Monitoring of Nuclear Material Movements at a Reprocessing Plant

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Abstract:

A process monitoring software tool has been developed, which allows inspectors a remote verification of nuclear material movements based on the interpretation of neutron and gamma signals, which are measured during the trajectory and online analysed. Neither supervision nor control is intended with the software but a checking of the required coherency and conformity with safeguards purposes. The data analysis and interpretation kernel supports the inspector in the back-end of the nuclear fuel cycle and allows in particular near real time accountancy in a reprocessing plant.

To monitor the nuclear material flow for near real time accountancy purposes a diagnostic aid for the inspectorate was conceived, which interprets data from solution and powder measurements of different kind and at different steps in the process.

In a first step tank transfers have been analysed by syntactic pattern recognition and introduction of functional blocks. A predefined sequence of functional blocks yields a tank signature and characterises unambiguously the filling rates, normal operation tank levels, levels for stirring and skimming, and the emptying rates. In a second step the same approach has been applied to the cyclic behaviour of a weighing scale. The weighing procedure with first scale-recalibration check, with the filling of Pu powder cans and with the final inventory weight determination could be verified remotely. Finally this syntactic pattern recognition approach has been applied to follow the movement of nuclear material by treating the neutron and gamma signals.

This paper reports on the analysis of the neutron and gamma signals for the remote follow-up of the spent fuel assemblies on their way to and from the measurement pit. A real-time analysis of the signal from the neutron counter simultaneously to the signal of the gamma counter positioned under a fixed geometry allows an identification of a movement signature. The functional blocks describing the movement signature consist of peaks and plateau's. The auto-correlation of a predefined sequence with the real sequence based on the measured neutron and gamma counts allows to characterise the nuclear material moved in the channel towards and from the measurement pit. With the appropriate parameters such as peak height and plateau length the software monitors if the material movement procedure is followed conform to the safeguards purposes.

Keywords: process monitoring; neutron/gamma signal interpretation.

1. Introduction

Process monitoring is an excellent tool to verify absences of undeclared activities or anomalities in industrial or semi-industrial processes. A software tool has been developed upon request of the Euratom inspectorate to monitor in real time the nuclear material (NM) flow of about twice 850 tons/yr through the whole PUREX process in UP2 and UP3 for the spent fuel of power reactors at the La Hague site. The about 800 kg of Pu

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processed per month through each line are for safeguards purposes measured accurately (with an error less than 1%, corresponding to less than 8 kg per month). However it is not satisfying to verify just the interim inventory, because it only identifies an eventual problem without any localisation in place and time and without any indication of the reason. Therefore it is needed to monitor the complete material flow, while surveying if the spent fuel batch is processed following the declared flow sheets and complying with the safeguards requirements on material losses. The monitoring includes:

- the status of health check
- the surveillance through gamma/ neutron counters for the displacement of nuclear material
- the NM liquid inventory follow-up through level and density measurements for the transfers between tanks,
- the NM powder inventory follow-up through the weighing scale signal for the final filling of recipients with the Pu powder product.

It especially verifies for Near Real Time Accountancy purposes the coherency with safeguards purposes and conformity in procedure.

2. Structure of the monitoring software

2.1. Data acquisition with a data historian

Process industries commonly work with a superposition of different acquisition systems. The data over a large time period, are usually collected in a first time-series database of non-relational type and compressed by a data historian, that allows fast real-time access to the significant reported data. The reported data are analysed and the results are exported in a second database of relational type.

Each significant signal variation has to be unambiguously detected with time and date stamp. The data historian either filters out data points at relatively large time intervals in case of no or constant variation of the signal (e.g. the auto regressive moving average filter) or the historian reports exceptions (exceeding the specified compression deviation blanket).

The software developed for solution monitoring was not intended to duplicate the operation of a data historian and therefore neither serves to compress nor to filter the original data but utilises the commercially available data historians such as Osisoft PI [1] or the Matrikon OPC [2].

2.2. Monitoring of a batch process by the Data Analysis and Interpretation (DAI) software

2.2.1 Data analysis & interpretation concept

As the nuclear material of the spent fuel is processed in batch mode or even in continuous mode, a certain cyclic behaviour in the measured signal profile can be observed. However the profiles of the measured signals in this large industrial plant is not strictly periodical and therefore no standard pattern recognition algorithms can be applied as such.

