verification method and stratum
4) Calculation of the optimized sample size for each verification method and stratum

2.1 Stratification

Stratification is a classification process of inventory items in a facility based on their physical and chemical properties. Each item with the same (or similar) physical and chemical properties is classified into a "stratum". For example, items with physical property "pellet" and chemical property "pure UO_2" are classified into the "pure UO_2 pellet" stratum.

Once items in a facility have been stratified, for sampling planning, the IAEA assumes all items in the same stratum are homogeneous.

2.2 Defect categorization

The fraction of diversion in an item is defined as a "defect". The IAEA classifies the defect types based on the possible diversion scenarios as follows.

- Gross defect (method H): divert small items with large defect sizes
- Partial defect (method F): divert more items with smaller defect sizes
- Bias defect (method D): divert much more items with bias level defect sizes

The IAEA determines the possible defect type(s) and selects verification methods for each defect type of the stratum based on the stratum characteristics. For example, the UF_6 stratum is verified for two defect types (gross and partial) and the UO_2 powder stratum is verified for three defect types (gross, partial and bias).

2.3 Initial sample size determination

The IAEA defines the "non-detection probability (β)" as the probability of non-detecting diversion in a stratum once one significant quantity of material is diverted. The non-detection probability becomes higher once the credibility of a member state becomes higher and the facility type becomes less sensitive. The IAEA calculates the number of samples for each stratum and defect type(s) based on the non-detection probability.

The IAEA calculates the initial sample size of a stratum for each defect type using binomial adjusted hyper-geometric distribution (Equations (1) and (2)) [3]. The binomial adjustment has been performed by on-site inspectors to calculate the sample size using hand-held calculators since its development in the early 1990s, with the following equations.

$$\mathrm{n_H} = roundup\left(N\left(1-\beta^{(1/D)}\right)\right) \quad (1)$$

$$\mathrm{n}_{F,D} = \frac{\ln(\beta)}{\ln\left(1-\left(\frac{M}{\gamma'_{F,D}Nx}\right)\right)} \quad (2)$$

where,

$\mathrm{n_{H/F/D}}$	Initial sample sizes for defect types (gross: H, partial: F, bias: D),
N	Number of inventory items in a stratum,
β	Non-detection probability for the facility,
D	Number of items required to divert 1 SQ,
M	Mass of 1 SQ,
$\gamma'_{F,D}$	Quantitative defect sizes for partial (F) and bias (D) defects based on the regression of previous IAEA inspection data,
x	Mass of nuclear material in an item.

The IAEA's method assumes all defected items are also homogeneous since hypergeometric distribution is used to calculate the initial sample size for all defect types.

2.4 Optimized sample size determination

The initial sample size is calculated based on an assumption that the verification of each defect type is independent of each other. However, the diversion of a stratum is non-detected once all verification processes for the stratum were non-detected at the same time. Therefore, the non-detection probability of stratum (Q) can be calculated using Equations (3) and (4), as folows [3].

$$Q = \beta_H \beta_F \beta_D \quad (3)$$

$$\beta_{H/F/D} = \begin{cases} \left[1 - \dfrac{m_{H/F/D}\, q_{H/F/D}}{N_{H/F/D} - 0.5\left(n_{H/F/D} - 1\right)}\right]^{n_{H/F/D}} & (n \leq mq) \\ \left[1 - \dfrac{n_{H/F/D}}{N_{H/F/D} - 0.5\left(m_{H/F/D}\, q_{H/F/D} - 1\right)}\right]^{m_{H/F/D}\, q_{H/F/D}} & (n > mq) \end{cases} \quad (4)$$

where,

Q Non-detection probability of a stratum,

$\beta_{H/F/D}$ Non-detection probability for defect types,

$m_{H/F/D}$ Number of remaining defected items for defect types (m: initial number of defect items),

$$\begin{cases} m_H = m \\ m_F = m_H - w_1 \\ m_D = m_F - w_2 \end{cases}$$

$w_{1/2}$ Number of defected items in gross (w_1) and partial (w_2) defect verification samples

$q_{H/F/D}$ Fraction of non-detection for defect types using verification detectors,

$$q_{H/F/D} = 1 - \phi\left(\nu_{H/F/D}\right)$$

$$\nu_{H/F/D} = \frac{3\delta_{H/F/D}\, x - \left(\frac{M}{m_{H/F/D}}\right)}{\delta_{H/F/D}\left(x - \frac{M}{m_{H/F/D}}\right)}$$

$N_{H/F/D}$ Number of inventory items in a stratum for defect types,

$n_{H/F/D}$ Number of samples drawn for verifying defect types.

