Sensitivity of MBA structure and KMP instrumentation on MUF

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Abstract:

A code SID (Sensitivity of Inventory Difference) has been developed in the JAVA-language to investigate the sensitivity of the inventory difference (ID) and its standard deviation on the precision of instruments and the inaccuracy of measurement procedures. The code is dedicated to training and academic sensitivity analyses. Emphasis has been put on the error propagation and on the localisation of important measurement points in the material balance area.

The purpose of the software tool is to make the user aware of a potential increase of the accountancy performance by a restructuring of the material balance areas (MBA) or by an upgrade of the instrumentation at a specific Key Measurement Point (KMP). The user can set up a simplified model of the MBA's with KMP's of the installation and instrument each KMP. For KMP's with liquid material, the user has to select at least a level, a density and a concentration measuring instrument. For the KMP's dealing with solid material (either powders or items) the selection of at least a weighing instrument and a concentration measuring instrument is needed as input.

Typical materials reprocessed in various batches are specified as examples. The reference Nuclear Material Accountancy and Control (NMAC) instrumentation of different type and number are listed with default errors conform to IAEA standards. Instruments can be added or their characteristics modified by the user. The measurement procedures with pre- and post-calibration and number of repetition, and the sampling procedure can be specified as prescribed in a nuclear plant. The code performs the ID calculations and allows investigations of the sensitivity of the ID on the measurement errors and procedures.

The ID value and the yes/no acceptance under the safeguards criteria are not very informative and have to be evaluated taking into account the standard deviation of the ID. The SID software gives a training and feeling about the sensitivity of the standard deviation on the instrument errors, measurement procedure (e.g. repetition frequency) and MBA structuring.

Moreover it is very useful to localize weaknesses and to identify optimization potential, which are the outcome of a sensitivity assessment. To bring this to the attention of the operator, training in NMAC and especially on the sensitivity of ID is needed. Nowadays e-learning becomes common practice and this tool, available on web site http://tamepc25/sid supports this.

Keywords: Standard Deviation of Material Unaccounted For, Material Balance Area, Key Measurement Point

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1. TOWARDS THE CURRENT REQUIREMENTS FOR NUCLEAR MATERIAL BALANCES

1.1 Historical Evolution

The Nuclear Material Accountancy and Control (NMAC), the first pillar of the Non-Proliferation Treaty, requires a reporting on the measured inventory difference (ID) or material unaccounted for (MUF) for all material balance areas. The order of ID relative to its standard deviation is not the only objective in the evaluation assessment, more important is to localize major error sources and their propagation in the ID computation. This has been investigated with the code MACSSA by Argentesi and Mousty (1987) in the early eighties to guarantee the safeguards requirements for an extrapolated capacity of handling MOX fuel in reprocessing plants. In the early nineties this code was replaced by Foggi (1997) with the SAMBA code in a bilingual English/Russian version, which calculated for all data batches in one material balance area the ID with the random and randomized systematic error. In order to allow a sensitivity analysis of the ID on the various error sources on the one hand and a graphical demonstration of the error propagation on the other hand, the SID code has been developed recently.

1.2 Objectives of the SID code

Although physical inventory taking and verification in installations are standard, a State System for Accountancy and Control (SSAC) has been discussed in the late nineties, during the transfer of the Western safeguards methodology to the Commonwealth of Independent States. These discussions, strongly supported by Touzov and Pshakin (1994) resulted in the famous basic rules for NMAC by the Gosatomnazdor (2002). Franklin et al. (2003) reports on the comparison of the French and the Russian SSAC and demonstrates a mutual benefit of this co-operation.
Although accountancy is coupled with performance and product quality of the process plant, the economic aspect does not guarantee a safeguards culture. Training of the operator has been recognised as opportune for increasing accountancy performance by indicating the important measurement points in the installation. The code is dedicated to training and academic sensitivity analyses, and serves as an online-available support.

2. FEATURES FOR INVENTORY DIFFERENCE COMPUTATIONS

2.1. Ingredients of the Code

The code addresses several material balance areas and specifies typical material reprocessed in various batches as examples. The reference NMAC instrumentation of different type and number, the measurement procedures with pre and post re-calibrations and number of repetition, and the sampling procedure can be specified as prescribed in a nuclear plant. The code performs the inventory difference (ID) calculations and allows investigations of the sensitivity of the ID on the measurement errors and procedures. It also evaluates the safeguards criteria of Euratom and IAEA as it is based on the EC (1976) regulation 3227 and on the IAEA concepts by its Safeguards Department (1998).

2.2. Plant Modeling with Functional Blocks

The basic assumption in the code for inventory difference computations is the conversion of the plant in a structure node model. A plant is divided in material balance areas (MBA's), as described by Foggi (1997). Each MBA is linked to key measurement points (KMP's). These KMP's are defined in terms of the principal stage of the technological process as central collective point at which a balance of the inventory can be made very accurately, such as the input and output accountancy tank, stores for nuclear material received and shipped, output of process line for nuclear material conversion . The choice of the KMP allows for a facilitated internal accountancy of the nuclear material. Fig. 1 represents a typical MBA structure with $i=1,\ldots N$ MBA's and $ij\ (i=1,\ldots N;\ j=1,\ldots M)$ KMP's .

