PNL Nuclear Materials Safeguard Studies 1968-1975

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PNL NUCLEAR MATERIALS SAFEGUARDS STUDIES 1968-1975

by

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SUMMARY

This overview report summarizes nuclear materials safeguards studies sponsored at Pacific Northwest Laboratory since 1968 by the Division of Safeguards and Security, Energy Research and Development Administration (ERDA). The scope of the studies includes an investigation of the sources of error in MUF uncertainty, in the disparity between shipper and receiver measurements, and in inventory verification. Primary and secondary verification points have been differentiated, with emphasis on the additional measurements necessary to verify both inventories and flows. Studies also address the problems of verifying the plutonium input to the fuel cycle and determining the composition of various types of measurement bias.

The studies' findings are organized in two groups: those associated with the operator (contractor or licensee) and those associated with an agency (ERDA, Nuclear Regulatory Commission (NRC), or International Atomic Energy Agency (IAEA)). Numbers in parentheses refer to report sections discussing the particular contributions. Within the two groups, the findings appear in the same order as they appear in the main text. The featured contributions are intended to be key points of interest to those in ERDA directly concerned with safeguards inspection.

OPERATOR APPLICATIONS

- a. Materials unaccounted for (MUF) is the estimated difference between the amount of material estimated to be on hand from book inventory and the amount estimated to be on hand from physical inventory. Limits of error of material unaccounted for (LEMUF) are a measure of the sensitivity of an operator's SNM accounting system to detect a loss. $[-LEMUF, LEMUF]$ is the acceptance interval around zero for MUF due to measurement error alone, assuming that all losses are measured. It needs to be distinguished from MUF uncertainty based upon historical records (3.1.1.1).
- b. An investigation begins at the occurrence of an out-of-control condition, as indicated whenever the observed MUF exceeds LEMUF. When there has been no loss of material, 5% of the out-of-control conditions occurs because of measurement uncertainties, causing a Type I error. A Type II error exists when material has been lost, yet actual and expected MUF differ by less than LEMUF (3.2.2.1).
- c. A MUF covering several accounting periods (cumulative MUF), in addition to individual MUF, helps detect systematic diversion (3.2.2.3).

- d. Criteria for safeguards design are identified for future reprocessing plants (3.3.1).
- e. Random errors are reduced by converting special nuclear material (SNM) into more easily measured compositions (e.g., metal versus nitrate) and placing it in preferred locations, by minimizing process holdup, by controlling scrap accumulation and measurement, and by utilizing trained personnel and standard procedures (3.3.2).
- f. In reprocessing 40 tons of fuel, losses exceeding 0.6 ton of U or 6 kg Pu are detectable 80% of the time at a 5% false alarm rate (3.3.2).
- g. In processing 0.6 ton of Pu at Hanford, losses exceeding 6 kg are detectable 80% of the time at a 5% false alarm rate (3.3.2).

AGENCY APPLICATIONS

- a. Inspection plans should account for systematic error variances (3.1.1.2).
- b. Three levels of assurance are used for inspection activities: (I) operator capability, (II) operator performance, and (III) independent agency assurance (3.1.2).
- c. Primary verification points (steps in the operator's process or in the fuel cycle) are those beyond which there is no further measuring (3.1.3).
- d. Redundant measurements, such as independent shipper/receiver measurements, strengthen verification and discourage diversion (3.1.3).
- e. The operator must be considered a potential adversary under Level III assurance (3.1.4).
- f. Search and surveillance of personnel are a necessary complement of mass balance accounting (3.1.5).
- g. Three inspection sampling plans are identified: (1) game theory, (2) maxi-min, and (3) crossover. All three are designed to counter similar threats and there is good correlation among the three plans.
- h. Pu and U isotopic dilution is usually the best way to verify the Pu input to reprocessing, as other methods are more prone to introduce errors in compositing and volume measurements (3.2.1.2.1).
- i. The differences in expected shipper/receiver amounts of U and Pu are 0.05% and 0.6%, respectively, with moisture pickup being mainly responsible for the larger Pu discrepancy (3.2.1.2.1 and 3.2.1.2.2).

- j. Isotopic correlation is such a successful verification technique that a diverter must be highly skilled for his diversion to go undetected (3.2.1.2.1 and 3.2.1.2.2).
- k. For inventory verification, the attribute sampling plan assumes that the operator removes large portions, or all, of a few items to acquire his goal quantity. The inspection strategy, therefore, is devised to detect with high probability (95%) the absence of 20% to 100% of SNM from a single item (3.2.1.3).
- l. For inventory verification, a \$150K to \$200K real-time nondestructive analysis (NDA) system is proposed, with automated data handling, contained in a vehicle suitable for highway use (3.2.1.3).
- m. Tamperproof seals cut inventory verification costs as much as 50% (3.2.1.3.1).
- n. Waste verification costs are minimized by applying knowledge of process capability instead of inspecting each waste discard and sample packaging (3.2.1.4).
- o. The $(\hat{D} + MUF)$ statistic is a powerful verification because it is (1) an unbiased estimate of the discrepancy between the operator's stated inventory and the true, or physical, inventory and (2) an identification of any discrepancy statistically different from zero (3.2.2.2).
- p. Operator specifications are outlined for UO_2 and reprocessing plants (3.3.1).
- q. Nondestructive analysis is a satisfactory test for the Pu attributes sampling plan, but inadequate for inspecting other portions of the fuel cycle (3.3.3).
- r. The neutron well-coincidence counter (NWCC) and the gross neutron counter inspect Pu and PuO_2 inventory and give errors of 4% and 3% with 60-second and 30-second analysis times, respectively (3.3.3).
- s. Real-time automated data handling is needed to inspect Pu inventory (3.3.3).
- t. Verification cost for a given number of items depends upon the number of independent locations to be inspected and the operator strategy to be detected (3.3.4).

TABLE OF CONTENTS

SUMMARY	<i>i</i>
Operator Applications	<i>i</i>
Agency Applications	<i>ii</i>
1. INTRODUCTION	1
2. OBJECTIVE	1
3. CONTRIBUTIONS	1
3.1 Contributions to the Understanding of Safeguards Concepts	2
3.1.1 MUF Uncertainty	2
3.1.1.1 Limits of Error of MUF (LEMUF)	3
3.1.1.2 Systematic Error	3
3.1.1.3 Operator Decisions	4
3.1.2 Levels of Assurance Needed by the Agency	4
3.1.3 Redundancy and Primary/Secondary Verification Points	5
3.1.4 The Operator as an Adversary	5
3.1.5 Safeguards System Design and Evaluation	6
3.2 Contributions to Inspection and Verification Techniques	6
3.2.1 Verification of Source Data	6
3.2.1.1 Verification Sampling Plans	7
3.2.1.2 Verification of Pu Reprocessing Input	8
3.2.1.3 Inventory Verification	11
3.2.1.4 Waste Verification	14
3.2.2 Evaluation of Mass Balance Data	14
3.2.2.1 MUF as an Indication of Unexpected Loss	14
3.2.2.2 $\hat{D} + \text{MUF}$	15
3.2.2.3 Cumulative MUF for Increased Sensitivity in Detecting Loss	15
3.2.2.4 Timeliness of MUF	15
3.3 Applications and Examples	16
3.3.1 Determination of Design Criteria and Operator Strategies	16
3.3.2 Examples of Verification and Evaluation of Mass Balance Accounting	17
3.3.3 Evaluation of Inspection	18
3.3.4 Cost Effectiveness	19
3.3.5 Field Office Assistance	20
3.4 Evaluation of Documents	20
4. PNL PUBLICATIONS IN SAFEGUARDS	20
5. GLOSSARY	23

LIST OF TABLES

1. Operator Information for Verification by Isotopic Correlations	12
2. Inventory Control Parameters to be Evaluated	13

LIST OF TABLES (cont'd)

3. Effect of Inventory Frequency on Detecting a Loss Event and on Detecting a Rate of Loss in MUF	15
4. Material Balance Measurement Uncertainties in UO ₂ Manufacturing	17
5. Probability of Detecting Diversion in UO ₂ Manufacturing	18
6. Operator and Agency Strategies	20

PNL NUCLEAR MATERIALS SAFEGUARDS STUDIES 1968-1975

1. INTRODUCTION

This report is prepared in response to the request of the Division of Safeguards and Security, Energy Research and Development Administration (ERDA), that PNL identify the principal findings of its nuclear materials safeguards research since 1968. A complete bibliography of PNL reports issuing from this research appears as Chapter 4 and a glossary of terms is given as Chapter 5.

