Approaches on Uncertainty Expression in Nuclear Material Accounting

Presented to the 2024 KNS Spring Meeting

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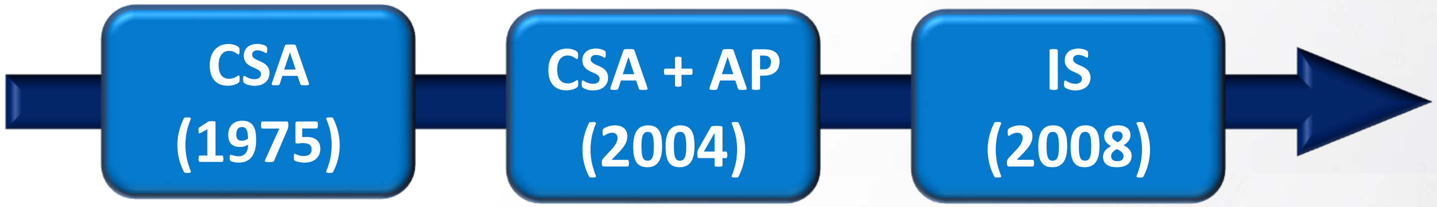
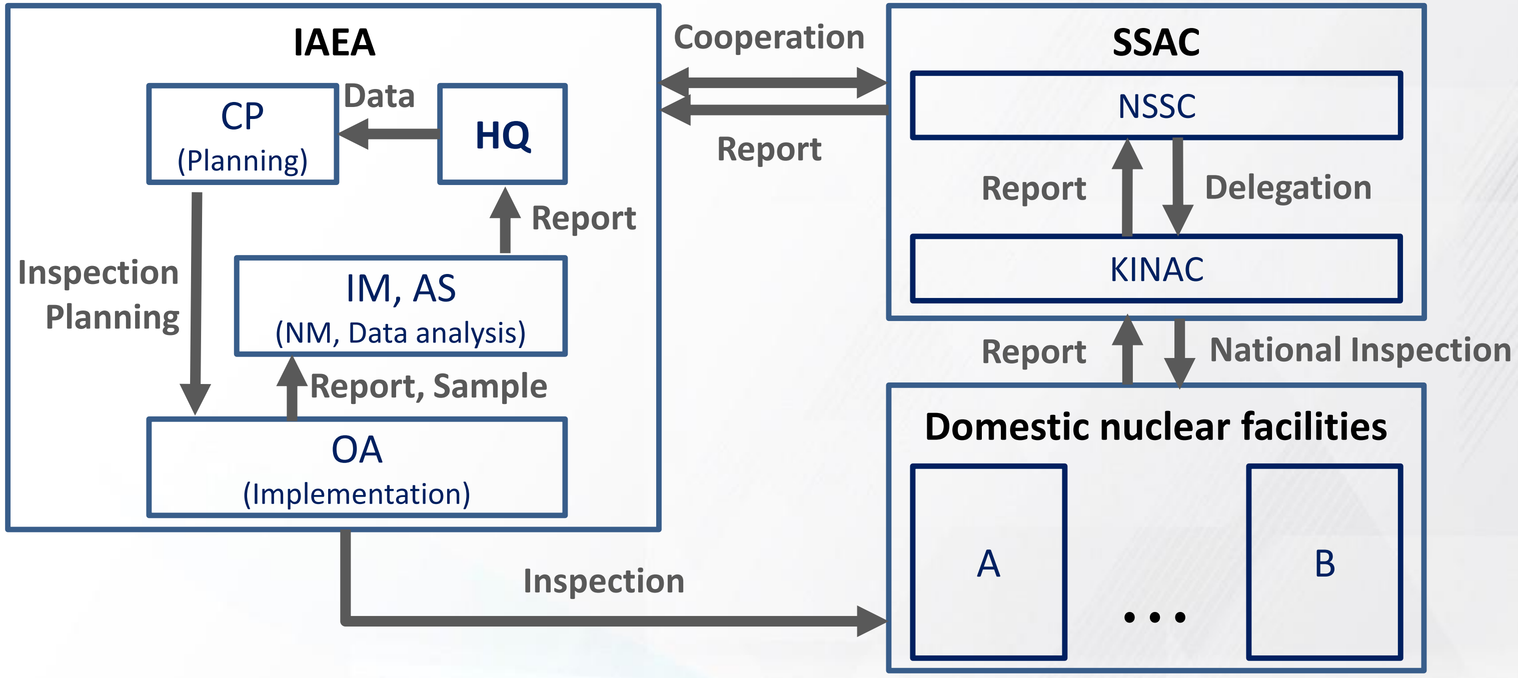
01 Background

- **Implementation of IAEA Safeguards in the ROK (before SLA)**



CSA: Comprehensive Safeguards Agreement, **AP**: Additional Protocol, **IS**: Integrated Safeguards.



BASIC UNDERTAK **Target of the IAEA safeguards**

1. The Agreement should contain, in accordance with Article III.1 of the Treaty on the Non-Proliferation of Nuclear Weapons [1], an undertaking by the State to accept safeguards, in accordance with the terms of the Agreement, on all source or special fissionable material in all peaceful nuclear activities within its territory, under its jurisdiction or carried out under its control anywhere, for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or

CO-OPERATION BE **Obligation of member states**

3. The Agreement should provide that the Agency and the State shall co-operate to facilitate the implementation of the safeguards provided for therein.

OBJECTIVE OF SAFI **Objective of IAEA safeguards**

28. The Agreement should provide that the objective of safeguards is the timely detection of diversion of significant quantities of *nuclear material* from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.

29. To this end the Agreement should provide for the use of material accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures.

30. The Agreement should provide that the technical conclusion of the Agency's verification activities shall be a statement, in respect of each *material balance area*, of the amount of *material unaccounted for* over a specific period, giving the limits of accuracy of the amounts stated.

