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THE CHOICE OF NUCLEAR MATERIAL MEASUREMENT STRATEGY IN "BULK-FORM" IN MATERIAL BALANCE AREA

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INTRODUCTION

During the life cycle (from mining to final disposal), all nuclear materials (NM) appear in the "bulk-form" [1] at certain stages of the technological process, and sometimes, of the usage. Besides, the amount and content of the NM as "items" [1] are determined objectively by the measurement of the material quantities and isotopic composition of the bulk-form at technological stages preceding the appearance of items themselves. These data are registered in the forms and records (Technical specifications [TU], passport, special form, etc.). After that, these data, with results of indirect measurements, verification, or radiation pasportization, appear to be the most reliable and accurate during the whole period of the use of this "item".

Therefore, one of major conditions determining the accuracy and reliability of nuclear material balance at federal level, as well as the guarantee of their non-proliferation (non-diversion) is a substantiated choice of strategy for NM measurement in "bulk-form" available and shipped-received by the nuclear material balance area (MBA) during material balance periods.

BATCH OF NUCLEAR MATERIAL

In practical production and use of NM, the term "batch" is used in the following variants of meaning:

- Dispatching (shipment) batch of NM;
- Technological batch of NM;
- Accounting batch (portion) of NM [1,2].

The choice of quantitative characteristics of batch in each case is determined by various considerations. Let us consider the concepts and assumptions used as a basis for quantitative estimations.

"Dispatching (shipment)" batch of NM

It follows from the caption that the quantity of material in the batch is determined by economic justification for the transportation of such batch, or other ones (e.g., radiation-related). The quantity of material in such batch is indicated in technical requirements for the transportation referred to in the specifications, passport, form, etc, as well as in the shipment list. Obviously, the quantity of material in a shipment batch is not directly related to the choice of strategy.

"Technological batch" of NM

When designing technological processes of production or use of NM, as dependent on the capacity of technological equipment available and modes of its operation, NM is subdivided into parts – technological batches – according to quantitative requirements. This part of the flow is technological batch of NM. Thus, for example, a technological batch for NPP reactor is the number (mass) of fuel subassemblies (SA) loaded into reactor core for operation cycle. For the section of pellet sintering it implies the number (mass) of pellets per one loading into electrical furnace. Obviously, the choice of quantity in technological batch is not directly related to the choice of measurement strategy of NM in MBA.

"Accounting batch", or simply "batch" of NM

According to [2], batch is "...a portion of nuclear material treated as a unit of measurement (weighing) for the accounting purposes at a key measurement point (KMP), its composition and quantity being determined by a unified complex of NM specifications or measurements. Nuclear material in the batch can be in "bulk-form" or "items".

As it is obvious from this definition, this batch must be in a certain way associated with the NM measurement strategy in the MBA. However, the publication referred to does not give any idea, how this association is realized, and which is the effect dividing the total amount of NM in MBA into batches in the measurements.

Let us attempt to show with statistical approach to the mathematical processing of results that the latter variant makes it possible to considerably decrease the error in estimates of measured amounts of nuclear materials in MBA with a pre-specified confidence level vs. the former two variants.

MEASUREMENT STRATEGY CHOICE

Let us consider the following case of the realization of technological process for NM production within a certain MBA, for which primary information [3] and the value of MBA transfer function [4].

Structurally, this MBA includes storage for raw materials, technological sector for NM processing, storage for finished products, and that for "scrap" [1] formed as a result of the raw material processing as wastes and rejects. For a simplification, let the transfer function of technological process be assumed as:

$$Q_k = KQ_k = 0.9 \cdot Q_H, \qquad (1)$$

where: Q_k - quantity of ready products ready for further use (kg);
Q_H- quantity of source materials (kg);
K - data transfer coefficient equal to $K=1-K_n$,
K_n - percentage of losses in the processing of raw materials (here assumed as $K=1-K_n$).