The Laboratory's traditional safeguards strength is materials accounting and use of its techniques to detect diversion and establish credibility of comprehensive safeguards. The Laboratory has also considered the relationship between physical protection and materials accounting, and the combined value of these protective measures.

With the increase of domestic and international concern for special nuclear materials (SNM), the effectiveness of materials accounting has become a matter of public concern going beyond the financial and safety interests of a single operator, or even a single country. The safeguards effort at large is conducted on a shared basis by the operator and by a Federal agency.* The agency, whether ERDA, NRC, or IAEA, is constrained in its efforts because the SNM being safeguarded is held by the operator, whose rights include protection of basic freedoms. Ultimately, both the agency and the operator are responsible to the public.

The ability to implement inspection strategies based on materials control measures has advanced significantly since 1968. The contributions of various types and sources of measurement error to the uncertainty in MUF, to shipper/receiver differences, and to inventory verification have been thoroughly investigated, and the primary verification points and necessary redundancies for determining both operator capability and performance have been established. Particular attention was placed on the additional measurements required for verification of both inventories and flows, and on the independent assessment of operator performance. Problems included the inability to verify adequately plutonium input to the fuel cycle, as well as the difficulty of determining the contribution and composition of various types of measurement bias. Over the past 8 years, the Laboratory's record includes numerous contributions in those areas, as well as identification of techniques to solve those problems (see Sections 3.1 and 3.2). Applications and examples of these techniques are discussed in section 3.3.

2. OBJECTIVE

From inception, the project's objective has been to define alternative strategies the agency can use to be assured that an operator's safeguards not only meet agency requirements but also indicate any significant SNM diversion or assure the occurrence of none.

3. CONTRIBUTIONS

The Laboratory's contributions fall mainly into three categories: (1) understanding safeguards concepts, (2) techniques of inspection and verification, and (3) applications of

*"Operator" designates contractor, licensee, and adversary; "agency" designates ERDA, NRC, and IAEA.

the techniques. The Laboratory's studies also included, though to a lesser degree, inspection costs, evaluations of domestic and internal safeguards documents, and staff training. The project's total scope is reflected in the bibliography on page 20.

3.1 CONTRIBUTIONS TO THE UNDERSTANDING OF SAFEGUARDS CONCEPTS

Before 1968, the use of MUF in materials accounting was limited by inadequate understanding and description of MUF uncertainty and its sources. There was a need to identify the sources of errors and to resolve their propagation, aimed finally at identifying a limit of error in MUF due to measurement errors at any operation. The influence of biases, bias corrections, and other systematic errors throughout an operator's sampling/measurement process needed description in practical terms of use in the field by both operator and agency. The importance of the operator's choices of sampling/measurement methods was discussed only in general terms.

There was a need to incorporate the ideas of the different levels of assurance (operator capability, operator performance, and independent assurance elements) and their objectives into the inspection process. The Laboratory's opinion was, and remains, that inspection/assurance can be obtained and the results passed along to interested parties more easily by treating it in steps - one element, or level, at a time.

Also needed was a characterization of the differences between points supported by only single measurements, or primary points, from secondary points supported by redundant measurements and from other checks normally available elsewhere in processing. Such a classification system is important to the verification effort.

The Laboratory took the position that the adversary can be regarded most simply as an arm of the operator, consisting of his own employees or intruders who use illicitly the operator's system. Characterization of options open to the dishonest operator was needed. Before 1968, inspection and control systems were being characterized under the containment/surveillance/materials accounting components, and their effectiveness was being assessed (Bennett and Granquist, 1967). However, systems based upon physical protection and materials control measures and upon the broad concept of societal risk had not yet been characterized; the Laboratory has since addressed those systems (Bennett et al., 1975).

Section 3.1 comprises the Laboratory's contributions toward understanding the numerous concepts for meeting the above needs. The discussion is in five parts:

- MUF uncertainty
- Levels of assurance
- Redundancy and primary/secondary verification points
- The operator as an adversary
- Safeguards system design and evaluation.

This grouping of the Laboratory's more fundamental contributions provides a framework for interrelating individual portions of the total effort.

3.1.1 MUF Uncertainty

MUF is the estimate of material unaccounted for. MUF is the difference between the amount of material estimated to be on hand from the book inventory and the amount estimated to be on hand by the physical inventory. MUF uncertainty is the general expression for

variability in this quantity due to measurement errors and is expressed by σ_{MUF}^2 , σ_{MUF} . LEMUF is the estimate of limits of error of MUF due only to measurement errors. $LEMUF = 2\sigma_{MUF}$, with σ_{MUF} being the standard deviation. LEMUF is discussed further in the following section. The uncertainty in MUF is directly related to the number of measurements (and costs), but it also is affected by improved analysis of the operator's data, including Pu and U isotopic concentrations (Stewart and Jaech, 1970a). The following sections discuss various contributions to the understanding of MUF uncertainty, including an explanation of the basis for evaluating MUF uncertainty deriving from systematic errors and operator decisions.

3.1.1.1 Limits of Error of MUF (LEMUF)

LEMUF, used in Federal regulations, is the 95% confidence interval of (an ideal) MUF's departing from zero only because of measurement error. $LEMUF = 2\sigma_{MUF}$. LEMUF values are used in a number of ways. The interval $[MUF - LEMUF]$ to $[MUF + LEMUF]$ is the 95% confidence interval in MUF. MUF values outside the interval $-LEMUF$ to $+LEMUF$ are statistically significant at the 95% probability level. MUF values exceeding LEMUF indicate a loss. LEMUF is derived from combining or propagating all the measurement errors identified by quality control, considering both plant flow and inventory if it has to be included in the mass balancing.

$$\sigma_{MUF} = \sqrt{\sigma^2_{\text{Flow}} + \sigma^2_{\Delta \text{ Inventory}}}$$

The σ_{MUF}^2 so obtained differs from the variance based on historic records, which incorporates both measurement and process errors. Historic records are not a good basis for determining σ_{MUF} because:

- (a) amounts and rates of losses fluctuate although they can be normalized,
- (b) an accounting period can include recovery of material held up in earlier periods,
- (c) accounting adjustments may be included, and
- (d) no insight is given to the source of error in σ_{MUF} .

Even if accounting adjustments are withdrawn, historical accounts can serve only as a rough check on σ_{MUF} determined from measurement quality control. It is expressed both in kilograms and as a percent of plant throughput. Its size indicates the sensitivity of the mass balancing. Good plant performance is achieved through the following indices:

- (a) For accounting frames ≤ 30 days: $\sigma_{MUF} < \text{twice long-term measurement error of flow (combined inventory measurement uncertainty} \leq \text{combined flow measurement uncertainties)}$.
- (b) For accounting frames < 1 year: $\sigma_{MUF} < 0.2\%$ ($LEMUF < 0.4\%$).
- (c) All frames: $\sigma_{MUF} < 0.125\%$ ($LEMUF < 0.25\%$) - even for cumulative MUF.
- (d) Good control of long-term systematic error for feed or product: No single error exceeding $\sigma = 0.1\%$.

Plant performance and capability are considered further in Section 3.3.1 (Schneider, 1973a).

3.1.1.2 Systematic Error

Systematic error is one which propagates itself over more than one item. Thus, bias corrections and uncorrected biases are both instances of systematic errors. Systematic errors

have more influence on the MUF variance than their magnitudes suggest because they do propagate themselves over more than one item. Findings take several forms:

- (a) Estimation of their magnitude and applying them to calculating MUF variance (Schneider and Wirfs, 1970a; Schneider, 1970e; and Stewart and Wirfs, 1973a).
- (b) Contributions to the literature on bias corrections (Stewart, 1975a and 1975c).
- (c) Recognition of the limitation that rising systematic error places on sampling plans (Hough, Schneider, Stewart, Jaech, and Bennett, 1974).