NATIONAL SYSTEM OF ACCOUNTING FO
NUCLEAR MATERIAL **Role of SSAC**

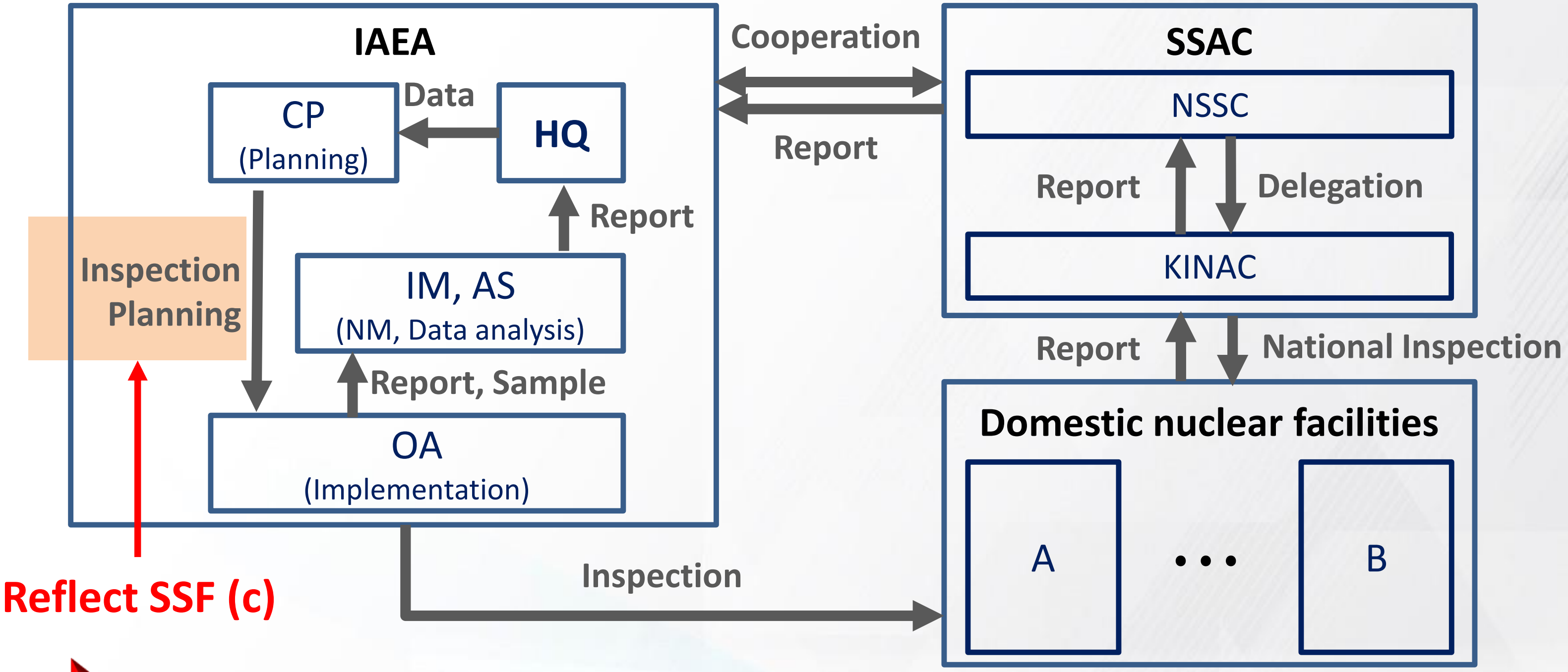
31. The Agreement should provide that pursuant to paragraph 7 above the Agency, in carrying out its verification activities, shall make full use of the State's system of accounting for and control of all *nuclear material* subject to safeguards under the Agreement, and shall avoid unnecessary duplication of the State's accounting and control activities.

** IAEA, INFCIRC/153 (Corr.)*

01 Background

- **Implementation of IAEA Safeguards in the ROK (under SLA)**

SLA: State-level Approach



3.1. State-level concept (SLC). The general notion of implementing *IAEA safeguards* in a manner that considers a State's nuclear and nuclear related activities and capabilities as a whole, within the scope of the *safeguards agreement*.

3.3. State-specific factors (SSFs). The six objective safeguards relevant factors that are particular to a State which are used by the IAEA Secretariat in the development of a *State-level safeguards approach (SLA)* and in the planning, conduct and evaluation of *safeguards activities* for that State. The SSFs are based on factual information and are objectively assessed.

The exhaustive list of six SSFs is as follows:

(a) The type of *safeguards agreement* in force for the State and the nature of the *safeguards conclusion* drawn by the IAEA. For example, a State has a *comprehensive safeguards agreement (CSA)* and an *additional protocol (AP)* in force and the *broader conclusion* has not been drawn.

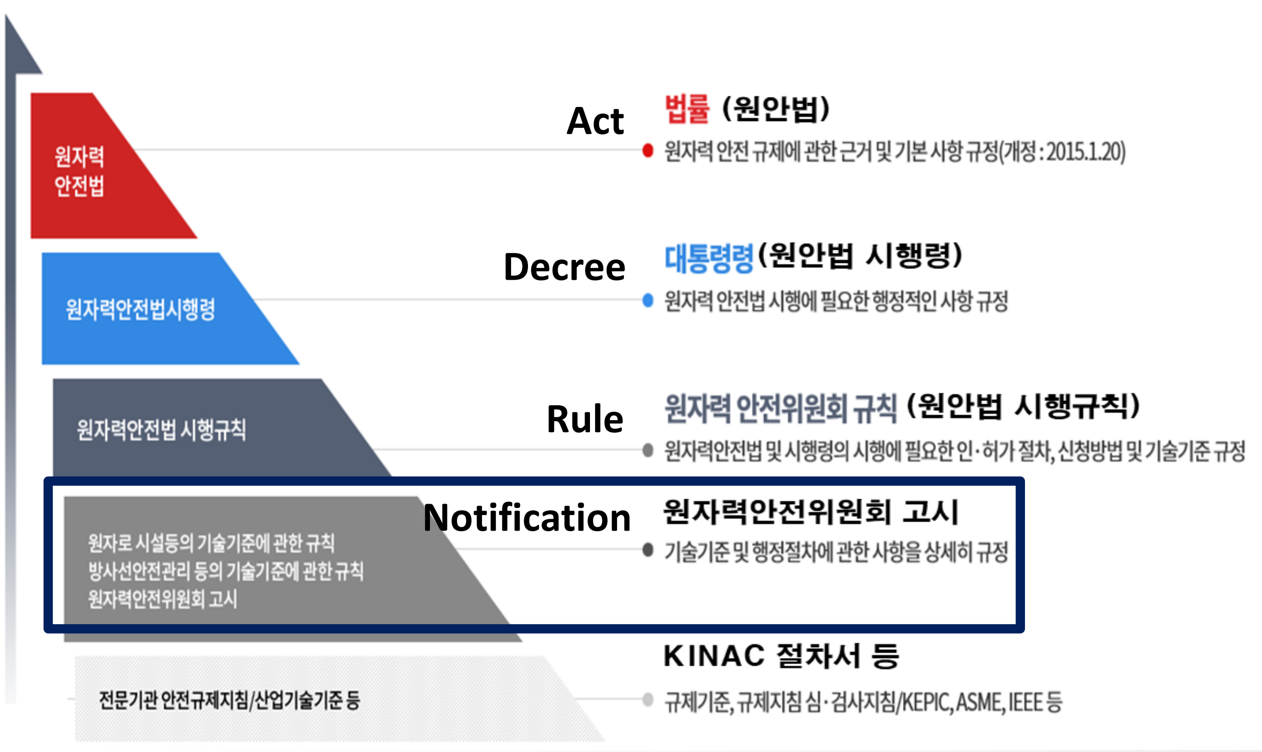
(b) The *nuclear fuel cycle* and related technical capabilities of the State. For example, the State has a nuclear *power reactor* and *locations outside facilities (LOFs)*, and limited *nuclear fuel cycle* related industrial capabilities.

(c) The technical capabilities of the *State (or regional) system of accounting for and control of nuclear material (SSAC/RSAC)*. For example, the *State or regional authority responsible for safeguards implementation (SRA)* conducts national/regional inspections or audits and the *nuclear material* measurement methods at bulk facilities meet *international target values (ITVs)*.

