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AUTHOR(S): E. A. Hakkila, R. G. Gutmacher, J. T. Markin, J. P. Shipley, and W. J. Whitty

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THE ROLE OF MATERIALS ACCOUNTING IN INTEGRATED SAFEGUARDS SYSTEMS FOR REPROCESSING PLANTS

E. A. Hakkila, R. G. Gutmacher, J. T. Markin, J. P. Shipley, and W. J. Whitty
Nuclear Safeguards Systems Group
Los Alamos National Laboratory
Los Alamos, New Mexico, USA

Abstract

Integration of materials accounting and containment/surveillance techniques for international safeguards requires careful examination and definition of suitable inspector activities for verification of operator's materials accounting data. The inspector's verification procedures are designed to protect against data falsification and/or the use of measurement uncertainties to conceal missing material. Materials accounting activities are developed to provide an effective international safeguards system when combined with containment/surveillance activities described in a companion paper.

1. Introduction

International safeguards requirements and the capabilities of materials accounting and containment/surveillance to meet these requirements were evaluated for a large nuclear fuel reprocessing facility of the type that may be operational in the latter part of this century.[1] The Allied-General Nuclear Services (AGNS) reprocessing plant at Barnwell, South Carolina, was used as the reference facility. This plant has an annual throughput of 1500 metric tonnes of heavy metal per year (MTHM/y) and a storage capacity of 4 MT of plutonium as the nitrate solution. The materials balance areas (MBAs) structure and key measurement points (KMPs) are shown in Fig. 1 and are discussed further in the text.

This paper describes materials accounting activities in the reference facility that the International Atomic Energy Agency (IAEA) may use to implement its verification system and summarizes the effectiveness of these activities. The containment/surveillance activities and their effectiveness are reviewed in a companion paper at this symposium.[2]

2. International Safeguards Concerns

The effectiveness of IAEA safeguards is related to its capability to detect diversion of nuclear material by verifying the findings of the State's System of Accounting and Control of nuclear material. The inspector's verification procedure is based on periodic examination of the materials balance equation for each MBA. The inspector must determine that:

- materials accounting data are valid and complete, and
- the materials balance equation closes sufficiently closely to zero.

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These verification activities include (1) examination of safeguards-related information provided by the State, (2) collection of independent information by the IAEA, and (3) comparison of the two sets of information to establish the completeness, accuracy, and validity of the State's data.

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 estimate 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 MBAs in the reprocessing facility, 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.

3. Safeguards Concerns and Verification Activities for the Reference Facility

A combination of conventional materials accounting and near-real-time accounting was assumed for the operator's accounting system for the reference facility. In near-real-time accounting, the in-process inventories of major process vessels and columns are measured or estimated to permit frequent closure of materials balances.

Three MBAs of the reference facility were considered (Fig. 1): MBA 1, the fuel receiving, storage-chop/leach area; MBA 2, the chemical separations process; and MBA 4, the plutonium-nitrate storage area. The input, output, and inventory KMPs for these MBAs were identified.

The inspector must establish a sampling plan and an independent verification capability for each KMP, and must assure integrity of appropriate operator's measurements by participation in measurement control programs and surveillance

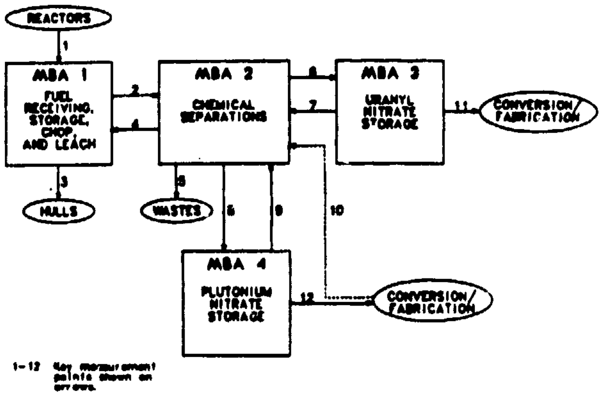

Fig. 1. MBAs for the reference facility.

of measurement procedures. He may assure integrity of some operator instruments with inspector-controlled surveillance devices. The inspector examines the operator's and his own materials accounting data to obtain an assurance that diversion has not occurred. Continuous IAEA inspector presence and on-site laboratory facilities are assumed.

