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THE ROLE OF NEAR-REAL-TIME ACCOUNTING IN INTERNATIONAL SAFEGUARDS FOR REPROCESSING PLANTS*

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ABSTRACT

The effectiveness of conventional nuclear materials accounting systems, both national and international, is constrained by the fundamental process features of high-throughput nuclear facilities and the economic limits of effective nuclear materials management consistent with production goals. Conventional accounting, complemented by near-real-time accounting, may meet projected IAEA performance goals for detecting diversion in medium- and high-throughput reprocessing facilities projected for the late 1900's.

The design of materials accounting systems for international safeguards in reprocessing plants is discussed, paying particular attention to the question of international verification. Specific problems in measurement techniques, data evaluation, and systems structure are identified, and the current status of research and development efforts is reviewed.

I. INTRODUCTION

At present, performance criteria for international safeguards systems, and the technology required to meet those criteria, are undergoing intense scrutiny.[1,2] This is especially true of nuclear materials accounting. Current accounting practices may be adequate for low-throughput facilities such as pilot-scale reprocessing plants. However, the effectiveness of conventional nuclear materials accounting systems, both national and international, is constrained by the fundamental process features of high-throughput nuclear facilities and the economic limits of effective nuclear materials management consistent with production goals. These in turn affect both the sensitivity of the accounting system to diversion and the timeliness of detection.

Because of its dependence on physical inventories, conventional materials accounting must rely primarily on enhanced measurement technology to improve its sensitivity. However, it is unlikely that measurement technology can be improved sufficiently by this method alone to meet safeguards needs for facilities much larger than some now operating. Furthermore, the timeliness question probably cannot be answered satisfactorily through evolutionary development of present accounting practices.

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A. Near-Real-Time Accounting

Drawing a materials balance depends on the ability to measure, or estimate, the initial and final inventories for the materials balance period. In the past, available measurement technology generally has required the shutdown, cleanout, and physical inventory of a process to permit such inventory determinations. With the advent of improved measurement and estimation techniques and devices, measurement of nuclear material during processing is becoming possible.

Recent developments foster the use of near-real-time accounting,[3-11] which is based on evolving NDA capability, conventional measurement methods, and sophisticated data-analysis techniques, supported by computer and data-base management technology. The fundamental idea is to draw dynamic materials balances in near-real time about relatively small portions of the process, called unit-process accounting areas. This approach increases the timeliness and sensitivity of materials accounting because balances can be drawn more frequently about smaller amounts of material.

It must be emphasized that near-real-time or dynamic materials accounting supplements, but does not replace, the shutdown, cleanout, physical inventory procedures currently in use. Physical inventories are still necessary to provide materials accounting fiducials and a periodic zero-base inventory.

The choice of materials balance period, that is, the timeliness of near-real-time accounting, is based on both sensitivity and detection-time criteria. Thus, even though a small-throughput facility might achieve the desired sensitivity (say, 8 kg) with a materials balance period of six-months, the desired timeliness criterion would not be met unless materials balances were drawn more frequently, for example over two-week periods.

B. Basis for International Safeguards

The basis for most current international safeguards arrangements is the Treaty on the Non-Proliferation of Nuclear Weapons,[12] agreed to by over 100 signatory nations since 1970. The detailed terms and conditions under which specific facilities are safeguarded under the Non-Proliferation Treaty (NPT) are negotiated with the International Atomic Energy Agency (IAEA), in accord with the general conditions of Article III of the NPT, set forth in the IAEA document INFCIRC/153.[13]

The objective of international safeguards, as declared by these documents, is the "....timely detection of diversion of activities...." The emphasis is on nuclear materials control with "....the use of materials accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures...."[13] The manner and frequency of inspections for compliance are negotiated between the IAEA and the host nation on a case-by-case basis, and are documented in the so-called "Subsidiary Arrangements and Facility Attachments."