➡ **Strengthened national inspection may result in less inspection**

* *IAEA, Safeguards Glossary 2022*

• Legal basis for national safeguards inspection and MBE



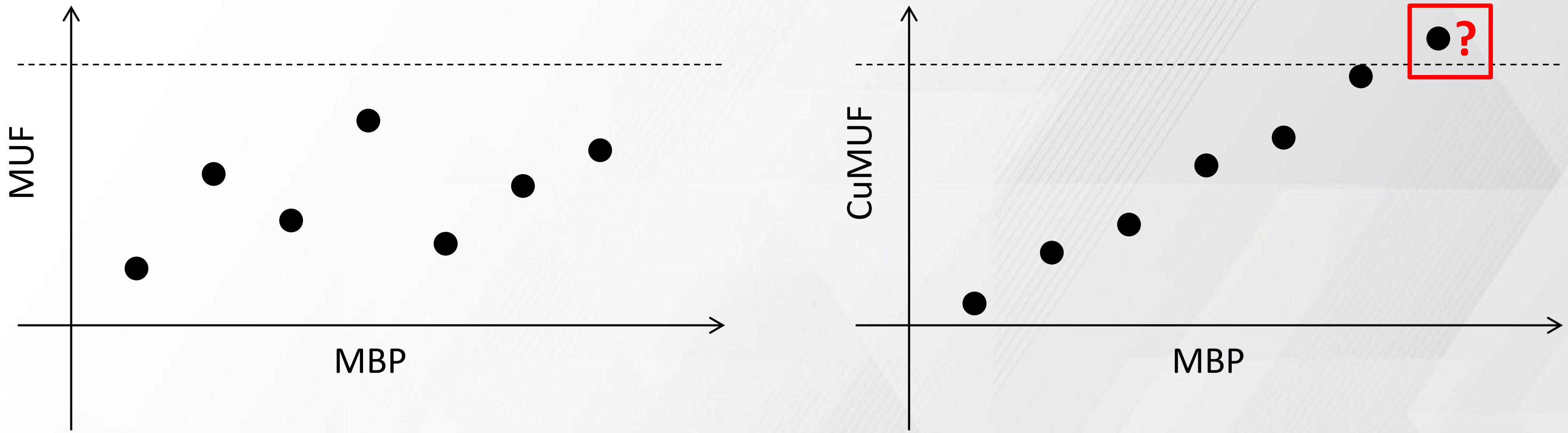
※ nsic.mssp.go.kr/nsic.do?nsicKey=300101

NSSC notification No. 2017-83

- **(Article 4) National safeguards inspection includes**
- Book examination
- Verification of declared information
- Verification of accounting equipment
- Verification of C/S system
- Verification of records
- Design information verification (DIV)
- Examination of MBAs and KMPs
- **Material balance evaluation (MBE)**
- Examination of accounting process
- Verification of other required processes

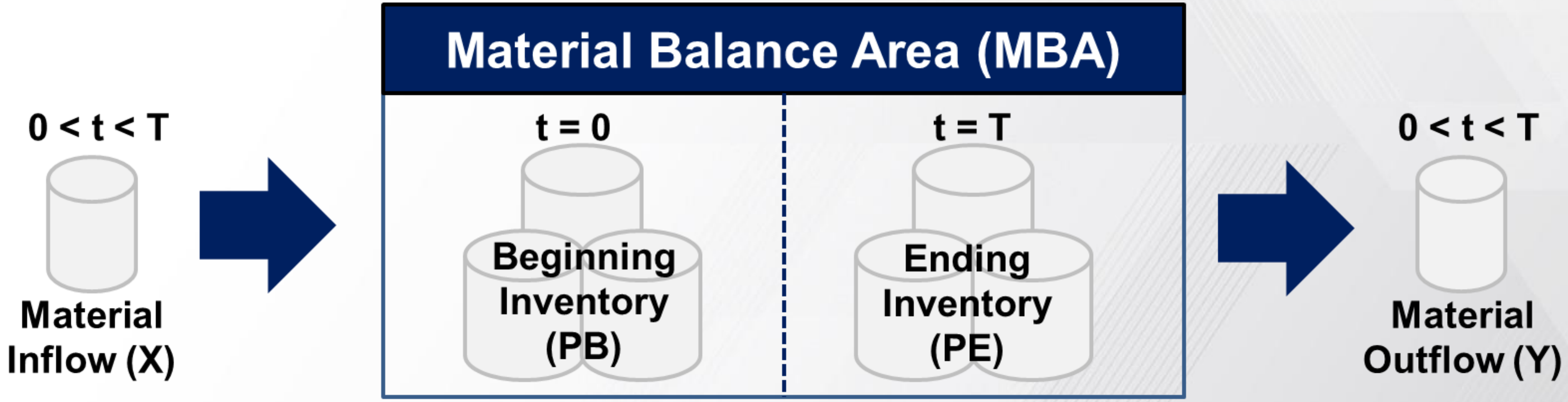
➡ **Need to perform an independent MBE (MUF evaluation) to satisfy domestic notification**

- **Practical requirements for an MBE in national safeguards inspection**
  - Accumulation of cumulative MUF for a series of MBPs in domestic MBAs
    - MUF is not significant for a single MBP
    - Cannot identify the key accounting process for the MUF accumulation

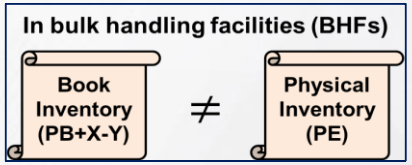


Need to conduct an independent MBE (MUF evaluation) to evaluate the accounting system as well as to detect diversion

- **What is MBE (MUF evaluation)?**



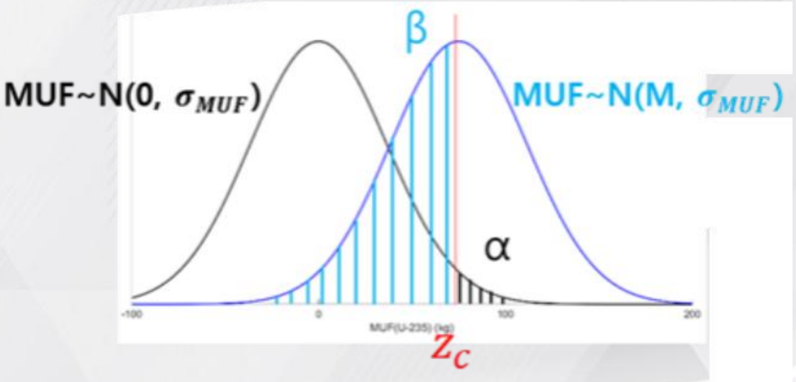
MUF evaluation process



1) Calculate MUF

$$MUF = PB + X - Y - PE$$

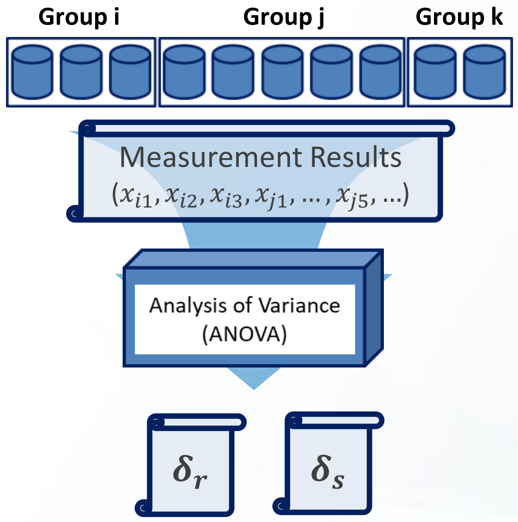
2) Calculate measurement uncertainty of MUF (σ_{MUF})
3) Evaluate the MUF by comparing it to σ_{MUF}



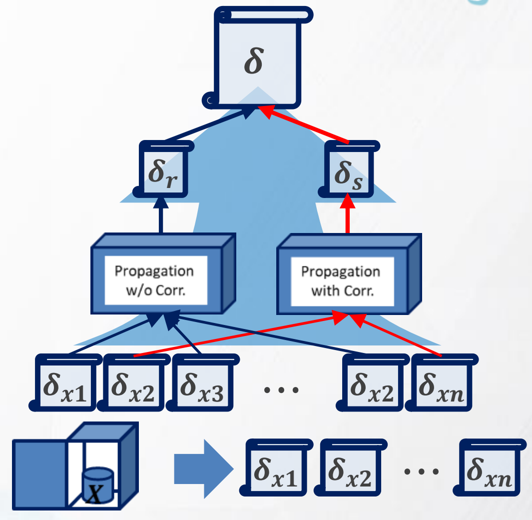
- **Uncertainty expression in MBE**
  - MUF is calculated using the inventory of individual items(X_i) $MUF = f(X_1, X_2, \dots, X_n)$
  - An item(X_i) is calculated using the individual measurement(x_{ij}) $X_i = f(x_{i1}, x_{i2}, \dots, x_{in})$

Quantifying Individual Uncertainty (Error)

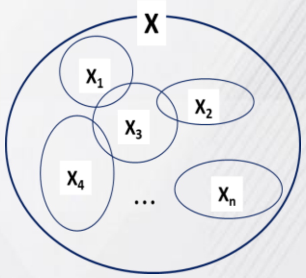
Top-down approach ?



