KOREA INSTITUTE OF NUCLEAR
NONPROLIFERATION AND CONTROL

Feasibility Demonstration of SAMEVAL and MUFEVAL for National Safeguards Inspections

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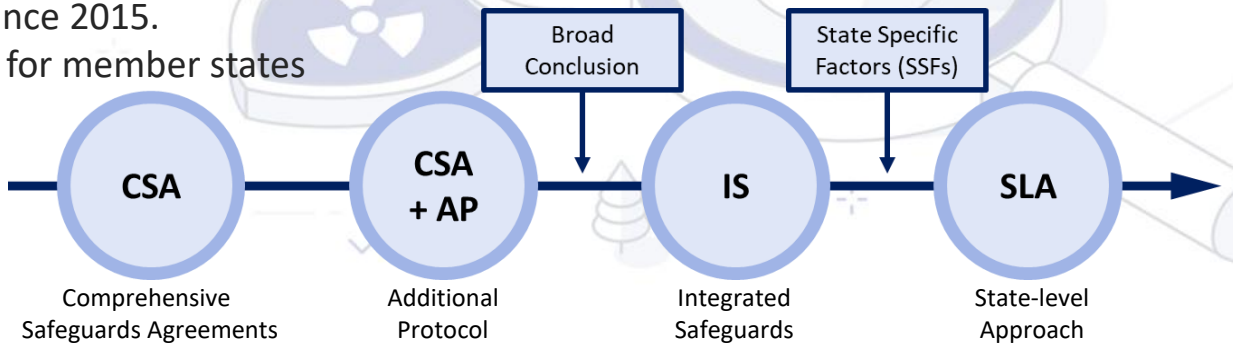
I Background

- **Safeguards Inspection: Obligation of Non-nuclear Weapon States (NNWS) under NPT**
  - **Obligation of Safeguards**
    - (NPT, Article 3) Each Non-nuclear-weapon State Party to the Treaty undertakes to accept safeguards, in accordance with the statute of the IAEA and the Agency's safeguards system. …
    - (CSA, Article 3) … the Agency and the State shall co-operate to facilitate the implementation of the safeguards …
  - **State System of Accounting for and Control (SSAC) of nuclear material**
    - (CSA, Article 7) … the State shall establish and maintain a system of accounting for and control of all nuclear material subject to safeguards under the Agreement, …
  - **IAEA Safeguards Inspections**
    - (CSA, Article 70) The Agreement should stipulate that the Agency shall have the right to make inspections as provided for in paragraphs 72 - 82
- **IAEA Safeguards Implementation for the ROK**
  - **State Level Approach (SLA)**
    - The ROK adopted SLA as the IAEA safeguards since 2015.
    - The IAEA considers state-specific factors (SSFs) for member states under SLA to plan inspections.
    - SSF(c) is defined as the technical capability of the SSAC, for example whether the SSAC conducts independent national inspections (SG Glossary 2022)



I Background

Amendments in Domestic Notification

- **Scope of National Safeguards Inspection (NSSC No. 2025-2, Article 4)**
  - National safeguards inspection includes the following “information analysis” activities
    (2) Verification of declared information
    (8) Verification of material unaccounted for (MUF) and shipper-receiver difference (SRD)
    (9) Examination of accounting process

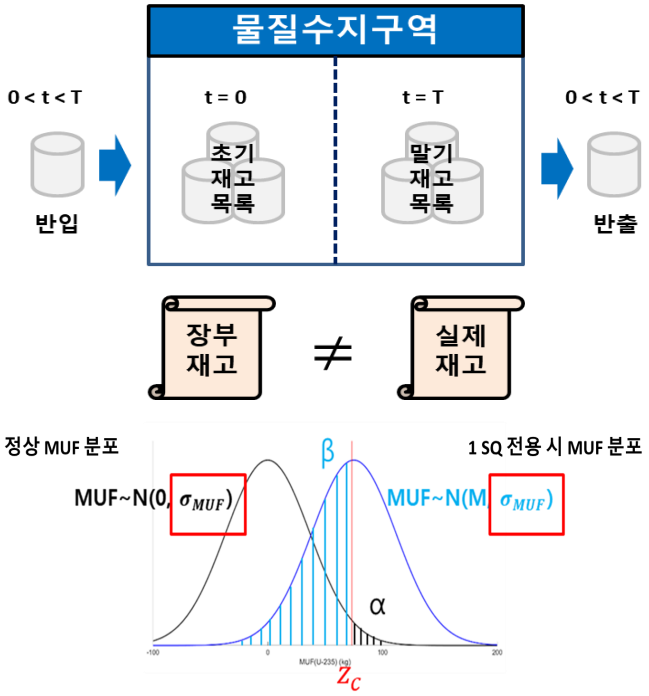
Purpose of the Research (R&D project, 2021 - 2026)

- **Develop Information Analysis Methods & Software for National Safeguards Inspection**
  - To reinforce the technical capability of the ROK SSAC
  - To establish quantitative basis of the IAEA – KINAC discussion for the IAEA safeguards conclusion
- **Identify Requirements & Establish Regulation Documents to Apply the Software for National Safeguards Inspection**

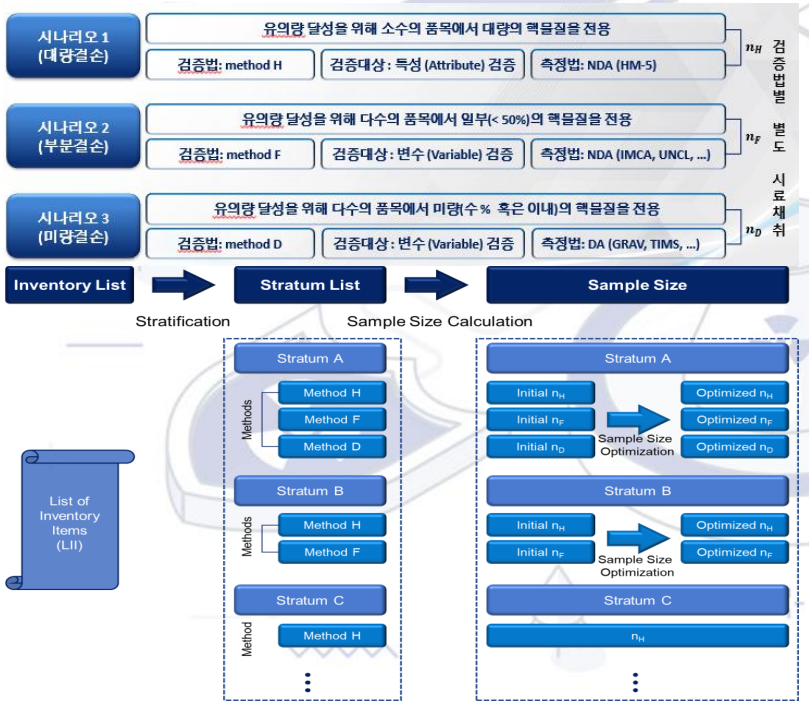
I Background

What is Information Analysis in Nuclear Material Accountancy?