Verification Activities in MBA 1

MBA 1 includes the cask-unloading and spent-fuel pools, the shearing operation, and the dissolution process. The flow KMPs are:

(1) KMP 1a - cask unloading pool. Receipt of irradiated fuel in MBA 1.
KMP 1b - spent-fuel transfer tunnel. Transfer of irradiated fuel to the chop/leach process.
(2) KMP 2 - accountability tank. Transfer of dissolved nuclear material from MBA 1 to MBA 2.
(3) KMP 3 - leached-hulls monitor. Leached hulls are monitored for residual plutonium and uranium content before they are discarded.
(4) KMP 4 - dissolver acid surge tank. Transfers of recycle acid from MBA 2 to MBA 1.

The inventory KMP (KMP A) is located in the spent-fuel storage pool.

Verification activities in MBA 1 are based upon an examination of the MBA and adjoining MBAs to determine safeguards concerns. Understatement of spent fuel inputs is a concern. Understatement of recycle inputs from MBA 2 is not of concern because of the effectiveness of near-real-time accounting in MBA 2. Significant understatement of material entering MBA 1 through KMP 4 would result in a positive MUF for MBA 2.

Output streams from MBA 1 are either product entering MBA 2 or waste (assumed to be leaving safeguards). Overstatement of outputs that enter MBA 2 will result in a positive MUF for MBA 2 and hence is not of concern. However, understatement of outputs from MBA 1 to MBA 2 is of concern in MBA 2 because the dissolved fuel material introduced into the separations MBA could then be used to cover diversion of plutonium in a more attractive form (such as plutonium-nitrate product solution) without detection by materials accounting in MBA 2. The understatement would tend to result in a positive MUF in MBA 1. However, the goals for timeliness of detection in MBA 2 are more stringent and would not be met in MBA 1.

Overstatement of the MBA 1 inventory is a concern because it would allow material to be diverted without detection by the accounting system. Overstatement of waste measurements could result in material being available for diversion unless sufficiently low limits can be placed on the quantities of plutonium normally present.

Two types of nondestructive measurements can be identified for inspector verification of accounting in the spent-fuel receiving area: (1) rapid qualitative measurements of spent-fuel assemblies (attributes check), and (2) quantitative measurements of a limited number of the fuel assemblies (variables test). The inspection effort is limited by the available manpower and by legal constraints. An IAEA Advisory Group on the Nondestructive Measurement of Spent Power Reactor Fuels has recommended six levels of verification, ranging from verifications of the physical characteristics to measurements of the fissile contents of fuel assemblies.[3] The specific level of verification depends on the available resources and the desired level of assurance.

A rapid verification of fuel assemblies that enter the spent-fuel transfer tunnel is of use in closing shipper/receiver differences at the time fuel is dissolved as well as in verifying item accounting data for the spent-fuel storage area. The verification activities at this point would be very similar to those in the cask-unloading pool.

Operator's Measurements in MBA 2.

The separations and plutonium purification process MBA extends from the input accountability tank to the uranyl- and plutonium-nitrate product sample tanks. The flow KMPs for conventional materials accountability are:

(1) KMP 2 - accountability tank. Transfer of dissolved nuclear fuel to MBA 2 from MBA 1.
(2) KMP 4 - dissolver acid surge tank. Recycle acid transferred to MBA 1.
(3) KMP 5a - high-level liquid-waste sample tank.
KMP 5b - general process-waste check tank.
KMP 5c - solid-waste assay station.
KMP 5d - solvent-burner feed tank.
KMP 5e - central stack.
(4) KMP 6 - uranium product sample tank. Transfers of uranyl-nitrate product from MBA 2 to MBA 3.
(5) KMP 7 - uranium rework tank. Recycle of off-specification uranyl nitrate from MBA 3 to MBA 2.
(6) KMP 8 - plutonium product sample tank. Transfers of plutonium-nitrate product solution to MBA 4.
(7) KMP 9 - plutonium product recycle tank. Recycle of off-specification plutonium nitrate from MBA 4 to MBA 2.

(8) KMP 10 - plutonium rework tank. Transfers to MBA 2 from the conversion process.

KMP 10 was not be considered in the study.

The inventory KMPs are KMP B1, the two feed adjustment tanks, and KMP B2, the 1BP surge tank. Other inventory measurement points are used only when the process line is cleaned and flushed.

For near-real-time materials accounting, if MBA 2 is considered as a single accounting area, measurements (or estimates) of inventories must be made at the following additional points: centrifuge, HA feed tank, HA contactor, HS column, 1B column, 1BX column, 2A column, 2B column, 3A column, 3B column, 3PS wash column, 3P concentrator, and plutonium catch tank. We consider these points to be strategic points, but not KMPs, because the required level of verification is less than for KMPs.

Near-real-time accounting in MBA 2 allows frequent materials balance closure with a minimum of measurement uncertainty. Hence, the main concerns in MBA 2 are those related to falsification of measurements through understatement of inputs, overstatement of outputs, or overstatement of inventory.