The number of defected items (m) changes as the size of the defect changes ($M/x \leq m \leq m_{00}$). The minimum defect items occur if all defected items were gross defects. The IAEA defines the maximum defect items (m_{00}) as "the number of defect items in a stratum whose defect size is 16 % of detection probability using the most precise verification detectors". For example, once the stratum is verified for gross, partial and bias defects, the possible defect size becomes the fraction of an item, which satisfies 16 % of the detection, using a bias defect detector [3].

The IAEA calculates "Q" in Equation (3) for all possible defected items and identifies the "maximum Q (Qmax)" for a stratum. They then adjust sample sizes for defect types by comparing the "Qmax" and "β", as described below [3].

Case 1. ($m_{00} \leq N$)

1-a) Qmax occurs at $m = M/x$ or $m = m_{00}$
1-b) Qmax occurs at $M/x < m < m_{00}$, $Qmax \leq \beta$
1-c) Qmax occurs at $M/x < m < m_{00}$, $Qmax > \beta$

For Cases 1-a) and 1-b), the IAEA adopts the optimized sample sizes for defect types as the initial sample sizes. For Case 1-c), the IAEA optimizes the sample size as described in case 2-a)

Case 2. ($m_{00} > N$)

2-a) $Qmax > \beta$
2-b) $Qmax \leq \beta$

For Case 2-a), the IAEA decreases the Qmax by increasing the most sensitive defect type (bias for 3 defect types and partial for 2 defect types) and reducing the sample size for the less sensitive defect type (partial for 3 defect types and gross for 2 defect types). They then re-calculate the Qmax for the revised sample sizes until the Qmax becomes smaller than β. For Case 2-b) the IAEA increases the Qmax by decreasing the most sensitive defect type and increasing the sample size for the less sensitive defect type until right before the Qmax becomes larger than β.

For a stratum with two defect types, sample size optimization is finished by following the process of Case 1 and 2. However, for a stratum with three defect types, the two cases do not optimize the sample size for gross defect verification; therefore, the IAEA performs an additional iteration process. The process calculates an indicator "c" using Equation (5) and iterate it using Equations (6) and (7) until the "c" becomes zero [3]. The overall IAEA sample size optimization process is depicted in Figure 1.

$$c = \text{roundup}\left(n_F \frac{\ln(Q_{max}) - \ln(\beta)}{\ln(\beta_F)}\right) \quad (5)$$
$$n'_H = n_H + c \quad (6)$$
$$n'_H = n_H - c \quad (7)$$