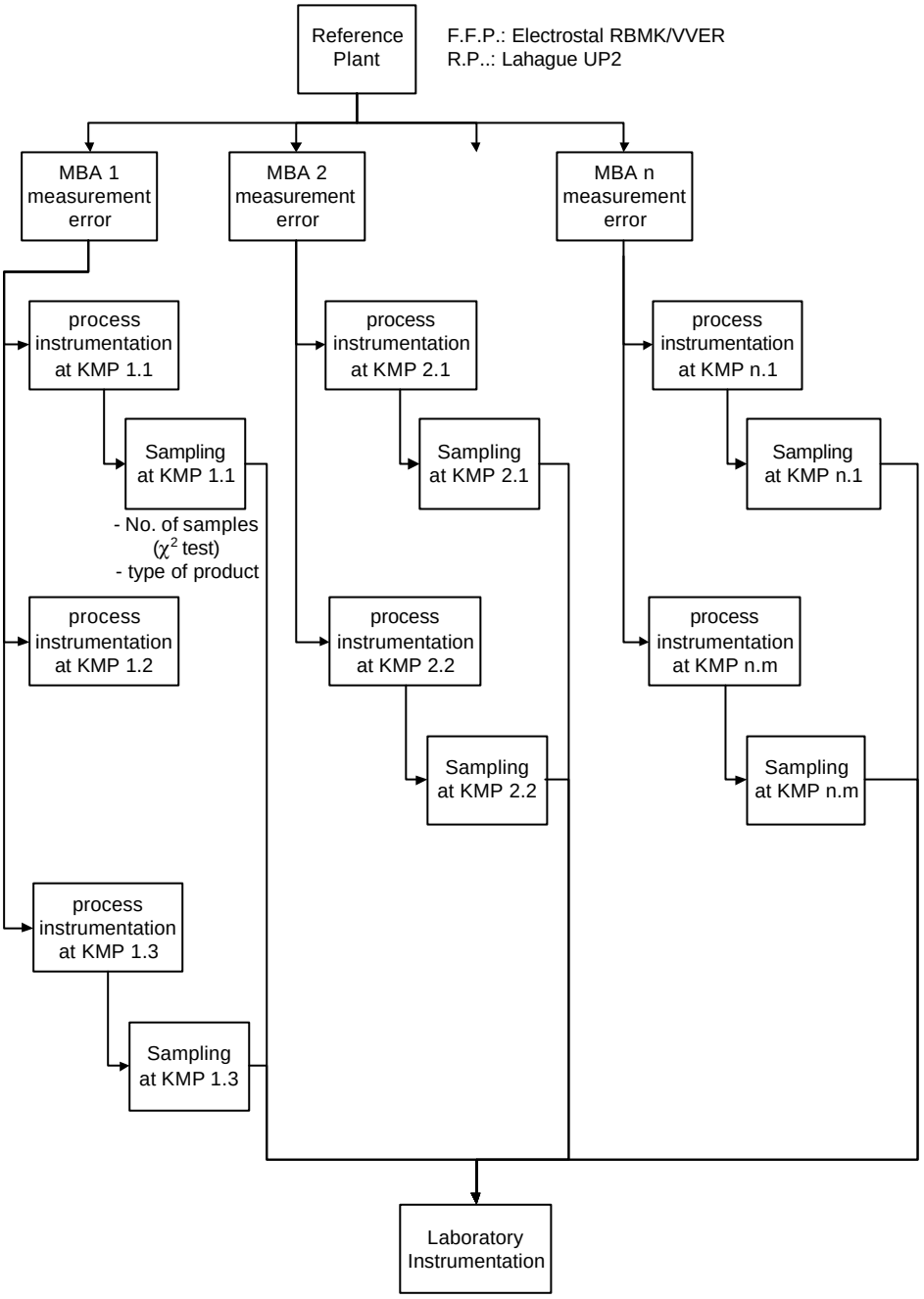

Fig. 1: Model for calculating the ID and its standard deviation of a reference plant

A fictitious example of this Functional Block model for the MBA-structure example of Fig. 1 is given in Fig. 2. Declaring an MBA needs a description of the MBA with the quantity of incoming and outgoing material. This “quantity” specifies the capacity of the MBA, because there is a continuous flow of incoming and outgoing material. Declaring a KMP needs a description of the KMP with specification of the material and the capacity of the KMP.

In a KMP the error calculation has to be done, separately for each batch. The icons "Measure i" in Fig.2 indicate the measurements, which have to be done such as volume (based on level), density (based on pressure and temperature), concentration, (based on sample measurement) to define the mass of nuclear material in the batch. To determine the total mass in case of a liquid, a density, level and temperature measurement onsite is sufficient. To determine the composition of the solution or powder a sample needs to be taken for destructive or non destructive analysis in an analytical laboratory. A sample icon "Sample *i*" is linked with the KMP icon and the values from the sample are represented by value icons "Values *i*".