Input Measurements. The three input measurements to MBA 2 are the accountability tank, the plutonium product recycle tank, and the uranium rework tank. Understatement is a concern for the first two measurement points. Conventional materials accounting in MBAs 1 and 4 may be insufficient to meet this concern from the viewpoint of sensitivity and timeliness, so that other safeguards measures may be required. Understatement of inputs at the accountability tank can result from improper concentration measurements or through understatement of level and density measurements.

Output Measurements. Outputs in MBA 2 include recycle to MBA 1, product transfers to MBAs 3 and 4, and waste. The output measurements in which overstatement is of particular concern are:

(1) high-level liquid waste (HWW) sample tank and
(2) plutonium product sample tank.

Overstatement can be accomplished by manipulating materials transfers, but in a different way than for understatement. Overstatement can result if material remains in a vessel to be measured a second time. Overstatement of waste measurements is a concern when the measurement limits cannot be set sufficiently close to zero that repeated overstatement will not result in a significant amount of material being available for diversion.

Inventory Measurements. Overstatement is a concern at the following inventory measurement points:

(1) feed adjust tanks,
(2) 1BP surge tank,
(3) HA feed tank,
(4) 3P concentrator,
(5) HS column,
(6) 1B column,
(7) 2A column,
(8) 2B column,
(9) 3A column,
(10) 3B column, and
(11) 3PS column.

Measurements at these points are used to estimate the in-process inventory for near-real-time materials accounting. Diversion of material at these points is not as great a concern as at the input and output KMPs because process constraints limit the amount of material that could be contained in these vessels and because removal of material would tend to result in column or process upset.

In-process inventory measurements for columns are inferred from measurements of flow and concentration on inlet process, extractant, and scrub streams and outlet product and waste streams. Overstatement of inlet concentration measurements, understatement of outlet concentration measurements, or erroneous measurement of extractant or scrub flow rates can allow overstatement of the column inventory.

Other measurements are made only during physical inventories when the process line is cleaned out and flushed. The following tanks should normally contain negligible quantities of uranium and plutonium:

(1) 1SF tank,
(2) LAWB check tank,
(3) recovered-acid storage tank,
(4) solvent system feed tanks (2),
(5) solvent batch stripping tank,
(6) service concentrator feed tank,
(7) service concentrator check tank, and
(8) sump collection tank.

Verification of measurements at these points is generally not required.

Verification Activities in MBA 2.

The inspector's verification activities in MBA 2 are concerned with accurate volume, density, concentration, and, to a lesser extent, flow measurements. Flow measurement verification is associated primarily with the estimation of pulsed-column in-process inventories. The verification of tank calibration is of particular concern for input and output accountability tanks. The accuracy of the tank calibration and the assigned probe separation value can be verified by witnessing and evaluating multiple calibration passes to be sure that the correct relationship between liquid level and volume is established. The inspector may be able to participate in the initial and subsequent calibrations of the tank and of differential pressure instruments if he has an independent readout device or calibrating device that is connected to the pressure transducers.[4] The inspector may compare his readings with the operator's readings or perform independent calibrations.

The inspector must ascertain that solution is circulated through the sampling loop for a sufficient period to ensure that the samples are reproducible and representative of the bulk solution in the tank. The inspector may request duplicate samples for analysis in his laboratory or for submittal to the operator's laboratory as blind samples. Analysis must be based on a statistically sound variables sampling plan. Submission of samples to the operator's laboratory can be effective only if the laboratory does not know and cannot trace the identity of the samples. Such samples may be used to assess the accuracy and precision of an analytical method.

Verification Activities in MBA 4

The plutonium-nitrate product storage area, MBA 4, contains 3 interim 400-L storage tanks, a 100-L product measuring tank, and 48 slab tanks, each capable of storing up to ~800 L of plutonium nitrate at a concentration of 250 g/L. Solution residence time in each of the interim storage tanks is 48 h. The flow KMPs for this MBA are:

(1) KMP 8 - plutonium product sample tank. Transfers of plutonium-nitrate product solution to MBA 4 from MBA 2.
(2) KMP 9 - plutonium product recycle tank. Recycle of off-specification plutonium-nitrate product from MBA 4 to MBA 2.
(3) KMP 12 - receipt tanks. Transfer of plutonium-nitrate product from MBA 4 to the conversion process area.

The inventory KMPs are KMP C1 to KMP C3, the interim plutonium-nitrate product storage tanks; KMP C4, the 100-L measuring tank; and KMPs C5 to C52, the 48 slab tanks.