By materials accounting the IAEA seeks to obtain to a satisfactory degree of confidence (which is now accepted as 95%) assurance that a significant amount of nuclear material is not diverted from a materials balance area over a certain period. INFCIRC/153, para. 31 also requires that the IAEA "shall make full use of the State's system of accounting for and control of all nuclear material subject to safeguards under the Agreement, and shall avoid unnecessary duplication of the State's accounting and control activities." This statement and para. 7 set the tone of international safeguards: the IAEA shall verify findings of the State's system. At the same time, para. 6 requires that the Agency "take full account of technological developments in the field of safeguards, ..." The phrase most descriptive of the IAEA safeguards ideal would seem to be "simultaneously effective and nonintrusive through technological sophistication."

II. NEAR-REAL-TIME ACCOUNTING AND INTERNATIONAL SAFEGUARDS

Because the IAEA's accounting activities depend fundamentally on the State's system of accounting and control, it is most likely that a near-real-time accounting system would be owned and operated by the State. Presumably, the IAEA would be allowed to make independent measurements in a fashion similar to current practice, and would interact with the State's system in a well-defined manner. This IAEA-State interface vis-a-vis near-real-time accounting is the heart of the matter and is the subject of intensive, ongoing study.[14] To examine the interface logically, consider first the kinds of techniques the State might use to deceive the IAEA.

A. State Activities Pursuant to Diversion

The State may attempt to deceive the IAEA's accounting system by two primary methods: (1) hiding diversion in the normal statistical uncertainties associated with materials accounting, and (2) falsifying the information received by the IAEA from the State's accounting system. The second technique may be further subdivided into four categories: (a) tampering with the material being measured, (b) tampering with the measuring devices, (c) tampering with the measurement data, or (d) tampering with the measurement control program to miscalibrate the measuring devices or to overstate their uncertainties. Of course, combinations of these methods might be used; we assume that independent measurements by the IAEA can be made sufficiently secure that we can disregard the possibility of tampering by the State.

B. IAEA Near-Real-Time Verification Activities

The most extensive and costly IAEA efforts are aimed at ensuring the integity of the information from the State's accounting system, that is, addressing diversion method 2 outlined above. Treating methods 2(a), (b), and (c) requires containment and surveillance techniques coupled with sophisticated calibration checks and data encryption for authentication. References 15 and 16 provide some preliminary ideas on the subject. Addressing method 2(d) requires IAEA involvement in the measurement control program.

Additional assurance of data integrity comes from checking the internal consistency of the State's accounting data, which are much more comprehensive with a near-real-time accounting system. Statistical analysis of the State's data to address diversion method 1, as discussed in Sec. III.E below, provides a bound on the best accounting sensitivity to be expected; the bound will be achieved if the State has not pursued method 2.

There are two possible disadvantages of near-real-time accounting relative to the more conventional methods. One concerns the degree of inspector presence and the amount and nature of facility information and process operating data. However, inspection effort sufficient to accommodate a near-real-time accounting system would appear to be allowed under current agreements. Furthermore, although it is probably unavoidable for individual inspectors to be familiar with some of the details of the process, it is likely that most information would be of a type useful only at the facility for day-to-day analysis and, indeed, need not leave the site. In addition, the sensitive information required for near-real-time accounting will not differ significantly from that required for a properly operating conventional materials accounting system.

The second consideration is the cost of the near-real-time accounting system. However, a recent study[6] estimates the capital cost to be 5-10% of the facility capital cost. This figure allows no credit for such benefits to the operator as improved process control and operating histories.

III. IMPLEMENTING NEAR-REAL-TIME ACCOUNTING FOR A NUCLEAR FUEL REPROCESSING PLANT

Near-real-time or dynamic materials accounting systems have been proposed at several nuclear facilities both in the U. S. and abroad.[17] Implementation in a nuclear fuel reprocessing plant provides a special challenge because material flows are batched at the head end and product loadout, but are continuous and have numerous recycle loops in the reprocessing area. Dynamic materials accounting will require periodic volume and concentration measurements for batch operations, and continuous flow and concentration measurements for continuous streams. In-process inventory must be estimated or measured, and specially tailored techniques are required for data evaluation.