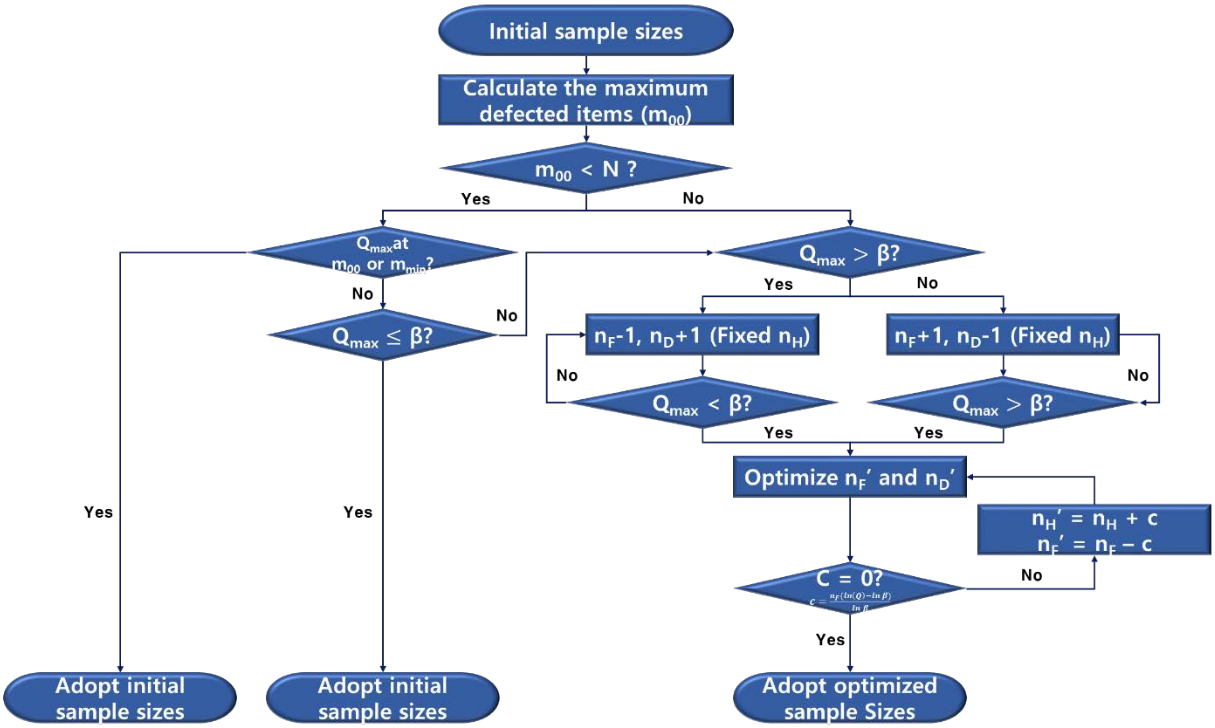

Fig. 1. Overall process of the IAEA sample size optimization.

2.5 Limitations of IAEA's method

However, the IAEA's sampling planning method has the following limitations:

1) Items in the same stratum are not homogeneous
2) Sample size is overestimated due to the binomial adjustment
3) Sample size is a specific solution of a specific diversion scenario (same defect size for all items)

Therefore, we have investigated a revised sampling method for on-site inspection which minimizes the effect of these limitations.

3. Sampling method for national inspection

The revised sampling method for national inspection calculates the exact solution of the hypergeometric distribution rather than adjusting it to the binomial distribution. For this study, we developed a MATLAB based sampling planning program, which includes stratification, defect categorization and initial sample size calculation, as depicted in Figure 2.

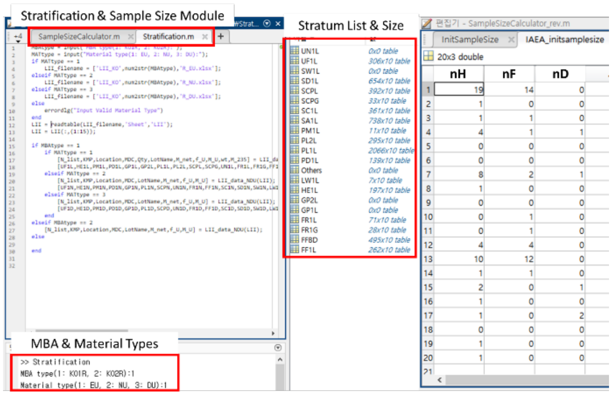

Fig. 2. Configuration of sample size calculator

We examined the effect of binomial adjustment on the sample size by comparing the results of the conventional and revised methods. The list of inventory item (LII) used for the comparison was previous inspection data of a fuel fabrication plant. Table I describes the LII for a stratum (UO_2 powder, PD1L).

Table I. List of inventory item of PD1L stratum.