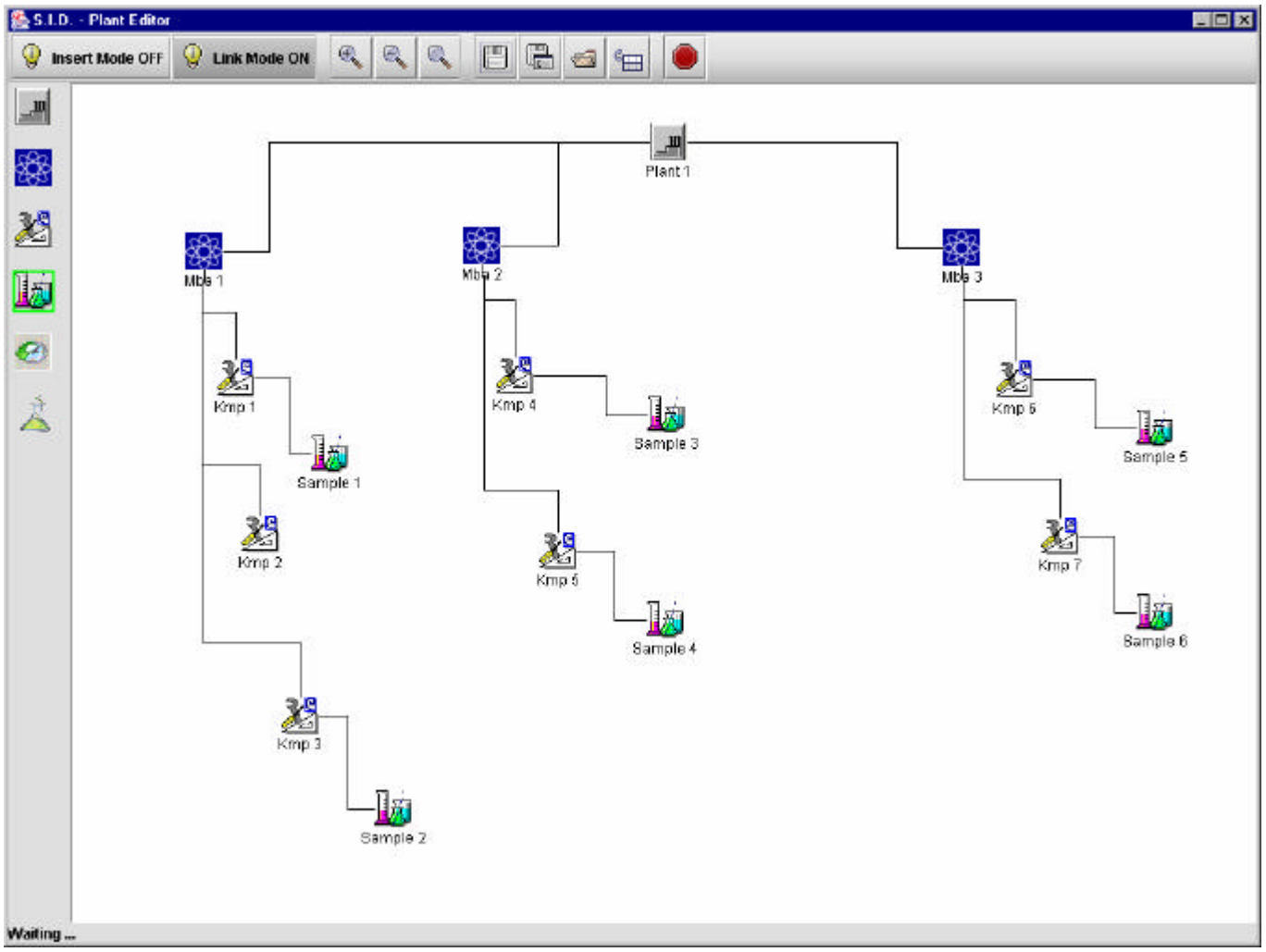

Fig. 2: Functional block model for the MBA structure of Fig. 1 with $N=3$ MBA's with respectively $1M=$3KMP's, $2M=$2 KMP's and $3M=$2KMP's

2.3. Algorithms for the Derivation of the ID with Standard Deviation

2.3.1 Inventory Difference (ID)

According to the rules of international safeguards, a separate Nuclear Material Accountancy (NMA) shall be kept for Uranium and Plutonium. Each of these materials will therefore have a specific Material Balance (MB) in a well-defined Material Balance Area (MBA). The ID, also called Material Unaccounted For (MUF), has to be calculated with all the materials in the MBA. For each material, the imbalance after a well defined period between the Beginning Inventory (BI) and Receipts (R) at one side and the Shipments (S) and End Inventory (EI) at the other side is given. The total ID of all materials is:

$$ID = \sum_i BI_i + \sum_i R_i - \sum_i S_i - \sum_i EI_i \qquad (1)$$

The amount of material recorded in one entry of the MB generally results from several measurements, rather than from one measurement only. The reasons are:

(i) the material of the entry may have been subdivided into a certain number of batches, each of which has been individually measured

(ii) the determination of Uranium or Plutonium requires a minimum of two different measurements.

Therefore the error associated with one entry results from the combination of several errors.