Bottom-up approach ?



Propagation of Uncertainty (Error Propagation)



Equation for the mesurand X

$$X = f(x_1, x_2, \dots, x_n)$$

Apply Taylor series

$$X = X_o + \sum_{i=1}^{n} \frac{\partial X}{\partial x_i}(x_i - x_{i0}) + \sum_{k=1}^{n} \sum_{j=1}^{n} \frac{1}{2!} \frac{\partial^2 X}{\partial x_j x_k}(x_j - x_{j0})(x_k - x_{k0}) + \cdots$$

Approximation

$$X \cong X_o + \sum_{i=1}^{n} \frac{\partial X}{\partial x_i}(x_i - x_{i0})$$

Estimate the variance of the mesurand X

$$E[(X - X_o)^2] = \mathrm{E}\left[\left(\sum_{i=1}^{n} \frac{\partial X}{\partial x_i}(x_i - x_{i0})\right)^2\right]$$

$$u_c(X)^2 = \sum_{i=1}^{n} \left(\frac{\partial X}{\partial x_i}\right)^2 \mathrm{u}(\mathrm{x_i})^2 + \sum_{j=k+1}^{n} \sum_{k=1}^{n-1} \frac{\partial^2 X}{\partial x_j \partial x_k} r(\mathrm{x_j}, \mathrm{x_k}) \mathrm{u}(\mathrm{x_i}) \mathrm{u}(\mathrm{x_j})$$

Independent factors (Random components) | **Correlation factors (Systematic components)**

- **Characteristics of uncertainty expression methods**

	Top-down method (ANOVA)	Bottom-up method (GUM)
Requirements	- **Pair-wise difference data** for a number of grouped items - **Mathematical adjustments** (DODGRU, CELEX) for negative variances	- **Detailed facilities' accounting information** to identify, quantify, and propagate individual uncertainty components **(Bayesian statistics)**
Advantages	- Do not require facilities' detailed accounting information **(Can maintain independency)**	- Can analyze the contribution of individual uncertainty components **(Have high traceability)**
Disadvantages	- Cannot analyze the contribution of individual uncertainty components **(Have low traceability)** - Cannot modify the IAEA's adjustments	- Assumptions on facilities' accounting information in individual uncertainty components **(Cannot maintain independency)**
Application	- IAEA and national inspection(back-up) • Target: all BHFs in member states • Purpose: diversion detection	- National inspection (KINAC) • Target: domestic BHFs • Purpose: diversion detection & evaluation of accounting system

02 Methods

- **Governing equation for MUF in a LEU fuel conversion & fabrication plant**

$$M = \sum_{l=PB,X,Y,PE} A_l \sum_{i=1}^{I} \sum_{j=1}^{J} (p_j f_{U,ij} w_{235,ij} \sum_{k=1}^{K} (m_{ijk}))$$

A_l: type of physical inventory (+1 (PB, X), -1 (PE, Y),)
I: number of stratum for an inventory ($i = 1,2,\dots,I$),
J: number of lots in a stratum (j $= 1,2,\dots,J$),
K: number of items in a lot (k $= 1,2,\dots,K$).

- **Individual measurement uncertainty components**
  - Weighing (m) with EBAL
    - EBAL indicator (X), buoyancy factor (f_b), and calibration factor (f_c)
  - Sampling (p) for destructive analysis ($p \sim N(1, \delta_p^2)$)
  - U concentration analysis (f_U) with GRAV
    - Oxygen to Uranium ratio (O/U)
    - ➢ Mass ratio (m_i/m_f), impurity concentration (w_I, w_F), and ^{235}U enrichment (w_{235})
  - ^{235}U enrichment (w_{235}) with TIMS
    - Isotopic ratio (R_{234}/R_{238}, R_{235}/R_{238}, R_{236}/R_{238})
    - ➢ Sample meas. ratio ($RS(m)_{23x/238}$), cert. meas. ratio ($RC(m)_{23x/238}$), certificate ratio ($RC(c)_{23x/238}$), BKG ($RB_{23x/238}$), det. eff. ($\delta(Y), \delta(L), \delta(F)$)

Individual uncertainty

Uncertainty components

- **(IAEA) ANOVA-based uncertainty quantification (1/4)**
  – Setup a pair-wise difference statistics & separate random and systematic components

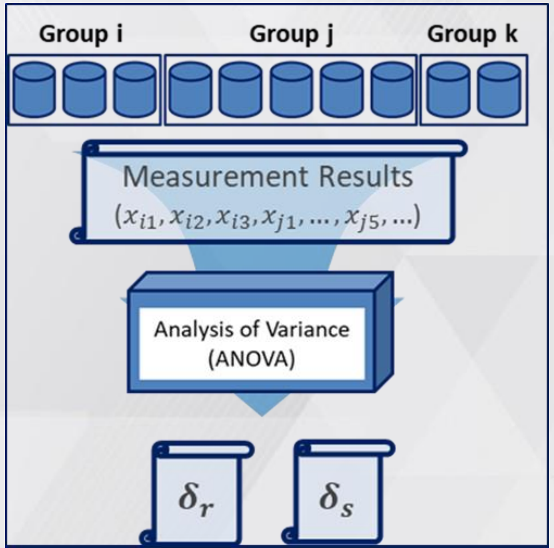
** IAEA, IAEA-SG-PR-2016*

1. Establish a database of pair-wise differences for a number of groups of samples
2. Let x_{gi} and y_{gi} be the facilities' and inspectors' measurement results for an item whose group is g and ID is i
3. Let m_g and G be the number of items in group g and the number of groups.
4. Let d_{gi} and V_{gd} be the pair-wise difference $x_{gi} - y_{gi}$ and its variance for items in group g
5. Estimate the random variance (V_{rd} $(= \widehat{\sigma_{rd}}^2)$) of the pair-wise differences

$$\widehat{\sigma_{rd}}^2 = \frac{\sum_{g=1}^{G}(m_g - 1)V_{gd}}{\sum_{g=1}^{G}(m_g - 1)}$$

6. Estimate the systematic variance (V_{sd} $(= \widehat{\sigma_{sd}}^2)$) of the pair-wise differences

$$\widehat{\sigma_{sd}}^2 = \left(\frac{\sum_{g=1}^{G}\left(\sum_{i=1}^{m_g}\frac{d_{gi}}{m_g}\right)}{G}\right)^2 - \frac{\left(\frac{\sum_{g=1}^{G}\left(\frac{1}{m_g}\right)}{G}\right)\widehat{\sigma_{rd}}^2}{G}$$



δ_r^2: Avg. variance within groups

δ_s^2: Avg. variance between groups

- **(IAEA) ANOVA-based uncertainty quantification (2/4)**
  - Separate operator's and inspector's variance