- **Statistical Evaluation based Safeguards Data Analysis**
  - **Material Balance Evaluation (MBE) (Article 4 (8) and (9)):** Evaluate the significance of accounting statics ($MUF, SRD, CuMUF$ …) using statistical testing methods
  - **Sampling Plan (Article 4 (2) and (9)):** Calculate the number of samples for inspection verification, which satisfies the given detection probability for possible diversion scenarios.



MBE (MUF evaluation) Overview



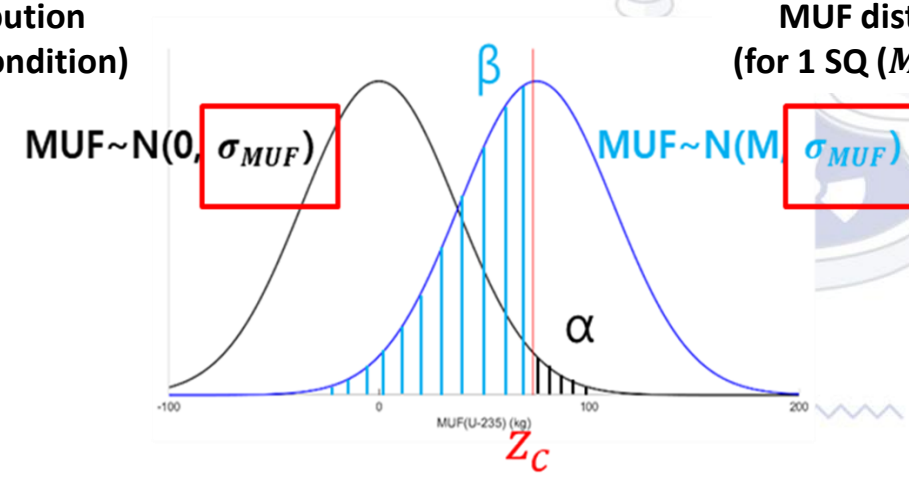
Sampling Plan Overview

II MUFEVAL & SAMEVAL

MBE Methods for National Safeguards Inspection (1/2)

- **MBE Methods**
  - Evaluate the significance of MUF & SRD for an MBP and cumulative MUF (CuMUF) for a series of MBPs
  - Calculate accounting statistics (MUF, SRD, …) and evaluate the significance by comparing it to the uncertainty (σ_{MUF}, σ_{SRD}, …) and confidence level (z_c)
    - Optimize methods to calculate the combined uncertainty of accounting statics (σ_{MUF}, σ_{SRD}, …)
  - Application of near real-time accountancy (NRTA) methods for CuMUF evaluation(Lee et al., INMM 2025)
    - Shewhart test, SPRT, GEMUF, Page's test, χ^2 test, LRT

MUF distribution (for normal condition)



MUF distribution (for 1 SQ (M) diversion)

II MUFEVAL & SAMEVAL

MBE Methods for National Safeguards Inspection (2/2)

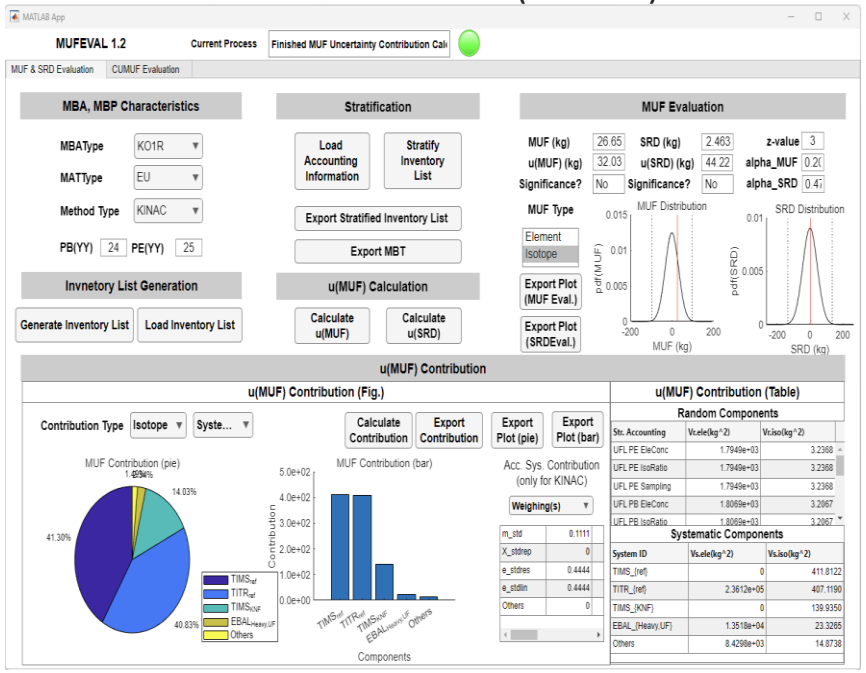
- **Optimized MBE Methods for the MUFEVAL Program**
  - KINAC method for national Safeguards inspection & IAEA method for the backup and IAEA comparison