2.3.2 Variance of Inventory Difference

The ID is the result of adding all the measurement errors, and is therefore a statistical variable itself. If we assume that:

(i) the error made in measuring the amount of each entry of the MB has a normal distribution

(ii) the measurements related to the various entries are independent from each other,

then the variance of the ID can be simply obtained as the sum of the variances of all the entries of the MB. This calculation only requires knowledge of:

(i) the amounts of materials recorded in the MB

(ii) the reported errors for the measurement of each entry. The hypothesis about the normality of the measurement errors is reasonable.

The hypothesis about the independence of the errors of the various entries has at least two notable exceptions. The first one concerns materials which are not processed nor manipulated during their stay in the MBA and which therefore do not contribute to the ID nor to its variance s_{ID}. The second one concerns materials which are measured with the same instrument and the same procedure. The systematic components of the error will partially or totally compensate.

2.3.3 Variance of a function of Different Measurements

The discrepancy between the real and the measured value, which depends on the technical defects of the tool or of the method used during the measurement, is called the systematic error or bias, which affects the accuracy of all observations. Additionally a discrepancy due to the unpredictable influence of the environmental conditions exists, which is called the random error and which represents the precision of the measurement. For the evaluation of a measured data set of $i=1,...,N$ values a stochastic treatment of the discrepancy of a measured value y enables to distinguish the random error a_i and the systematic error b from the reel value m, represented as

$$y_i = m + a_i + b \qquad (2)$$

The ID of a batch, as defined by (1), is then calculated by

$$s^2 = \frac{1}{N}\sum_{i=1}^{N}(y_i - m)^2 \qquad (3)$$

The corresponding variance of the ID is statically determined by

$$s^2_{ID} = s^2_{BI}\left(\sum_i BI_i\right) + s^2_R\left(\sum_i R_i\right) + s^2_S\left(\sum_i S_i\right) + s^2_{EI}\left(\sum_i EI_i\right) + 2Cov\left(\sum_i BI_i \sum_j R_j\right) - 2Cov\left(\sum_i BI_i \sum_j S_j\right)$$
$$- 2Cov\left(\sum_i BI_i \sum_j EI_j\right) - 2Cov\left(\sum_i R_i \sum_j S_j\right) - 2Cov\left(\sum_i R_i \sum_j EI_j\right) + 2Cov\left(\sum_i S_i \sum_j EI_j\right) \qquad (4)$$

The determination of s^2_{ID} consists in calculating the variance s^2_{ID} of the inventory mass as a function of other random variables. As described in Jaech (1973) Chapter 4, under assumptions that

(i) the random variables have finite means and variances

(ii) the standard deviations are small compared to the means

the Taylor series approximations can be applied. The variance of an inventory difference mass ID $(x_1, x_2, ..., x_n)$ is approached as

$$s^2_{ID} \approx \sum_{r=1}^{n}\left(\frac{\partial ID}{\partial x_r}\right)^2 s^2_{x_r} + 2\sum_{r=1}^{n-1}\sum_{r\neq s}\left(\frac{\partial ID}{\partial x_r}\right)\left(\frac{\partial ID}{\partial x_s}\right) s_{x_{rs}} \qquad (5)$$

In the case all variables are independent measured from each other (4) and (5) can be simplified to

$$s_{ID}^2 = \sum_i \left(s_{BI_i}^2 + s_{R_i}^2 + s_{S_i}^2 + s_{EI_i}^2 \right) \quad (6)$$

and

$$s_{ID}^2 \approx \sum_{r=1}^{n} \left(\frac{\partial ID}{\partial x_r} \right)^2 s_{x_r}^2 \quad (7)$$

The software focussed mainly on the instrumental errors and all standard instruments are introduced as specified by Guardini et al. (2002). Fig. 3 lists all these instruments, with their application, their random and systematic error for U and Pu measurement as implemented in the software.