The innovative algorithm in the software is to detect the predefined elementary functional behaviours in the signal. These functional behaviours represent in a small block one function in the process cycle. The process cycle can be defined as a sequence of events with certain functions. The specific task of the software is to interpret the recorded points of the data historian and to detect the different events by recognising the sequential functional behaviours with an accurate identification of the start and end of those functional behaviours.

The innovative aspect is that the data interpretation is done on the following abstract level:

- each typical process cycle is modelled by composing series of succeeding functional behaviour blocks, and
- the analysis is completely performed in a symbolic way by evaluating the sequence of functional behaviour blocks.

As the NM monitoring has to operate efficiently, the analysis includes also all basic information of the plant design and of the procedure for each reprocessing step. The functional behaviour, that is associated to the measured signal, is online compared with the possible functional behaviours, that are predefined in the plant design.

To analyse the evolution of the signal in time, an observation window moves from one data point to the next and calculates for each point the average of the signal variation over the time with the data point values, just before and after the window. This characterises each data point with a mean variation, which allows the detection of the start of a new functional behaviour by comparing with the predefined variations with lower and upper limits. A detailed description is given in [3].

2.2.2 Cross-correlation

To facilitate finding out the correlated signals a status code is introduced to associated functional behaviour with the following rules:

- all potentially correlated signals are marked by a change in status code of the associated functional behaviour from passive to ready
- a significant signal variation for a ready functional behaviour changes its status into active if no additional requirements have to be fulfilled
- a significant signal variation for a ready functional behaviour changes its status into checking in case of additional requirements and passes finally to active if all requirements are fulfilled.

The DAI kernel evaluates all correlated functional behaviours, which are simultaneously in an active mode. By means of cross-correlation the comprehensiveness between the active correlated functional behaviours is checked and coherency with safeguards purposes verified.

2.2.3 Auto-correlation

The repetition of a certain process cycle is recognised as the looping of a sequence of functional behaviours. This looping is controlled by means of auto-correlation, this means that the completeness of a cycle is verified by comparing with the predefined design. Errors, such as incompleteness of the cycle, inadvertent repetition of a functional behaviour, or falling out of a part of the process cycle, are reported with a diagnosis on the global constraint violation.

3. DAI application on the neutron & gamma signals

3.1 The fuel insertion process step

All the spent fuel (SF) assemblies with their declared characterisation are at receipt roughly checked by total weighing and passive neutron counting before storing in the spent fuel pool. Before entering the process a second more accurate check is foreseen with the burn-up detector. The first process step can be localised in the input cell for the fuel insertion with the burn-up check. Thereby the fuel is taken from the pool and moved inwards the measuring pit, moved backwards and tilted for introducing in the chopping channel. To follow the fuel movement in the input cell a neutron counter and gamma spectrometer are placed at the entrance of the chopping channel. The different movements of the spent fuel assembly in the input cell are presented in Fig.1. (a-b-c-d-e-f-g-h).

With the data historian the neutron and gamma signals are collected and compressed. A homothetic scaling is applied to standardise the signal range and to feed the DAI software with clear cyclic signals.