** IAEA, IAEA-SG-PR-2016*

- Estimate the random variance of an operator ($V_{rx}(=\widehat{\sigma_{rx}}^2)$) and inspector ($V_{ry}(=\widehat{\sigma_{ry}}^2)$) using the Grubbs' method

$$\widehat{\sigma_{rx}}^2 = \frac{\sum_{g=1}^{G}(m_g-1)\widehat{\sigma_{rgx}}^2}{\sum_{g=1}^{G}(m_g-1)}, \quad \widehat{\sigma_{ry}}^2 = V_{rd} - \widehat{\sigma_{ry}}^2$$

$$\begin{cases} \widehat{\sigma_{rgx}}^2 = v_{gx} - v_{gxy} \\ v_{gx} = \dfrac{\left(\sum_{i=1}^{m_g} x_{gi}^2 - \frac{\left(\sum_{i=1}^{m_g} x_{gi}\right)^2}{m_g}\right)}{m_g-1} \\ v_{gxy} = \dfrac{\left(\sum_{i=1}^{m_g} x_{gi}y_{gi} - \frac{\left(\sum_{i=1}^{m_g} x_{gi}\right)\left(\sum_{i=1}^{m_g} y_{gi}\right)}{m_g}\right)}{m_g-1} \end{cases}$$

$\widehat{\sigma_{rgx}}^2$: operator's random variance for items in group *g*

v_{gx}: operator's variance for items in group *g*

v_{gxy}: operator's and inspector's co-variance for items in group *g*

- **(IAEA) ANOVA-based uncertainty quantification (3/4)**
  – Separate operator's and inspector's variance

  ** IAEA, IAEA-SG-PR-2016*

  - If impossible ($\mathrm{V_{rx,ry}} < 0$), estimate the random variance of a facility based on the DODGRU (DOD and GRUbbs' estimator) method

$$\widehat{\sigma_{rx}}^{2} = \mathrm{S}\frac{I_0}{I_1}$$

DODGRU parameters

$$\begin{cases} S = \dfrac{\sum_{g=1}^{G}(m_g-1)\,\widehat{\sigma_{rgx}}^{2}}{\sum_{g=1}^{G}(m_g-1)} + \dfrac{\sum_{g=1}^{G}(m_g-1)\,\widehat{\sigma_{rgy}}^{2}}{\sum_{g=1}^{G}(m_g-1)} \\ n = \sum_{g=1}^{G}(m_g-1) \\ S_1^2 = \sum_{g=1}^{G}(m_g-1)\,v_{gx}/n \\ S_2^2 = \sum_{g=1}^{G}(m_g-1)\,v_{gy}/n \\ S_{12} = \sum_{g=1}^{G}(m_g-1)\,v_{gxy}/n \\ Q = (1+(S_2^2-S_{12})/(S_1^2-S_{12}))^{-1} \end{cases}$$

$$\begin{cases} I_0 = \int_0^1 vf(v)dv \\ I_1 = \int_0^1 f(v)dv \\ f(v) = (Sv^2 + 2(S_{xy}-S_x^2)v + S_x^2)^{-0.5n} \end{cases}$$

$$\begin{cases} (for -1 \le Q \le 2) \\ \begin{cases} S_x^2 = S_1^2 \\ S_{xy} = S_{12} \end{cases} \\ (for\ Q < -1\ or\ Q > 2) \\ \begin{cases} S_x^2 = 3S\dfrac{S_1^2}{|S_2^2 - S_1^2|} \\ S_{xy} = \begin{pmatrix} S\dfrac{(S_1^2+2S_2^2)}{(S_1^2-S_2^2)}\ (for\ S_1^2 > S_2^2) \\ S\dfrac{(2S_1^2+S_2^2)}{(S_2^2-S_1^2)}\ (for\ S_2^2 > S_1^2) \end{pmatrix} \end{cases} \end{cases}$$

→

- Determined by numerical estimation of the likelihood analysis
- The estimated results have low traceability

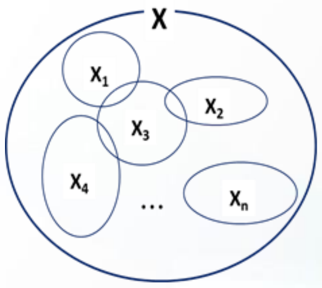
- **(IAEA) ANOVA-based uncertainty quantification (4/4)**
  - Separate operator's and inspector's variance

    ** IAEA, IAEA-SG-PR-2016*

  - Estimate the systematic variance of a facility ($V_{sx}(=\widehat{\sigma_{sx}}^2)$) based on an assumption ($\widehat{\sigma_{sx}}^2 = \widehat{\sigma_{sy}}^2$)

    $\widehat{\sigma_{sx}}^2 = \frac{1}{2}\left(\widehat{\sigma_{sd}}^2\right)$

- **(National Inspection) GUM-based uncertainty quantification (1/5)**
  - Setup an equation to quantify a measurement result
    - $X = f(x_1, x_2, x_3)$
  - Establish standard accounting procedures
    1. Identify initial characteristics of a sample (x_1, x_2, x_3)
    2. Measure the sample using an accounting system with the initial characteristics (X)
  - Identify individual uncertainty components
    - $x_1 = f\left(x_{1r_1}, \dots, x_{1r_n}, x_{1s_1}, \dots, x_{1s_{n'}}\right), x_2 = f\left(x_{2r_1}, \dots, x_{2r_m}, x_{2s_1}, \dots, x_{2s_{m'}}\right), x_3 = f\left(x_{3r_1}, \dots, x_{3r_k}, x_{3s_1}, \dots, x_{3s_{k'}}\right)$
  - Propagate them based on their characteristics



Equation for the mesurand X

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Apply Taylor series

$X = X_o + \sum_{i=1}^{n} \frac{\partial X}{\partial x_i}(x_i - x_{i0}) + \sum_{k=1}^{n} \sum_{j=1}^{n} \frac{1}{2!} \frac{\partial^2 X}{\partial x_j x_k}(x_j - x_{j0})(x_k - x_{k0}) + \cdots$

Approximation

$X \cong X_o + \sum_{i=1}^{n} \frac{\partial X}{\partial x_i}(x_i - x_{i0})$

Estimate the variance of the mesurand X

$E[(X - X_o)^2] = \mathrm{E}\left[\left(\sum_{i=1}^{n} \frac{\partial X}{\partial x_i}(x_i - x_{i0})\right)^2\right]$

$$u_c(X)^2 = \sum_{i=1}^{n} \left(\frac{\partial X}{\partial x_i}\right)^2 \mathrm{u}(\mathrm{x_i})^2 + \sum_{j=k+1}^{n} \sum_{k=1}^{n-1} \frac{\partial^2 X}{\partial x_j \partial x_k} r(\mathrm{x_j}, \mathrm{x_k}) \mathrm{u}(\mathrm{x_i}) \mathrm{u}(\mathrm{x_j})$$

Independent factors (Random components)

Correlation factors (Systematic components)

Assumption: $r(x_j, x_k) = \pm 1$ (for conservatism)

- **(National Inspection) GUM-based uncertainty quantification (2/5)**

  (Example) measurement uncertainty for U concentration analysis using GRAV method

  – Setup an equation to quantify U concentration ($\boldsymbol{f}_U$)

$$f_U = \frac{A_U}{A_U + A_O(O/U)}$$

  - Consider A_U and A_O as a constant, O/U as the only uncertainty source

  – Setup an equation to quantify the oxygen-to-uranium ratio (O/U)

$$O/U = \frac{[(1-w_I)(m_i/m_f) - F_S(1-w_F)]A_U}{F_S(1-w_F)A_O} \qquad F_S = \frac{3A_U}{3A_U+8A_O},\ A_U \cong w_{235}A_{U-235} + (1-w_{235})A_{U-238}$$