Let the NM production capacity for the given MBA during the material balance period be Q=3000 kg. For the rythmical operation of this MBA shipping the source material, reliable source material stock of 50% of production capacity is stipulated for the inter-balance period: Q_1=1500 kg. Raw materials are shipped by batches distributed as approximately equal by time three times during the inter-balance period. Batch sizes are: Q_2'=1000 kg; Q_2''=1300 kg; Q_3=700 kg. The material balance period - τ=2 months. The personnel of the section works in one shift, 6 h a day, 5-day working week. There are 40 shifts during the material balance period (3 shifts for the production section outage to "clean" the equipment and physical inventory taking and closing the balance). Technological cycle - τ_c = 6 hours (one shift). The size of technological batch Q_T=75 kg. Three key measurement points (KMP) have been established for this material balance area (MBA):

KMP 1 verification of source material quantity (input);
KMP 2 verification of finished product quantity (output 1);
KMP3 verification of the amount of "scrap" (output 2).

It is assumed here for a simplification of further considerations, that isotopics of NM in this MBA is not verified; the isotope composition is ensured by previous measurements, as well as by the use of tools and devices for preservation and surveillance, access control tools, and physical protection).

The instruments for NM quality assurance installed at each KMP are calibrated.

The system component of the instrument error is excluded by the use of corresponding standards.

The random component of the error - Δ_{random}=1% of the value measured, the confidence limit being γ =0.95.

And this value of error is ensured to be preserved for the whole range of measurements carried out at KMP1, KMP2, and KMP3.

The following strategies for NM quantity at MBA are possible, to be considered below.

STRATEGY 1. Single measurement of dispatching, technological, and shipment batches

Measurement of NM received by/shipped from MBA and those present in the MBA during the physical inventory taking is carried out by total quantity, i.e.:

1. The quantities of nuclear materials in the MBA are measured at the moment of reception, as one weight

a. Q_2'=1000 kg;

b. Q_2''=1300 kg;

c. Q_2''=700 kg.

2. The quantity of NM present at the MBA at the beginning of material balance period is measured as one weight.

Q_1=1500 kg.

3. Each NM shipment is measured as one weight

a. Ten shipments Q_4=270 kg each (finished product);

b. One shipment Q_5=300 kg ("scrap").

If it is assumed that no thefts occurred during the material balance period in this MBA, then the balance equation for the data of previous inventory taking, as well as for shipment and receiving data must give a result as:

$$Q_1 + (Q_2' + Q_2'' + Q_2'') - 10Q_4 - Q_5 - Q_3 = ID, \qquad (2)$$

where Q_3 - result of physical inventory taking (NM quantity actually available by the end of the material balance period);
ID – inventory difference (MUF, see [1]).

When all these values are measured (Q_i) with the error at γ=0.95 taken into account, we have:

$Q_1 = Q_3^k = 1500\,kg \pm 15\,kg$ (first and last measurements), or 1485 kg <=$Q_{1,3}$<= 1515 kg.

$Q_2^{'} = 1000\,kg \pm 10\,kg$ or $990\,kg \le Q_2^{'} \le 1010\,kg$;

$Q_2^{''} = 1300\,kg \pm 13\,kg$ or $1287\,kg \le Q_2^{''} \le 1313\,kg$;

$Q_2^{'''} = 700\,kg \pm 7\,kg$ or $693\,kg \le Q_2^{'''} \le 707\,kg$;

$Q_4 = 270\,kg \pm 2.7\,kg$ or $267.3\,kg \le Q_4 \le 292.7\,kg$;

$Q_5 = 300\,kg \pm 3.0\,kg$ or $297\,kg \le Q_5 \le 303\,kg$.

Since we measure Q_4 10 times (10 shipments 270 kg each), then total error for $10Q_4$ will amount to: $\Delta_4 = 2.9 : \sqrt{10} = 0.92\,kg$.

Using the methods of mathematical statistics for total error of several independent measurements (which do not belong to one general aggregate), in this case, according to [5], we have:

$$\Delta_{\gamma=0.95} = \sqrt{\left(\Delta_1^2 + (\Delta_2^{'})^2 + (\Delta_2^{''})^2 + (\Delta_2^{'''})^2 + \Delta_4^2 + \Delta_5^2 + \Delta_3^2\right)} = |ID|, \qquad (3)$$

where , $\Delta_1 \ldots \Delta_5$ - extreme values of error measurement for $Q_1 \ldots Q_5$;
|ID| - maximum admissible (critical) value of ID.