Statistical approaches have been generally successful by designing around systematic errors using such techniques as blocking and contrasts. In mass balance accounting, completely avoiding systematic errors and systematic error variances is not possible. However, systematic error variances can be estimated (Stewart and Wirfs, 1973a; Schneider and Granquist, 1970c) and taken into account in planning inspection verification activities (Hough, Schneider, Stewart, Jaech, and Bennett, 1974).

3.1.1.3 Operator Decisions

MUF uncertainty is much affected by decisions the operator makes as to his mode of operation. For example, his selection of measurement methods is important; actual performance may be far below his capability, as shown in Section 3.3.2. As discussed in Section 3.1.4, an adversary may be working through the operator, thus increasing the likelihood of diversion (alternative hypothesis) masked by purposefully increased variance. In contrast, the fully honest operator (null hypothesis) will not purposefully increase his variance.

3.1.2 Levels of Assurance Needed by the Agency

The Laboratory has made a major contribution towards general recognition of the definitions for the various levels of required assurances (Schneider and Granquist, 1970e). The assurance levels were defined as follows:

- Level I - assurance that the operator has the capability to safeguard SNM
- Level II - assurance that the operator's safeguards performance is satisfactory
- Level III - assurance independently that the operator's safeguards have been effective and that unreported diversion by the operator is detectable (with the objective being no diversion at all)

Briefly, the agency seeks three kinds of assurances: (1) capability, (2) performance, and (3) independent assurance (Schneider, 1972b). Assurance is closely related to inspection and verification. Generally, inspection and verification are agency activities aimed at achieving the necessary state of assurance that the operator is giving adequate protection to SNM.

Level I inspection has been a continuing agency action for several years, based upon ERDA manual chapters and directives. Capabilities both in physical protection and material balance accounting are inspected.

Level II inspection considers physical protection and materials accounting. It includes Level I assurance. Some physical protection is inspected by testing the operator's equipment, such as sensor systems; otherwise, the agency only observes. Generally, the agency inspects materials accounting by auditing measurements, records practices, item counting, physical inventory practices, and mass balance accounting including the operator's basis for designating normal operating loss (NOL) (Schneider and Sorenson, 1974).

A complete Level III assurance, which includes Levels I and II, requires that the agency independently establish the credibility of all evidence the operator uses to demonstrate

that his safeguards measures have been effective. This requires an independent determination that stated quantities for receipts, shipments, inventories, and discards are credible. Most of the Laboratory's inspection findings ultimately apply to obtaining Level III assurance.

3.1.3 Redundancy and Primary/Secondary Verification Points

Primary verification points, or steps in the operator's process, are those beyond which the operator does no further measuring. Pu product, long-term inventory, and waste are the usual primary measurement points. Inventory is included because, for conservatism, no further measurement is assumed until well into the future, beyond the time frame in which diversion is considered to be possible. Laboratory effort leading to techniques discussed in Section 3.2 is directed largely toward plutonium shipments/receipts and inventory. Waste is not emphasized because diverting strategic quantities from waste would be relatively more difficult.

Secondary verification points in the operator's process are those for which redundant measurements are made at other points in the process. Secondary points simply record inventory shifts and fix the size and location of inventory between primary points within an operator's (a nation's) bounds. They are useful in optimizing timeliness and sensitivity for immediate accountability periods. Measurements at secondary points do not reduce the need for verification at primary points.

Redundancy, in the sense of assays of a given amount of SNM at successive processing points, deters falsification and strengthens verification by (1) requiring that diversion be matched at successive processing stages, thus increasing the probability of detection, and (2) utilizing previous patterns for helping the agency fix robust bounds for quantities that can be diverted without detection. The redundancy of measurements at secondary verification points is mentioned in the previous section. Such redundancy is sometimes regarded as "structural" because it is a necessary part of the operator's process structure. It is available to the safeguards effort at small cost.

Cross-checks with operator measurements and known fuel cycle performance represent a different kind of redundancy. They bolster but do not replace conventional verification; some have immediate value. They consist of process capability, reactor predictions of end-of-life content, Pu/U ratio isotopic correlations, consistency of isotopic compositions, and use of step functions for obtaining process inventory (Schneider, Stewart, Bennett, and Granquist, 1971).

3.1.4 The Operator as an Adversary

Safeguards studies began to show that an operator or people working through his organization must be regarded as adversaries; that for purposes of systems design and evaluation, honest operation cannot be assumed. Several mechanisms for diversion are considered:

- (a) Diversion into MUF
- (b) Deliberately biasing measurements
- (c) Falsifying records
- (d) Removing items
- (e) Removing material and leaving a disguised substitute
- (f) Removing material below the capability of the attribute sampling plan
- (g) Bleeding the operation over an extended time period.

Understating input to chemical processing has been a verification gap toward which isotopic correlation techniques are directed (Section 3.2.1.2.1).

Diversion mechanisms are the subject of recent discussions, including a number of protective strategies discussed under verification sampling plans (Stewart and Schneider, 1974; and Hough, Schneider, Stewart, Jaech and Bennett, 1974).

3.1.5 Safeguards System Design and Evaluation

The Laboratory early recognized the relationship between the contributions of materials accounting and physical protection. The former gives after-the-fact, ultimate assurance; the latter, immediate protection (Bennett and Granquist, 1967). The effort recognizes containment, surveillance, and material(s) accounting as the three essential elements of the safeguards system.

Physical protection, from the operator's viewpoint, is the first line of defense. For the agency, personnel search and surveillance is a necessary complement of mass balance accounting, particularly for high throughput operations where losses of critical quantities cannot be detected (as MUF) with high probability (Schneider, 1973c). In verification, physical protection plays a supportive role. For the international agency, physical protection played a minor role at the time, with verification fully dependent upon materials accounting.

The safeguards system is characterized also as a system of immediate measures and deferred measures. Immediate measures are those of physical protection; deferred measures, those of materials accounting (Schneider and Sorenson, 1974 [see Figure 1-4 and Appendix A]).

Most recently, the Laboratory contributed to the development of a framework for the design and evaluation of safeguards systems as viewed broadly from a societal risk standpoint. The traditional objectives of deterrence, detection, and defense are accomplished by means of passive and active mechanisms, the latter being those whose effectiveness changes in response to the occurrence of detection (Bennett, et al., 1975).

3.2 CONTRIBUTIONS TO INSPECTION AND VERIFICATION TECHNIQUES

The Laboratory's contributions in this area are given in two parts: verification of source data and evaluation of mass balance data.

3.2.1 Verification of Source Data

Systems for identifying effective sampling plans were very approximate at the start of the period. Many refinements were needed that would give the inspector more options for coping with diversion options available throughout the range of operator facilities. Most of the refinements were not completed until recently, as indicated in the discussion of sampling plans in the next section.

As the emphasis on sampling plans suggests, inspection strategies were most in need of sampling plans to be used for Level III verification. A much more satisfactory data base for using Pu/U measurements and isotopic correlations for both metals was needed in order to verify the Pu input to reprocessing plants; the effort was sponsored largely by U.S. Arms Control and Disarmament. A relatively detailed discussion of the sampling techniques is given. A comparison of shipper/receiver measurements also promised to be an effective means of verifying input. In addition, a compilation of the various inventory

verification strategies was needed. Less attention was required for waste verification because of the extreme expense to an operator to obtain strategic SNM amounts from such dilute and often hazardous sources. Following the discussion of sampling plans, this section discusses strategies developed for verifying (1) input to reprocessing, (2) inventory, and (3) waste.

3.2.1.1 Verification Sampling Plans

Sampling techniques are of fundamental importance to inspection strategies based upon materials accounting, itself so dependent upon measurement. Sampling plans must have a number of characteristics, some differing from those of traditional quality control.