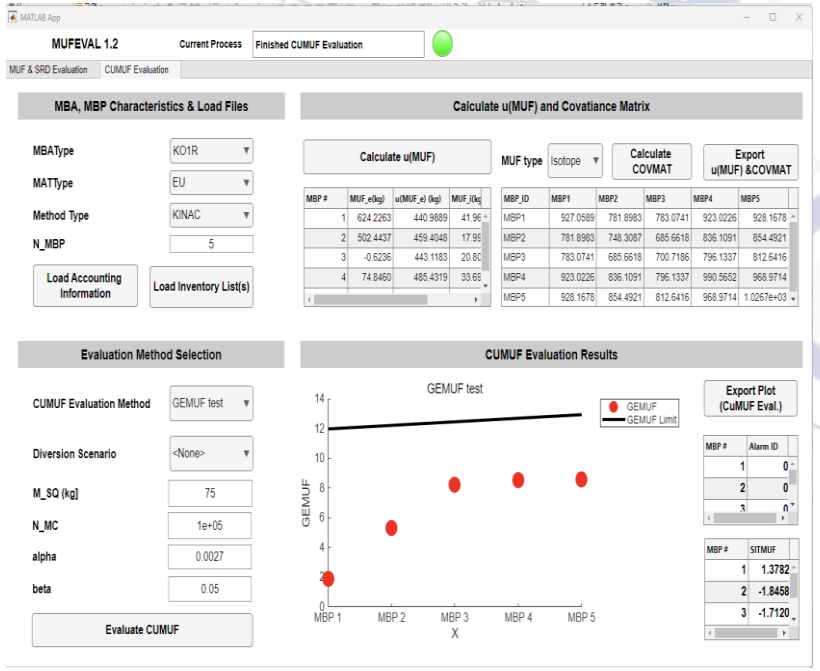
Methods	KINAC method (Lee et al., 2024)	IAEA method (IAEA STR-326)
Purpose	• Diversion detection • Accounting system verification & contribution analysis in accounting process level	• Diversion detection • Accounting system verification
UQ & σ_{MUF} Calculation Methods	• Bottom-up uncertainty quantification (GUM) • Stratification for entire MBP • Systematic uncertainty in accounting system level • Static inventory removal by material balance calculation	• Top-down uncertainty quantification (ANOVA) • Stratification for each MBC • Systematic uncertainty in stratum level • Static inventory removal between MBCs
Propagation of σ_{MUF} (example for a stratum)	$\sigma_{r,MUF}^2 = \frac{S_{PB}M_{PB}^2}{n_{PB}}\delta_r^2 + \frac{S_X M_X^2}{n_X}\delta_r^2 + \frac{S_Y M_Y^2}{n_Y}\delta_r^2 + \frac{S_{PE}M_{PE}^2}{n_{PE}}\delta_r^2$ $\sigma_{s,MUF}^2 = S_{PB}M_{PB}^2\delta_s^2 + S_X M_X^2\delta_s^2 + S_Y M_Y^2\delta_s^2 + S_{PE}M_{PE}^2\delta_s^2$ $\sigma_{MUF}^2 = \sigma_{r,MUF}^2 + \sigma_{s,MUF}^2$	$\sigma_{r,MUF}^2 = \frac{M_{PB}^2}{n_{PB}}\delta_r^2 + \frac{M_X^2}{n_X}\delta_r^2 + \frac{M_Y^2}{n_Y}\delta_r^2 + \frac{M_{PE}^2}{n_{PE}}\delta_r^2$ $\sigma_{s,MUF}^2 = (M_{PB} + M_x - M_Y - M_{PE})^2\delta_s^2$ $\sigma_{MUF}^2 = \sigma_{r,MUF}^2 + \sigma_{s,MUF}^2$
Advantages	• Precise uncertainty component analysis • Conservative (smaller) σ_{MUF}	• Maintain Independency • Lower false alarm probability (α)
Limitations	• Depending on the facility information • Higher false alarm probability (α)	• Limited uncertainty component analysis • Subjective judgement in static removal & overestimated σ_{MUF} without static removal

II MUFEVAL & SAMEVAL

MUFEVAL Overview

- **MUFEVAL: MATLAB based Standalone Program to Evaluate MUF & SRD & CuMUF for National Safeguards Inspection**
- **MUFEVAL Operation Requirements**
  - Nuclear material accounting records & reports (LII or PIL & ICR), stratification rules, accounting information & RSDs
- **MUFEVAL Capabilities**
  - σ_{MUF} & σ_{SRD} calculation using the KINAC or IAEA method
  - MUF, SRD evaluation & contribution analysis
  - Cumulative MUF (CuMUF) evaluation for a series of MBPs

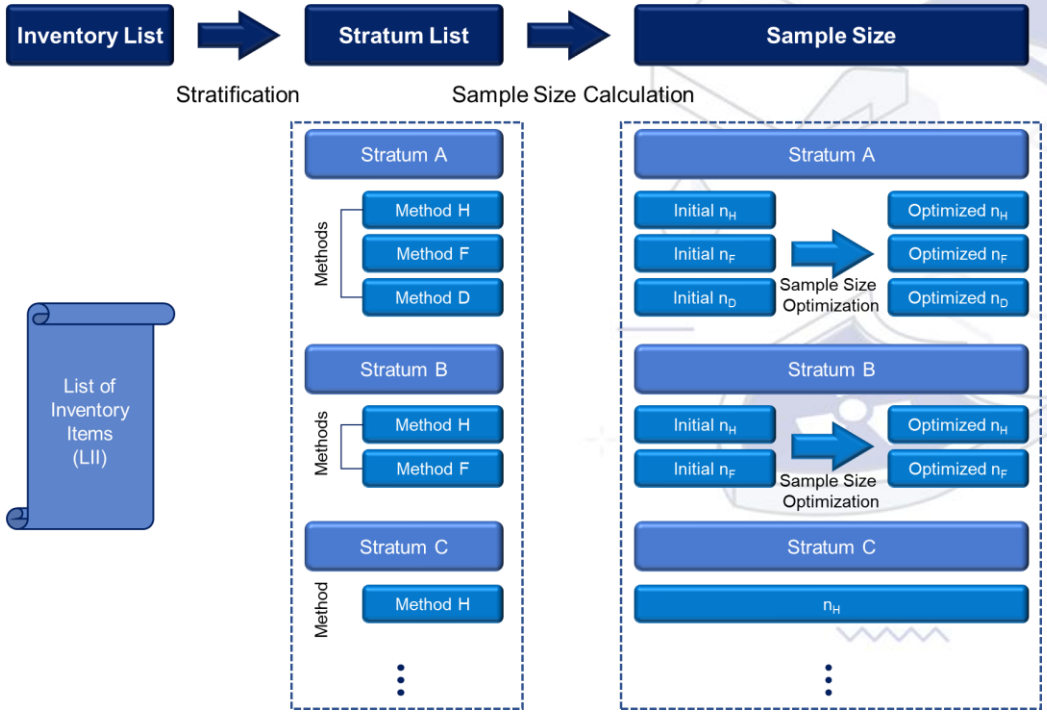




II MUFEVAL & SAMEVAL

Sampling Plan Methods for National Safeguards Inspection (1/2)

- **Sampling Plan Methods**
  - Calculate sample sizes for verification methods & test effectiveness for the given detection probability (DP)
  - Stratify inventory, identify verification methods, and calculate sample sizes
    - Calculate initial sample sizes for each verification method to the given DP
    - Optimize sample sizes between each verification method to satisfy overall DP



II MUFEVAL & SAMEVAL

Sampling Plan Methods for National Safeguards Inspection (2/2)