Substituting the error values, we have:

$$|ID| = \sqrt{(15^2 + 10^2 + 13^2 + 7^2 + 0.92 + 3^2 + 15^2} = 27.9\,kg \cong 28\,kg.$$

Thus, if physical inventory taking carried out by this strategy renders the value of NM physically available at this MBA (Q_3) in the range of {1472-1528 kg} this will mean that no theft of nuclear material is recorded.

As we can see, the range of uncertainty in this strategy amounts to 56 kg, with confidence range of γ=0.95. This may be not acceptable, because significant amount of U^{233}, e.g., is equal to 8 kg , whereas U^{235} - 25 kg.

STRATEGY 2. Measurement of NM by technological batches.

As it has been stated before, the size of technological batch for this MBA amounts to Q_T=75 kg. The nuclear material from the raw material storage is given to the custodian of the shift in the amount needed to ensure the work of the shift, and at the end of the working day (shift), as technological cycle is completed, the same custodian returns this material to the storage for finished product and storage for scrap, it might be convenient and expedient to subdivide all the material into technological batches and measure it by these batches, even at the input and output sections of this MBA.

The measurement strategy, in this case, includes the following:

1. The quantity of NM received at the storage for source materials of this MBA is measured by technological batches {Q_T=75 kg).

a. $Q_2^{'}$=1000 kg ($13\frac{1}{3}$ batch 75 kg each);

b. $Q_2''=1300$ kg ($17\frac{1}{3}$ batch 75 kg each);

c. $Q_2''=700$ kg ($9\frac{1}{3}$ batch 75 kg each);

Total: 40 batches 75 kg each.

2. The quantity of NM available at the storage facility of this MBA by the beginning of material balance period is measured by technological batches.

$Q_1=1500$ kg (20 batches 75 kg each)

3. Each shipment of NM is measured by batches.

$Q_4=270$ kg (3.6 batches 75 kg each)

Note: It might be justified to increase the size of shipment batch to 300 kg (9 shipments 300 kg each).

a. One shipment of scrap $Q_5=300$ kg. (4 batch 75 kg each).

Balance equation (2) in this case can be written as:

$$20Q_T + 13\tfrac{1}{3}Q_T + 17\tfrac{1}{3}Q_T + 9\tfrac{1}{3}Q_T + 36Q_T + 4Q_T + 20Q_T = ID, \qquad (4)$$

where $Q_T=75$ kg – the size of technological batch.

Random component of measurement error in this case amounts to $\Delta_{random}=1\%$ x $Q_T=0.01x75=0.75$ kg, and total error of all measurements can be calculated according to [6].

$$\Delta_{\Sigma_{random}} = |ID| = \pm t_{\gamma,k}\Delta_{random} / \sqrt{n}, \qquad (5)$$

where $t_{\gamma,k}$ - Student's coefficient for the pre-set confidence level $\gamma=0.95$ and the number of degrees of freedom $k=n-1$;

n - the number of measurements (in our case = 120);

Δ_{random} - random component of error of single measurement ($\Delta_{random}=0.75$ kg).

Substituting, we have: $|ID| = \pm 1.98\frac{0.75}{\sqrt{120}} = \pm 0.135$ kg.

Thus, with physical inventory taking by this strategy, the quantity of NM practically available at this MBA – Q_3 will be within the range Q_3I{1499.865 kg – 500.135 kg} - this will mean that no theft took place.

As we can see, with this strategy of measurement, the range of uncertainty for the estimation of NM practically available is {0.27}=|ID|, which is significantly less, than for the first strategy case. (Equivalent error of the metering instrument, which would allow to measure 1500 kg with this accuracy level: $\Delta_{eq}=0.007\%$ is unlikely to be achieved).