- (a) The main aim is to detect anomalies induced by the operator (or more properly, a diverter working under the operator's mantle) to disguise diversion superimposed on natural anomalies.
- (b) A corollary is that measurement must have sensitivity sufficient to prevent a diversion from being hidden under a large measurement variance error.
- (c) Strategic size losses are to be detected with a high probability.
- (d) The sample size and frequency are dependent both upon plant lot size and the strategic amount of SNM present.
- (e) The inspector has an attribute instrument and a variable instrument (see Terms). Sample size is determined partly from options available to a diverter. They generally are of three types:

- (a) Nearly 100% of the SNM is taken from some items.
- (b) SNM per item is taken above 4σ of the difference (from true amount) due to the measurement error with the variable instrument, but below the amount that probably would be detected by the attribute instrument.
- (c) SNM taken is slightly below the 4σ , above.

The Laboratory identified three sampling plans to cope with the diversion options open to the operator: (1) game theory, (2) the maxi-min, and (3) the crossover game theory (Stewart, 1974). All three plans are designed to counter any strategy the operator, or diverter, uses for obtaining a strategic amount of SNM. The inspector has an attribute and a variable tester. The operator's best strategy in any situation is to confine his removals (or falsifications) to three regions: (1) total removals, (2) removals just below the attribute instrument threshold, and/or (3) smaller removals that would be detected only by the variable instrument in a bias test. The inspector's total effort is constrained by cost or other limits; the diverter's goal is fixed. Within the inspector's total effort, he can vary his plan. The operator can vary how he obtains strategic amounts of material among the three options. For both the inspector's and the operator's conditions, there is a probability of nondetection of diversion and all such probabilities can be represented on a matrix. It can be construed as a payoff matrix in game theory and treated under the extensive amount of associated knowledge.

The game theory solution is obtained by finding the relative frequencies with which the operator and agency should employ their techniques. This mixed strategy game is solved numerically by the computer using the simplex algorithm. The game theory plan is developed under the constraint that the amount of effort is fixed and that the costs of a variable

measurement usually exceed those of an attribute measurement. The operator has many ways to obtain a strategic amount of SNM. The probability of nondetection of the out-of-control condition is used to fill out the tabular values in the payoff matrix. Computer programs using the simplex algorithm are used to determine the relative frequencies with which the operator and inspector should apply their strategies. The criterion for the agency is to find the relative frequencies, f_i ($i = 1, 2, \dots, n$), with which he should employ his sampling and inspection techniques when the operator applies his m strategies with relative frequencies, g_j ($j = 1, 2, \dots, m$). The inspector wants to minimize his probability of nondetection; the operator, to maximize his in this mixed strategy game. Results agree well with those of the crossover plan for the examples studied.

The maxi-min solution uses the set of inspector conditions for which the operator's maximum probability of nondetection is a minimum. The plan takes into account the agency's effort needed to sample and make the attribute and variable measurements. The plan provides an upper bound on how well the operator can divert a fixed amount of material. The upper bound is expressed as the probability of nondetection. More easily developed than the maxi-min solution, the crossover plan gives an adequate solution that agreed with the maxi-min in the several cases tested. Its maximum probability of nondetection must be small enough to be acceptable to the inspector. To prevent diversion by falsifying values below the crossover point, a variable measurement is used to detect bias. Formulae to calculate sample sizes are given for the number of items to be measured. The formulae take into account the possibility that the scatter of amount values below the crossover may be increased in order to make the bias detection more difficult (Stewart, 1974; Hough, Schneider, Stewart, Jaech, and Bennett, 1974).

The number of samples selected by the agency for the crossover plan is sufficiently large to have a $100(1 - \beta)\%$ chance of detecting gross loss in at least one item, with β (see Figure 1 in Section 3.2.2.1) defined as the probability of a Type II error; i.e., that none of the gross defectives will be detected.

Of specific application to the question of sample size, the Laboratory constructed tables enabling the agency to specify the 90%, 95%, and 99% confidence limits on the number of defective items in a random sample where results are based on hypergeometric distribution. The tables are unique in that a large number of cases and sample sizes are represented (Stewart, 1973b). Other tables let the agency specify the sample size needed to detect at least one defective item, given a total population and assumed total number of possible defective units up to 25. The random sample size varies depending on the desired confidence levels.

In the very broad sense, sample sizes are influenced when safeguards are viewed from the standpoint of societal risk with its treatment of potential SNM diversion from the standpoints of anticipated frequency, success, and consequences (Bennett, 1975).

3.2.1.2 Verification of Pu Reprocessing Input

Obtaining Level III assurance on the Pu input to reprocessing is best accomplished by Pu to U ratio measurements and Pu and U isotopic measurements. Isotopic measurements, or mainly the correlations among them, are used to verify both the reprocessing operator's Pu/U

measurements and his Pu and U isotopic measurements. Verifying Pu input is emphasized because of its high strategic value. Finally, the shipper's Pu measurements are compared to those of the receiving operator. Assuming no missing material, the comparisons will show only minor discrepancy and thus justify the agency's position of assuming no collusion between shipper and receiver.

3.2.1.2.1 Pu Verification by Pu/U Ratio. Pu input to reprocessing can be obtained by multiplying the Pu/U by the initial weight of U (in the reactor core) reduced by the amount burned, ΔU . The agency can obtain the initial U and U burned independent of the reprocessing operator. The Pu/U is available from the reprocessor. To verify the Pu input independently, the agency must measure the Pu/U (see next section).

The Pu/U method for verifying Pu input is superior to other methods, such as volume-concentration, for several reasons. The method is only slightly affected by variations of Pu and U concentrations in the process. Secondly, samples can be composited without introducing significant error; the ratio is unaffected. Finally, volume measurements are unnecessary. The error comes essentially from the mass spectrometer measurement of Pu/U (Stewart and Schneider, 1970d). At Nuclear Fuel Services, the initial uranium corrected for burnup or the shipper's value of final uranium shows excellent agreement with the reprocessor's measured uranium values or the receiver's values. Long-term shipper/receiver differences average +0.05% of total uranium receipts, with an observed σ for individual campaigns of 0.56% as compared to a σ of 0.54% due to measurement uncertainties (Schneider, Stewart, and Christensen, 1972a).

To divert Pu, the operator would have to associate each batch with its original reactor core location. He would need to know either the reactor's enrichment profile or, within the plant, become aware of Pu concentrations and the Pu/U's before he ever could report volume determinations. His strategy would be to overstate the volumes of batches having below average Pu/U's and correspondingly understate the volume of above average batches. The result would be an understated Pu input. Reported Pu/U's would be truthful and the U input to the plant would agree with the shipper's value. The volume-concentration method is subject to the same potential for defeat by a skillful operator (Stewart and Schneider, 1970d).

3.2.1.2.1.1 Verification of Pu/U Ratios Using Isotopic Correlations. The purpose of the techniques discussed here is to verify Pu/U values obtained by the reprocessor. The verification is necessary in order to determine an independent value of Pu input using the Pu/U ratio method discussed above. "Correlation" is used to mean the relationship between Pu, U, and their isotopic compositions rather than correlation in the normal statistical sense.

Historically, heavy metal isotopic data from Pressurized Water Reactor (PWR) and Boiler Water Reactor (BWR) dissolver solutions show complete internal consistency (Christensen, Matsen and Schneider, 1970a). The operator's Pu and U isotopic measurements in reprocessing Yankee Rowe Core V and VI are used to verify the operator's Pu input, characterize the fuel, evaluate the consistency of the operator's measurements, and compare Pu receipts with those calculated from reactor operation codes (Christensen, Matsen, Schneider and Wolkenhauer, 1970b). The Mol III experiment (Mol, Belgium) and CANDU fuels clearly indicate

relationships among Pu, U and their isotopic compositions (Christensen, Schneider and Stewart, 1971). The IAEA accepts the techniques as having safeguards value (Schneider, Stewart, and Christensen, 1972a). By now, a substantial data base of established values exists and is being used to develop further correlations for inspection (Christensen and Schneider, 1975).