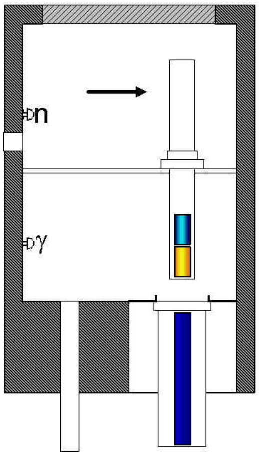

Fig.1a: SF from pool

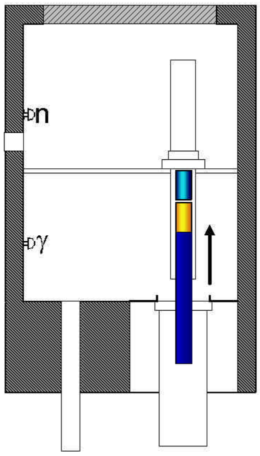

Fig.1b: SF transport

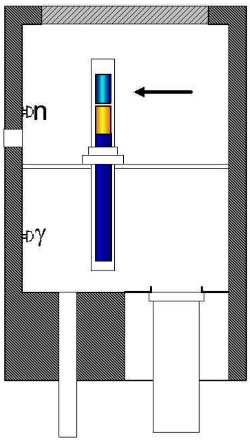

Fig.1c: SF towards pit

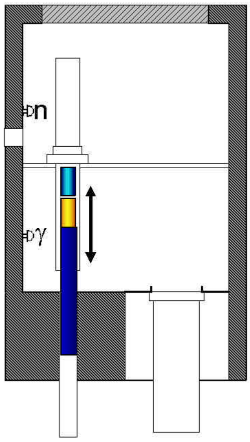

Fig.1d: SF in meas. pit

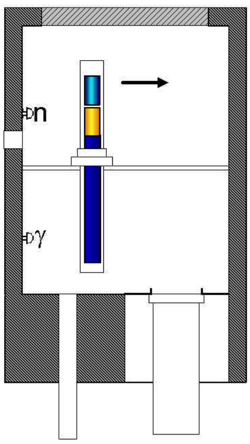

Fig.1e: SF withdrawal

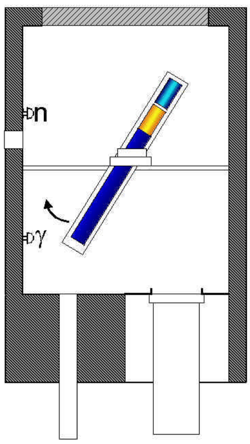

Fig.1f: SF tilting

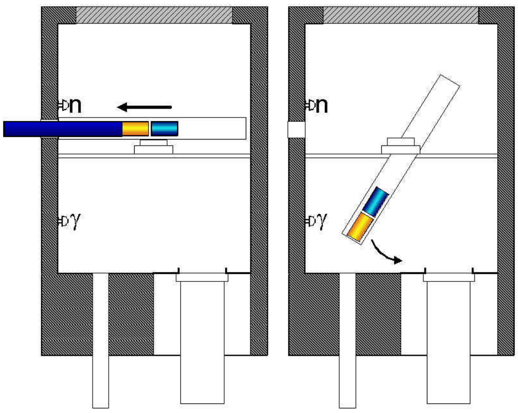

Fig.1g: insert chopper   Fig.1h: reset

3.2 The neutron/gamma cyclic signals in the input cell

Both signals, gamma and neutron that are reported by the data historian are analysed and interpreted simultaneously by DAI.
Two typical cycles, rescaled by the data historian, are presented in Fig. 2. The neutron and gamma signal behave in a similar way, but the presence of both with the given scale are characterising the real spent fuel composition. During the SF movement from the SF storage pool to the measurement pit, the SF approaches differently the detectors. As soon as the fuel is entering the solid angles of respectively the gamma and neutron detectors, the count rate directly goes up to a certain plateau, which is specific for the isotopic content of the spent fuel pellets in the Zirkaloy cladding. The waiting of the fuel in the loading machine before the start of the movement does not alter the registration in the solid angle of the detectors and thus gives an almost constant count rate. As soon as the fuel is approaching the detector by horizontal displacement a steep increase in signal is observed.
Once the fuel is descending in the measurement pit a very fast change in count rate is observed. The head and end of the spent fuel pins are of stainless steel and under the long-term irradiation Co-60 isotopes are present. The passing by of the head/end of a fuel leads to significant increases in count rate of the detectors and explains the first peak of Fig. 2. Once the fuel is completely in the measurement pit, zero counts are recorded. The number of counts increases again very fast when the fuel is moved out of the measurement pit, especially a second peak is recorded when the head/end is passing by the detectors. Then the fuel is tilted from its vertical position to a horizontal position in order to enter the chopping channel. At about 45° tilted position the head/end of fuel is passing closely at the gamma counter and this is recognised by the third peak in Fig. 2. Finally the fuel is inserted in the chopping channel and this is registered with the second plateau, at another level than the first one because the detectors have a different view on the fuel in the horizontal position.