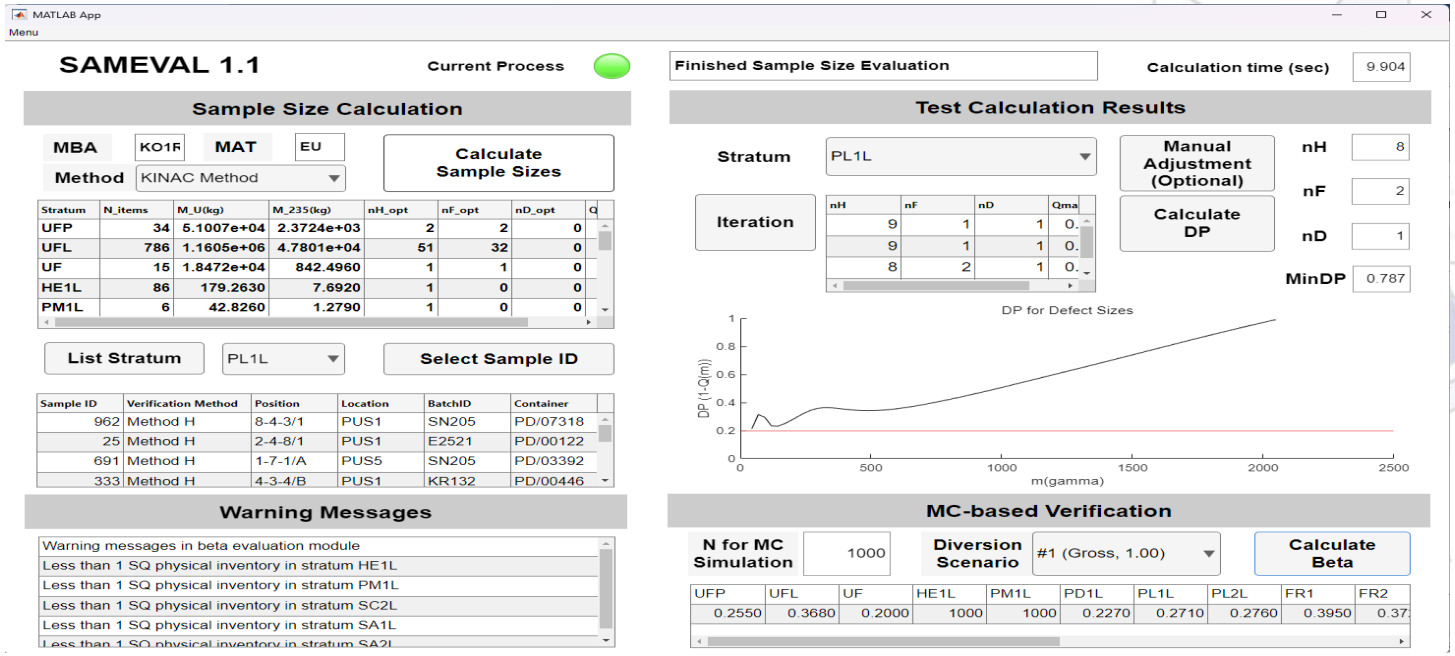
- **Optimized Sampling Plan Methods for the SAMEVAL Program**
  - KINAC method for exact sampling size calculation & IAEA method for the backup and IAEA comparison

Methods	KINAC method (Lee et al., 2025, IAEA STR-261)	IAEA method (IAEA STR-261, CIOSP)
Purpose	• Diversion detection • Accounting system verification & UQ	
Calculation Methods	• Exact hypergeometric distribution calculation • Precise optimization	• Hypergeometric distribution with approximation • Coarse optimization steps
Initial Sample Size Calculation	$n_{H,init} = n_H - n_F, n_{F,init} = n_F - n_D, n_{D,init} = n_D$ $n_{H,F,D} = \min(n)$, which satisfies $\beta_c \geq \frac{\binom{M}{x}\binom{N-\frac{M}{x}}{n_H}}{\binom{N}{n}}, \beta_c \geq \sum_{j=0}^{n} \frac{\binom{m(\gamma)}{j}\binom{N-m(\gamma)}{n_{F/D}-j}}{\binom{N}{n}}(1-p_{F,D})^j, p_{F,D} = 1-\Phi\left(\frac{3\delta_{F,D}-\gamma}{\delta_{F,D}(1-\gamma)}\right)$ **Exact hypergeometric calculation**	$n_{H,init} = n_H - n_F, n_{F,init} = n_F - n_D, n_{D,init} = n_D$ $n_H = N\left(1-\beta_c^{\frac{x}{M}}\right), n_{F/D} = \frac{ln\beta_c}{ln\left(1-\left(\frac{M}{\gamma'_{F,D}Nx}\right)\right)}, \gamma'_{F/D} = 4.737\Delta_{F/D} - 5.49\Delta_{F/D}^2,$ $\Delta_F = max(\delta_F, 0.0075 - 0.053\delta_H + 2.37\delta_H^2), \Delta_D = max(\delta_D, 0.331\delta_F)$ **Binomial & regression based estimated hypergeometric distribution**
Sample Size Optimization	Optimize sample sizes which converges $\max(Q(m))$ to β_c	
	$Q(m) = \sum_{j=1}^{n} \frac{\binom{m}{j}\binom{N-m}{n-j}}{\binom{N}{n}} \sum_{w_H=1}^{W_H} \sum_{w_F=1}^{W_F} \frac{\binom{n_H}{w_H}\binom{n_F}{w_F}\binom{n_D}{j-w_H-w_F}}{\binom{n}{j}}$ $(1-p_H)^{w_H}(1-p_F)^{w_F}(1-p_D)^{j-w_H-w_F}$ **One-step & exact $Q(m)$ calculation with precise optimization**	$Q(m) = \beta_H\beta_F\beta_D, \beta_{H,F,D} = \begin{cases} \left(1-\frac{mp_{H,F,D}}{N-0.5(n_{H,F,D}-1)}\right)^{n_{H,F,D}} & (n \leq mp_{H,F,D}) \\ \left(1-\frac{n_{H,F,D}}{N-0.5(mp_{H,F,D}-1)}\right)^{mp_{H,F,D}} & (n > mp_{H,F,D}) \end{cases}$ **Multi-steps & estimated $Q(m)$ calculation with coarse iteration steps**
Characteristics	• Reduces inspection burden (sample sizes)	• Reduces computation burden (calculation time)

II MUFEVAL & SAMEVAL

SAMEVAL Overview

- **SAMEVAL: MATLAB based Standalone Program to Calculate & Evaluate Sample Sizes**
- **SAMEVAL Operation Requirements**
  - Nuclear material accounting records (LII), Stratification rules & standard list (verification information for each stratum)
- **SAMEVAL Capabilities**
  - Sample sizes calculation for each stratum using the KINAC or IAEA method
  - Effectiveness test for the calculated sample sizes
  - Manual sample size adjustment and effectiveness test



II MUFEVAL & SAMEVAL

- **ROK – IAEA Technical Workshop for MUFEVAL & SAMEVAL Verification**
  - **Comparison between the Results of KINAC,IAEA, KAERI Programs**
    - Compared the MUF, SRD, σ_{MUF} and top 5 σ_{MUF} contributor (IAEA mode for MUFEVAL)
      MUFEVAL's IAEA mode calculates static σ_{MUF} (without static removal)
    - Compared the calculated sample sizes (IAEA mode for SAMEVAL)