For ease of safeguards application, only linear relationships or correlations are used and developed. Linear relationships have straightline, or constant, slopes. In the terminology of isotopic correlations, the slope is called a correlation ratio and as a result of using linear correlations, correlation ratios are constants for a given fuel. Thus, even though the Pu/U's and isotopic values do vary from batch to batch of dissolved fuel, the correlations' ratios do not vary, but yield a single value within measurement uncertainties for a given fuel.

An example of a linear relationship or correlation is Pu/U versus ^{235}U where the slope or correlation ratio is $(\text{Pu}/\text{U})^{235}\text{D}$. The ^{235}D is the initial enrichment minus the final enrichment of a fuel. Constant correlation ratio values from a given correlation prove correct measurement of each Pu/U. Many correlations are available to verify both Pu/U and isotopic values. In addition, correlations are used to verify initial enrichments of fuels, deduce operating history and test for possible substitution of irradiated fuel with unirradiated or less enriched fuels (Schneider, Stewart and Christensen, 1972a, pp. 34-37). All verifications utilize the reprocessor's data, along with minimal additional information such as shipping records of the spent fuel.

3.2.1.2.1.2 Verification of Isotopic Data Using Isotopic Balance. A companion verification of the reprocessor's Pu/U and isotopic data is to establish the isotopic balance of the total spent fuel for the operator's input and output. The operator has two sets of measurements, input and output, representing the same material from the same source. Chemical processes cannot alter the isotopic composition or balance between input and output. If input and output weighted isotopic compositions of the total fuel differ by more than expected measurement error, reason is established for investigating the difference.

The test is performed by summing the isotopic weights contributed by each batch in a campaign, those at input resulting in one sum and those at product resulting in a second sum. Thus, ^{239}Pu from all streams is considered and, in turn, each other Pu and U isotope. Isotopic weight percents are obtained by dividing the isotopic sums by the elemental (Pu and U) sum. With the exception of the small effect on variable waste losses, the weighted isotopic percents of total input for a given spent fuel lot approximately equal the weighted isotopic percents of output when beginning and ending inventories are taken into account. Typical results from Nuclear Fuel Services show that major isotopes ^{235}U and ^{239}Pu agree within 0.2%. Random variation results only from the measurement procedures; volume measurements have no effect.

The comparison has the practical advantage of verifying measurements for bias in addition to detecting mismeasurement or data mixup. Selectively biasing measurements in order to mask diversion of more than 1% is apparent when comparing weighted isotopic data of input and product (Schneider, Stewart and Christensen, 1972a).

3.2.1.2.2 Verification Using Isotopic Data From the Entire Fuel Cycle. Falsification of Pu and U isotopic data is nearly impossible, given the complete ring of operator isotopic

data from enrichment plant feed and product to reprocessing plant input and product. Timely collection and analysis of the operator's isotopic data are meaningful deterrents to falsification of measurements for any reason and give the agency needed information on measurement bias.

The isotopic information to be obtained from the various operators, including reactor operators, is outlined in Table 1. Priority 1 information allows full use of state-of-the-art correlations for achieving verification. Priority 2 data allow extended use. Priority 3 data reinforce other data; for example, Pu fabrication input data may be used to confirm reprocessing output data (Schneider, Stewart and Christensen, 1972a).

3.2.1.2.3 Comparison of Shipper/Receiver Measurements. Shipper/receiver differences are compared for Pu nitrate and Pu oxide from various sources at Hanford. For the nitrate and the oxide, standard deviation of the bias is 0.6%. For the oxide, moisture pickup is the main cause of the bias. For the principal Pu isotopes, ^{239}Pu and ^{240}Pu , the standard deviation of the bias is 0.04% and 0.03% (Stewart and Wirfs, 1973a). The comparisons justify the agency's position of assuming no collusion between operators and using a third operator to referee the differences that do occur.

In general, Pu/U ratios, Pu and U isotopic measurements, and a history of shipper/receiver differences are more useful as verification tools when the operator's SNM is largely in process. The data are less useful when an operator's SNM is largely in inventory. Other verification techniques are needed. A major part of the Laboratory effort is directed toward inventory verification.

3.2.1.3 Inventory Verification

The objective of inventory verification is to assess the operator's state of inventory control, particularly whether his statements fairly represent actual SNM holdings. A completely independent verification is relatively expensive and could raise the question of intrusion on the operator's civil rights. In order to obviate those objections, some other planning basis is desirable. One basis, the sourcebook for inventory verification indicates, is to aim for (1) an unbiased estimate of the discrepancy between the operator's stated inventory and the true inventory ($\hat{D}$) (Section 3.2.2.2) and (2) an identification of any discrepancy statistically different from zero. The estimate $\sigma_{\hat{D}}$ is important in determining the size of the sampling plan (Stewart, 1972a).

Sampling plans for inventory verification are more extensive than plans for assuring product acceptability in the commercial sector (Stewart, 1974). Estimating substantiation goal quantities (SGQ's, see Glossary) is important for determining the size of the plan. The plan must carry a high probability of detecting (1) a single grossly defective item along a lot of good ones, (2) an important bias comprising many small, subtle ones across a lot of items, and (3) the loss of an SGQ from any independent location (Section 3.2.1.3.2). The attribute sample size is selected to detect one or more defective items in the random sample with the desired probability where there is a specified number of defectives in the lot. The number of defectives to be detected in the lot is determined from the SGQ (Stewart, 1974).

The sourcebook gives guidance on planning and conducting the inventory, analyzing and storing the data, and gives a general model for inventory verification techniques (Stewart,

TABLE 1. Operator Information for Verification by Isotopic Correlation^(a)

<u>Fuel Fabrication Data</u>		<u>Chemical Reprocessing Data</u>		<u>Reactor Data</u>	
<u>Priority #1</u>		<u>Priority #1</u>		<u>Priority #1</u>	
1) <u>Each Fuel Assembly</u>		1) <u>Each Input and Product Batch</u>		1) <u>Each Spent Fuel Assembly</u>	
Total U Weight		Total U Weight	Total Pu Weight	Total U, Total Pu, ²³⁵ U,	
²³⁵ U Wt. %		²³⁵ U Wt. %	²³⁹ Pu Wt. %	Exposure.	
²³⁶ U Wt. %		²³⁶ U Wt. %	²⁴⁰ Pu Wt. %	2) <u>Reactor Design Characteristics</u>	
			²⁴¹ Pu Wt. %	Type, moderator, fuel design data -	
2) Fuel element design (b)			²⁴² Pu Wt. %	cladding, dimensions, within assembly	
information, e.g. dimensions		2) Order of dissolution by assembly.		enrichment, lattice pitch.	
cladding, burnable poison,		3) Correspondence between dissolution		3) Operational history for core, assembly	
etc. If graded bundle, rod		and input batches.		history, core position, charge and	
pattern in bundle by individual		4) Input tank and dissolver heel		discharge times.	
enrichment giving nominal		volumes per batch.			
enrichment of rods.		5) Hull or chemical decladding losses			
		per dissolution batch.			
		6) Normal accountability data.			
<u>Priority #2</u>		<u>Priority #2</u>		<u>Priority #2</u>	
1) <u>Each Fuel Assembly</u>		1) <u>Each Input and Product Batch</u>		1) <u>Each Spent Fuel Assembly</u>	
²³⁸ U Wt. %		²³⁸ U Wt. %	²³⁸ Pu Wt. %	²³⁶ U, ²³⁹ Pu, ²⁴⁰ Pu, ²⁴¹ Pu, ²⁴² Pu	
²³⁴ U Wt. %		²³⁴ U Wt. %			
2) <u>Each Input Batch</u>					
Total U Weight					
²³⁵ U, ²³⁶ U, ²³⁸ U, ²³⁴ U					
<u>Priority #3</u>		<u>Priority #3</u>		<u>Priority #3</u>	
<u>Isotope Separation</u>		<u>Uranium Conversion</u>		<u>Plutonium Fabrication</u>	
<u>Plant Data</u>		<u>Plant Data</u>		<u>Plant Data</u>	
1) <u>Each Input and Product Batch</u>		1) <u>Each Input and Product Batch</u>		1) <u>Each Input Batch</u>	
Total U Weight		Total U Weight		Total Pu	
²³⁵ U Wt. %		²³⁵ U Wt. %		²³⁹ Pu Wt. %	
²³⁶ U Wt. %		²³⁶ U Wt. %		²⁴⁰ Pu Wt. %	
²³⁸ U Wt. %		²³⁸ U Wt. %		²⁴¹ Pu Wt. %	
²³⁴ U Wt. %		²³⁴ U Wt. %		²⁴² Pu Wt. %	
				²³⁸ Pu Wt. %	

(a) Schneider, Stewart, Christensen; 1972a, Table VII and VIII.