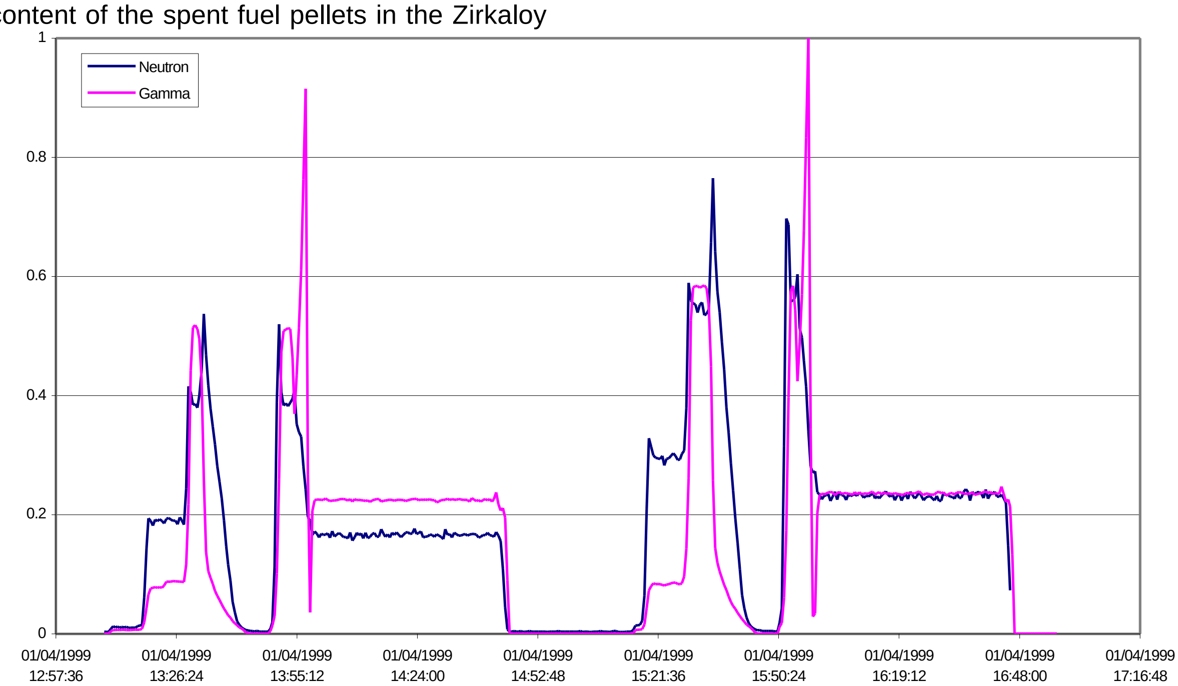

Fig. 2: Scaled n/gamma signal typically returned by the data historian for two consecutive cyclic input operations on the SF.

3.3 Symbolic modeling with the DAI software for automatic recognition of the neutron/gamma cycles

A fuel in the loading machine waiting an OK for movement can be identified with a plateau whereas a horizontal or vertical displacement or even a tilting of the spent fuel assembly is characterised with a steep slope. This is modelled with three normal kinds of functional behaviour:

- increasing slope with unknown value,
- decreasing slope with unknown value,
- plateau with unknown value.

For the detailed definition of these functional behaviours the reader is referred to the DAI user manual [4].

To analyse the signal for one cycle three subregions are indicated:

The first part concerns the displacement of the fuel in vertical position; The second part concerns the tilting of the fuel and the third part covers the insertion of the fuel into the chopping channel.

The symbolic model for one loop of the cyclic gamma/neutron signal is given in Fig. 3. A waiting time after the tilting is allowed in the model by the optional “plateau after decreasing slope” functional behaviour that can be bypassed. A synchronisation point has been introduced in the model after the insertion in the chopping channel. This has been selected by the modeller on a free basis at the end of the cycle to anticipate difficulties in addressing the complete loop and to allow resetting of the analysis for the next loop.

The fine tuning of all parameters for all functional behaviours was done with all available neutron /gamma signals, in particular the deviations of the standard signal, as shown in Figs. 4 and 5.