Instruments Manager

ID	METHOD CODE	DESCRIPTION	RANDOM ERR. (U)	SYSTEM. ERR.(U)	RANDOM ERR. (PU)	SYSTEM. ERR.(PU)	MEASURE TYPE
1	ANCC	Advanced Neutron Coin...	0.000	0.000	0.200	0.200	M
2	AWCC	Active Well Coincidenc...	3.000	2.000	0.000	0.000	M
3	CALR	Calorimeter	0.000	0.000	0.400	0.400	M
4	COMP	Combined Product Uran...	0.200	0.150	0.000	0.000	C
6	EBAL	Electronic Balance	0.050	0.050	0.050	0.050	M
7	FRSC	Fuel Rod Scanner	1.000	1.000	1.000	1.000	M
8	GRAV	Gravimetry	0.050	0.050	0.050	0.050	C
9	GSMS	Gas Source Mass Spect...	0.100	0.100	0.000	0.000	I
10	HKED	Hybrid K-Edge/K-XRF D...	0.200	0.150	0.600	0.300	C
11	HLNC	High Level Neutron Coi...	0.000	0.000	2.000	1.000	M
12	HRGS	Infield High Resolution ...	0.000	0.000	2.000	2.000	I
13	IDMS	Isotope Dilution Mass S...	0.150	0.100	0.150	0.100	I
14	INVS	Inventory Sample Coinc...	0.000	0.000	2.000	1.500	M
15	KED	K-Edge Densitometer	0.200	0.150	0.200	0.150	C
16	LCBS	Load-Cell Based weighi...	0.050	0.050	0.050	0.050	M
17	LMCA	Laboratory Multichanne...	0.000	0.000	1.500	1.500	I
18	LMCN	Laboratory Multichanne...	0.300	0.300	0.000	0.000	I
19	PCAS	Plutonium Canister Assa...	0.000	0.000	8.000	2.000	M
20	PHDN	Photon Neutron interrog...	2.000	1.000	0.000	0.000	M
21	PMCG	Portable Multichannel ...	3.000	2.000	0.000	0.000	I
22	PMCN	Portable Multichannel ...	2.500	1.000	0.000	0.000	I
23	PSMC	Plutonium Scrap Multip...	0.000	0.000	8.000	2.000	M
24	TIMS	Thermal ionisation Mas...	0.200	0.200	0.150	0.100	I
25	TITR	Titration	0.100	0.100	0.150	0.150	C
26	UNCL	Uranium Neutron Coinci...	4.000	2.000	0.000	0.000	M
27	VTDM	Vibrating Tube Density ...	0.050	0.050	0.050	0.050	D
28	WDAS	Waste Drum Assay System	0.000	0.000	8.000	2.000	M
30	DIPT	dip tube	0.300	0.200	0.300	0.200	D
5	DIPT	Dip Tube	0.300	0.200	0.300	0.200	V
31	PT100	PT 100	0.100	0.100	0.100	0.100	T

Fig. 3: List of instruments and their errors, utilised to calculate the sigma of the inventory

3. EXAMPLE OF A REPROCESSING PLANT

3.1. Plant Model

The possible MBA structures of a reprocessing plant respectively a fuel fabrication plant are given in Fig. 4. Each MBA is enshrined by a dashed line in Fig. 4.

In the reprocessing plant the spent fuel is stored after a non destructive analysis (NDA) in a pool which is surveilled by camera's (C/S). After chopping the fuel assembly, dissolving in HNO_3, and removi ng the fission products the solution is stored in the input accountancy tank (IAT). A mass/volume (M/V) measurement is performed and a sample is taken, to analyse the concentration and U/Pu content of the solution by e.g. NDA. Then the solution is separated in U and Pu. Depending on the spent fuel at the input (form a standard WWER or a research reactor with higher enriched U), either the low enriched U (LEU) purification line or the high enriched U (HEU) purification line is utilised. The most important KMP in the MBA of separation and purification are the output product (accountancy) tanks or storages. The Pu is stored in powder condition (PuO_2) and the U leaves the reprocessing plant in