(b) Information may be available from either fabricator or power company.

1972a). Parameters are specified in Table 2 for verification on a continuing basis. The sourcebook demonstrates the statistical analysis of data from the authentication of bookkeeping, weight rechecks, calibration checks, and estimates of SNM. The sourcebook also includes an example of the analysis along with references to computer programs for processing the data (Stewart, 1972a).

TABLE 2. Inventory Control Parameters to be Evaluated^(a)

Verification Procedure	Parameters
Authentication	<ol style="list-style-type: none"> 1. the proportion of missing items 2. the proportion of items found in the inventory but not on the operator's listing. 3. the proportion of items obviously substandard as regards the listed gross weight or nuclide weight. The test for nuclide weight may involve the use of a gamma spectrometer.
Bookkeeping	<ol style="list-style-type: none"> 1. The proportion of gross errors
Weight Checking	<ol style="list-style-type: none"> 1. The proportion of gross errors 2. The weight bias 3. The weighing precision
Amount Calculation (Amount = weight x conc x ratio)	<p>The following parameters are to be controlled for the weight, concentration, ratio and amount values.</p> <ol style="list-style-type: none"> 1. The average difference between operator and sample measurements 2. The standard deviation of measurement 3. The proportion of defective operator values.
Amount Calculation (weight x nuclide factor)	<p>The following parameters are to be controlled for the weight and amount variables.</p> <ol style="list-style-type: none"> 1. The average difference between the operator and the sample values. 2. The proportion of defective operator values. <p>Monitoring the standard deviation of the process variance also is helpful. This variable is not, however, controlled as are the others on this list.</p>

(a) Stewart, 1972a, p. 6-15.

Data must be presented clearly and be traceable easily over long-term storage. Uniform presentation of data covering all operators is desirable. The Laboratory proposes a real-time \$150K to \$200K system using nondestructive analysis (NDA) and automated data handling equipment housed in a vehicle suitable for highway use (Sorenson and Kaye, 1974). The system would improve the timeliness of detecting losses.

3.2.1.3.1 Security Seals. The importance of seals is stressed in containing any large, stagnant inventory, both in the sourcebook (pp. 2-13) and in other treatments. For example, security seals are characterized as to value in detecting diversion and reducing diversion attempts. They may reduce inventory verification costs by approximately halving the required number of samples (Sorenson, Stewart and Schneider, 1973a). A 100% item check for seal integrity is needed, but other inspections can be curtailed. The evaluation included considering seals for Pu stored in the 35 compartments of the Hanford 324 Building storage vault (Sorenson and Stewart, 1973b).

3.2.1.3.2 Independent Locations. Establishing independent locations reduces the costs of verifying inventory, particularly at operations having the conglomerates of SNM holdings,

as at some ERDA locations. Independent SNM locations are those that are inspectable at any time, are remote from similar SNM locations (miles apart or in parts of a single building operated by separate contractors), and are susceptible to diversion only through extensive collusion. The agency can have reasonable assurance that SNM inspected one day at an independent location will not, by normal operational transfer in a geographically widespread material balance area or under the condition of an active adversary, show up a day or two later for inspection (and double accounting) at another location. The agency and the operator should concur on the definition of each independent location (Schneider and Sorenson, 1974).

3.2.1.4 Waste Verification

Again, the intensity of verification is determined from estimates of SGQ's. The agency substantiates calibration of the final waste tank. Other waste verification is done directly or indirectly. Under direct verification, the agency verifies each waste discard, as well as sampling and sample packaging, followed by measurement on a random basis by another operator. Under less costly indirect verification, the agency uses a rule of reason based upon historic knowledge of the operator's process capability; the amounts of waste discards are judged acceptable if they match past records.

Independent locations are especially useful for waste stored several years (Schneider and Sorenson, 1974).

3.2.2 Evaluation of Mass Balance Data

Materials accounting consists of item accounting and mass balance accounting. Before the period, there was some appreciation of the usefulness of mass balance data for keeping track of SNM and guarding against loss. However, its usefulness and limitations were not in quantitative form and not generally understood. To define the capability of mass balance data to detect and discourage unauthorized diversion (Section 3.1.4), MUF needed to be related to power curves for detecting loss, cumulative MUF needed characterization, and the time discrepancy between the occurrence of loss and the boundaries of accounting periods had to be reconciled. The Laboratory's contributions in those areas are discussed below.

3.2.2.1 MUF as an Indicator of Unexpected Loss

A MUF value larger than that expected from measurement errors may indicate diversion, although unexpected losses may have many other causes. The probability of detecting loss increases with the amount of material diverted as shown by the rising curve in Figure 1, indicating a false alarm rate, α . Such curves are often called "power" curves because they indicate the power of the test to detect an out-of-control condition as a function of the amount of loss.

FIGURE 1. Probability of Detecting SNM Loss

Two types of decision errors can occur. Type I, the false positive, occurs when a result such as a MUF arises from normal measurement error but is regarded as indicating an abnormal loss. The false positive is especially troublesome when inspection plans lead to a multiplicity of decisions (Bennett, 1973). Type II errors occur when an actual loss is masked by measurement variability (Stewart and Jaech, 1970a; Wirfs, 1970a; Bennett, 1973).

3.2.2.2 $\hat{D} + \text{MUF}$

The agency's power of detection is improved by using the composite statistic ($\hat{D} + \text{MUF}$) in the evaluation stage. $\hat{D}$, or the "difference statistic," is the difference between the operator and the inspecting agency taken over all strata for the paired comparisons of results from the operator's and the agency's variable measurements. The agency's use of the composite statistic is preferred in two ways over use of $\hat{D}$ and MUF separately. First, the composite statistic includes only the agency's systematic error variance, which depends upon agency actions; whereas $\hat{D}$, used separately, includes also the operator's systematic variance, with much of its background outside of full agency awareness. Secondly, the composite statistic is an unbiased estimate of diversion both as MUF and as concealed by intentional or nonintentional subtle biases (Hough, Sorenson, Stewart, Jaech, and Brouns, 1974).

3.2.2.3 Cumulative MUF for Increased Sensitivity in Detecting Loss

Cumulative MUF provides information over more than one accountability period. The pattern portrayed by cumulative MUF provides insights into the performance of the materials accounting system and is more sensitive in checking for a systematic loss of material than an individual MUF. The variance of a cumulative MUF must take into account the amounts successive MUF's together change (or covariances) when the inventories are not closed out (Stewart, 1970b). Comparing the cumulative MUF with the individual MUF is useful in detecting large individual or large cumulative systematic diversions (Stewart, 1970b; Bennett, 1973).

3.2.2.4 Timeliness of MUF

The effectiveness of MUF is reduced because of the time lapse between closings of the mass balance. The length of the accounting period, or frequency of inventory taking, is important in the promptness with which SNM loss can be detected, as shown in Table 3 (Schneider, 1973b). For example, if a 5 kg loss occurs in a 15-day accounting period, the observed MUF would exceed the critical region 99% of the time. Performance would be just about as good at 30 days. By contrast, if the diversion event of 5 kg occurs once during the year, the yearly observed MUF would exceed the critical region only 13% of the time.

