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TITLE: STATE-OF-THE-ART OF NEAR-REAL-TIME ACCOUNTING

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ABSTRACT

An essential step in the development of international safeguards technologies is the demonstration that safeguards elements are cost effective and operationally acceptable in actual nuclear facilities, and that safeguards data can be verified independently by the Agency. Near-real-time accounting is being pursued as a method for improving the timeliness and diversion detection sensitivity of conventional accounting procedures. Acceptability of near-real-time accounting for international safeguards depends on:

- Development of measurement techniques (process control, NDA, laboratory) that provide the required sensitivity and timeliness. The measurements must address transfers through the materials balance area (MBA) and material in process. The latter often can limit detection sensitivity for short-term diversion.

- Proper consideration of measurement control programs. The calibration procedures and frequencies are important in controlling correlated measurement errors, and significant improvements in detection sensitivity can be realized through changes in the measurement control program.

- Development of statistical techniques to evaluate measurement data. The statistical evaluation procedures should test a spectrum of diversion scenarios (abrupt or protracted) and should be adapted to the specific process and understood by safeguards personnel.

- Demonstration that the materials accounting results can be verified independently by the Agency. Independent verification should address possible diversion through data falsification and diversion hidden in measurement uncertainties.

- Demonstration of the safeguards system under operational plant conditions. Demonstration of the effectiveness should address process operator requirements with respect to improvements in process control and minimal intrusion on process operations.

Each of these areas is considered in the Los Alamos development program for near-real-time accounting and is discussed in the paper.

1. DEVELOPMENT OF MEASUREMENT PROCEDURES

Most facility, State, and international safeguards materials accounting systems provide requirements for measurement of all nuclear materials transfers into and out of an MBA. For conventional materials accounting these transfer measurements are augmented by periodic inventory measurements, made either directly or by cleaning out difficult-to-measure process equipment so that better measurements can be performed. These shutdown, cleanout inventories generally are performed at intervals between one and twelve months long. The fundamental difference between conventional and near-real-time accounting is that in the latter in-process material is measured more frequently and without equipment cleanout. Thus, timeliness in closure of materials balances, and hence sensitivity to short-term detection of materials loss, is improved.

Transfer-measurement requirements for near-real-time accounting are essentially the same as for conventional accounting, with the possible exception that some measurements, e.g., batched wastes, may require more frequent measurement. Product transfer measurements for both conventional and near-real-time accounting generally are obtained by the most accurate and precise analytical methods available, usually in analytical laboratories with skilled analysts.

The major practical difference between conventional and near-real-time accounting is the requirement to measure the in-process inventory, often while the process continues to operate. These measurements do not have to be of the same quality as transfer measurements, and may be performed using process-control or NDA instrumentation. Inventories in tanks can be obtained if the tanks are instrumented with process level and density probes. These measurements can be updated with more refined laboratory measurements as they become available. For complex equipment such as solvent-extraction contactors, predictive models using process measurements can provide adequate estimates of in-process inventory [1]. Hold-up in process equipment such as precipitators and filters can be measured using NDA techniques or may be estimated using predictive models [2].

2. MEASUREMENT CONTROL

Certain guiding principles govern effective materials control and accounting in any nuclear materials process. Each measurement is important for its impact on the sensitivity of loss detection. The desired quality of each measurement should be judged by systematically analysing the anticipated effects on materials-accounting sensitivity.

In high-throughput processes, the relative accuracy between feed and product measurements limits the long-term detection sensitivity of both conventional and near-real-time materials accounting [3,4]. Consequently, a significant effort should be directed at controlling long-term relative biases between feed and product measurements. Theoretically, the limiting factor is the uncertainty in the relative bias between the physical standards used for these measurements, which may be $\sim 0.1\%$. To approach this limit, sources of long-term measurement bias other than standards must be controlled by careful design of the sampling, measurement, and calibration hardware and procedures [5-9]. Feed and product accountability vessels must be designed for accurate calibration and should be accessible for calibration checks and periodic recalibrations. The best available sampling and assay methods must be used, and analysts must be carefully trained in the use of calibration and analysis procedures.