There are two primary safeguards concerns for MBA 4. The first concern is diversion concealed by measurement uncertainties. Large quantities of plutonium may be present in this MBA. If all 3 interim storage tanks and all 48 product storage tanks are filled with solution having a plutonium concentration of 250 g/L, MBA 4 could contain as much as 9900 kg of plutonium. In actual plant operation, all tanks will not be full; material from storage tanks will be transferred to the conversion process, and at least one interim storage tank will be empty, awaiting transfer of solution from the plutonium product sample tank through KMP 8.

When large quantities of material are to be measured, even small errors in the concentration measurement can lead to an appreciable uncertainty in the total quantity. Estimates of systematic and random errors in the volume and concentration measurements for individual tanks, in the worst case, with all storage tanks full, lead to an uncertainty in the total inventory ranging from 5.4 to 10.9 kg of plutonium, depending on whether the instrument used to determine concentration is recalibrated after each measurement.

The second concern is deliberate overstatement of the inventory measurement. Overstatement would allow material to be removed from the MBA without appearing as MUF. Deliberate overstatement of input measurements at KMP 8 or output measurements at KMPs 9 and 12 is not a concern because a positive MUF would appear in the materials balances of MBA 2 or the conversion MBA.

Safeguards concerns for MBA 4 can be addressed through (1) verification of the conventional accounting measurements and the use of containment/surveillance to assure that all transfers pass through the appropriate measurement points or (2) providing improved materials accounting in MBA 4. The first approach is similar to that used in MBA 1. Improved materials accounting is achieved by on-line measurement of volume and concentration in the storage tanks. For timeliness and improved sensitivity, these measurements should be performed as frequently as possible.

4. Effectiveness of Materials Accounting

The inspector's problem of detecting falsified data and diversion hidden by measurement uncertainties can be addressed by applying the inspector's sufficient statistics.[5,6] The performance of these statistics in detecting abnormalities was evaluated for the chop/leach area of MBA 1, for MBA 2, and for MBA 4 over a range of diverted amounts. In each case the analysis assumed an optimal operator data falsification strategy. Also, all of the detection sensitivities presented assume that the inspector either has a measurement method with uncertainty comparable to the operator's method or can verify the operator's measurement and use it as his own. In all other cases, the inspector's detection probability is less than shown here.

MBA 2 of the reference facility is the most likely area for application of these statistics because quantities of material are relatively small and measurement techniques for this area are well developed. If the inspector uses inspector's data only in testing for missing material without regard to operator falsification, the sensitivity of the inspector's sufficient statistic to missing material meets the IAEA goal for detecting abrupt diversion. For 8 kg of plutonium diverted in 7 days, the inspector has a detection probability of 0.97. If the inspector has not verified operator's measurements, then he must use a statistic to test for data falsification or diversion and accept a slightly reduced sensitivity. For this test, the detection probability is 0.94.

Although the chop/leach area and MBA 4 have not traditionally been considered in near-real-time accounting, evaluation of the inspector's sufficient statistics in these areas shows that substantial probabilities of detecting missing material can be attained. In the chop/leach area, 8 kg of plutonium diverted in 7 days is detected with probability 0.64 if the inspector tests only for diversion and with 0.56 probability by testing for diversion and falsification. For MBA 4 the respective probabilities are 0.26 and 0.21. However, if the current 48 slab tanks each containing 200 kg of plutonium were reduced to <16 tanks each containing 100 kg of plutonium, then the IAEA goals for abrupt diversion could be met in MBA 4. If we assume storage capacity for 20 days of throughput is sufficient for a plant with a collocated conversion facility, 10 storage tanks each with 100 kg of plutonium would be adequate for MBA 4.

Sensitivities of the inspector's sufficient statistic that is independent of the operator's falsification is summarized in Table I. Sensitivities of the inspector's sufficient statistic that uses unverified operator's data to test for data falsification or diversion are summarized in Table II. Sensitivities for MBA 4 were calculated for the present 9.9 MT storage capacity and for the proposed capacity of 1 MT.

TABLE I

SENSITIVITY OF INSPECTOR'S SUFFICIENT STATISTIC: FALSIFICATION INDEPENDENT

	Detection Probability[a]			
	Balance Period (days)			
Balance Area	7	30	180	360
Chop/leach	0.64	0.25	0.11	0.09
MBA 2	0.97	0.82	0.25	0.20
MBA 4; 9.9 MT	0.26	0.24	0.17	0.13
MBA 4; 1 MT	0.99	0.90	0.26	0.15

[a]Diversion of 8 kg, 0.05 false-alarm probability.