TABLE 3. Effect of Inventory Frequency on Detecting a Loss Event and on Detecting a Rate of Loss in MUF

Physical Inventory Frequency, Days	Measurement Error, kg			Probability of Detecting a MUF Event of 5 kg ^(b)	Probability of Detecting a Rate of Loss in MUF of 2 kg/mo ^(c)
	Flow	Inventory	M.E. σ_{MUF} ^(a)		
15	0.5	1.0	1.12	99%	23%
30	0.9	1.0	1.34	98	44
60	1.7	1.0	1.97	81	65
90	2.6	1.0	2.78	63	69
180	5.0	1.0	5.1	25	76
one year	9.8	1.0	9.85	13	79

(a) Standard deviation of MUF due only to measurement error.

(b) Probability of observed MUF exceeding a critical region of 1.645 (M.E. σ_{MUF}) if a true MUF of 5 kg occurs during the accounting period.

(c) Probability of observed MUF exceeding a critical region of 1.645 (M.E. σ_{MUF}) if the true MUF is 2 kg/mo for every month of the accounting period.

Timeliness can be improved by limiting the mass balance to portions of a plant instead of taking the entire plant at once (Schneider, Stewart, et al., 1971). More frequent mass balance closings can be done for portions of the plant having relatively large SNM holdings.

3.3 APPLICATIONS AND EXAMPLES

Applications of safeguards techniques are summarized in these five subsections. Optimum reprocessing plant design, from a safeguards viewpoint, is suggested in these referenced studies. Pro formae are given specifying conditions to be met by operators of UO_2 and reprocessing facilities. Examples are given for verification and evaluation of mass balance accounting in principal portions of the fuel cycle. The Laboratory participated in a number of inspections and interpreted the results, both for flow-dominated and inventory-dominated operations. Examples of cost effectiveness of safeguards are given, followed finally by a brief consideration of assistance provided directly to the ERDA field office.

3.3.1 Determination of Design Criteria and Operator Specifications

The Laboratory identifies the following design criteria, important to safeguarding SNM, for fuels reprocessing:

- a. Equipment design incorporating adequate quality assurance features.
- b. Surveillance and accountability equipment allowing in situ maintenance.
- c. Records of equipment design, installation, testing and altering.
- d. Physical protection devices providing adequate barriers, communications access, isolation, lighting, and storage.
- e. Process vessels and lines allowing complete drainage and easy flushing.
- f. Accountability tanks permitting adequate measurement of SNM being out-loaded, with optimum means for sampling dense, radioactive liquid.
- g. Process cell liners permitting recovery and measurement of spilled SNM.
- h. Fuel storage permitting item counting.
- i. Office and laboratory facilities meeting inspection needs.

Many of the design requirements also have safety and financial accounting importance, relieving safeguards costs (Granquist, 1970 and 1973).

Materials accounting pro formae are given for (1) a 1000 ton/year UO_2 plant, 3% ^{235}U enrichment, and (2) a chemical reprocessing plant of similar size, according to titles in the "Proposed Guide for Preparation of Fundamental Material Controls and Nuclear Material Safeguards Procedures." The pro formae specify for the operator:

- a. Location of safeguards responsibility in his organization.
- b. His material balance areas.
- c. His measurement plan, including allowable error limits for individual assays and MUF.
- d. His procedures for material receipts, storage, transfer, inventories, records, and reports to the agency.
- e. His control limit of 5 to 15 kg ^{235}U for inventory periods of 1, 2, 3, 6, and 12 months.
- f. His physical security needs.

The Laboratory states baseline measurement accuracies and improved accuracies capable with the

best technology, about halving the errors under the baseline case (Wirfs, 1971a; Wirfs, Schneider and Granquist, 1971b).

3.3.2 Examples of Verification and Evaluation of Mass Balance Accounting

The following discussion of 1969 performance of mass balance accounting as a safeguards tool for UO₂ manufacture, chemical reprocessing, and Hanford plutonium processing considers both actual performance and capability assuming use of the best then-available technology (Wirfs, 1970a; Schneider and Granquist, 1970c; Wirfs, 1970b).

For UO₂ manufacturing, the absolute measurement uncertainty increases with throughput (see Table 4 for the plant characteristics); expressed as a percentage, it decreases with throughput because of balancing random measurement errors. Within the 95% confidence level, measurement uncertainty for all operations at a ton/day UO₂ plant is 1300 kg at the end of 3 months and 1800 kg at 12 months. Relative to plant throughput, the measurement uncertainty is 1.5% at 3 months and only 0.5% at 1 year. The operator has the capability of reducing the uncertainty threefold to fourfold, whether on the absolute or relative basis. Table 4 shows a similar case for ²³⁵U, but at much more sensitivity because of the more accurate ²³⁵U assays. For timespans longer than 6 months, measurement uncertainty results mainly from systematic laboratory errors reflected in the calculated quantities of material transferred. Random errors contribute to measurement uncertainty for short time periods. They are minimized by placing material in preferred forms and locations, carefully controlling scrap accumulation and measurement, and by adequately utilizing trained personnel and standard procedures.

TABLE 4. Material Balance Measurement Uncertainties
in UO₂ Manufacturing^(a)

Per- form- ance mo	Uranium ^(b)			²³⁵ U		
	Conversion kg/%	Fabrication kg/%	Integrated ^(c) kg/	Conversion kg/%	Fabrication kg/%	Integrated ^(c) kg/%
3	610/0.7	1100/1.4	1300/1.5	28/1.1	45/1.9	48/2.0
6	820/.5	1300/.8	1400/.8	41/.8	58/1.2	57/1.2
12	1400/.4	1800/.6	1800/.5	72/.7	91/0.9	82/.8
Capa- bility mo						
3	120/.1	290/.4	320/.4	7/.3	13/.5	13/.5
6	210/.1	360/.2	360/.2	13/.3	19/.4	17/.3
12	420/.1	570/.2	510/.2	25/.3	34/.3	27/.3

(a) Wirfs, 1970a, Table 1 and 2

(b) One ton/day; 3% enrichment

(c) Integrated combines conversion and fabrication.

The ton/day UO₂ plant's performance shows a 20% probability of detecting a diversion of 500 kg of uranium under a 3-month material balance span and the capability of increasing the probability to 95%. For a 1-year timespan, the same detection probabilities are less sensitive, going down only to 800 kg. Similar patterns apply to ²³⁵U as shown in Table 5, again with much more sensitivity. The probability estimates assume the operator tolerates

a 5% false alarm rate; in other words, a willingness to have a measurement error regarded as diversion for about one alarm in 20. Sensitivity for detecting diversion is increased by tolerating a higher false alarm rate.

TABLE 5. Probability of Detecting Diversion
in UO₂ Manufacturing^(a)

Amount of Diversion kg	Performance			Capability		
	Conversion Probability, %	Fabrication Probability, %	Integrated	Conversion Probability, %	Fabrication Probability, %	Integrated
3 months' Material Balance Span						
Uranium						
500	50	22	20	100	96	94
800	86	42	37	100	100	100
1300	99	74	68	100	100	100
2000	100	96	94	100	100	100
2700	100	100	100	100	100	100
²³⁵ U						
15	29	17	17	100	74	75
25	57	31	29	100	98	99
40	88	56	52	100	100	100
60	100	84	81	100	100	100
80	100	97	96	100	100	100
12 Months' Material Balance Span						
Uranium						
500	18	14	15	78	56	62
800	34	23	24	99	89	94
1300	62	43	46	100	100	100
2000	91	71	74	100	100	100
2700	99	91	92	100	100	100
²³⁵ U						
15	11	10	10	34	23	30
25	17	15	15	66	44	58
40	30	23	26	95	78	90
60	41	39	43	100	98	100
80	71	57	62	100	100	100

Assumptions: Those of Table 4 and a False Alarm Rate of 5%.

^(a)Wirfs, 1970a, Table 4 and 5.