  - Consider A_O, F_S as constants and $m_i,\ m_f,\ w_I,\ w_F,\ w_{235}$ as uncertainty sources

- **(National Inspection) GUM-based uncertainty quantification (3/5)**

  (Example) measurement uncertainty for U concentration analysis using GRAV method

  – Establish standard accounting procedures

1. Calibrate electric balance (EBAL) before measurement
2. Measure sample mass before oxidation (m_i) using the EBAL ($m_i = m_i(gross) - m_i(tare)$)
3. Identify ^{235}U enrichment (w_{235}) and impurity concentration before oxidation (w_I) using the QC paper
4. Oxidize the sample using a thermogravimetric analyzer (TGA)
5. Measure sample mass change (Δm) inside TGA and calculate sample mass after oxidation (m_f) ($m_f = m_i + \Delta m$)
6. Identify impurity concentration after oxidation (w_F) using the QC paper
7. Calculate O/U ratio using the identified $m_i, m_f, w_I, w_F, w_{235}$
8. Calculate f_U using the calculated O/U ratio

- **(National Inspection) GUM-based uncertainty quantification (4/5)**

(Example) measurement uncertainty for U concentration analysis using GRAV method

– Identify individual uncertainty components

1. Calibrate electric balance (EBAL) before measurement
2. Measure sample mass before oxidation (m_i) using the EBAL
3. Identify ^{235}U enrichment (w_{235}) and impurity concentration before oxidation (w_I) using the QC paper
4. Oxidize the sample using a thermogravimetric analyzer (TGA)
5. Measure sample mass change (Δm) inside TGA and calculate sample mass after oxidation (m_f) ($m_f = m_i + \Delta m$)
6. Identify impurity concentration after oxidation (w_F) using the QC paper
7. Calculate O/U ratio using the identified m_i, m_f, w_I, w_F, w_{235}
8. Calculate f_U using the calculated O/U ratio

$u(f_c) = f(m_{std}, X_{std}, \varepsilon_{lin}, \varepsilon_{res})$

$u(X_s) = f(x_{s1}, \ldots)$

$u(m_i) = f(m_g, m_t)$

$u(m_{g,t}) = f(X_s, f_b, f_c)$

$u(f_b) = f(x_{b1}, \ldots)$

$u(w_{235}) = a(w_{235})/\sqrt{3}$

$u(w_I) = a(w_I)/\sqrt{3}$

$u(\Delta m) = f(\Delta m_{TGA}, drift, buo.)$

$u(m_f) = f(m_i, \Delta m)$

$u(\Delta m_{TGA}) = f(x_{\Delta 1}, \ldots)$

$u(drift) = f(x_{d1}, \ldots)$

$u(w_F) = a(w_F)/\sqrt{3}$

$u(buo.) = f(x_{b1}, \ldots)$

$u(O/U) = f(m_i, m_f, w_I, w_F, w_{235})$

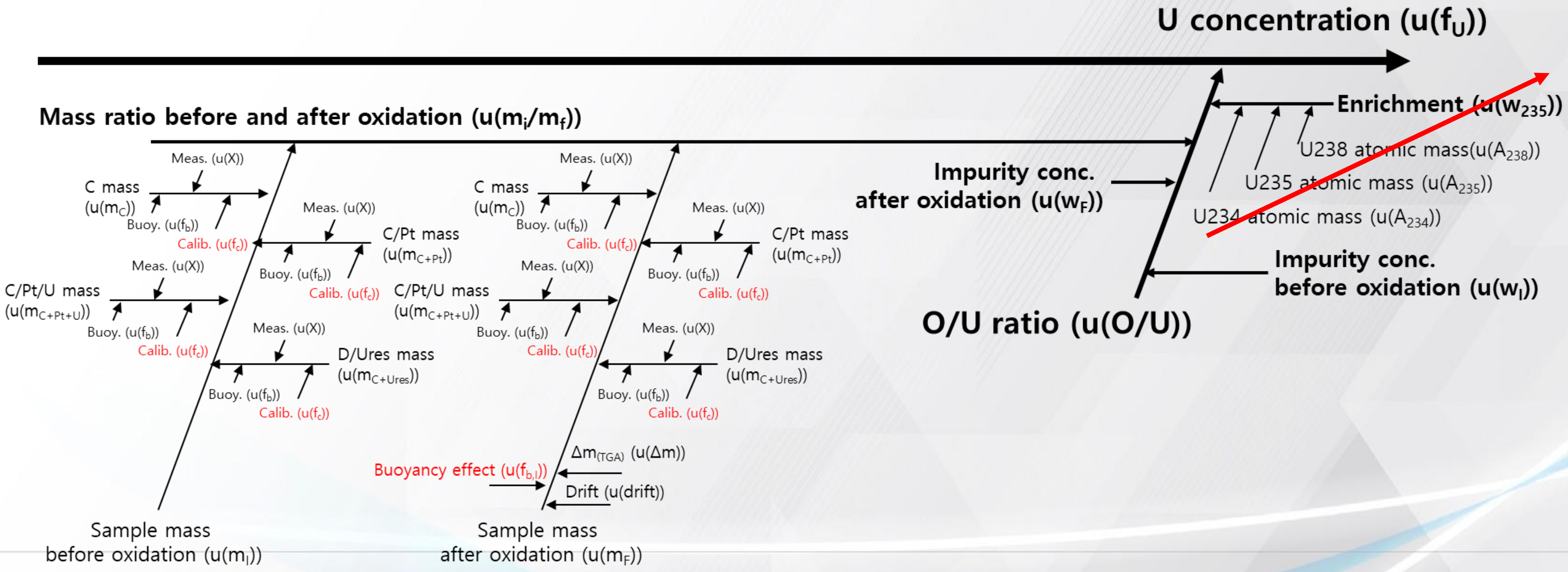
$u(f_U) = f(u(O/U))$

02 Methods

- **(National Inspection) GUM-based uncertainty quantification (5/5)**

  (Example) measurement uncertainty for U concentration analysis using GRAV method

  – Propagate individual uncertainty components based on their characteristics



- **Quantifying $u(f_U)$ using previous inspection data for two methods**
  - Results of U concentration analysis for pure UO_2 pellets in KO1R
    - 6 groups, 53 items
    - Sampled between 2020 ~ 2023
  - Both KNF and KINAC analyzed U concentration using GRAV method

Group		Item	KNF (x_{gi})	KINAC (y_{gi})	d
1	B0011 (2020)	1	[redacted]	[redacted]	1.200E-03
		2	[redacted]	[redacted]	-1.700E-03
		3	[redacted]	[redacted]	6.600E-02
	B0013 (2020)	1	[redacted]	[redacted]	7.700E-03
		2	[redacted]	[redacted]	-1.880E-02
		3	[redacted]	[redacted]	1.110E-02
	B0016 (2020)	1	[redacted]	[redacted]	-6.500E-03
		2	[redacted]	[redacted]	5.800E-03
		3	[redacted]	[redacted]	8.000E-04
	B0017 (2020)	1	[redacted]	[redacted]	-1.090E-02
		2	[redacted]	[redacted]	-1.700E-03
		3	[redacted]	[redacted]	1.260E-02
2	B0022 (2021)	1	[redacted]	[redacted]	4.260E-02
		2	[redacted]	[redacted]	3.030E-02
	B0023 (2021)	1	[redacted]	[redacted]	4.590E-02
		2	[redacted]	[redacted]	3.490E-02
	B0024 (2021)	1	[redacted]	[redacted]	4.740E-02
		2	[redacted]	[redacted]	3.850E-02
	B0026 (2021)	1	[redacted]	[redacted]	4.040E-02
		2	[redacted]	[redacted]	3.080E-02
	B0028 (2021)	1	[redacted]	[redacted]	1.900E-02
		2	[redacted]	[redacted]	2.670E-02
	B0029 (2021)	1	[redacted]	[redacted]	3.420E-02
		2	[redacted]	[redacted]	3.980E-02
	B0045 (2021)	1	[redacted]	[redacted]	2.200E-02
		2	[redacted]	[redacted]	-1.400E-02
	B0047 (2021)	1	[redacted]	[redacted]	-1.200E-02
		2	[redacted]	[redacted]	2.600E-02
	B0051 (2021)	1	[redacted]	[redacted]	9.000E-03
		2	[redacted]	[redacted]	-9.000E-03