II MUFEVAL & SAMEVAL

Verification of MUFEVAL Program

- **Consistent Results for Domestic MBAs (KO1R, KO-W) and MBPs (2010 – 2024 MBPs)**
  - Consistent MUF, SRD, σ_{MUF} and top 5 σ_{MUF} contributor (IAEA mode for MUFEVAL & IAEA's $static - \sigma_{MUF}$)
    - Slight difference came from the differences in stratification rules between KINAC and IAEA (KAERI)
  - Use of the same accounting information (hypothetical RSDs) to evaluate the statistical model

	IAEA	KINAC	KAERI
$MUF\ (kg^{2\ 235}U)$	20.81	20.81	20.81
$\sigma_{MUF}\ (kg^{2\ 235}U)$	72.28	73.86	71.72
$V_{r,MUF}\ (kg^{2\ 235}U)$	65.76	163.0	82.22
$V_{s,MUF}\ (kg^{2\ 235}U)$	5158.0	5291.8	5058.746

	IAEA	KINAC	KAERI
$V_{s,MUF}$(UFL,PE) $(kg^{2\ 235}U)$	2051.0	2290.8	2051.8
$V_{s,MUF}$(UFL,PB) $(kg^{2\ 235}U)$	1213.0	1208.2	1208.3
$V_{r,MUF}$(UF-,X) $(kg^{2\ 235}U)$	1084.7	1079.0	1079.9
$V_{r,MUF}$(FF2,SD,Y) $(kg^{2\ 235}U)$	447.89	447.22	447.23

KO1R, 2022-2023 MBP

	IAEA	KINAC	KAERI
$MUF\ (kg^{2\ 235}U)$	0.0570	0.0570	0.0570
$\sigma_{MUF}\ (kg^{2\ 235}U)$	1.3679	1.3681	1.3680
$V_{r,MUF}\ (kg^{2\ 235}U)$	0.0280	0.0280	0.0280
$V_{s,MUF}\ (kg^{2\ 235}U)$	1.8431	1.8434	1.8434

	IAEA	KINAC	KAERI
$V_{s,MUF}$(ME2L,PB) $(kg^{2\ 235}U)$	0.9155	0.9156	0.9156
$V_{s,MUF}$(ME2L,PE) $(kg^{2\ 235}U)$	0.9155	0.9156	0.9156
$V_{r,MUF}$(ME2L,PB) $(kg^{2\ 235}U)$	0.0105	0.0105	0.0142
$V_{r,MUF}$(ME2L,PE) $(kg^{2\ 235}U)$	0.0105	0.0105	0.0142
$V_{r,MUF}$(SC2L,PE) $(kg^{2\ 235}U)$	0.0033	0.0033	0.0031
$V_{r,MUF}$(SC2L,PB) $(kg^{2\ 235}U)$	0.0033	0.0033	0.0031
$V_{s,MUF}$(SC2L,PE) $(kg^{2\ 235}U)$	0.0032	0.0032	0.0032
$V_{s,MUF}$(SC2L,PB) $(kg^{2\ 235}U)$	0.0031	0.0031	0.0031

KO-W, 2022-2023 MBP

II MUFEVAL & SAMEVAL

Verification of SAMEVAL Program

- **Consistent Results for Domestic MBAs (KO1R) and MBPs (end of 2023 MBP)**
  - Consistent sample sizes & DP plot
    - Slight differences from different stratification rules
  - Use of the same accounting information (hypothetical RSDs) to evaluate the statistical model

계층 정보		KINAC						IAEA			KAERI		
		근사식 활용			수치해 산출								
KINAC	IAEA·KAERI	n_H	n_F	n_D	n_H	n_F	n_D	n_H	n_F	n_D	n_H	n_F	n_D
UFP	UFL1	2	2	0	2	2	0	2	2	0	2	2	0
	UFL2							0	1	0	0	1	0
UFL	UFL	36	26	0	37	25	0	36	26	0	36	26	0
UF-	UF-	1	1	0	1	1	0	1	1	0	1	1	0
HE1L*	HE1L*	1	0	0	1	0	0	1	0	0	1	0	0
PM1L*	PM1L*	1	0	0	1	0	0	1	0	0	1	0	0
PD1L	PD1L	5	1	1	5	1	1	5	1	1	5	1	1
PL1L	PL1L	8	2	1	8	2	1	8	2	1	8	2	1
PL2L*	PL2L*	1	0	0	0	0	1	0	0	1	0	0	1
FR1*	FR1*	1	0	0	1	0	0	1	0	0	1	0	0
FR2	FR2	0	1	0	0	1	0	0	1	0	0	1	0
FF*	FF*	0	0	0	0	0	0	0	0	0	0	0	0
FFP	FFP	4	0	0	3	0	0	4	0	0	4	0	0
FF1	FF1	1	3	0	1	3	0	1	3	0	1	3	0
FF2	FF2	2	5	0	2	5	0	2	5	0	2	5	0
SC1L	SC1L	3	0	1	3	0	1	3	0	1	3	0	1
SC2L*	SC2L*	1	0	0	1	0	0	1	0	0	1	0	0
SD1L	SD1L	2	1	0	0	3	0	2	1	0	2	1	0
SA1L*	SA1L*	1	0	0	1	0	0	1	0	0	1	0	0
SA2L*	SA2L*	1	0	0	1	0	0	1	0	0	1	0	0

※ 재고량이 1 SQ 이하이거나 재고가 없는 계층

III Feasibility Demonstration

Overview of National Safeguards Inspection

- **Target Inspection: 2025 Regular Inspection for LEU Fuel Fabrication Plant (KO1R)**
- **Facility Configuration**
  - Consists of reconversion, pelletizing, rod insertion, assembling process
  - Accounting process for ^{235}U (M_{235}): $M_{235} = M_{net} \times p \times f_U \times w_{235}$
  - RSD for MUFEVAL: GUM & ANOVA based UQ result, ITV-2020 value for systems without information
  - RSD for SAMEVAL: Former IAEA's facility configuration (mid 2010s)

