

Importance of Material Balances and Their Statistical Evaluation in Russian MPC&A¹

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Abstract

While substantial work has been performed in the Russian MPC&A Program, much more needs to be done at Russian nuclear facilities to complete four necessary steps. These are (1) periodically measuring the physical inventory of nuclear material, (2) continuously measuring the flows of nuclear material, (3) using the results to close the material balance, particularly at bulk processing facilities, and (4) statistically evaluating any apparent loss of nuclear material. The periodic closing of material balances provides an objective test of the facility's system of nuclear material protection, control and accounting. The statistical evaluation using the uncertainties associated with individual measurement systems involved in the calculation of the material balance provides a fair standard for concluding whether the apparent loss of nuclear material means a diversion or whether the facility's accounting system needs improvement. In particular, if unattractive flow material at a facility is not measured well, the accounting system cannot readily detect the loss of attractive material if the latter substantially derives from the former.

Introduction

Safeguarding nuclear material includes several aspects, in particular, material protection, control, and accounting (MPC&A). While the boundaries between the protection, control, and accounting activities are not always clear, the following generally apply. "Protection" provides a visible and practical physical deterrent to material diversion, in particular by outsiders, and needs to be the first step in a MPC&A program. It includes the physical constraints on material such as secure buildings, doors, and fences. and a properly equipped and trained security force. "Control" includes the use of tamper indicating devices (TIDs), computerized inventory tracking, sensor alarms, and two-person rules. "Accounting" consists of monitoring inventories and inventory changes (primarily material flows for the present paper), which are summarized in material balances through the computation and evaluation of inventory differences. An unusually large inventory difference (loss or gain) would prompt immediate investigation to discover its cause.

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Protection and control measures may fail to prevent diversions of nuclear material, in particular through the actions of an insider. Accounting activities provide the means to detect and characterize such diversions and thereby aid in investigation and recovery.

A material balance consists of an inventory difference obtained from the material balance equation:

$$ID = BI + R - S - EI$$

Here ID = Inventory Difference, BI = Beginning Inventory, R = Receipts, S = Shipments, and EI = Ending Inventory. The beginning inventory is the amount of nuclear material present at the beginning of an inventory period; receipts are those materials obtained throughout the inventory period; shipments are those materials transferred out throughout the inventory period; and ending inventory is the amount of nuclear material present at the end of an inventory period. Ideally the ID should be equal to zero, but this essentially never happens at a bulk processing facility since ID may result from many individual measurements of nuclear material. These measurements cannot all be perfectly accurate or precise, so discrepancies will arise. The significance of nonzero IDs is evaluated statistically using variance propagation of the measurement uncertainties associated with the many measurements that make up the ID calculation. These uncertainties are obtained through the examination of the underlying measurement systems. Commonly used measurement techniques include determining liquid volumes, determining masses or weights, nondestructive assay, and concentration assays by means of destructive assay analytical methods.

Roughly speaking, the variance of the inventory difference is the sum of the variances of the inventory difference terms:

$$\sigma^2(ID) = \sigma^2(BI) + \sigma^2(R) + \sigma^2(S) + \sigma^2(EI)$$

It is $\sigma(ID)$ that characterizes the uncertainty of the material balance. If the range of values $ID \pm 2\sigma(ID)$ exceeds zero, then one concludes that ID is statistically significant; and if it exceeds a (positive) nonzero quantity Q (given through regulations) then ID is furthermore of safeguards significance. In these cases, an investigation would be undertaken to determine the cause.

Russian MPC&A Program

Current Tasks In the Russian Program more efforts appear to have been expended towards the protection and control aspects of MPC&A. This is certainly reasonable since upgrades in these areas were certainly needed and are an obvious first step towards improvement. However, as the Program matures with many accomplishments along the protection and control lines, the threat of diversion by insiders must be countered by additional means. Adequate determination of material inventories and inventory changes and the evaluation of material balances are needed for the detection of such diversion as well as to give positive statements that the material is accounted for.

Related tasks in the program include the following:

Russian Methodological Training Center (RMTC) – Several courses that address material accounting are offered, including an MPC&A introductory course, a physical inventory

taking course, several courses on measurement methods, and a three-course sequence in statistical topics, in particular, a measurements course and an ID course. The measurements course deals with the statistical aspects of measurements including measurement control, error modeling and uncertainty estimation. The ID course discusses propagation of variance for the evaluation of IDs, the examination of sequential historical IDs, and associated computer software.

Russian Statistics Working Group (RSWG) – Technical experts from several nuclear sites meet and discuss statistical topics in material accounting and their proposed role at Russian sites. The RSWG charter is to provide guidelines to Minatom on the statistical content of the Minatom regulatory documents. Initial topics considered were the evaluation of IDs through variance propagation. Subsequent topics proposed include various measurement issues.

Site tasks – Many site tasks have dealt with measurement activities associated with newly obtained measurement equipment. Related tasks have included widely varying content with respect to measurement control and uncertainty estimation. Another major category of tasks is initial inventory verification activities, which have proceeded well at several facilities but require much more widespread implementation. However, only isolated, fairly simple tasks involving material balances have been completed.