A. Volume Measurement

Volume can be determined using load cells or by measuring liquid level and density. With load cells, a relative standard deviation of 0.2% has been obtained under ideal conditions, but precision was 2% in an operating plant environment.[18] The pneumatic bubbler has been used routinely for tank volume measurements. Electronic readout is replacing the sight glass and can provide continuous computer-compatible information. Volume measurement methods are summarized in Table I.

TABLE I

VOLUME MEASUREMENT METHODS

Instrument	Accuracy	Comments	Ref.
Load cell	0.2-2%	Has not been demonstrated effectively under plant operating conditions	18
Pneumatic bubbler	0.1%	Used routinely. Electromanometer provides continuous readout. Subject to probe plugging	19,20
Time-domain reflectometer	0.1%	ICPP-developed instrument being evaluated at Saluggia	20,21

B. Flow Measurement

Flow-measuring instruments are used in reprocessing plants primarily for process control where high precision is not required. Monitoring of process streams is held to a minimum, and only those instruments essential for plant operation are generally provided. These instruments are not usually intended for use in accountability systems.

Systems and equipment in a reprocessing plant are subject to severe radiation and corrosion environments. Instruments must be simple and reliable with minimum potential for mechanical failure or degradation from radiation or solvents. Meters without moving parts are preferred.

In operating reprocessing plants fluid transfers are effected by airlifts to headpots to provide gravity feed to the various separation units. Using air flow rates, liquid flow rates are generally monitored to within 5-10%, although orifice meters in headpots can measure flow to <1%. Orifice meters generally are used if more refined measurements are required.

Various types of flowmeters have been considered for flow measurement in reprocessing plants.[6] Present applications and R&D efforts in the US for flowmeters in materials accountability are summarized in the Table II.

TABLE II

IN-LINE FLOW MEASUREMENT METHODS

Instrument	Expected Accuracy	Comments	Ref.
Orifice meter	0.5-10%	Installed at AGNS in some areas	22
Vortex flowmeter	0.5%	To be evaluated at LASL, ORNL; cost ~$1000	23,24
Gyroscopic-coriolis	0.5%	To be evaluated at AGNS, ICPP	25
Ultrasonic flowmeter	0.5%	For pipes >4-cm diameter	26
Electromagnetic flowmeter	1%	Requires conducting fluid; used at Hanford	24
Bubble-transit flowmeter	0.5-3%	Developed at ICPP	19
Correlation flowmeter	1%	Developed at ICPP	19

C. Concentration Measurement

Concentration measurements for near-real-time accounting can be made on line, off line, or in the laboratory, with on line generally preferred for speed and freedom from potential sample tampering. Conventional analytical methods are performed as usual to serve as calibration checks. The status of measurement methods applicable to dynamic materials accounting is summarized in Table III.

D. In-Process Inventory

The measurement of in-process inventory in process equipment is essential for applying dynamic accountability in nuclear fuel reprocessing plants. In cooperation with other US laboratories, LASL has initiated a modest effort to identify possible approaches to estimating contactor inventories. The General Atomic Company is supplying experimental data on holdup in pulsed columns from process development work at the Solvent-Extraction Pilot Facility. Researchers at Clemson University have initiated limited studies of the effects of mass-transfer dynamics and chemical kinetics on contactor behavior and of modern system-identification techniques that might be useful for on-line estimation of contactor inventory. Iowa State University/DOE-Ames Laboratory is providing expertise on solvent-extraction theory and is developing improved models of pulsed-column behavior.

E. Data Evaluation Techniques

Analysis of nuclear materials accounting data for indications of possible diversion is one of the major functions of the dynamic materials accounting system. Diversion may occur in two basic patterns: abrupt diversion (the single theft of a relatively large amount of nuclear material), and protracted diversion (repeated thefts of nuclear material on a scale too small to be detected in a single materials balance because of measurement uncertainties).

The use of unit-process accounting and dynamic materials balances enhances the ability to detect losses, but it also means that the operator of the safeguards system will require efficient means of processing large amounts of materials accounting data. Furthermore, the significance of any isolated set of measurements is seldom readily apparent and may change from day to day, depending on plant operating conditions.