The result cited $Q_3=1500\pm0.135$ kg seems to be giving hopes from the standpoint of safeguards for non-diversion of nuclear materials, because it ensures safeguards related to critical values for NM. I.e., for example, the amount of theft is 8 kg (Pu or U^{233}), will be recorded beyond a doubt in both single measurement, and in inventory taking, because |ID|=±0.135 kg <<8 kg. However, as we agreed for this example, the period of physical inventory taking is 2 months, but the theft (e.g., 0.5 kg per shift) can take place at the beginning of the material balance period, and to detect this theft, we shall have to wait till the beginning of inventory taking procedure.

- Note: The quantity of theft is 0.5 kg/cm in weighing of 75 kg of NM falls within the range of uncertainty of a single measurement $\Delta_i=1.5$ kg). I.e., in intended inaccurate weighing and formation of the technological batch by the lower tolerance limit for a batch (Q_T>=74.25 kg) 16 shifts would be enough to withdraw 8 kg of NM from the production line. Here, the gamesmanship is observed: results of measurements are within the tolerance limits for measurement error.

Therefore, the strategy of measurement (weighing) NM by "technological batches" could prove insufficient for the safeguards objectives, because the time of evaluation of the material conversion into ready components from metallic uranium or plutonium (according to [1]) is 7-10 days.

STRATEGY 3. Measurement of NM by "accounting batches"

Now let us consider the notes necessary for the definition of numerical value of the "accounting batch".

Significant quantity – approximate amount of nuclear material, for which the possibility of creating a nuclear explosive cannot be excluded, taking into account any conversion processes used [1,6].

For the same sources numerical values of significant quantities of NM are established as well.

For the nuclear material, which can be directly used for fabricating nuclear explosives:

Plutonium (containing less than 80% Pu_{238}) - 8 kg (for all isotopes);

Uranium-235 – 8 kg (for the isotope only) ;

Uranium (containing 20% or more U^{235}) – 25 kg (U^{235}).

For nuclear materials of indirect use (material, which can be used for the fabrication of nuclear explosive only after a corresponding conversion processing):

Uranium (containing less than 20% of U^{235} – 75 kg (U^{235});

Thorium – 200 kg (for all isotopes of the element).

As we have seen already, for the case of withdrawal of a significant amount of NM from technological cycle in fractions smaller than the value of error for a single measurement, there is a possibility during a certain time period to withdraw this quantity, without detecting this fact.

Consequently, either more strict requirements should be addressed to single measurements' accuracy (which is not always feasible), or the quantity of NM measured (size of "accounting batch") should be diminished so that the error of single measurement made it possible to accumulate the amount of NM necessary only during the whole material balance period, when theft of this amount of NM will be registered beyond a doubt when physical inventory taking will be performed. In this case, the value of "accounting batch" can prove small enough, and labor input for measurements – considerable enough, which can prove economically non-efficient, especially in case of high production output of technological section, in a low accuracy of measuring tools available (e.g., Δ_{random}>=5%). Therefore, it is expedient, simultaneously with the optimization of the "accounting batch" size, to use statistical approaches to the estimation of possible thefts during a time shorter, than the material balance period (1,2,3... n shifts).

- Note: It should be noted that the size of "accounting batch" thus defined (further to be termed as "critical value of accounting batch size") will depend on the accuracy of measurements and the quantity of NM, which had passed the MBA and remained therein for the period between two inventory taking procedures consecutive in time.

Since there are four unknowns in this task (the "critical value of accounting batch size" , value of random component of error for its measurement, the amount of NM passed through the MBA and remaining therein by the moment of physical inventory taking, as well as the material balance period parameter), then this task should be solved by the method of consecutive approximations, decreasing the "critical value of accounting batch size" stepwise. The solution of the optimization task with four unknowns in a general presentation would not be expedient from the engineering standpoint because of large labor input necessary and complicated calculations).

The first step of iteration (approximation)

The size of "accounting batch"(Q_y) is equal to the size of "technological batch" (Q_y\Q_t\=75 kg). Measurement error (random component) Δ_{random}=75 kg.
The size of thefts anticipated (X) is assumed to be for variants as follows:

Variant 1 – X_1=0.5 kg/sh.;
Variant 2 – X_2=0.2 kg/sh.;
Variant 3 – X_3=0.1 kg/sh.