TABLE II

SENSITIVITY OF INSPECTOR'S SUFFICIENT STATISTIC: FALSIFICATION DEPENDENT

	Detection Probability[a]			
	Balance Period (days)			
Balance Area	7	30	180	360
Chop/leach	0.56	0.20	0.09	0.08
MBA 2	0.94	0.75	0.20	0.17
MBA 4; 9.9 MT	0.21	0.20	0.15	0.11
MBA 4; 1 MT	0.98	0.84	0.21	0.13

[a]Diversion of 8 kg, 0.05 false-alarm probability.

5. Quantifying the Assurance for Materials Accounting and Containment/Surveillance

The overall assurance is a combination of the assurance

- provided by materials accounting, $a_{MA}(d,T)$,
- of inspector's materials accounting information integrity, $a_{AI}(d,T,i)$,
- provided by surveillance of boundary penetrations, $a_{BPS}(d,T,i)$,
- of surveillance information integrity, $a_{SI}(i)$, or
- provided by additional inspector activities, $a_O(i)$.

The designators d, T, and i denote dependence of a particular assurance on the diversion level, diversion time, and specific diversion path, respectively. If we assume total independence of information provided by materials accounting, penetration monitoring, and other inspector activities, the overall safeguards assurance, A(d,T,i), can be given by

$$A(d,T,i) = 1 - [1 - a_{MA}(d,T)a_{AI}(d,T,i)]$$

$$\cdot [1 - a_{BPS}(d,T,i)a_{SI}(i)][1 - a_O(i)] .$$

The factors contributing to this equation are difficult to quantify; hence, at present it can only provide a qualitative indication of the relationship among the component assurances.

An alternative to quantifying the total assurance is that the safeguards system should detect improper facility operation that could be related to diversion; thus, one important element of safeguards performance is measured by the likelihood of detecting such operational anomalies. For all materials accounting instruments and for some containment/surveillance instruments such as portal monitors, an anomaly is any measurement exceeding a statistically defined threshold, whereas for containment/surveillance equipment such as film cameras, an anomaly is any observed activity of facility personnel or use of equipment that is not normal. Thus, materials accounting and containment/surveillance can be considered in a coherent framework with the possibility of assigning, albeit subjectively, a quantified measure of combined assurance.

6. Recommendations

This study has identified certain features of the verification approach and facility design that could result in improvements in safeguards effectiveness. We recommend that these features be considered in future approaches to safeguards systems design and verification.

Verification Approach.

An approach to inspector verification of safeguards materials accounting data for a reprocessing facility was developed. This approach incorporates:

- appropriate statistical test procedures for materials accounting data from each MBA to detect diversion of a significant quantity of nuclear material,
- inspector participation in the measurement control program for materials accounting and surveillance instruments, and
- an on-site inspector's analytical laboratory with appropriate analytical instruments and standards.

Facility Design to Improve Verification Effectiveness.

Materials accounting and containment/surveillance should be designed and integrated in a manner that will allow the most reasonable compromise between safeguards performance goals and constraints associated with process design, operating economics, health and safety, technical safeguards capability, and Agency resources.

Features of facility design and operation affect application of conventional and near-real-time accounting techniques to reprocessing facilities. Process design and operational features that affect measurement quality include:

- relative accuracy between input and output measurements (the limiting factor will be the uncertainties in the relative bias between reference materials and methods used for measurements);
- precision and relative accuracy of cleanout physical inventory measurements;

- redundant methods at KMPs to reduce systematic errors; and
- for near-real-time accounting, the precision of in-process inventory estimates and measurements.

7. Conclusions

In this study a safeguards strategy was developed that includes materials accounting and containment/surveillance tradeoffs without requiring explicit assurance functions or combined systems evaluations. The functional relationships among the various safeguards elements were examined in detail to guide the development.

The study indicates that the implementation of near-real-time accounting in the reference facility would not impose a substantial additional operational burden beyond that required for process control measurements and conventional materials accounting measurements originally planned for the facility. Appropriate statistical test procedures can combine accounting information verified by the inspector with potentially falsified operator's accounting information to provide a significant level of safeguards assurance. In particular, these techniques should allow the inspector to meet the IAEA goals for detecting abrupt diversion in MBA 2. The amount of plutonium in MBA 4 limits safeguards effectiveness of materials accounting in this MBA. If plutonium storage is limited to the amount required for reprocessing and conversion operations, goals for detecting abrupt diversion in MBA 4 also can be met. Achievement of the IAEA goals for timely detection of protracted diversion from MBAs 2 and 4 remains a safeguards problem caused by irreducible measurement uncertainties and high plant throughput.

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