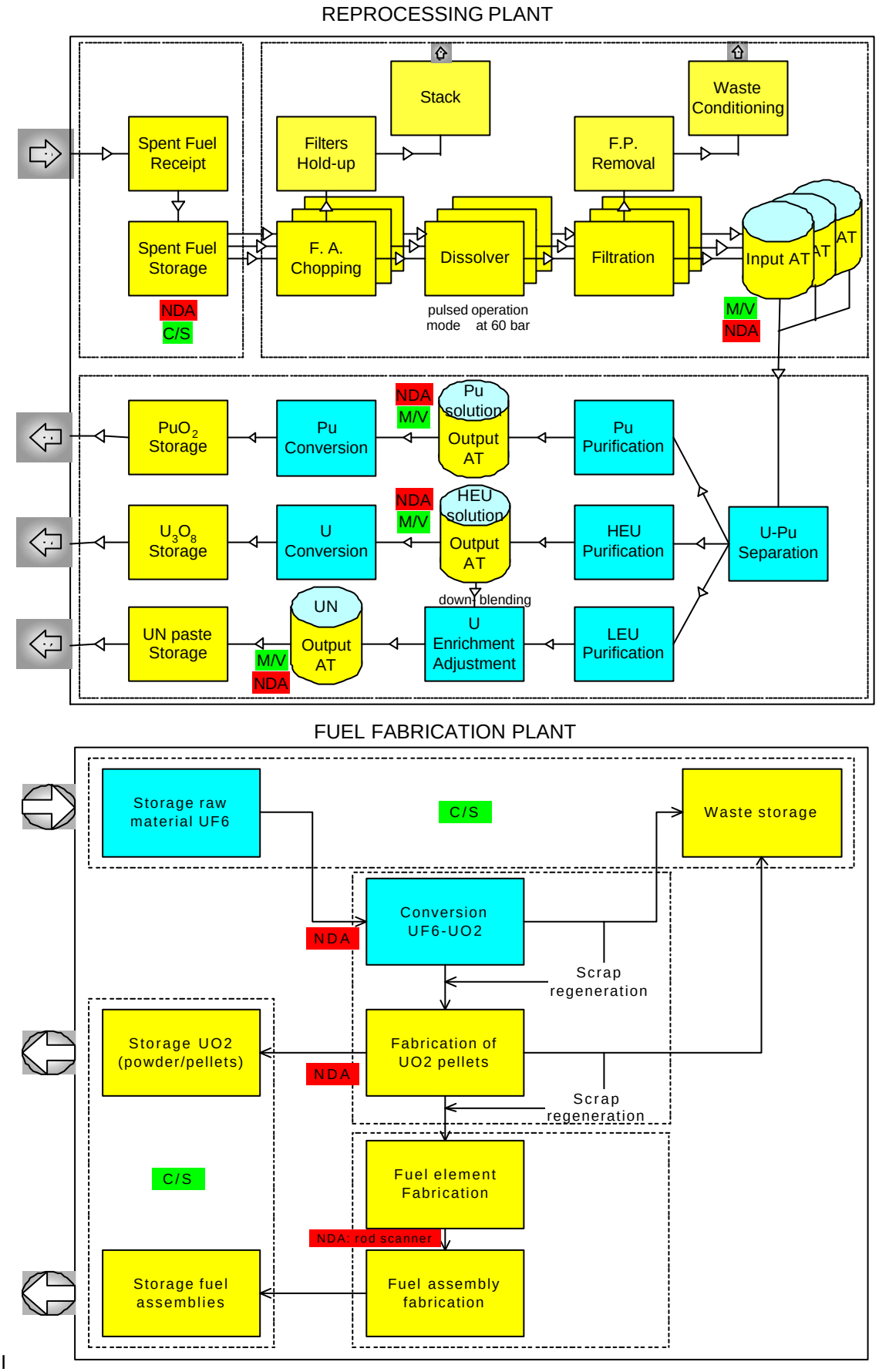

Fig. 4: possible MBA structures for safeguards at a reprocessing/ fuel fabrication plant

U_3O_8 and Uranyl Nitrate (UN) paste. The U products which leave the reprocessing plant, go to the fuel fabrication plant, where they are converted into UO_2 pellets. The pellets are then filled in fuel rods, which are put together in fuel assemblies.
In the fuel fabrication plant, the gas-containers with raw UF6 are converted into UO2 and then the UO2 is sintered into pellets in the first process, covered in a second MBA. The first MBA contains the storage of input and waste. Another process for fabrication of the fuel pins, verifying and assembling them, is present in the third MBA. The storage of the output products is reunited in the fourth MBA.

This paper we investigates the example of a reprocessing plant and simplified the model for the total plant by focussing on the input accountancy tanks in the second MBA and on the output products (powder and uranyl product solution) in the separation/purification process MBA. Fig. 5 indicates the 5 modelled KMP's in orange and the considered two MBA's with a dashed line.