Assuming the material under study to be Pu^{239}, we take the significant quantity of NM to be equal to $|Q_{sq}|$=8 kg.
Thus, in order to "accumulate" this quantity, the intruder has to carry out thefts during period (T_i).

Variant 1: - $T_1 = \frac{|Q_{sq}|}{X_1} = \frac{8}{0.5} = 16$ shifts (16 batches 75 kg each);

Variant 2 - $T_2 = Q_y = 40$ shifts (equal to material balance period);

Variant 3 - $T_2 = \frac{|Q_{sq}|}{X_3} = \frac{8}{0.1} = 80$ shifts (exceeding the material balance period).

It is clear that with error of Δ_{random}=±0.75 kg, a single measurement would not give reliable data to state that theft had taken place, if in a repeated measurement (at the end of the shift) the quantity of NM became 74.5 kg.(74.8; 74.9) instead of 75 kg, measured at the beginning of the shift. Using expression (5), we find the time, during which the theft can be registered for variants 1, 2, 3.

1.1. 3 shifts ΣX_1=1.5 kg (ΣX_2=0.6 kg, ΣX_3=0.3 kg).

$$|ID| = \pm t^*_{\lambda,k} \frac{\Delta_{random}}{\sqrt{n}} = 4.3\frac{0.75}{\sqrt{3}} = \pm 1.86 \text{ kg} > 1.5 \text{ kg} > (0.6 \text{ kg}) > (0.3 \text{ kg}).$$

* - value $t_{y,k}$ is tabulated in [7].
Thus, for the three shifts one cannot state with certitude that no thefts (X_1;X_2 or X_3) had occurred.

1.2. 4 shifts ΣX_1=2 kg (ΣX_2=0.8 kg, ΣX_3=0.4 kg).

$$|ID| = \pm t_{\lambda,k} \frac{\Delta_{random}}{\sqrt{n}} = 3.182\frac{0.75}{4} = \pm 1.19 \text{ kg} < 2 \text{ kg } (>0.8 \text{ kg}; >0.4 \text{ kg}).$$

i.e., it can be stated with certitude that theft took place for the 4 shifts case, if the withdrawal per each shift had exceeded X_1>=0.5 kg (in the extreme case, registered amount is X_i>0.3 kg/sh);

1.3. 5 shifts ΣX_2=1 kg (ΣX_3=0.5 kg).

$$|ID| = \pm t_{\lambda,k} \frac{\Delta_{random}}{\sqrt{n}} = 2.776\frac{0.75}{\sqrt{5}} = \pm 0.93 \text{ kg} < 1 \text{ kg } (<0.5 \text{ kg}).$$

i.e., it can be stated with certitude that theft took place for the 5 shifts case, if each withdrawal had exceeded X_2>=0.2 kg/shift (instead of 40 shifts !)

1.4. 6 shifts ΣX_3=0.6 kg.

$$|ID| = \pm t_{\lambda,k}\frac{\Delta_{random}}{\sqrt{n}} = 2.571\frac{0.75}{\sqrt{6}} = \pm 0.78 > 0.6$$

i.e., total theft amounting to 6 kg (0.1 x 6) is not registered.

1.5. 7 shifts ΣX_3=0.7 kg.

$$|ID| = \pm t_{\lambda,k}\frac{\Delta_{random}}{\sqrt{n}} = 2.365\frac{0.75}{\sqrt{7}} = \pm 0.67 < 0.7 \text{ kg}$$

i.e., total theft of ΣX_3=0.7 kg in this case is reliably registered for 7 shifts (<<40 shifts).

The second step of iteration (approximation)

2. Let us decrease the size of "accounting batch" Q_y to 25 kg (i.e., "technological batch" ($3Q_{sq}=3Q_y$).
In this case, $\Delta_{random}=\pm 0.25$ kg=0,01Q_y.
Let us assume the amount of anticipated thefts:
Variant 1 - X_1=0.2 kg (of one "accounting batch");
Variant 2 - X_2=0.1 kg
In order to accumulate a "significant amount" of NM |Q|=8 kg, it is necessary:

Variant 1 - $T_1 = \frac{|Q|}{X_1 \cdot m} = \frac{8}{0.2 \cdot 3} = 14$ shifts, where m – the number of accounting batches per shift.