Group		Item	KNF (x_{gi})	KINAC (y_{gi})	d
3	B0077-78 (2022)	1	[redacted]	[redacted]	3.700E-03
		2	[redacted]	[redacted]	-4.470E-02
		3	[redacted]	[redacted]	-3.000E-02
		4	[redacted]	[redacted]	-1.200E-03
	B0089-90 (2022)	1	[redacted]	[redacted]	2.900E-02
		2	[redacted]	[redacted]	-1.520E-02
		3	[redacted]	[redacted]	3.460E-02
		4	[redacted]	[redacted]	-9.700E-03
4	B0100	1	[redacted]	[redacted]	3.600E-02
	B0104	1	[redacted]	[redacted]	2.800E-02
	B0107	1	[redacted]	[redacted]	-1.400E-02
	B0112	1	[redacted]	[redacted]	-1.400E-02
5	B0115	1	[redacted]	[redacted]	2.500E-02
		2	[redacted]	[redacted]	-1.400E-02
	B0118	1	[redacted]	[redacted]	-1.150E-01
		2	[redacted]	[redacted]	2.450E-01
	B0124	1	[redacted]	[redacted]	2.000E-02
		2	[redacted]	[redacted]	-2.300E-02
6	B0126	1	[redacted]	[redacted]	1.800E-02
	B0131	1	[redacted]	[redacted]	3.900E-02
	B0132	1	[redacted]	[redacted]	-1.600E-02
	B0133	1	[redacted]	[redacted]	1.500E-02
	B0137	1	[redacted]	[redacted]	4.300E-02

03 Results

- **Quantifying $u(f_U)$ for the ANOVA method**
  - Estimate variances for pair-wise differences

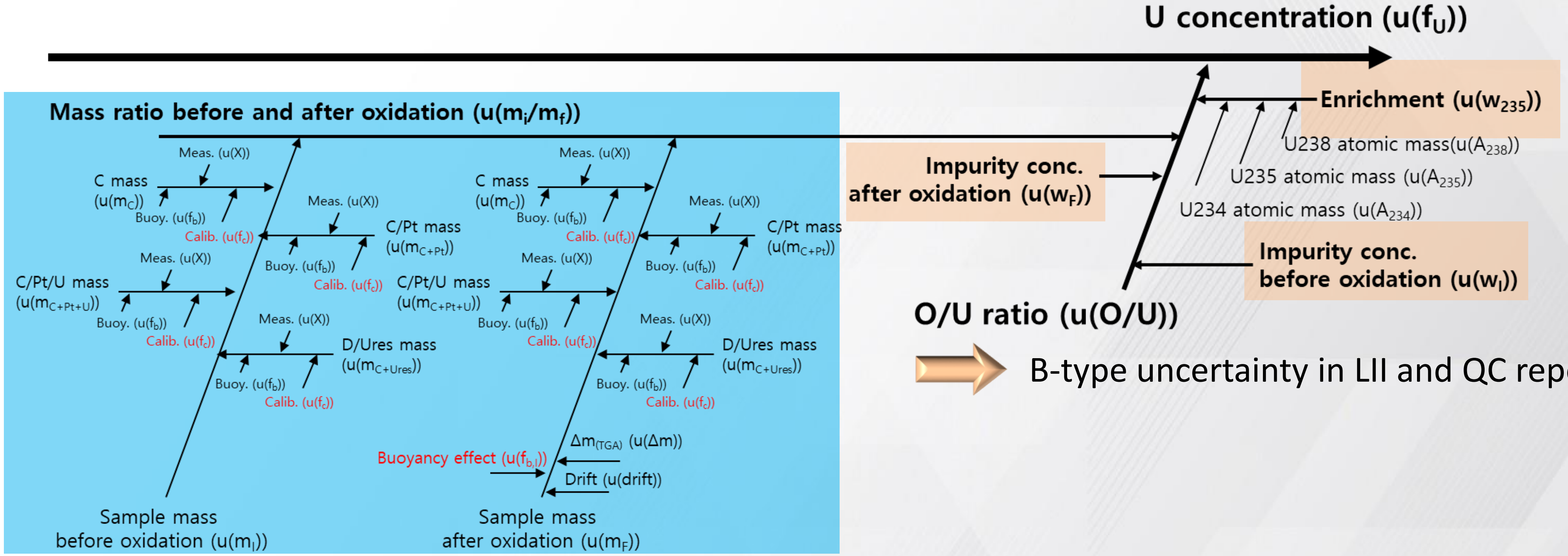
Group	G	m_G	1/m_G	m_G-1	V_gd	(m_G-1)*Vgd	(σ_r)^2	Avg(d_g)	Avg(d_g)^2	V(d)	(σ_s)^2
1	6	12	0.0833	11	0.00044	0.00489	0.00197	5.467E-03	2.988E-05	1.323E-04	1.217E-04
2		18	0.0556	17	0.00038	0.00648	σ_r	2.514E-02	6.320E-04		σ_s
3		8	0.1250	7	0.00073	0.00514	0.0444	-4.187E-03	1.754E-05		0.0110
4		4	0.2500	3	0.00072	0.00215	δ_r (%)	9.000E-03	8.100E-05		δ_s (%)
5		6	0.1667	5	0.01437	0.07183	0.0504	2.300E-02	5.290E-04		0.0125
6		5	0.2000	4	0.00055	0.00221		1.980E-02	3.920E-04		