For near-real-time materials accounting, the precision of the in-process inventory measurements and the variability of any unmeasured holdup are the limiting uncertainties in short-term detection [4]. The majority of the inventory should be in tanks and vessels that are instrumented for on-line measurements. These measurements need not be of high quality, precisions of 1 to 5% generally being adequate. However, even with very precise measurements, large buffer-storage tanks for intermediate products can introduce large absolute errors that seriously degrade the short-term detection sensitivity. On the other hand, relatively minor holdups and sidestreams will have little effect on detection sensitivity, and estimates based on historical data can be used until these components are measured, for example, during a physical inventory.

If all major in-process-inventory and process-stream components are measured, timely materials balances can be drawn around transfers between tanks and across vessels. Such balances may not have the relative precision and accuracy usually associated with conventional accountability, but they can be both sensitive and timely in absolute terms.

Process operating modes also affect materials-accounting sensitivity. Well-defined input and output batches facilitate accounting; if the process is operated continuously, batch definition requires continuous stream measurements. If there are significant recycle streams, input-output correlations will be of limited value.

3. STATISTICAL TECHNIQUES TO EVALUATE MEASUREMENT DATA

The statistical tests used to examine materials accounting data must be specially structured to meet operating and safeguards procedural requirements [10]. The task can be made easier by recognizing that materials accounting activities occur in three stages: detection, assessment, and statement. The overall statistical procedure must satisfy, at least, five criteria:

- timeliness,
- flexibility with respect to time interval and loss patterns,
- stability of decisions,
- availability on demand of the materials accounting status, and
- quantifiability of performance.

The procedural requirements listed previously are stringent and severely constrain the choice of statistical tests for detection. Tests having well-defined values of false-alarm and detection probabilities are particularly desirable because the detection stage is the initiator of subsequent events, such as assessment, that may have significant consequences. However, the other criteria force consideration of procedures that are somewhat more complicated than those usually encountered in the literature. Currently, preliminary results from work based on sequential testing procedures using a test threshold derived from the law of the iterated logarithm are encouraging [11].

During the assessment stage, estimation of the diversion amount and time pattern are of primary interest. Consequently, loss estimators play an important role, and several loss estimators extending over all possible time intervals will have to be used to cover all loss patterns. Generally, the estimation algorithms can be carried out sequentially in time, as materials balances become available, and there are advantages to doing so [12-17].

The statement stage should culminate in a report of the materials accounting results, that is, a statement of the material unaccounted for and its limit of uncertainty. The statement can be made at specified points in time covering the maximum time interval, or it can be made following a detection and assessment that a significant loss has occurred. One possible method is to report the most significant results in the maximum time interval. This technique is being investigated at the present time.

4. IAEA VERIFICATION

Materials accounting for international safeguards depends on the inspector's ability to verify the operator's materials accounting results. The IAEA verification of the operator's nuclear materials accounting system is based on examination of the materials balance equation with respect to:

- diversion hidden by measurement uncertainties and
- diversion hidden by falsification of operator's data.

Diversions hidden by measurement uncertainties are possible because of the statistical uncertainty of the material unaccounted for (MUF) calculation. It is important that measurement uncertainties be reduced to decrease the amount that could be diverted, but that the estimates of measurement uncertainties be realistic to maintain false-alarm rates at an acceptable level.

Concerns with diversion hidden by falsification of operator's data fall into three categories:

- understatement of inputs,
- overstatement of outputs, and
- overstatement of the current inventory.

For consecutive MBAs, falsifications are correlated from one MBA to the succeeding MBA. Thus, an overstatement of outputs from one MBA will result in an overstatement of inputs to the next MBA. Detection of diversion in one MBA depends on adequacy of safeguards in adjacent MBAs, and correlation of verification activities among MBAs is important.

Verification techniques of individual measurements, which is sometimes called authentication, depends on the details of each measurement, which is dictated by the particular type of facility and its location in that facility. The following example is taken from a study of international safeguards for reprocessing plants [18].

No matter what kind of materials accounting is used, the inspector must verify the operator's accountability tank measurements. For the gravimetric procedure, the original fuel fabricator's data must be verified so that they can be correlated with the uranium and plutonium concentration measurements in the accountability tank. For the volumetric procedure, the plutonium and uranium concentration measurements and the volume measurements, for example, the operator's liquid-level and density measurements, must be verified. The uranium and plutonium concentration may be verified by preparation of resin-bead samples that are submitted to the operator or transferred to the Agency laboratory for mass-spectrometric analysis. The inspector may also measure the uranium-to-plutonium ratio by a rapid method such as x-ray fluorescence spectrometry or determine the plutonium concentration by a simple spectrophotometric method.