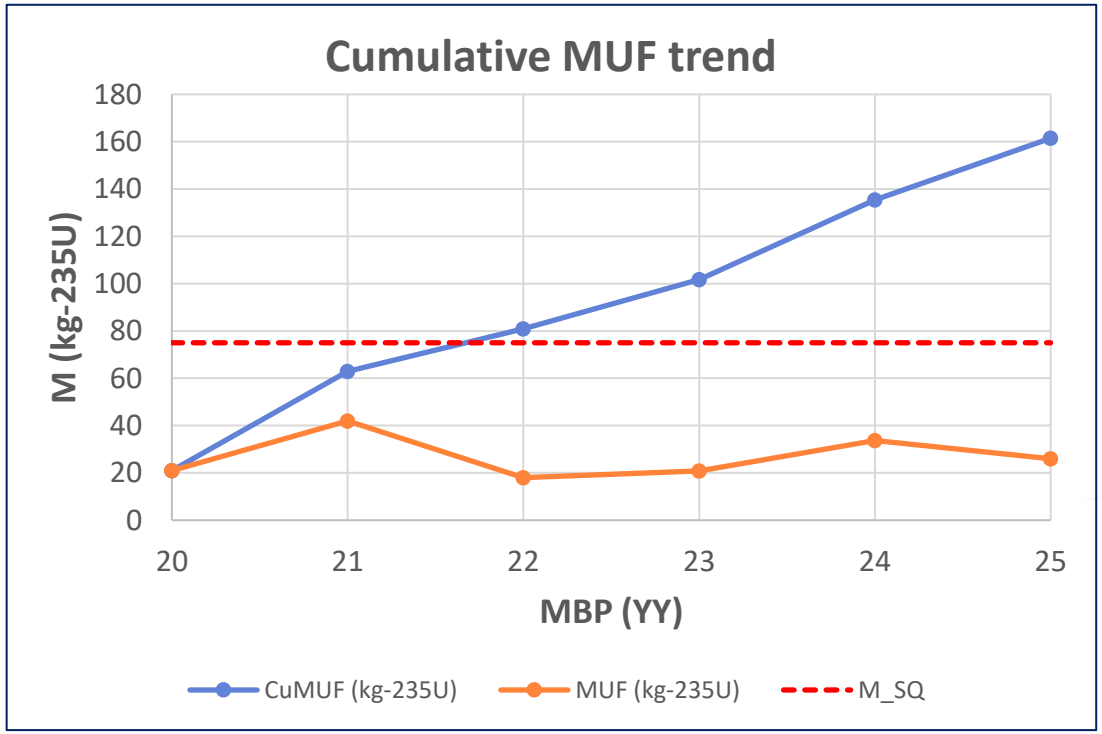
Scope of Feasibility Demonstration

- **IAEA results for MUF evaluation of current MBP and RSD values for sample size calculation are classified for member states**
- **MUFEVAL**
  - MUF evaluation for 2024 – 2025 MBP using the KINAC and IAEA methods
  - SRD evaluation for 2024 – 2025 MBP using the KINAC and IAEA methods
  - σ_{MUF} contribution analysis for 2024 – 2025 MBP using the KINAC and IAEA methods
  - CuMUF evaluation for recent 5 MBPs (2020 – 2025) using all NRTA methods
- **SAMEVAL**
  - Sample size calculation for all strata for 2025 physical inventory using the KINAC and IAEA methods
  - Compare the results to the IAEA's in-field sample size calculation results

III Feasibility Demonstration

Current Issues in Nuclear Material Accountancy

- **Cumulative MUF exceeds 2 SQs for recent 5 MBPs**
  - Where does the CuMUF from?
- **Continuous inconsistency in ^{235}U enrichment for specific enrichment range (1.5 ~ 3 wt%)**
  - Importance of sampling & verification increases



year	Item ID	U-235 enrichment				Notes
		KNFC	KINAC	d	u(k=3)	
2023	2320115	2.226	2.22	0.0060	0.0012	Gd PL
2024	A/00609	1.8	1.8126	-0.0126	0.0067	Scrap (Gd PL)
	UC/00122	2.92	2.951	-0.031	0.010	PD
	UD/05331	1.745	1.735	0.0100	0.0061	Scrap (PD)
2025	2410125	2.225	2.2131	0.0119	0.0039	Gd PL
	UD/01171	2.2	2.2114	-0.0114	0.0064	Scrap (Gd PD)
	B/15326	2.2	2.2457	-0.0457	0.0064	Scrap (Gd PL)

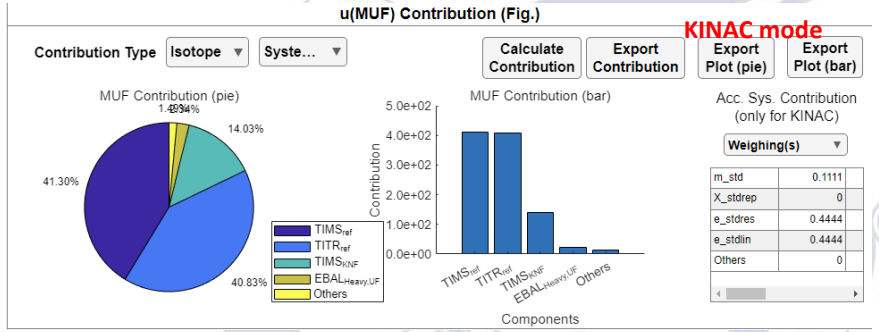
III Feasibility Demonstration

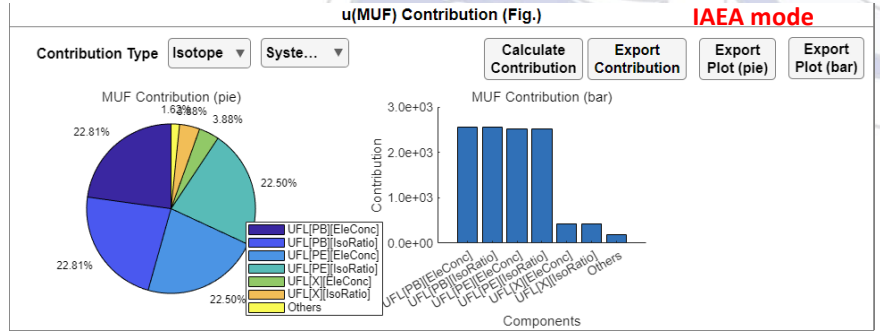
MUFEVAL Results

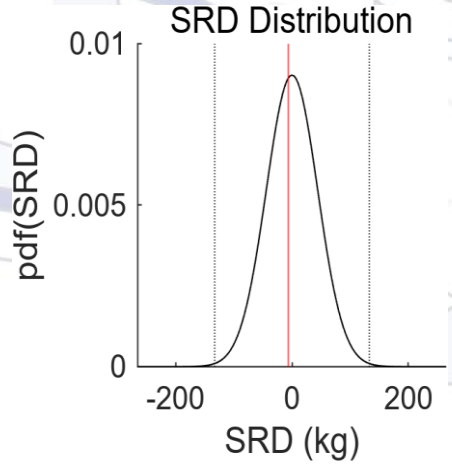
- **MUFEVAL results using KINAC mode and IAEA mode**
  - Both results indicated the MUF and SRD were insignificant for ($z_{\alpha/2} = 3$)
  - Considering high σ_{MUF}, static removal process is required for the IAEA mode
  - The KINAC and IAEA modes analyze σ_{MUF} contribution in accounting system & process level and stratum level
    - Considering high contribution, the UF6 cylinder's accounting systems need to be examined in detail