  - Estimate operator's random & systematic variances using PADCEL $(V_y < 0)$

Group	G	m_G	m_G-1	sum(x_g)	sum(y_g)	sum(x_g^2)	sum(y_g^2)	sum(x_g*y_g)	V_gx	V_gy	V_gxy	(σ_rgx)^2	rgx)^2*(m_g	(σ_rgy)^2	rgy)^2*(m_g-	**(σ_rx)^2**	(σ_ry)^2	**(σ_sx)^2**	(σ_sy)^2	
1	6	12	11	1057	1057	93186	93174	93180	8.291E-04	1.046E-03	7.151E-04	1.141E-04	1.255E-03	3.309E-04	3.640E-03	**4.852E-05**	1.924E-03	**7.726E-05**	7.726E-05	
2		18	17	1587	1586	139849	139769	139809	1.069E-05	4.115E-04	2.045E-05	-9.758E-06	-1.659E-04	3.910E-04	6.648E-03					
3		8	7	705	705	62149	62155	62152	1.143E-04	5.312E-04	-4.414E-05	1.584E-04	1.109E-03	5.753E-04	4.027E-03					
4		4	3	353	353	31079	31073	31076	1.667E-06	6.590E-04	-2.767E-05	2.933E-05	8.800E-05	6.867E-04	2.060E-03					
5		6	5	529	529	46618	46594	46606	1.067E-06	1.439E-02	1.507E-05	-1.400E-05	-7.000E-05	1.438E-02	7.190E-02					
6		5	4	441	441	38848	38831	38840	5.800E-06	5.272E-04	-1.035E-05	1.615E-05	6.460E-05	5.376E-04	2.150E-03					
DODGRU parameters							DODGRU MATRIX(nu_x(g,h))							DODGRU MATRIX(nu_y(g.h))						
S_0	V1	V2	S_1	Rev(S_0)	V_x0	V_y0	m_g^(-1)	0.083333333	0.0555556	0.125	0.25	0.16666667	0.2	m_g^(-1)	0.083333333	0.05555556	0.125	0.25	0.16666667	0.2
-1.571E-04	1.323E-04	1.972E-03	9.433E-06	9.433E-06	2.153E-04	1.961E-04	Avg(x_g)	88.1219	88.1441	88.1400	88.1465	88.1457	88.1456	Avg(x_g)	88.1219	88.1441	88.1400	88.1465	88.1457	88.1456
DOD(σ_gx)^2		DOD(σ_gy)^2					Avg(y_g)	88.1164	88.1190	88.1442	88.1375	88.1227	88.1258	Avg(y_g)	88.1164	88.1190	88.1442	88.1375	88.1227	88.1258
4.938E-06		4.495E-06						1	2	3	4	5	6		1	2	3	4	5	6
							1	-4.043E-06	2.153E-04	-9.254E-05	3.542E-05	2.025E-04	1.632E-04	1	-1.603E-04	-1.588E-04	-6.631E-05	-3.579E-04	-2.953E-04	-3.399E-04
							2		2.695E-06	5.590E-05	2.669E-05	7.054E-06	1.017E-05	2		1.069E-04	1.961E-04	1.444E-04	2.098E-04	2.276E-04
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	…05
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	…04
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	…04
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	…04

$\delta(f_U)$	$\delta_r(f_U)$	$\delta_s(f_U)$
0.00015	0.000079	0.00012

- **Quantifying $u(f_U)$ for the GUM-based method**



→ B-type uncertainty in LII and QC report

→ Replaced to the KINAC's repeated measurement process (Standard U concentration analysis using GRAV(TGA))

$\delta(f_U)$	$\delta_r(f_U)$	$\delta_s(f_U)$
0.00038	0.00038	0.000014

- **Analysis of uncertainty components in accounting process level**

– Estimated $u(f_U)$: $u_r(m_i/m_f)$

δ(f_U)	f_U	u(f_U)	δ(O/U)	O/U	u(O/U)	u_r(mi/mf)	u_s(mi/mf)	u_r(w_I)	u_r(w_F)	u_r(w_235)
3.8317E-04	8.8130E+01	3.3768E-02	3.2279E-03	2.0027E+00	6.4647E-03	3.6782E-04	1.3260E-05	2.1252E-05	5.9525E-06	3.1220E-05
δ_r(f_U)	nu(f_U)	u_r(f_U)	δ_r(O/U)	nu(O/U)	u_r(O/U)	c(mi/mf)	c(mi/mf)	c(w_I)	c(w_F)	c(w_235)
3.8292E-04	5.0640E+04	3.3747E-02	3.2259E-03	5.0640E+04	6.4605E-03	1.7535E+01	1.7535E+01	-1.6873E+01	1.6873E+01	7.2002E-03
δ_s(f_U)		u_s(f_U)	δ_s(O/U)	c(O/U)	u_s(O/U)	frac_r(mi/mf)	frac_s(mi/mf)	frac(w_I)	frac(w_F)	frac(w_235)
1.3781E-05		1.2146E-03	1.1610E-04	-5.2235E+00	2.3252E-04	9.9539E-01	1.2936E-03	3.0769E-03	2.4137E-04	1.2091E-09

– Estimated $u_r(m_i/m_f)$: $u_r(m_f)$

mi/mf	u(mi/mf)	u_r(mi)	u_r(mf)	u_s(mi_fc)	u_s(mf_fc)	u_s(mf_m_b)
0.96217	3.681E-04	1.9217E-04	3.4709E-04	6.5149E-06	6.5149E-06	1.44339E-05
nu(mi/mf)	u_r(mi/mf)	c(mi)	c(mf)	c(mi)	c(mf)	c(mf)
5.0663E+04	3.678E-04	0.95464	-0.91853	0.95464	-0.91853	-0.91853
	u_s(mi/mf)	frac(u_r(mi/mf)_mi	frac(u_r(mi/mf)_mf)	frac(u_s(mi/mf)_fc)		frac(u_s(mi/mf)_mb)
	1.326E-05	2.4875E-01	7.5125E-01	3.1481E-04		9.997E-01

– Estimated $u_r(m_f)$: $u_r(\Delta m)$

mf	u(mf)	u_r(m(C))	u_r(m(C+Pt))	u_R(m(C+Pt+U))	u_r(m(C+U_res))	u_s(m(C))	u_s(m(C+Pt))	u_s(m(C+Pt+U))	u_s(m(C+U_res))	u(Δm)	u(m_b)	u(drift)
1.0475	3.4745E-04	6.40086E-05	0.000112463	0.000126828	6.40081E-05	2.5556E-05	4.9620E-05	5.6135E-05	2.5556E-05	1.4435E-05	1.4434E-05	2.8868E-04
nu(mf)	u_r(mf)	c(m(C))	c(m(C+Pt))	c(m(C+Pt+U))	c(m(C+U_res))	c(m(C))	c(m(C+Pt))	c(m(C+Pt+U))	c(m(C+U_res))	c(Δm)	c(m_b)	c(Δm)
3.1130E+04	3.4709E-04	1	-1	1	-1	1	-1	1	-1	1	-1	1
	u_s(mf)	frac(m(C))	frac(m(C+Pt))	frac(m(C+Pt+U))	frac(m(C+U_res))	frac(u_s(mf))				frac(Δm)	frac(m_b)	frac(Δm)
	1.5836E-05	3.4009E-02	1.0499E-01	1.3352E-01	3.4009E-02	1.6925E-01				1.7296E-03	8.3075E-01	6.9174E-01

➡ Drift effect is the most significant uncertainty component in GRAV ➡ Need to manage sample mass

03 Results

- **Quantifying uncertainty with different expression methods**
  - Both method satisfied target $\delta(f_U)$ in ITV 2020 ** IAEA, IAEA-STR-368 (rev.1.1)*

	$\delta(f_U)$	$\delta_r(f_U)$	$\delta_s(f_U)$
ITV 2020	0.0007	0.0005	0.0005
ANOVA	0.00015	0.000079	**0.00012**
GUM	0.00038	**0.00038**	0.000014

- **Comparison between two uncertainty expression methods**

Methods	ANOVA	GUM
Future works to check	- Too small $\delta_r(f_U)$, need to check whether sample analysis is for the QC and adopt nominal values - Need to pile up more pair-wise differences	- Too many assumptions in estimating facilities' accounting process - Need to reflect facilities' detailed accounting process

04 Conclusions

- KINAC has been developing an MBE method to strengthen the technical capability of SSAC as well as to solve cumulative MUF issue
- We are considering to adopt a GUM-based method for domestic MBE since it can analyze contribution in accounting process level
- Two uncertainty expression methods were examined for U concentration analysis using the GRAV method for previous national inspection results
- Results indicated the both method satisfy the value in ITV 2020
- However, we need more detailed information of facility to achieve more realistic value

Thank you for your attention!

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