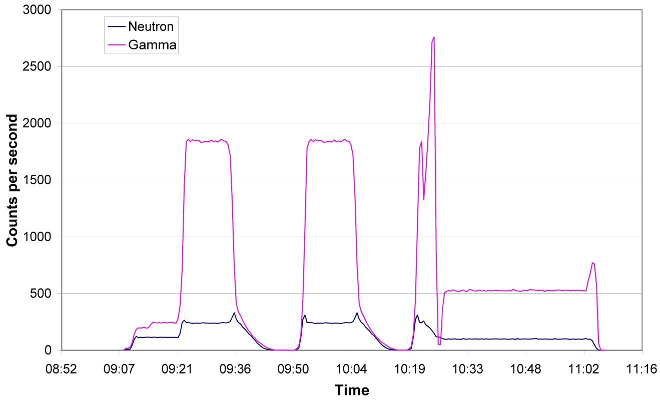

Fig. 4: Neutron and gamma signal for first case of common anomality: repeated (two) measurements in the pit before the approval for insertion in the chopping channel

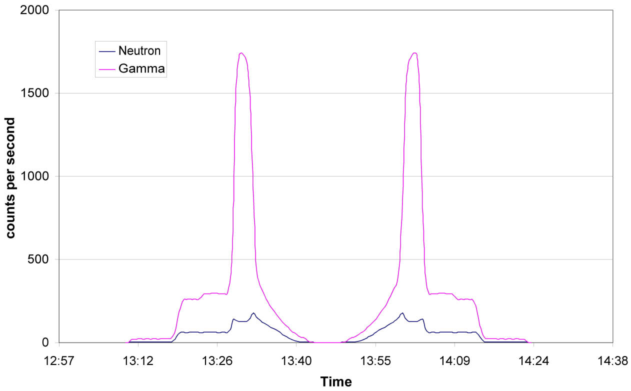

Fig. 5: Neutron and gamma signal for second type of anomaly with absence of the second part, because the spent fuel is only moved from pool to measurement and back and is not inserted in the chopping channel.

3.4 Final application: inspector tool for automatic follow-up of the spent fuel in the input cell.

This application example of DAI on the neutron-gamma signal allows the inspector to monitor the nuclear material of the SF into the chopping channel and after a more detailed characterisation of the SF with the burnup detector in the measurement pit. In view of the Near Real Time Accountancy a diagnostic support for the inspectors is in direct use with this DAI software. This application illustrates how the DAI software can utilise the described algorithms of cross- and auto-correlation and the formalisms of symbolising the signal profile and of assigning a status to an event in a generic way.

The displacement of the fuel from the storage pool into the chopping channel is correlated with the burnup characterisation of this SF assembly. The coherence in nuclear material flow further down in the process with the burnup signature can be verified in real time and each error is alarmed with a diagnosis (inclusive the necessary messages and early warnings). Moreover, the conformity of the consecutive actions in the fuel insertion process step with the prescribed model is evaluated in an efficient and transparent way.