	KINAC mode	IAEA mode
MUF (kg)	26.040	
σ_{MUF} (kg)	32.030	97.338
Significance?	No	No

KINAC mode		IAEA mode	
Contributor	**Var. (kg^2)**	**Contributor**	**Var. (kg^2)**
TIMS (Ref.)	411.812	UFL (PB)	3827.68
TITR (Ref.)	407.119	UFL (PE)	3776.06
TIMS (KNF)	139.935	FF2 (Y)	951.123
EBAL (UF_6)	23.3265	UFL (X)	651.305
Others	14.8738	PL1L (PB)	43.6564



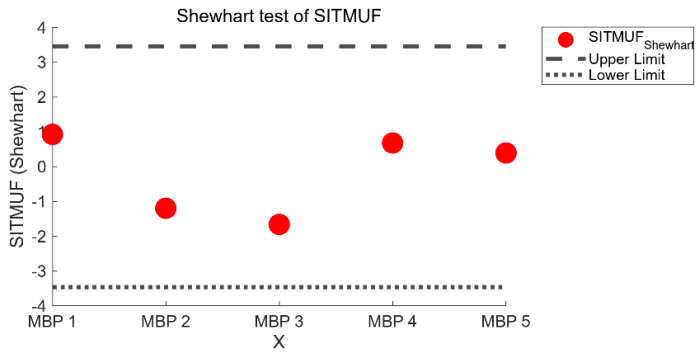


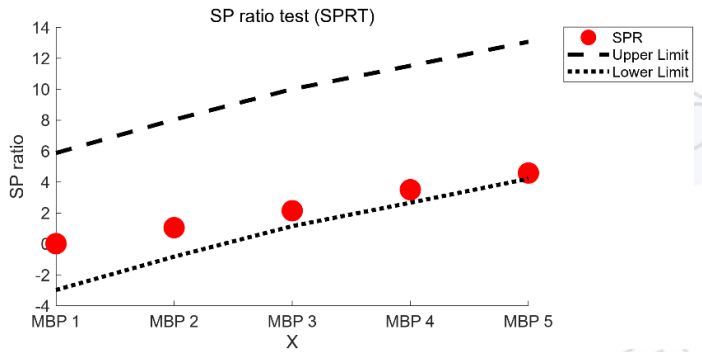


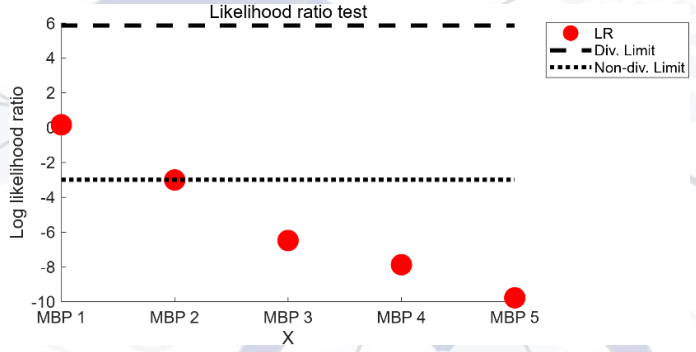
III Feasibility Demonstration

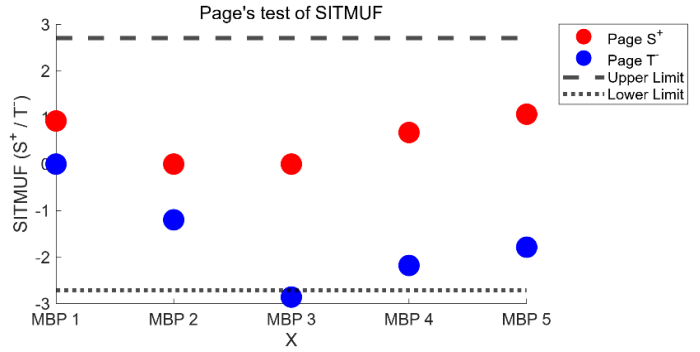
MUFEVAL Results

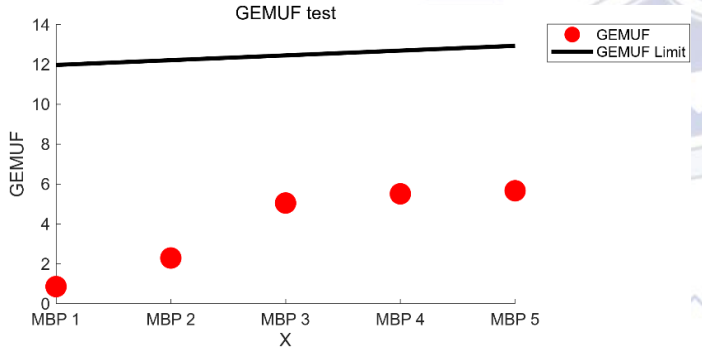
- **MUFEVAL results for CuMUF evaluation**
  - Cumulative MUF exceeds a few SQs for recent 5 MBPs ($M_{CuMUF} \approx 2\, M_{SQ}$)
  - The CuMUF was insignificant for all NRTA methods for $\alpha = 0.0027$ and $\beta = 0.05$
    - The MUF may be cumulated due to the biases in systematic uncertainty components or accounting process