Decision analysis,[42-49] which combines techniques from estimation theory, decision theory, and systems analysis, provides a coherent, logical framework of analysis tools and is well suited for statistical treatment of the dynamic materials accounting data that become available sequentially in time. Its primary goals are detection of nuclear materials losses, estimation of the amount(s), and determination of the significance of the estimates.

The detection and estimation functions are based on classical hypothesis testing and modern state-variable estimation techniques. The systems analysis portion attempts to set thresholds for the hypothesis tests in a rational fashion, for example by using utility theory to determine acceptable false-alarm and detection probabilites.

The decision tests examine all possible sequences of the available materials balance data because, in practice, the times at which a sequence of losses might begin and end are never known beforehand. Furthermore, to ensure uniform application and

TABLE III

CONTINUOUS CONCENTRATION MEASUREMENT METHODS

Instrument	Expected Accuracy	Comments	Ref.
X-ray fluorescence	0.5%	For dissolver solutions; wave-length dispersive	27
X-ray fluorescence	1%	Energy dispersive, K x-rays; being developed by LLL for test at SRL	28
X-ray fluorescence	1-3%	For dissolver solutions; energy dispersive developed by LLL, tested at SRP	29
K-absorption edge	0.3-1%	Developed at LASL for U, Pu product, 20-500 g/L;	30
		LLL designed system evaluated at AGNS	31,32
L_{III}-absorption edge	0.4-1%	Developed at LASL for U, Pu, 5-30 g/L	33,34
Gamma-ray emission	0.5%	Designed at LLL for test at Tokai	32
Gamma-ray emission	1%	Unirradiated Pu at LASL	35,36
Gamma-ray absorption	0.5%	Developed at ICPP; other elements interfere	19
Alpha monitors	10%	Evaluated at AGNS for Pu determination in waste streams	37
Polarography	10%	Evaluated at Hanford and SRP for U determination in waste streams	38,39
Fluorimetry	6%	Automated fluorimeter developed at ORNL	40
Spectrophotometry	1%	Automated spectrophotometer for waste developed at LASL	41

interpretation, each test is performed at several levels of significance (false-alarm probabilities). Thus, graphic displays that indicate those sequences that exceed specified alarm limits, identifying each by its length, time of occurrence, and significance, are essential. One such tool is the alarm-sequence chart, a type of pattern recognition device that has proven very useful for summarizing the results of the various tests and for identifying trends.[46,47]

Mathematical tests for examining materials accounting data are being developed and evaluated at LASL. The application of the methodology to conventional as well as dynamic materials accounting data will be evaluated.

Decision analysis also can be invaluable to the international inspector. If the inspector has access to the operator's accounting data, then decision analysis facilitates checks of internal consistency of the data. If not, decision analysis still provides the inspector with the most efficient and effective means of analyzing the data.

V. SUMMARY

International safeguards accounting methods traditionally have relied on Agency verification of State's materials balances by periodic shutdown, cleanout, and physical inventory. The materials accounting system and the complementary containment and surveillance system are established individually for each facility in accord with the facility attachments.

Dynamic or near-real-time accounting has been proposed to supplement (not replace) conventional accounting to provide, in a more transparent manner, more sensitive and timely measurement information. The dynamic accounting system would be protected and supported by improved containment and surveillance techniques. Materials accountability and containment and surveillance systems must be developed concurrently to maximize effectiveness and minimize cost.

Many individual components of a dynamic materials accounting system have been tested successfully in a process environment, but a full system has not been installed in a reprocessing plant. Computer modeling and simulation of the plutonium purification area of a 1500-MT/yr plant,[6] however, has shown that sensitivities to both abrupt and protracted diversion are significantly improved over conventional accounting systems, and could meet IAEA suggested goal quantities and detection times. These studies are being extended to include the complete reprocessing area for both the 1500-MT/yr plant and a smaller (∿200 MT/yr) plant.

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