Proposed Tasks Considerable resources have been invested in the Russian Program in anticipation of material accounting activities. A very large amount of new measurement and computing equipment has been installed and acceptance tested at various sites. Ongoing measurement control programs are evolving at some sites and have been proposed for others. Data from the equipment qualification and measurement control is now available to characterize the measurement capabilities of the new equipment, but this type of data usage has in fact been spotty in the Program.

Various inventory tasks are at widely different stages at various sites. Of particular interest is the verification of the accuracy of passport information and thereby the verification of material inventories. The association of the measurement capability data with the inventory and inventory change measurement results is the first step towards the evaluation of material balances. Yet few tasks appear to be carrying the data evaluation as far as this step. Considering all the measurement and computer equipment, the associated data for determining measurement capability, and initial inventory results, few tasks have been written to take the next logical step in performing data evaluation to make related decisions regarding inventory accuracy. Once such tasks are written and performed, particularly for bulk processing facilities, material balances can then be evaluated periodically to indicate if any inventory difference is significant. If so, an investigation can be undertaken to determine whether the facility's accounting system needs improvement, or if there is reason to believe that material was diverted.

Types of Facilities and Material Balances

Consider two types of facilities. The first is a storage or research facility that has an inventory of highly enriched uranium or plutonium that changes little; also, the facility does no processing. Thus the nuclear material retains its form as fabricated items or as bulk material in closed and sealed containers. The second is a processing facility whose annual flow of plutonium or highly enriched uranium is much greater than its inventory.

For the storage or research facility with an item inventory that changes little, the terms in the inventory difference equation will have the following character:

$$R, S \ll BI \approx EI$$

In the limiting case of no shipments or receipts, which does occur,

$$R = S = 0 \text{ and } ID = BI - EI = 0.$$

Of course it is possible that $ID \neq 0$ because something is missing, but the major point is that successive inventory takings will generally encompass the same items of nuclear material with little change. One sometimes refers to such a facility as “inventory-dominated.” In this case, periodic inventory takings provide good material accounting evidence about all the material at the facility.

In contrast, a large processing facility has an inventory of bulk material that changes continuously. Given that the feed is received at, and product is shipped from, the processing area itself (as opposed to associated storage areas) at a high rate, the terms in the inventory difference equation will have the following character:

$$R, S \gg BI \approx EI$$

The limiting case of

$$R = S > 0 \text{ and } ID = 0 \text{ and } BI = EI = 0$$

would never occur in practice because of holdup in the processing lines and because of measurement uncertainties. Moreover, the term for shipments, S , would generally be divided between product P and waste W , with $P \gg W$. One sometimes refers to such a facility as “flow-dominated.”

A particular danger from the viewpoint of material accounting is the absence of a good measurement of the receipts R , especially in situations where the actual amount of nuclear material can only be measured directly once it enters the process. This leads to two significant problems. The first is that the material would not be verified well in its receipt form because it is not present at an inventory taking (which would apply similarly to products with a short residence time at the facility). The second is that the uncertainty in R will propagate to a comparatively large uncertainty in ID . For either reason there would be considerable uncertainty as to the quantity of product to expect.

Translated into the terminology of MPC&A, the danger is not that receipts themselves would be a target for theft, but rather that the most attractive plant material in the process would be the target. The considerable uncertainty in the overall material balance would then significantly reduce the capability to detect the theft by material accounting alone. The reasoning is similar for any processing plant where plutonium or highly enriched uranium appears in an attractive form as either receipts or shipments, but where flows are not measured well.

Consider the case of irradiated fuel reprocessing (radiochemical) plant. We believe strongly that potential MPC&A upgrades to flow measurements should be judged on the basis of their potential to reduce the uncertainty in the material balance, $\sigma(\text{ID})$. Thus it is especially important to measure receipts and shipments (products) well. For this type of plant, we consider receipts as dissolved irradiated fuel and product as concentrated plutonium nitrate solution (intermediate) or plutonium dioxide powder (final), preferably both. The receipts themselves—plus most process materials within the plant—are not attractive to divert. But this is not a sufficient reason to refrain from upgrading receipt measurements. As we have indicated, if receipts are not well-determined, the expected production would not be well-determined. A malevolent and knowledgeable insider would attempt to divert purified product just before it undergoes product measurement. Indeed, as Bennett and coworkers noted many years ago, the measurement of dissolved irradiated fuel at a reprocessing plant is the most important plutonium accountability measurement in the entire nuclear fuel cycle.

Conclusion

We recognize that resource limitations impose a need to set priorities and that, accordingly, the MPC&A upgrades may need to be applied to the most attractive materials first. While acknowledging this point, we nevertheless feel strongly that upgrades to flow measurements at nuclear processing plants constitute a vital component of upgraded MPC&A systems and should be supported.

If unattractive flow material is not measured well, the accounting system cannot readily detect the loss of attractive material if the latter substantially derives from the former. If receipts are not well-determined, the expected production would not be well-determined. The diversion or loss of attractive product material at an irradiated fuel reprocessing plant could be confounded by the lack of good measurements of unattractive, impure, irradiated feed.

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