Variant 2 - $T_2 = \frac{|Q|}{X_2 \cdot m} = \frac{8}{0.1 \cdot 3} \cong 27$ shifts.

Similarly to the first iteration, we shall estimate the number of shifts necessary for registering the NM theft.

2.1. One shift – ΣX_1=0.6 kg (ΣX_2=0.3 kg) – because three "accounting batches" are dealt with during one shift

$$|ID| = \pm t_{\lambda,k}\frac{\Delta_{random}}{\sqrt{n}} = 4.3\frac{0.25}{\sqrt{3}} = \pm 0.62 \text{ kg} > 0.6 \text{ kg } (>0.3 \text{ kg})$$

i.e., theft of 0.6 kg (0.3 kg) is not registered during one shift.

2.2. Two shifts ΣX_1=0.1.2 kg (ΣX_2=0.6 kg).

$$|ID| = \pm t_{\lambda,k}\frac{\Delta_{random}}{\sqrt{n}} = 2.571\frac{0.25}{\sqrt{6}} = \pm 0.26 \text{ kg} < 1.2 \text{ kg } (<0.6 \text{ kg}).$$

Thus, during two shift-long observation, it can be stated with certitude that theft of more than X_i=43 g from each "accounting batch" is recorded reliably.

As we can see from the comparison with the first step of iteration, the last variant renders higher numerical guarantees against NM theft for a shorter period of time. Therefore, if we consider that this guarantee level is acceptable for us, we assume X_i=43 g as a significant amount of material from an "accounting batch" from the standpoint of possible theft to be (X_i<=43 g). Let this value be termed "criterion of material attractiveness" (or significance of a single theft)

($|X_i|$); but preference will be given to such strategy of measurement in MBA, for which $|X_{i+1}|<|X_i|$, provided that financial expenditures for the organization of such measurements would be less than such losses.

Thus, in order to define the limits of MBA with material in bulk-form present, and for the preparation of the input information on this MBA, strategy of NM measurement must be chosen, capable of ensuring the solution of the safeguards problem and attaining the objective of NM management at Federal level.

Both tasks are solved through the ensurance of standardized accuracy and reliability (sufficient confidence levels) of the quantitative estimations of NM in regular inventory taking procedures, as well as in each transfer of NM.

The estimation technology, including that of measurement intended to ensure this requirement must be based on the following complex of activities:

1. Estimation of NM quantity present in an assumed MBA which passes through this area during the material balance period.
2. Defining the "criterion of material attractiveness" which could result in an accumulation of critical amount of NM only during the material balance period.
3. Defining the numerical size of "accounting batch" for the given NM.
4. Defining periodicity of analysis of measuring "accounting batches" of NM, which could ensure meeting the chosen numerical characteristics of safeguards for non-diversion of NM.

- Notes: 1. For two consecutive MBAs along the NM flow, with different values of their parameters such measurement accuracy, production output, quantity of nuclear material, duration of material balance period, etc.), the choice of "accounting batch" size must be agreed upon.
  2. In order to ensure the uniformity of measurements and possibility of uniting the estimates of NM at Federal level, the information on NM quantity available in MBA with the material in the form of "items" also must be presented as "accounting batches, as well as for the adjacent MBAs with NM in bulk form.

CONCLUSIONS

Summarizing the discussion on strategy for bulk form NM measurement for MBA, the following statements can be made:

1. Concepts have been defined such as "Shipment batch", "Technological batch", and "Accounting batch".
2. It has been found out that Shipment and Technological batches should be formed through the arrangement of group of measured Accounting batches.
3. The strategy for NM measurement based on the Accounting batch is shown to give a possibility to use the above advantages for the accounting purposes:
   Ensure safeguards of non-diversion of NM at quantitative (numerical) level, which is a higher grade of safeguards compared to the systems of accounting and control now in force in the US and Euratom.
   Ensure a guaranteed accuracy and reliability (confidence level) when making up NM balance in MBA and at Federal level, which has been realized only in part in the NMC&A systems listed above.
4. Strategy of NM measurement for MBAs containing NM in bulk form has been proposed.

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