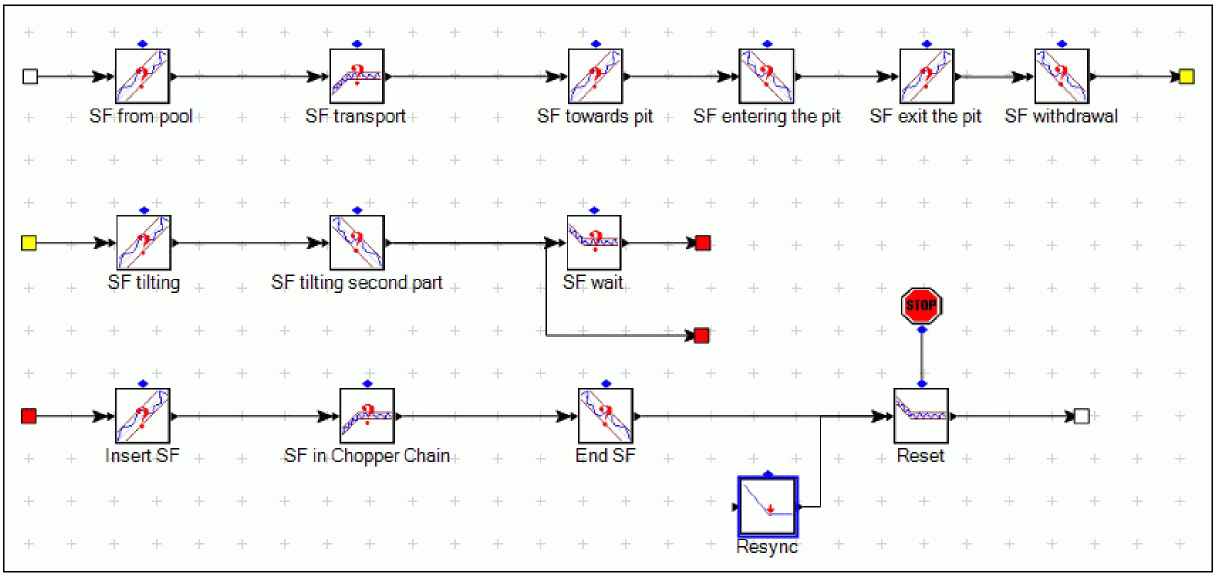

Fig. 3: Model for the cyclic neutron/gamma signal

Thanks to the pragmatic use of all on-line experience with the process, especially the vast amount of neutron/gamma signals, the monitoring system is tailored with a minimum of disabilities in the recognition of a cycle and a maximum of transparency. Those anomalies, which are no longer transparent, are due to the need of a higher level diagnosis, which is not envisaged with this process monitoring tool. The appearance of these anomalies is rare and neglecting them is acceptable according to Howell [5].

With the other applications, on the tank level/density for solution transfers as reported in [6], and on the weighing scale for the powder quantification as reported in [7], this application also demonstrates the general concept and modular structure of the DAI programme, that allows the analysis of very different kind of signals.

4. Conclusion

4.1 Results

A stand-alone software tool, that monitors the nuclear material flow for the different process steps, is successfully implemented at UP2 and UP3 facilities of the La Hague Reprocessing Plant and in operation under the so-called "System 7" application by the Euratom inspectorate. In a reprocessing plant the signals for each process step, such as the spent fuel insertion process step as addressed in detail here, are not only interpreted with identification of all functional behaviours but also evaluated carefully concerning the integrity of the material flow from and to the neighbouring places. Both coherence in material flow and conformity with the prescribed safeguards procedure are analysed and for each error an alarm and a diagnosis is given. A precise follow-up of the functional behaviour and of the sequence of behaviours allows a precise accounting of the mass of nuclear materials at the key measurement point in a material balance area.

The tool serves the inspector as a verification means for coupling the displace spent fuel assembly with its burnup signature. At each point, where an anomaly is detected, the cycle is interrupted. The tool then lists all possible procedural errors or constraint violations. It is left to the inspector to decide on the real cause, to remain consistent with their defined responsibility in the follow-up of the process. The tool is setup in a generic way, so that it can be applied for very different type of signals, such as the isotopic at different sites. Moreover this example demonstrates the usefulness of a simplified approach to follow-up the complete transfer of different material flows, in which all functional blocks of the design have been successfully validated.

4.2 Perspectives

The EURATOM inspectorate has asked to implement a similar monitoring tool at the reprocessing plant of Sellafield (THORP). The software has also been selected by the IAEA for the solution monitoring of the TETRA demonstration plant by the Japanese inspectors of NMCC, and for the inspection of the Tokai reprocessing plant (TRP) by IAEA itself. Apart from safeguards inspections the tool can be applied as a batch norm monitoring system (ISA-88 and ISA-95). The batch industry is still finalising the last ISA-95 norm to enhance the Material Flow Management and the traceability in Manufacturing Executing System (MES).

References

[1] Osisoft PI: user manual and documentation via web: http://www.osisoft.com/5_267.aspx

[2] Matrikon OPC: user manual and documentation via web of Matrikon: http://www.matrikonopc.dom/index.html

[3] Janssens-Maenhout, G. and Dechamp, L, Process Monitoring for Near Real Time Accountancy, *J. Inst. Nucl. Mat. Man.* XXXII (4), Spring 2004

[4] Janssens-Maenhout, G. and Dechamp, L. *DAI User manual*, JRC special publication, January 2005

[5] Scothern, S.J. and Howell, J. 1997. A Physical-Model-Based diagnostic aid for Safeguarding Nuclear Material in a Liquor Storage Facility, *J. Inst. Nucl. Mat. Man.*, XXV(4), 20-29.

[6] Thevenon, J.B., Janssens-Maenhout, G., Dransart, P. and Dechamp, L., Une approche du monitoring d'installation industrielle: exemple d'une application EURATOM pour COGEMA à La Hague, *Clubautomation,* Oct. 2003.

[7] Janssens-Maenhout, G. and Dechamp, L. and Brian, H. Process Monitoring at a Reprocessing Plant : Example of a Weighing Cycle, *Proc. of the ESARDA Ann. Conf. (Stockholm)*, May, 2003