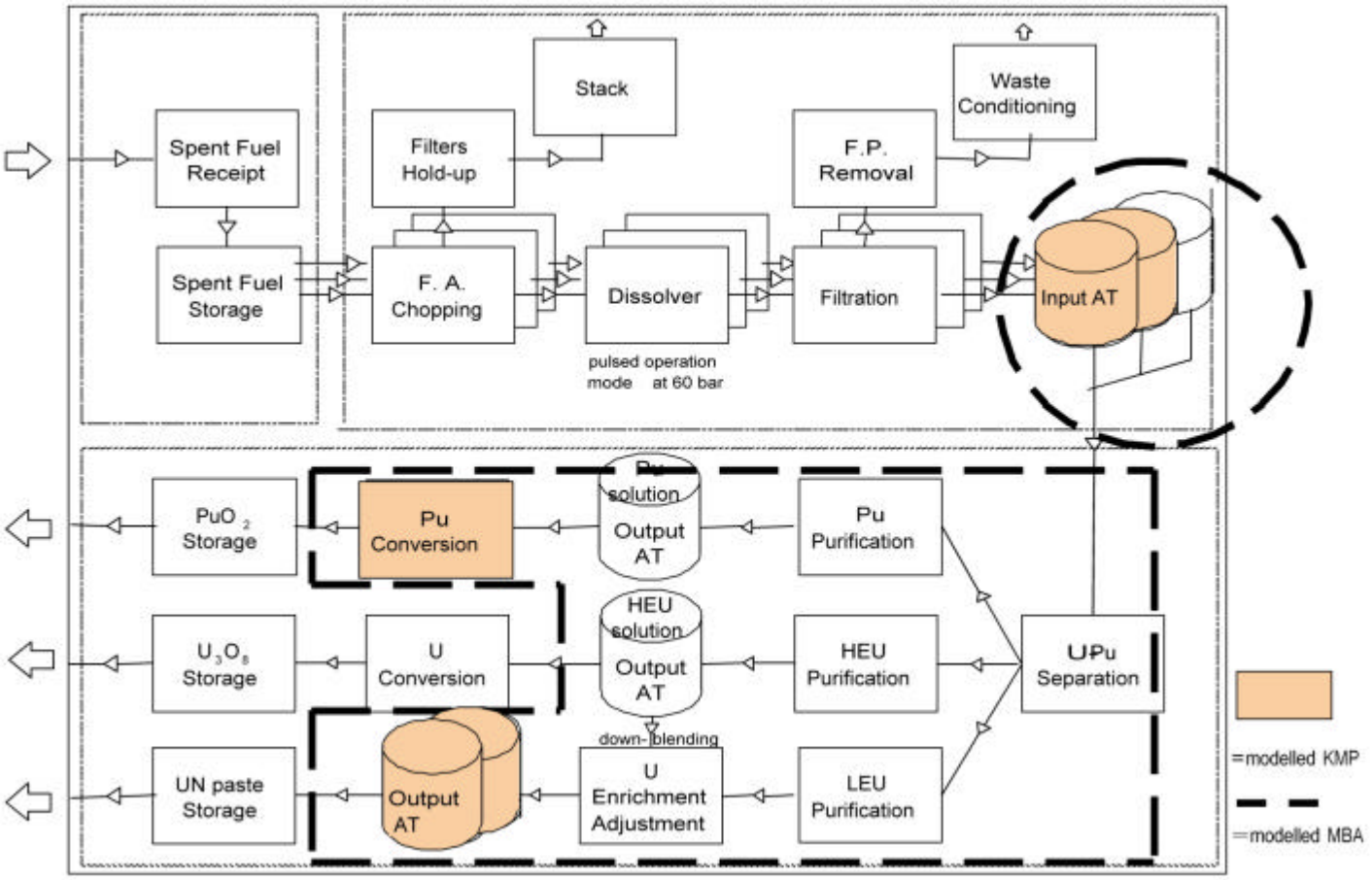

Fig. 5: Simplified MBA structure example for a realistic reprocessing plant

Fig. 6 gives the functional block model for the indicated areas of Fig. 5, with the two MBA's and the 5 KMP's, all represented by separate symbols. The user has to specify the measurement procedure and equipment for each symbol by introducing the requested parameters, as shown in the case of the Value2 example in Fig. 6.
For the first two KMP's the nuclear material in the input accountancy tank solution is measured by taking a density measurement (measure 1 via pressure measurement with dip tube system), a volume measurement (via level measurement with dip tube system), and a sample for measuring the U/Pu concentration of the solution in the analytical lab. The same structure applies for KMP3 and KMP4, representing the output accountancy tanks, filled with the product solution.
A different structure is behind KMP5, which contains the Pu powder. Here the total mass of the Pu powder is directly weighed by an accurate scale and the isotopic composition is measured by an on site gamma-spectrometer. Also a sample is taken to have a precise characterisation of the Pu powder. A combination of advanced neutron coincidence counting measurements with gamma-spectrometry