Item ID	KMP for item	MDC for item	Quantity	Lot for item	Mass of item (kg)	U mass of item (kg)	U conc. of item	M(^{235}U) of item (kg)	wt% (^{235}U) of item
1 n	2 KMP	3 MDC	4 Qty	5 LotName	6 M_net	7 M_U	8 U_conc	9 M_235	10 wt
1	"C"	GQRC	1	"H0-16N-20"	327.1000	287.2070	0.8780	6.3588	0.0221
2	"C"	GQRC	1	"H0-16N-20"	326	286.2410	0.8780	6.3374	0.0221
3	"C"	GQRC	1	"H0-16N-20"	232	203.7050	0.8780	4.5100	0.0221
4	"C"	GQRC	1	"H0-16N-20"	324.5000	284.9240	0.8780	6.3082	0.0221
5	"C"	GQRC	1	"H0-16N-20"	327.6000	287.6460	0.8780	6.3685	0.0221
6	"C"	GQRC	1	"H0-16N-20"	323.2000	283.8370	0.8782	6.3324	0.0223
7	"C"	GQRC	1	"H0-16N-20"	319	280.1490	0.8782	6.2501	0.0223
8	"C"	GQRC	1	""	90.7000	79.7250	0.8790	1.8656	0.0234
9	"C"	GQLC	1	""	64	56.2560	0.8790	0.7201	0.0128
10	"C"	GQRC	1	"P0-16-05"	473.9000	416.5580	0.8790	19.3699	0.0465
11	"C"	GQRC	1	"P0-16-05"	445.9000	391.9460	0.8790	12.3071	0.0314
12	"C"	GQRC	1	"H0-16-01"	456	400.5640	0.8784	12.6017	0.0315
13	"C"	GQRC	1	"H0-16N-20"	328.5000	288.4920	0.8782	6.3786	0.0221
14	"C"	GQRC	1	"H0-16-01"	454.4000	399.1990	0.8785	12.5708	0.0315
15	"C"	GQRC	1	"H0-16-01"	448.7000	394.2410	0.8786	12.4146	0.0315
16	"C"	GQRC	1	"P0-16-05"	447.3000	393.1770	0.8790	12.3458	0.0314
17	"C"	GQRC	1	"H0-16-01"	463.2000	406.9300	0.8785	12.8142	0.0315
18	"C"	GQRC	1	"H0-16N-20"	439.5500	386.1180	0.8784	15.8656	0.0411
19	"C"	GQRC	1	"UL-12-00"	212.8000	187.0510	0.8790	8.6979	0.0465
20	"C"	GQRC	1	"P0-11-05"	417	366.5430	0.8790	10.7031	0.0292
21	"C"	GQRC	1	"H0-16N-20"	325.8000	286.1210	0.8782	6.3261	0.0221
22	"C"	GQRC	1	"P0-16N-04"	454.4000	399.4180	0.8790	16.3761	0.0410
23	"C"	GQRC	1	"P0-16-05"	438.5000	385.4420	0.8790	12.1029	0.0314
24	"C"	GQRC	1	"P0-16-05"	462.6000	406.6250	0.8790	12.7680	0.0314
25	"C"	GQRC	1	"P0-16-05"	449.6000	395.1980	0.8790	18.3767	0.0465
26	"C"	GQRC	1	"P0-16-05"	435.3000	382.6290	0.8790	17.7922	0.0465
27	"C"	GQRC	1	"H0-16-00"	461.7000	405.6730	0.8787	18.8719	0.0465
28	"C"	GQRC	1	"P0-16N-04"	461.2000	405.3950	0.8790	16.6212	0.0410
29	"C"	GQRC	1	"H0-16N-20"	437	383.8780	0.8784	15.7735	0.0411
30	"C"	GQRC	1	"H0-16-01"	453.3000	398.2830	0.8786	12.5419	0.0315

The results of comparing the sample sizes for each stratum using the IAEA's method and the revised method are described in Table II. This indicates the binomial adjustment overestimates for both the total sample size and sample sizes for precise verification methods (sample sizes for method F and D). Therefore, the revised sampling method can minimize inspection resources for national inspection.

Table II. Initial sample size comparison between the IAEA and revised sampling method

Stratum	IAEA's method			Revised method		
	n_H	n_F	n_D	n_H	n_F	n_D
UF1L	19	14	0	21	12	0
HE1L	1	0	0	1	0	0
PM1L	1	1	0	1	1	0
PD1L	4	1	1	3	1	1
GP1L	0	0	0	0	0	0
GP2L	0	0	0	0	0	0
PL1L	8	2	1	9	1	1
PL2L	1	0	0	0	0	1
UN1L	0	0	0	0	0	0
FR1L	0	1	0	0	1	0
FR1G	0	1	0	0	1	0
FF1L	4	4	0	4	4	0
FFBD	10	12	0	10	12	0
SC1L	1	1	0	1	0	1
SCPL	2	0	1	2	0	1
SCPG	1	0	0	1	0	0
SD1L	1	0	2	2	0	1
SW1L	0	0	0	0	0	0
LW1L	1	0	0	1	0	0
SA1L	1	0	0	1	0	0

Future works will include sample size optimization of the sampling planning program. The sample size will be optimized using the Monte Carlo method with representative (possible) diversion scenarios.

3. Conclusions

As the importance of national safeguards inspection grows, an independent sampling planning for national inspection is required. This research reviewed the sampling planning method of the IAEA. The IAEA's method overestimates sample size due to the binomial adjustment of hypergeometric distribution to minimize computational burden.

This research developed a revised sampling planning method for national safeguards inspection which eliminates the binomial adjustment in the initial sample size calculation of the IAEA's method. We also developed a computational model based on the revised method. The revised sampling method resulted in smaller sample sizes compared to the conventional method, which can reduce the consumption of inspection resources.

Future works will include overcoming the limitations of the IAEA's sampling planning for the sample size optimization process.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety(KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission(NSSC) of the Republic of Korea. (No. 2106015)

REFERENCES

[1] Subparagraph 2 of Article 4 of Regulations on the Safeguards Inspection of Special Nuclear Materials of the ROK, NSSC notification No. 2017-83, 2017.

[2] IAEA, Reference Manual: Statistical Concepts and Techniques for IAEA Safeguards, IAEA-SG-SCT-5, 1998.

[3] J. L. Jaech, Algorithms to calculate sample sizes for inspection sampling plans, IAEA-STR-261(Rev.0), 1990.