5. SAFEGUARDS SYSTEMS DEMONSTRATION

The effectiveness of any proposed safeguards system can be evaluated through computer modeling and simulation of process operations and materials measurements. However, these models are subjective, and may not reflect accurately all process and measurement variables and interfaces. The confirmation of effectiveness comes from field demonstration and operation. The International Working Group on Reprocessing Plant Safeguards [19], in identifying areas of further work, has recommended:

"Demonstration in operating plants, beginning with the simpler concepts of in-process inventory measurement and selected flow monitoring progressing to more complete near-real-time accountancy systems, should be continued in order to assess the performance and utility of near-real-time accountancy."

Near-real-time accounting is being applied or demonstrated at several facilities around the world. Los Alamos has participated in field demonstrations of near-real-time accounting for nuclear fuel reprocessing at the Allied-General Nuclear Services (AGNS) facility at Barnwell, South Carolina. These experiments consisted of seven one-week operations of the plutonium purification cycle at AGNS. Experiments were conducted using a modified flowsheet to process natural uranium. Los Alamos participation in these experiments included:

- development and demonstration of estimation techniques for contactor inventories,
- evaluation of advanced data analysis and diversion detection techniques, and
- demonstration of near-real-time accounting concepts and principles.

5.1 Contactor Inventory Estimation

The pulsed columns in the plutonium purification section contain approximately 18 kg of plutonium during normal operation. If not measured, this inventory becomes the dominant factor in limiting short-term diversion sensitivity. Under the sponsorship of Los Alamos, techniques for estimating the inventory in pulsed-column contactors were developed [20]. Experimental verification of these models at AGNS using uranium indicates that the column estimates are good to 5 to 25% for individual columns and to about 10% for the total column inventory. Additional verification of the plutonium inventory estimation method under realistic operating conditions is required.

5.2 Evaluation of Advanced Data Analysis and Diversion Detection Techniques

The Los Alamos-developed computer codes studied during the AGNS experiments included a program called FUNNEL that estimates column in-process inventory from process measurements and flags measurement anomalies, such as plugged dip tubes for volume and density measurement, and the decision analysis program DECANAL. DECANAL [13-15] calculates sufficient statistics containing all accounting information, sets decision thresholds, and tests sequential data for losses. The DECANAL output includes various graphical displays that localize losses, show the amount of loss, and indicate the significance of the loss. Test statistics incorporated in the code include the Shewhart chart, CUSUM, uniform diversion test, and sequential variance test.

5.3 Demonstrations of Near-Real-Time Accounting Concepts and Principles

Accounting strategies studied by Los Alamos included defining several unit process accounting areas within the plutonium purification process and closing materials balances hourly. These strategies were selected to demonstrate the application of sequential data analysis techniques to areas where diversion detection could be localized. The UPAAs studied included:

- the full process,
- pulsed columns,
- pulsed columns and concentrator,
- 1BP surge tank, and
- any individual tank.

5.4 AGNS Demonstration Summary

The Los Alamos experiments at AGNS demonstrated that:

- near-real-time accounting can detect and localize diversions from complex bulk handling facilities such as reprocessing plants,

- process-control-quality flow and concentration measurements can be used to estimate uranium concentration in pulsed columns to ~10%,
- process-control-quality measurements can be used to measure uranium concentration in tanks under process operating conditions,
- the UPAA concept is helpful for detection and localization of losses,
- analysis and display methods are a necessary component of a near-real-time accounting and process control system, and
- the design of a safeguards materials accounting system depends on the process operation and existing process and nuclear materials accounting measurements.

6. SUMMARY AND CONCLUSIONS

Near-real-time accounting is being considered for facility, State, and IAEA safeguards systems in future, high-throughput, bulk-handling nuclear facilities. Measurement systems using some combination of process, NDA, and analytical laboratory data can be developed for most facilities and with minimal interference with process operations. Statistical techniques for treating sequential data and closing materials balances at frequencies satisfying short-detection-time criteria are well in hand. Additional work is required to develop verification techniques that allow Agency inspectors to maintain continuity of knowledge of all nuclear material through a facility. Finally, the techniques for near-real-time accounting require demonstration under actual plant operating conditions.

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