A series of small ²³⁵U withdrawals over a 3-month period could total as much as 5 kg and very likely go undetected even under the capability mode. Similar performance information is given in the reference for chemical processing and Pu handling. For a reprocessing plant handling 40 tons of low-enriched uranium containing 400 kg Pu on a campaign basis, losses exceeding 0.6 ton U or 6 kg Pu are detectable 80% of the time at a 5% false alarm rate. Under the capability mode, alarms can be triggered at half such losses. Again, systematic error limits further reduction in long-term MUF variance (Schneider and Granquist, 1970c; Schneider, 1970g).

In processing 0.6 ton of Pu at Hanford, losses exceeding 6 kg Pu are detectable 80% of the time at a 5% false alarm rate. Under the capability mode, alarms can be triggered at a loss of 2 kg Pu, even with a batch size up to 100 kg, again allowing a 5% false alarm rate. As in UO₂ manufacture and fuel reprocessing, systematic errors prohibit any further reduction in MUF variance (Wirfs, 1970b).

3.3.3 Evaluation of Inspection

The Laboratory evaluated FY-1968 resident inspections and interpreted a 1975 verification of Hanford Pu inventory. The evaluation of resident inspection takes into account the NFS chemical processing operation (West Valley, N. Y.) and four convertor-fabricators (Hematite, Mo.; Erwin, Tenn.; Apollo and Leechburg, Penna.). The inspection was done on three bases:

- (a) Isolated operator - agency verified or measured all data for a material balance
- (b) Operator included in a safeguards system - agency accepted some measurements from other operators
- (c) Operator in safeguards system
 - independent measurements obtained to detect diversion by mass balance accounting
 - inspection made sufficient to assure operator's compliance with safeguards standards.

An independent material balance around an operator is effective enough to detect diversion of 1% to 2% of plant throughput. The inspection team had to validate four parts of the material balance area (MBA): input, output, inventory, and discard. When an operator is part of a safeguards system, the agency may rely on shipper measurements, allowing less effort on input data and more on inventory. Intensity of effort depends directly upon the number of SGQ's present. The team regarded in-line instrumentation available at the time and in the foreseeable future as insufficiently reliable and accurate for safeguards (Schneider, Granquist and Stewart, 1969).

Interpretation of Hanford data, on the other hand, shows the neutron well-coincidence counter (NWCC) and the gross neutron counter (GNC) to be "very satisfactory" attribute testers for verifying Pu inventories. Errors of 4% to 3% at 1 σ are reported, with analysis times of 60 and 30 seconds, respectively. Much more time was spent moving samples back and forth. The identification frequency of potential defects is 1 to 2/100 items verified. Radiation exposure to agency and operator personnel is potentially serious. The use of GNC verification carried out under elements of the crossover sampling plan led to the discovery of erroneous ^{240}Pu concentrations as recorded by the operator. Handling the several thousand data suggests the need for a real-time automated data system such as the addition of a minicomputer and tape cassette to the LASL GNC system used (Stewart, Schneider, Sorenson and Walker, 1975b).

3.3.4 Cost Effectiveness

Annual required manpower and costs (1967 dollars) for the three types of inspections of the five operators listed in Section 3.3.3 are: (a) 104 (\$2.8 million), (b) 56 (\$1.7 million), and (c) 37 (\$1.1 million). The figures include efforts at agency headquarters, the central (New Brunswick) laboratory, and the five sites. For independent surveillance at all U.S. operations, projected manpower and costs (1970 dollars) are: 1970 - 192 (\$10.1 million) and 1974 - 378 (\$20.6 million) (Schneider, Granquist and Stewart, 1969).

Reliability of the verification and sampling plans is discussed from a cost minimization standpoint (Stewart, 1970e). Costs are minimized by choosing a number of measurements proportional to σ and inversely proportional to the square root of unit cost (Stewart, 1970b). The cost of verification depends upon its frequency, the number of independent locations, and the operator strategy to be overcome. Table 6 shows five operator strategies in the order of advancing complexity and costs. Agency costs under Strategy 3 are ten times those for Strategy 1, utilizing a balance between the tendency for more measurements and the prudent use of operator information (Schneider and Sorenson, 1974). General comments about costs appear elsewhere whenever they seemed necessary with the discussion at hand (Sections 3.1.1, 3.1.3, 3.2.1.1, 3.2.1.3, 3.2.1.3.1, 3.2.1.3.2, 3.2.1.4, and 3.3.1).

TABLE 6. Operator and Agency Strategies

Action on Item	Operator Strategy	Federal Agency Strategy	
	Action on Container	Verification	Frequency
1. Remove	No Replacement	Item Check	100%
2. Remove	Replace with Empty	Weight Check GO/NO-GO Attribute Test	Attribute Plan, 100% with Probe
3. Remove	Replace with Non-SNM Material	GO/NO-GO Attribute Test	Attribute Plan, 100% with Probe
4. Partial Removal (>20%)	Replace with Non-SNM Material	Variables Instrument	Attribute Plan
5. Shaving Item, Both All and Some (<20%)	No Replacement	Weight Check	Attribute Plan
	Replace with Non-SNM Material	Lacking IGA Instruments	Variable Plan; Ultimately, Mixed Plan

3.3.5 Field Office Assistance

The Laboratory provides specific guidance in response to field office requests. A Hanford description for use in verification emphasizes the SNM processing done by the four operators, United Nuclear Industries, Inc., Atlantic Richfield Hanford Company, Hanford Engineering Development Laboratory, and Pacific Northwest Laboratory (Sorenson, 1973c; Schneider and Sorenson, 1974). The Laboratory aided in performing Hanford experiments based upon plans in the latter reference and scoped automated data handling for inventory verification and promptly assessing Hanford's SNM inventory (Sorenson and Kaye, 1974; Sorenson and Walker, September 1974).

3.4 EVALUATION OF DOCUMENTS

The Laboratory evaluated a number of reports and documents published throughout the period. Some were reported formally (Wirfs, 1969; Bennett and Hough, 1969), some in informal letter reports, and some reported orally.

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5. GLOSSARY

Agency - the outsider imposing operating conditions and verifying an operator's materials accounting (MA).

Attribute - an SNM property characterizing an item either satisfactory or not satisfactory (see Variable).

Book Inventory - the estimate of the material which should be on hand.

$\hat{D}$ - an estimate of the difference between the stated MUF and true MUF based on inspection and agency paired-comparison measurements over all the strata in MUF.

Ending (physical) Inventory - the measured inventory at the end of an accountability period, i.e., an estimate of the amount of material on hand.

Inspection - the activities of the agency to test and evaluate the capability and performance of the operator and to obtain independent assurance of material control and operator credibility.

LEMUF - limit of error of MUF.

MA - materials accounting.

MBA - material balance area.

Material Unaccounted For (MUF) - the estimate of material unaccounted for based on the difference between the book inventory (the amount of material that should be on hand) and the ending inventory (the amount of material estimated to be on hand).

Operator - a contractor, or licensee holding a strategic amount of SNM.

Primary Verification Point - a stage in an operator's process, or portion of the fuel cycle, where falsification represents permanent defeat; that is a stage without redundancy (SNM input to the operator, SNM discard, SNM shipments).

Pu - plutonium.

Reliance - the extent to which the agency depends upon a verification procedure in making tests of significant standard deviation.

σ - standard deviation = $\sqrt{\frac{\sum^N (y_i - \bar{y})^2}{N}}$, N is the population size; $\bar{y}$, the population average.

standard deviation estimate = $\sqrt{\frac{\sum^n (y_i - \bar{y})^2}{n - 1}}$, n is the random sample size; $\bar{y}$, the average.

Substantial Goal Quantity (SGQ) - the quantity of SNM that the sampling plan is designed to detect with high probability.

Technical Reliability - the exactness of a method for measuring material quantities or composition.

^{235}D - weight % ^{235}U before irradiation minus weight % ^{235}U after irradiation.

Validity of Verification - the degree to which a verification procedure truly affirms the integrity and quality of MA data.

Variable - an SNM property characterizing an item on a continuous scale; for example, the weight of a package in ounces (see Attribute).

Variance - σ^2

Verification - establishing the truth by cross-checking of records, physical scrutiny, counting, checking, sampling, and measurement (IAEA); a major activity of inspection.

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