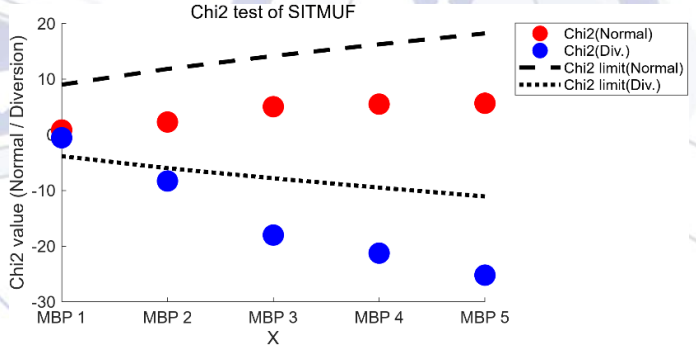












III Feasibility Demonstration

SAMEVAL Results

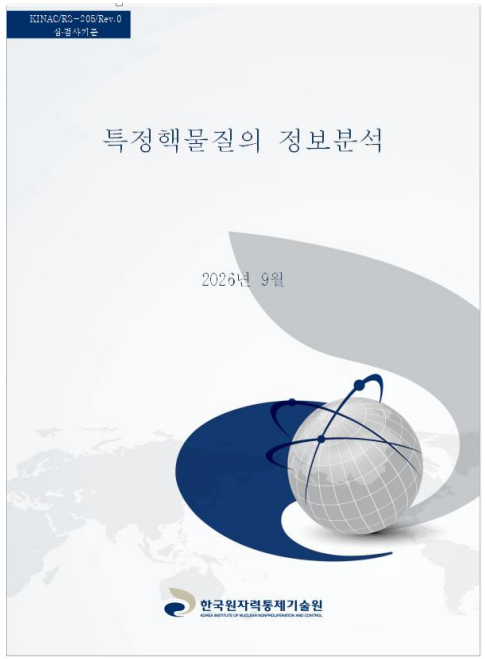
- **SAMEVAL results using KINAC mode and IAEA mode**
  - KINAC mode usually reduces inspection burden compared to the IAEA mode (PD1L, UFL)
  - IAEA (current) results and the SAMEVAL's KINAC mode results were almost consistent except for strata with advanced verification methods with reduced RSDs (FF1, FF2) and manual adjustments (SC2L, SD1L)

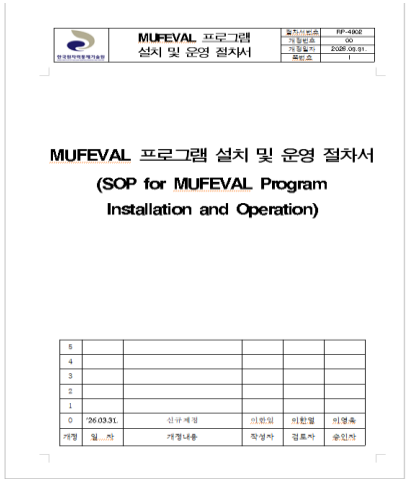
Stratum Name	SAMEVAL						IAEA		
	KINAC mode			IAEA mode					
	n_H	n_F	n_D	n_H	n_F	n_D	n_H	n_F	n_D
FF1	1	2	0	1	2	0	2	1	0
FF2	2	3	0	2	3	0	3	2	0
FF3	0	1	0	0	1	0	0	1	0
FFP	3	0	0	3	0	0	3	0	0
FR1	0	1	0	0	1	0	0	1	0
FR2	1	1	0	1	1	0	1	1	0
HE1L	1	0	0	1	0	0	1	0	0
PD1L	5	0	1	4	1	1	5	0	1
PL1L	8	2	1	8	2	1	8	2	1
PL2L	0	0	1	0	0	1	0	0	1
PM1L	1	0	0	1	0	0	1	0	0
SA1L	1	0	0	1	0	0	1	0	0
SA2L	1	0	0	1	0	0	1	0	0
SC1L	4	1	1	4	1	1	4	1	1
SC2L	1	0	0	1	0	0	0	0	1
SD1L	0	4	0	3	1	0	1	3	0
UF-	1	1	0	1	1	0	1	1	0
UFL	51	32	0	49	34	0	49	34	0
UFP	2	2	0	2	2	0	2	2	0

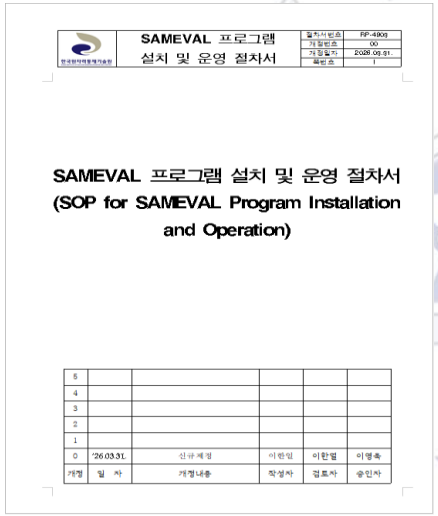
III Feasibility Demonstration

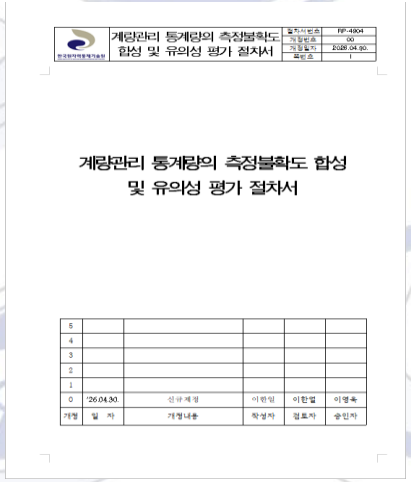
Requirements for Application

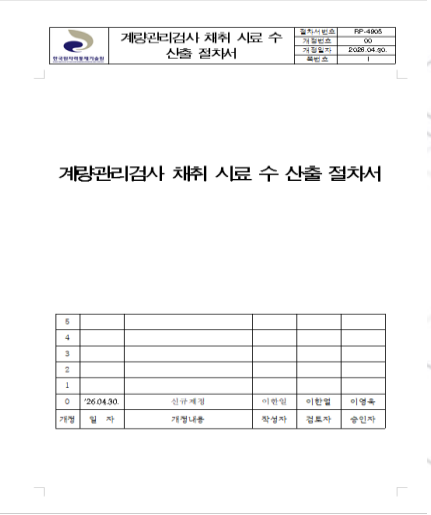
- **Establish Standard UQ Methods for Accounting & Verification Systems**
- **Regulatory Standard & Procedures for Applying Information Analysis in National Safeguards Inspection**
  - Publish a regulatory standard for applying information analysis in national safeguards inspection (KINAC/RS-205)
  - Publish regulatory procedures for applying information analysis methods & programs in national safeguards inspection (KINAC/RP-4901 ~ 4905)











IV Conclusion

Key Takeaways

- **KINAC's information analysis programs (MUFEVAL and SAMEVAL) were demonstrated to be applicable to national inspections, confirming that the KINAC satisfies the technical capability required by the domestic notification**

- **MUFEVAL results indicate that the recent cumulative MUF issue may be driven by biases in systematic uncertainty components, highlighting the need to review and refine the DA accounting procedures for UF_6 cylinders**
  - Discuss between the KINAC, IAEA and facility with the quantitative results

- **SAMEVAL results indicate that the inconsistent sampling plan results for strata with the IAEA's RSD update shows the need to develop an independent standard uncertainty quantification (UQ) method for national safeguards inspections**
  - Develop standard UQ procedures for national inspection ('26.4. ~ '28.12.)

- **KINAC plans to establish regulation documents to establish the basis of applying information analysis in national safeguards inspection**
  - Establish regulatory procedures (KINAC/RP – 4901 ~ 4905) ('26.4.) and standard (KINAC/RS - 205) ('26.9.)

Thank you!!

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