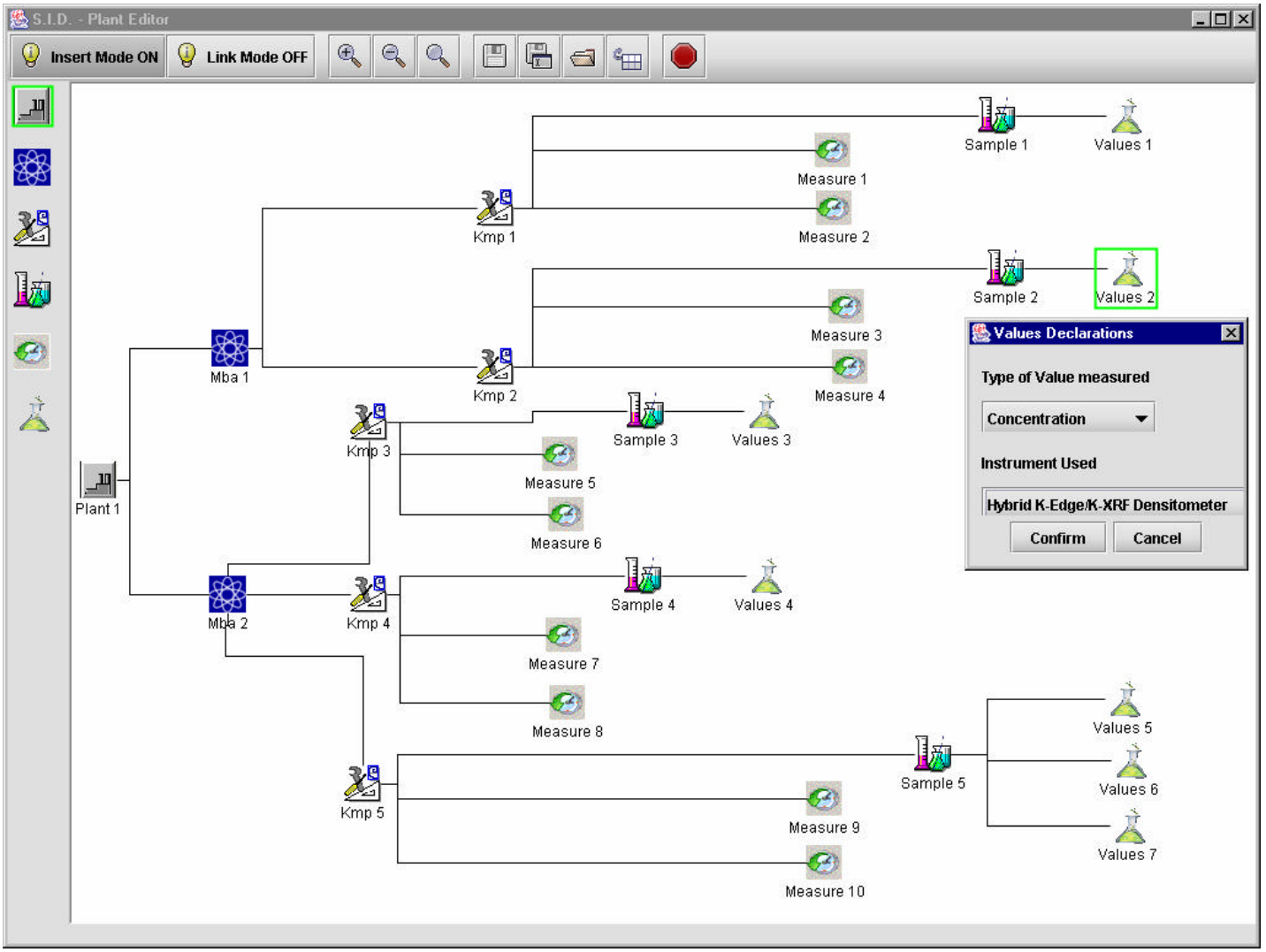

Fig. 6: Functional block model for the MBA structure of Fig. 3

allows the characterisation of the Pu vector and the precise determination of total mass of the most important Pu isotopes.

3.2. Validation of the ID computation

To determine the masses that circulate in a plant and to calculate the errors of the system, the plant structure has to be followed, for the successive batches. The masses and errors are calculated each time separately for U and Pu. The following theory is worked out for U, but can be repeated exactly in the same way for Pu.

If the unit concentration is given in gram U per gram solution, the U mass of one batch is given by

$$m_{B,U} = c_U \, r_U V_U \qquad (8)$$

with

- $m_{B,U}$ the match of a batch of U (gram U)
- c_U the concentration of U (gram U/ gram solution)
- r_U the density of the solution (gram solution/ liter solution)
- V_U the volume of U (liter solution)

If the unit of concentration is gram U per liter solution, the U mass of one batch is given by

$$m_{B,U} = c_U V_U \qquad (9)$$

Measuring a concentration in gram/liter is temperature dependent and therefore less recommended than a measurement of concentration in gram/gram.

The simplified formula (7) is applied to calculate the error of a batch under the assumption of independent measurements and therefore vanishing covariances. With the measured mass value $m_{B,U}$, the absolute random error a_Q, the absolute bias b_Q of a measurement of a quantity Q of a batch and with (8), the absolute random error $a_{B,U}$ and absolute bias $b_{B,U}$ of a batch is given by

$$\begin{aligned} a_{B,U} &= (r_U V_U)^2 (a_{c_U})^2 + (c_U V_U)^2 (a_{r_U})^2 + (c_U r_U)^2 (a_{V_U})^2 \\ b_{B,U} &= (r_U V_U)^2 (b_{c_U})^2 + (c_U V_U)^2 (b_{r_U})^2 + (c_U r_U)^2 (b_{V_U})^2 \end{aligned} \qquad (10)$$

The total error of the inventory for a KMP with N batches with mass $m_{B,U,I}$, $i=1...N$, is determined by the addition as commonly done, e.g. by Franklin (1996), Chapter 2, working with relative errors $a_{B,U}$ and $b_{B,U}$:

$$s^2(m_{KMP,U}) = \sum_{i=1}^{N} (a_{B,U,i})^2 + (N b_{B,U})^2 = N\overline{a^2} + (N b_{B,U})^2 \qquad (11)$$

As anticipated from formula 11 the random error increases with the number of batches N, whereas the systematic error increases with N². For the variance calculation of a MBA with P KMP's of mass $m_{KMP,U,j}$, j=1..P, the error on the total mass of U in the total MBA is given by the addition of the KMP variances, which yields

$$s^2(m_{MBA,U}) = \frac{1}{P} \sum_{j=1}^{P} s^2(m_{KMP,U,j}) \qquad (12)$$

More details and examples are given in the report of Uyttenhove [11]

4. CONCLUSION

4.1. Results

The acceptance of an inventory difference or MUF over the total process from the input accountancy tank till output accountancy tank in a reprocessing plant has to be evaluated in view of the standard deviation and is depending directly on the measurement errors. Large incoherency in declared and measured data is present at the receipt of the spent fuel in the reprocessing plant. The ID value and the yes/no acceptance under the safeguards criteria are not very informative. It is more useful and to localize weaknesses and to identify optimization potential, which are the outcome of a sensitivity assessment. To bring this to the attention of the operator, training in NMAC and especially on the sensitivity of ID is needed. Nowadays e-learning becomes common practice and this tool, available on web site http://tamepc25/sid supports this.

4.2. Perspective for further extension

To enhance the efficiency of NMAC inspections a large degree of automation and the concentration on experienced weak coherency in the fuel cycle are needed. This requires on the one hand a complete fuel cycle modeling, ideally from ore till waste, based on all online-available data (such as energy production of the plant). On the other hand inspectors have to pragmatically investigate the weak points with highest priority. Therefore an extension is foreseen for coupling the reactor-phase with the entry in the back-end. JRC is investigating the sensitivity of the spent fuel composition calculation on the irradiation specifications in addition to the Burnup and the sensitivity of the FORK

measurements errors at the receipt in the reprocessing plant on instrument precision and procedure imprecision.

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